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Effect of Mineral Filler Type and Particle Size on the Engineering Properties of Stone Mastic Asphalt Pavements

R Muniandy*, E Aburkaba and R Taha

Department of Civil Engineering, Faculty of Engineering, Univerity Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia

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Abstract: This study examines four types of industrial and by-product waste fillers, namely limestone dust (LSD), which was the reference filler; ceramic waste dust (CWD); coal fly ash (CFA), and steel slag mixture (SSD). The filler consisted of an aggregate (10% of total weight) with three proportions: 100% passing 75µm, 50% passing 75µm/20µm, and 100% passing 20µm. Comprehensive laboratory tests were performed to determine the impact of different types and particle sizes of fillers on the engineering and mechanical properties of fine mastics and stone mastic asphalt mixture. The results indicate that the application of industrial by-products used as fillers improves the engineering properties of stone mastic asphalt mixtures. The increased stiffness due to the addition of the filler is represented by an increase in the softening point, viscosity, stability, and resilient modulus, as well as a decrease in penetration. The optimum asphalt content increased with the decrease in filler particle size for LSD and SSD, and decreased for CWD and CFA. It was also determined that the filler type and particle size has a significant effect on the mixture properties. Among these three proportions, the samples prepared with the filler size proportion of 50/50 gave the best value in terms of stability, Marshall quotient, and resilient modulus than the other filler size proportions.

Keywords: Mineral fillers, Particle size, Stone mastic asphalt, Engineering properties

تأثير نوع وحجم الحشوات على الخواص الهندسية لأرصفة الأسفلت

ر. مونياند و الطاهر ابوركابا* و رمزي طه

الملخص: هذه الدراسة تفحص أربعة أنواع من الحشوات هي: الحجر الجيري(ويؤخذ كمرجع)، ومخلفات الخزف، ورماد الفحم الحجري، و مخلفات الحديد. تمثل الحشوات ١٠٪ من الوزن الكلي للمواد المكونة للأسفلت. درست ثلاثة أحجام من كل حشوة وهي: 100% أقل من 75 مايكروميتر ، 50% أقل من 20 مايكروميتر / 75 مايكروميتر ,100% أقل من 20 مايكروميتر . أجريت تجارب معملية شاملة لدراسة تأثير نوع وحجم كل حشوة على الخواص الهندسية لأرصفة الأسفلت. أثبتت الدراسة أن الحشوات حسنت الخواص الهندسية لأرصفة الأسفلت. الزيادة في الصلابة الناتجة في الحشوات أدت إلى زيادة نقطة الطراوة و اللزوجة والإستقرار ومعامل المرونة ونقصان الإختراق. زادت النسبة المثالية للأسفلت مع نقصان حجم حشوات الحجر الجيري ومخلفات الحديد لكنها نقصت مع نقصان حجم حشوات مخلفات الخزف ورماد الفحم الحجري. أكدت الدراسة أيضا التأثير الكبير لنوع وحجم الحشوات على خواص الخليط ومن الأحجام الثلاثة التي تمت دراستها كان الحجم ٥٠/٥٠ هو الأفضل من ناحية الاستقرار، معامل مارشال ومعامل المرونة.

المفردات المفتاحية: حشوات معدنية، حجم الحبيبات، أرصفة الأسفلت، الخواص الهندسية

*Corresponding author's e-mail:ratnas@eng.upm.com.my

1. Introduction

The continuing rapid growth in traffic demand, along with the increase in allowable axle loads, necessitates the improvement of the highway paving materials. The goal of highway authorities is to provide safe, economical, durable, and smooth pavements that are capable of carrying the anticipated loads. To achieve this goal, many experts, engineers, and researchers are eager and devoted to selecting paving materials that can minimize pavement distresses and improve the performance of asphalt pavements. Filler, as one of the components in an asphalt mixture, plays a major role in determining the properties and behavior of the mixture, especially its binding and aggregate interlocking effects.

Mineral fillers serve a dual purpose when added to asphalt mixtures. The proportion of mineral filler that is finer than the thickness of the asphalt film blends with asphalt cement binder to form a mortar or mastic that contributes to improved stiffening of the mix. Particles larger than the thickness of the asphalt film behave as mineral aggregate and hence contribute to the contact points between individual aggregate particles (Puzinauskas 1969).

Furthermore, they affect the workability, moisture sensitivity, stiffness and ageing characteristics of hot mix asphalt (HMA) (Mogawer *et al*. 1996). Also, fillers vary in gradation, particle shape, surface area, void content, mineral composition, and physico-chemical properties and, therefore, their influence on the properties of HMA mixtures also varies. The maximum allowable amount should be different for various types of filler.

The filler also influences the optimum asphalt content (OAC) in bituminous mixtures by increasing the surface area of mineral particles and, simultaneously, the surface properties of the filler particles modify significantly the rheological properties of asphalt such as penetration, ductility, and also those of the mixture, such as resistance to rutting. In order to improve the pavement performance, it is necessary to ensure that adequate behavior of the bituminous mixtures is achieved, which depends essentially on their composition. Therefore, selecting the proper type of filler in asphalt mixtures would improve the filler's properties and, thus, enhance the mixture's performance (Kandhal 1981).

1.1 Literature Review

Neubauer and Partl (2004) investigated the behavior of stone matrix asphalt (SMA) 11 and SMA 16 with different filler/binder proportion in order to find out whether Marshall and Gyratory methods provide the same optimum binder content. They found out that none of the optimum binder content values determined by the Marshall and the Gyratory compactor method were identical for any of the filler/binder proportions used. The optimum binder contents determined using the Marshall compactor were distinctly higher than those using the Gyratory compactor.

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 dust (LSD) fillers. Another conclusion was that even if the fillers stiffened the binders, they acted in such a way that they provided better resistance to micro cracking and, thus, increased fatigue life. Ramzi Taha *et al*. (2002) investigated the use of cement bypass dust (CBPD) as filler in asphalt concrete mixtures. Results indicated that the substitution of 5% CBPD for lime would essentially produce the same optimum asphalt binder content as the control mixture (4.5% by weight of aggregate) without any negative effect on the asphalt's concrete properties (stability, flow, and voids in total mix, mineral aggregate, and those filled with asphalt).

Kandhal and Parker (1998) stated that the influence that mineral filler can have on the performance of HMA mixtures depended on the particle size, fines can act as a filler or an extender of asphalt cement binder. In the latter case, an over-rich HMA mix can lead to flushing and rutting. In many cases, the amount of asphalt cement used must be reduced to prevent a loss of stability or pavement bleeding. Some fines have a considerable effect on the asphalt cement, making it act as a much stiffer grade of asphalt cement as compared with the neat asphalt cement grade and, thus, affecting the HMA pavement performance, including its fracture behavior.

Harris and Stuart (1998) studied the effects of fillers in SMA mixtures and argued that the gap graded nature of SMA means that coarse aggregate particles dominate the aggregate skeleton. In that case, all of the filler contributed to the mastic formed.

Tayebali *et al.* (1998) investigated the possibility of increasing the amount of fines in asphalt mixtures based on a washed sieve analysis, from a maximum of about 8% as currently specified, without adversely affecting the performance of the mixture. At the same time, it was also desirable to investigate the influence of the mineral filler type (crushed versus natural river sands, or combinations thereof) on asphalt (Marshall) mix design and on the shear permanent deformation performance. They found out that by increasing the amount of mineral filler, the Marshall stability and unit weight increased. This procedure led to a higher shear resilient modulus due to increased unit weight without adversely affecting its rutting during the repeated shear testing.

Previous research by Superior Performing Asphalt Pavements (Superpave) Mix Design (1996) showed that the addition of mineral fillers such as LSD to asphalt could improve the rutting resistance performance of asphalt. The mineral powder improved the high-temperature thermal properties, presumably because of its small particle size which resulted in a large area of interface between mineral powder and asphalt.

Ali *et al*. (1996) investigated the fly effects of fly ash on the material and mechanical properties of asphalt mixtures; results from this study indicated that fly ash can be used as a mineral filler to improve resilient modulus characteristics and stripping resistance.

Ishai *et al*. (1980) proposed that different fillers have different effects on the same bitumen and these are attributable to the surface activity of the fillers. The study was limited in regard to the range of fillers studied, but found that hydrated lime had both the highest geometrical irregularity and surface activity. These observations were based on hygroscopic measurements. Similarly, (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 its fineness and the surface affinity to bitumen.

Ward and McGougal (1979) study bag house fillers from 16 different sources with a wide variety of particle size distribution, mineralogy, and other physical properties. He indicated that fine dust, primarily that 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 through no. 200 sieves). They concluded that both the size of the filler and bitumen binder composition had a significant influence on the 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.

Kallas and Puzinauskas (1967) believed that filler performed a dual role in asphalt-aggregate mixtures. A portion of the filler with particles larger than the asphalt film will contribute in producing the contact points between aggregate particles, while the remaining filler is in colloidal suspension in the asphalt binder, resulting in a binder with a stiffer consistency. They also found that the stabilities of asphalt mixtures increased up to a certain filler concentration, then decrease with additional filler.

Since the effect of mineral fillers is more prominent in gap graded asphalt mixtures such as the SMA mixture that contains large amounts of fines, it is important to understand the changes that occur in the properties of the binder due to the fines. The primary objective of this study was to determine the impact of different types and particle size of fillers on the engineering and mechanical properties of fine mastics and stone mastic asphalt mixture. Four different types of fillers, namely LSD used as reference filler, ceramic waste (CWD), coal fly ash (CFA), and SSD with three proportions of particles containing different size distributions were graded and used in this study. One set of the proportion had a distribution of 100% passing the 75 micron (µm) sieve. The second set had a 50% passing rate, the 75 µm displayed 50% passing the 20 µm, and the third displayed 100% passing the 20 µm sieve.

This paper presents a laboratory investigation into the effects of filler particle size and different fillers on some laboratory-measured properties of asphalt mastics and SMA mixtures.

2. Investigation Program

This investigative study had four phases: Phase 1- Material properties; Phase 2- Fine mastics (filler + asphalt binder) testing; Phase 3-Mix design for the four fillers with three proportions of filler particle size and the determination of the volumetric and mechanical properties of the SMA mixtures; and Phase 4- Evaluation of mixtures.

In Phase 1, the material properties of the aggregate, asphalt, cellulose palm oil fiber, and fillers were determined. In Phase 2, mastics were tested for their physical properties such as viscosity, softening point, and penetration, and they were compared with the neat asphalt. In Phase 3, the OAC for the twelve mix designs were determined using the Marshall Mix Design Method American Standard Testing Method (ASTM) D1559. In Phase 4, the optimized mixtures were evaluated by several tests include Marshall stability and flow, Marshall quotient, and the resilient modulus test. The mastics and mixtures testing program is presented in Table 1.

3. Material Properties

3.1 Aggregate

The coarse and fine aggregates used were crushed granite rock from the Kajang Rock Quarry in Malaysia. Granite aggregates with a nominal maximum size of 12.5 mm and gradation as specified by the 1994 National Asphalt Pavement Association (NAPA) was used in this study. The laboratory tests performed to evaluate the properties of fine and coarse aggregates were the Los Angeles abrasion test, the measurement

Table 1. Asphalt-filler mastic and SMA mixture testing program

Mastic/Mixture Characteristic	Measured Response	Number of samples
Traditional rheological property	Penetration at 25°C	12 mastics + 1 neat asphalt
	Softening point	12 mastics + 1 neat asphalt
	Viscosity, at 135°C and165°C	12 mastics + 1 neat asphalt
	Specific gravity at 25°C	1 neat asphalt
Volumetric properties	Marshall Stability and Flow	12 mix design x 15 specimens = 180
	Theoretical maximum density (loose sample)	1 sample x 5 asphalt content x 12 mix design = 60
Load spreading ability	Resilient Modulus	12 mix design x 15 specimens = 180

12 Mix design = 4 types of filler x 3 filler particle size proportions
15 specimens = 5 asphalt content x 3 specimens each
The same no. of sample were used for resilient modulus and Marshall stability since the resilient modulus test is a non-destructive test.

Table 2. Aggregate physical propertis test results

Test	Standard used	Results
Los Angeles abrasion (%)	ASTM C 131	22.3
Aggregate impact value (%)	BS 812: Part 3	7.84
Flakiness index (%)	ASTM D 4791, BS 812	14.89
Elongation index (%)	ASTM D 4791, BS 812	1.55
Coarse aggregate angularity	Superpave Mix Design	
One or more fractured face (%)	ASTM D5821	97
Two or more fractured face (%)		93
Fine aggregate angularity, air voids % (loose)	Superpave Mix Design ASTM C1252	53
Water absorption (%)	AASHTO T 85	0.5
Specific gravity of coarse aggregate	ASTM C 127	2.63
Specific gravity of fine aggregate	ASTM C 128	2.58

Table 3. Aggregate particle size distribution

Sieve size (mm)	19.00	12.5	9.50	4.75	2.36	0.60	0.30	0.075
% passing	100	85-95	Max. 75	20-28	16-24	12-16	12-15	8-10
% used	100	90	70	24	20	14	13	10

of aggregate impact value, the evaluation of the flakiness and elongation index, a test of fine and coarse angularity, measurements of specific gravity and particle size distribution, and an assessment of the percentage of absorption. The results are shown in Tables 2 and 3. The aggregate particle size distribution is shown in Fig. 1.

3.2 Asphalt Binder

The traditional 80/100 penetration asphalt binder obtained from Petronas Malaysia was used for this study. The laboratory tests performed to evaluate the asphalt properties were those of penetration, softening point, viscosity, and specific gravity tests. The results are presented in Table 4.

3.3 Cellulose Palm oil Fiber

3.3.1 Particle Size Distribution

Cellulose oil palm fiber (COPF) is used in SMA as a stabilizer to prevent drain-down of the asphalt binder during construction. The COPF (Eco-fiber Technology SDN BHD, Kuala Lumpur, Malaysia) used in this study was provided in loose form. The results of particle size distribution of the COPF are given in Table 5 and shown in Fig. 2.

3.3.2 Oil Drain-Down Properties of Meshed Fiber

The oil-retaining ability of the COPF was determined using Dr. Scallenburg's in-house motor oil test. The COPF fiber was stirred at 1000 rpm in 160°C oil and placed on a 500 micron (µm) sieve. After 5 minutes, the mass of oil running through the sieve was

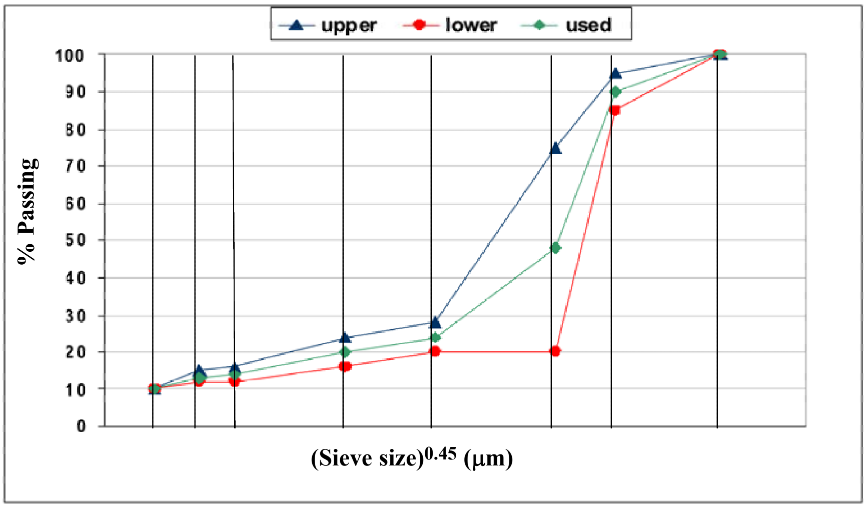

Figure 1. Aggregate particle size distribution

Table 4. Asphalt binder physical properties test results

Test	Measured Value	Standard used
Penetration (0.1 mm), 100g, 5s, 25°C	84	ASTM D 5-86
Softening point (°C)	48	ASTM D 36
Viscosity, (Pa.s) at		ASTM D 2171
135°C	0.413	
165°C	0.100	
Specific gravity at 25°C	1.0295	ASTM D 70

Table 5. Particle size distribution of cellulose oil palm fiber

Sieve size (μm)	500	400	250	160	125	pan	sum
Weight of fiber retained (g)	3.30	4.92	3.59	4.88	2.51	10.80	30.00
Weight of fiber passing (g)	26.70	21.78	18.19	13.31	10.80	0.00	
Percent of fiber passing	89.00	72.60	60.63	44.37	36.00	0.00	

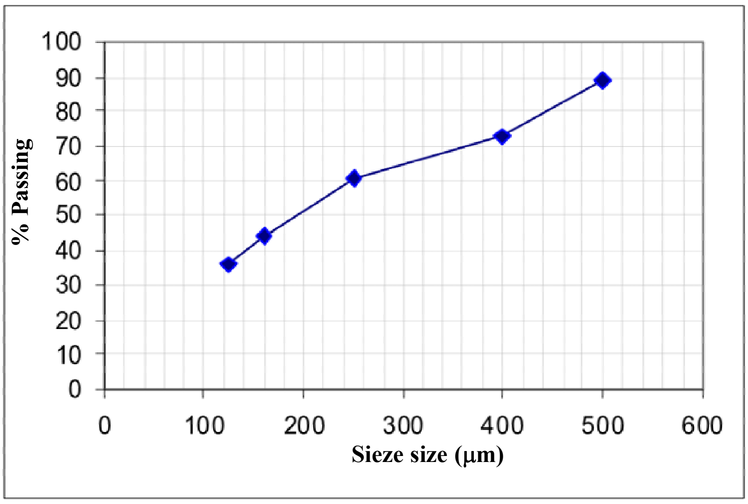

Figure 2. Particle size distribution of cellulose oil palm fiber

measured. Table 6 shows the results of the oil-retaining properties of COPF and the oil drain-down was recorded against time as shown in Table 7 and Fig. 3. The weight drained out of the COPF was about 96.5 grams. The maximum allowable value for any suitable fiber is 180.0 gram. As seen in Fig. 3, the COPF fiber settled within 60 seconds and the drain-down shows a similar trend as the graph becomes horizontal without any considerable changes.

Table 6. Results of oil retaining of COPF

Specimen	Cellulose oil palm Fiber
Weight of pan (g)	264.6
Weight of pan + Drained motor oil (g)	361.1
Weight of motor oil (g)	96.5

Table 7. Oil drain-down test result

Time (sec)	0	30	60	90	120	150	180	210	230	270	300
Weight of drained oil (g)	0	66.6	70.8	71.1	71.1	71.4	71.7	71.8	71.8	71.8	71.9

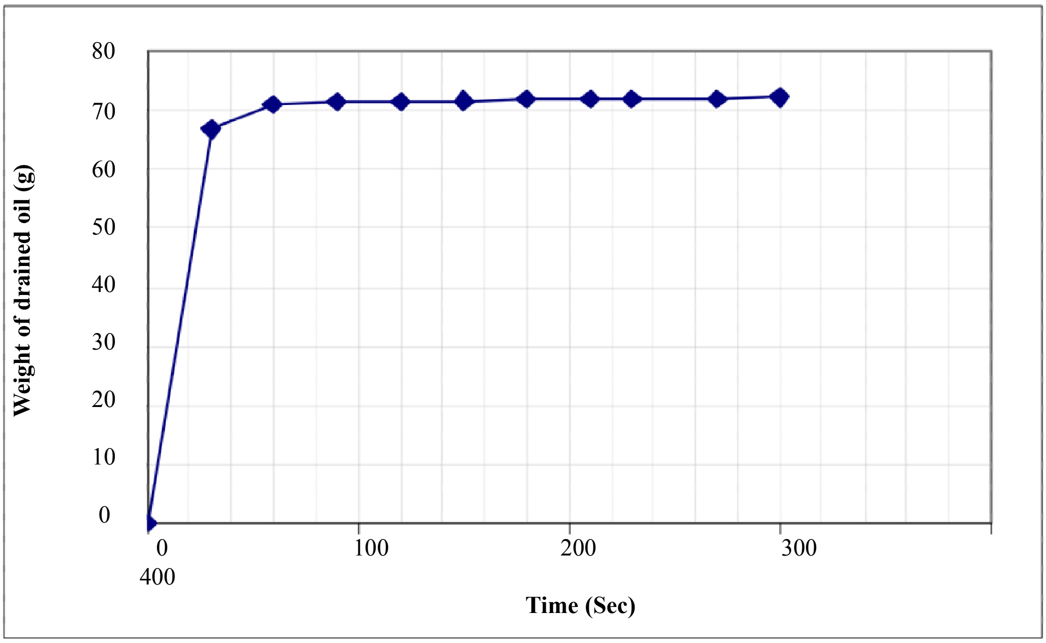

Figure 3. Weight of drain-down oil vs time

3.4 Mineral Fillers

Four filler types, namely LSD, CWD, CFA, and SSD with different particle sizes (passing 75 µm and 20 µm) with three proportions of filler 100/0, 50/50, and 0/100 were evaluated by direct comparison in this study. Fillers were crushed and ground to pass through standard sieve sizes of 0.075 mm and 0.02 mm.

3.4.1 Limestone Dust (LSD)

Limestone is widely used as crushed stone or aggregate for general building purposes, roadbeds, and railway lines. Finely crushed limestone is also used as filler in industrial products such as asphalt, rubber, plastic, and fertilizers. In this study, the LSD filler was obtained from the cement and steel (CSI) industry. A sample was collected from the supplier and was quartered into smaller representative portions for sieve analysis, and physical and chemical tests.

3.4.2 Ceramic Waste (CWD)

It has been estimated that about 30% of the daily production in the ceramic industry goes to waste; however, CWD is durable, hard, and highly resistant to biological, chemical, and physical degradation forces. The CWD used in this study was obtained from Seacera Tiles Berhad in Selangor, Malaysia.

3.4.3 Coal Fly Ash (CFA)

The CFA used in this study was obtained from the Manjung Coal-Fired Power Plant in Lumut, Perak, Malaysia. The plant uses low-sulphur and low-bitumen coal which is pulverized for burning in order to minimize pollution. The resulting ash is valuable to the cement industry and most is caught by electrostatic precipitators. The unique spherical shape and particle size distribution of CFA makes it good mineral filler in HMA applications and improves the fluidity of flowable fill and grout. The abundance of CFA in many areas presents unique opportunities for its use in structural fills and other highway applications.

3.4.4 Steel Slag Dust (SSD)

Iron ore, coke, and limestone are superheated in a

Table 8. Mineral filler particle size distribution

Sieve (mm)	% Passing Coal Fly Ash (CFA)	% Passing Lime Stone (LSD)	% Passing Ceramic Waste Dust (CWD)	% Passing Steel Slag Dust (SSD)
0.600	100	100	100	100
0.300	99.53	95.80	92.46	89.23
0.075	92.20	84.56	76.86	71.54
0.053	74.85	68.63	59.79	54.46
0.020	6.70	6.74	4.92	3.82
pan	0	0	0	0

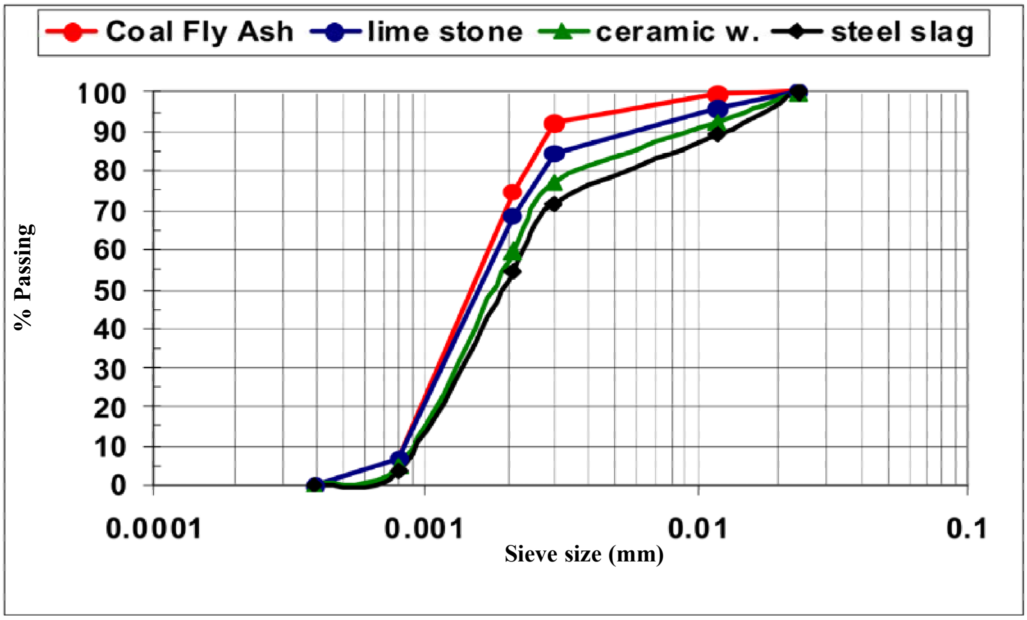

Figure 4. Mineral fillers particle size distribution

blast furnace to produce pig iron. A waste product of this procedure is blast-furnace slag, which essentially consists mainly of silicates and alumino-silicates of lime. The SSD used in this study was obtained from Perwaja Steel Berhad in Kemaman Terengganu, Malaysia.

3.5. Microstructure Investigation

Experiments were conducted at the laboratories of the Department of Civil Engineering at the University Putra Malaysia (UPM) in Serdang, Malaysia. Sieve analysis was carried out on representative CFA, CWD, and SSD samples, along with LSD. A dry sieve analysis was carried out according to American Standard Testing Methods (ASTM) D546 and American Association American Association of State Highway and Transportation Officials (AASHTO) T37 as shown in Table 8 and Fig. 4, respectively.

Standard methods were used to determine the physical and chemical characteristics of the industrial and by-product waste samples. The key physical characteristics of the mineral fillers included gradation, specific gravity, methylene blue, moisture content, solubility, pH value, plasticity index, surface area, and grain size. Particle shape fineness was also measured by calculating the percentage retained on a no. 325 sieve (45 microns). The results are displayed in Table 9. Test results indicate that SSD exhibits higher specific gravity, lower solubility, and a lower methylene blue, or harmful clay content value, than that found in the reference filler. A scanning electronic microscope (SEM) was used to inspect and observe the microstructure and geometric characteristics of the filler particles. Figures 5-8 show the geometric irregularity in surface texture and the non-spherical shape of LSD, CWD, and SSD particles (CFA particles have a spherical shape). An analysis indicated that the SSD filler particles have an angular shape and rough surface, which provides high internal friction and a good interlocking mechanism which makes an excellent bond with asphalt binder.

The chemical compositions of all four types of filler were analyzed quantitatively by using an energy dispersive analysis X-ray (EDX). The data in Table 10 and Figs. 9-12 show that oxides in the selected fillers consisted of SiO_2, Al_2O_3, CaO, and MgO. The sum total of SiO_2, $Al2O_3$, and Fe for all types of filler except the LSD filler were higher than that of the ASTM C618 class N minimum requirement of 70%

Table 9. Physical analysis of mineral fillers

Material Properties	Results			
	LSD	CWD	CFA	SSD
Moisture content, %	0.06	0.41	0.13	0.02
Specific gravity	2.55	2.39	2.63	3.40
Fineness %	15.93	17.07	17.35	17.08
Grain size (micron)	17.58	27.35	1.731 – 2.736	516.4
Surface area, μm^2	242.9	587.7	2.352	238434
Particle shape	flaky	flaky	spherical	irregular
% Insoluble	99.80	99.69	99.15	99.94
% Soluble	0.20	0.30	0.85	0.06
Methylene blue	1.2	1.8	0.90	0.30
pH – value @ 27ºC	9.82	9.26	10.86	9.25
Plasticity index	NP	NP	NP	NP

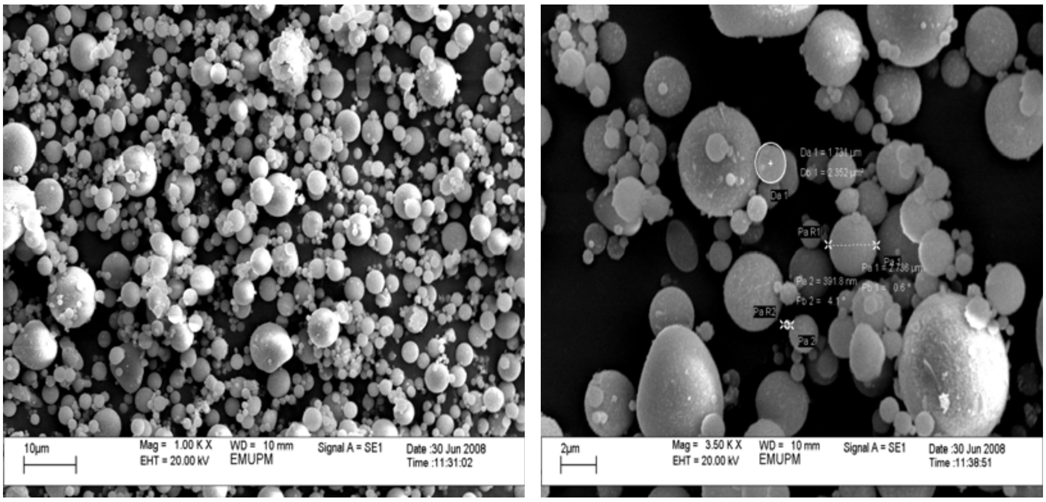

Figure 5. Fly ash particles at 1,000 x and at 3,500 x magnification

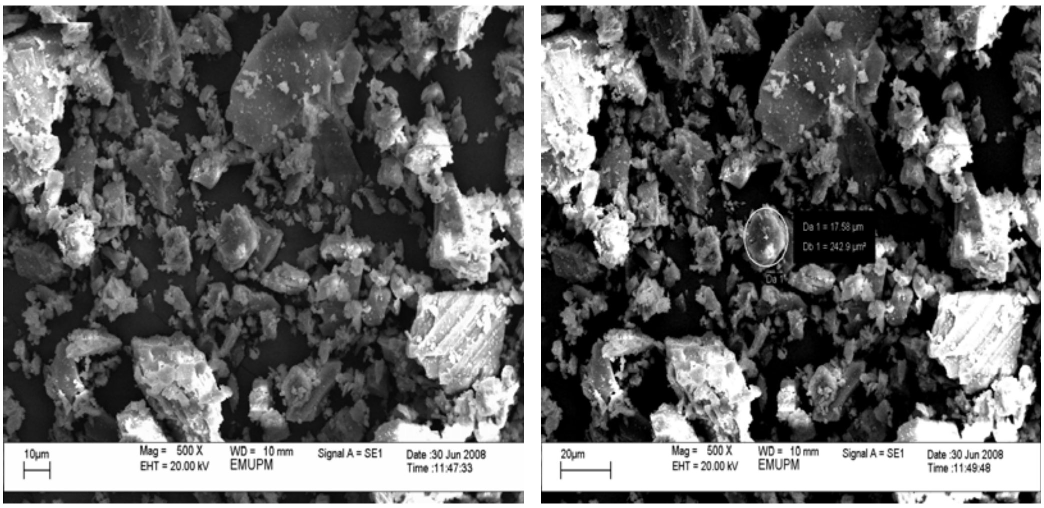

Figure 6. Grain size and particle shape of limestone dust at 500 x magnification

for CFA and raw or calcined natural pozzolan for use as a mineral admixture in concrete. Also, the high CaO content, which displays a greater affinity for oil than for water, can improve the adhesion between the particle and asphalt binder.

4. Mastics Properties

4.1 Filler Proportion

The mastic (asphalt binder and filler) affects the properties of the mix. Excessive filler dries out the

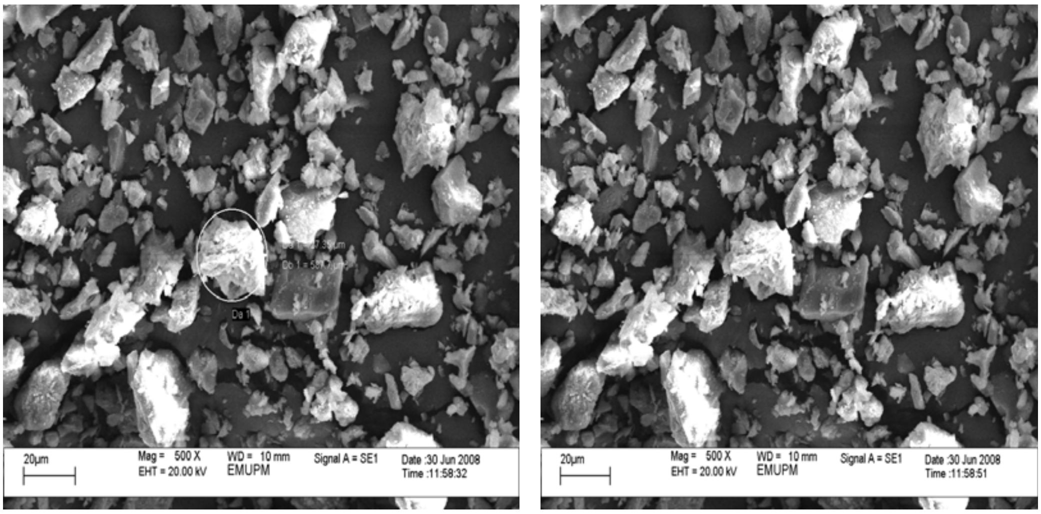

Figure 7. Grain size and particle shape of ceramic waste dust at 500 x magnification

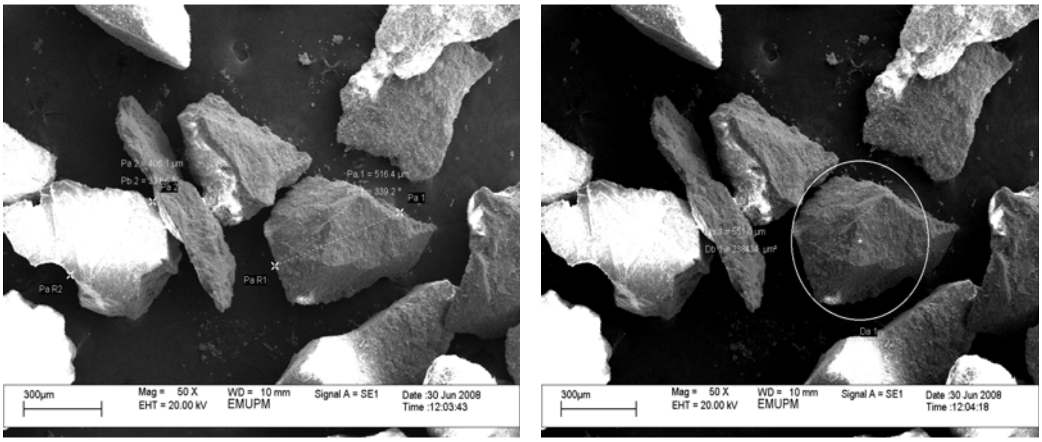

Figure 8. Grain size and particle shape of steel slag at 50 x magnification

mix, reducing asphalt film thickness and durability, while insufficient filler may allow excessive asphalt films, which may result in tender, unstable mixes. The filler proportion is computed as the ratio of the percentage by the weight of the aggregate finer than the no. 200 sieve to the calculated Marshall OAC for conventional mixtures as given in (1),

$$(\text{Filler}/\text{Asphalt})\,\text{ratio} = F/A = \frac{P_{200}}{P_b} \tag{1}$$

where P_{200} = the aggregate content passing through the no. 200 sieve, and measured in percentage of the weight of the aggregate, and P_b = the OAC.

4.2 Preparation of Filler-Asphalt Mastics

The twelve mastics were prepared by blending each mineral filler with the asphalt using the filler-to-asphalt ratio by weight at the OAC for each mixture. The proportions of the filler to the neat asphalt mastic and the mastics properties are presented in Table 11. A RW 20 DZM.N mechanical mixer module (IKA-Werke GmbH & Co. KG, Staufen, Germany) was used to blend the filler and asphalt binder at mixing temperatures of 160°C. The appropriate mixing temperatures were determined following AASHTO T316 using the rotational viscometer. The mixing process was carefully performed to break down chunks of filler and to improve homogenous dispersion. An X-shaped propeller was used to stir the filler-asphalt mastic and the mixing temperature was kept constant to produce homogeneous mixtures during the mixing process, as shown in Fig. 13. The following blending sequence was used for the filler-asphalt samples:

* Asphalt cement was heated in an oven to a temperature of at least 160°C.
* The stainless steel beaker used for mixing was cleaned and kept in the oven at a temperature of at least 160°C.
* The required amount of asphalt was weighed in the beaker and then the amount of filler required to yield the desired filler-to-asphalt ratio was weighed.
* The beaker was placed on a hot plate to maintain a mixing temperature of at least 160°C for a mini-

Table 10. Chemical composition of mineral fillers using EDX

Material	Weight Percent			
	LSD	CWD	CFA	SSD
Calcium Carbonate, Ca Co_3	7.27	8.00	10.33	4.25
Silicon Dioxide, Si O_2	45.70	74.94	54.57	41.41
Magnesium Oxide, Mg O	0.45	0.45	4.22	0.36
Aluminum Oxide, Al2 O_3	-	8.54	8.24	16.71
Calcium, Ca	40.77	40.77	6.85	1.07
Titanium, Ti	-	0.31	0.33	0.82
Iron, Fe	-	1.11	14.28	17.45
Sum of Si O_2, Al2 O_3, Fe	45.70	84.59	77.09	95.93
Feldspar, K Potassium oxide	-	1.55	0.76	0.38
Available Alkalis oxide as Na_2O	-	2.02	-	0.64
Sulfur Trioxide, S O_3	-	-	-	-
Manganese oxide, Mn	-	-	-	0.33

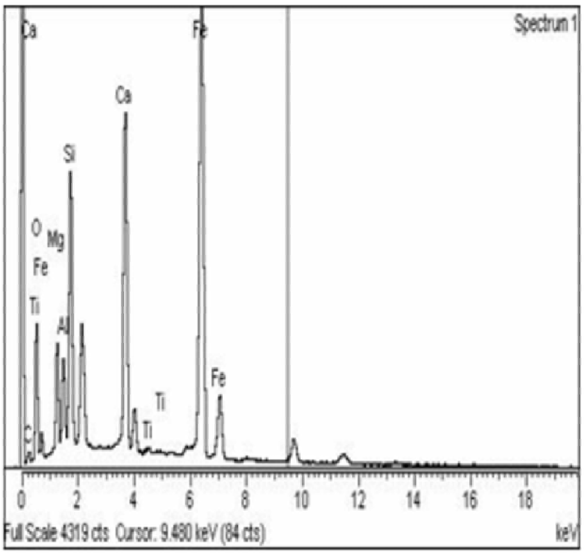

Figure 9. Chemical composition of coal fly ash

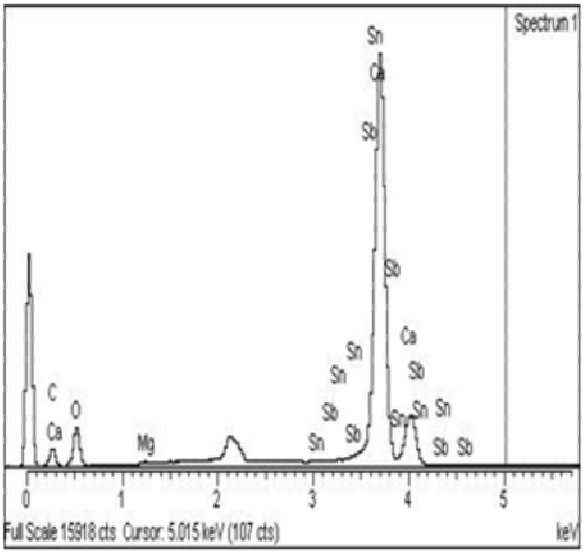

Figure 10. Chemical compositon of limestone

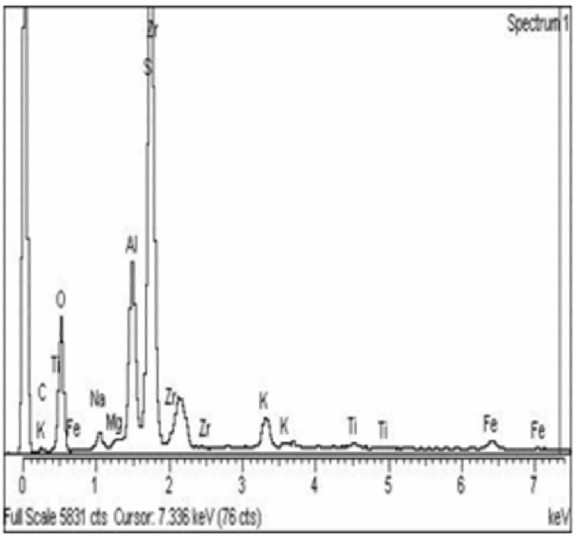

Figure 11. Chemical composition of ceramic waste

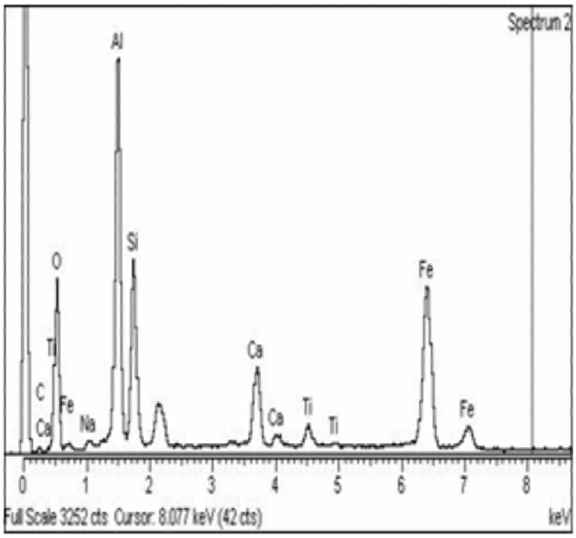

Figure 12. Chemical composition of steel slag

mum of 30 minutes. The laboratory mixer used was then placed so that the propeller was about 1.5 cm above the bottom of the beaker.

* The mixer was started, and the prepared amount of

Table 11. Asphalt mastic properties

Material	F/A	OAC	Softening Point °C (Stiffening power)	Penetration (mm)	Viscosity, Pa.s@ 135°C	Viscosity, Pa.s@ 165°C
Neat Asphalt	-	-	48	84	0.413	0.100
LSD (100/0)	1.72	5.81	59 (11)	40	3.375	0.967
LSD (50/50)	1.70	5.89	63 (15)	37	3.612	0.970
LSD (0/100)	1.69	5.91	64 (14)	35	3.713	1.034
CWD (100/0)	1.70	5.87	63 (15)	29	6.279	1.796
CWD (50/50)	1.72	5.80	66 (18)	26	6.652	1.812
CWD (0/100)	1.74	5.76	67 (19)	24	6.863	1.978
CFA (100/0)	1.73	5.68	55 (7)	49	1.775	0.542
CFA (50/50)	1.76	5.66	56 (8)	48	1.837	0.542
CFA (0/100)	1.77	5.64	57 (9)	46	1.862	0.563
SSD (100/0)	1.71	5.84	56 (8)	44	2.475	0.775
SSD (50/50)	1.70	5.87	57 (9)	43	2.550	0.673
SSD (0/100)	1.64	6.09	58 (10)	42	2.563	0.763

F/A = P200/Pb F = Filler, A =Asphalt, P200 = % passing no. 200 sieve
P_b = optimum asphalt content, Sp.gr.(LSD) = 2.55, Sp.gr (CWD) = 2.39
Sp.gr. (CFA) = 2.63, Sp.gr.(SSD) = 3.40, Filler = 10% of total wt. of aggregate

Figure 13. Blending of mastic

filler gradually was added to the beaker while stirring. The speed of the mixer was increased to 500 rpm.

* Mixing was continued for at least 30 minutes, until an homogenous asphalt-filler mastic was obtained.
* The mastic was continuously stirred as it cooled to prevent settling.
* At the end of mixing, the mastic was used to prepare specimens for the penetration, softening point, and viscosity tests.

4.3 Viscosity-Temperature Test

The viscosity tests of neat asphalt and mastics were conducted by a Brookfield viscometer (Brookfield Engineering Laboratories, Middleboro, MA, USA) according to ASTM D 4402. The viscosity test temperatures covered were 135ºC and 165ºC. The rotational viscosity was determined in Pascal second (Pa.s) 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. Figures 14 and 15 show that the viscosity increases with the decrease in

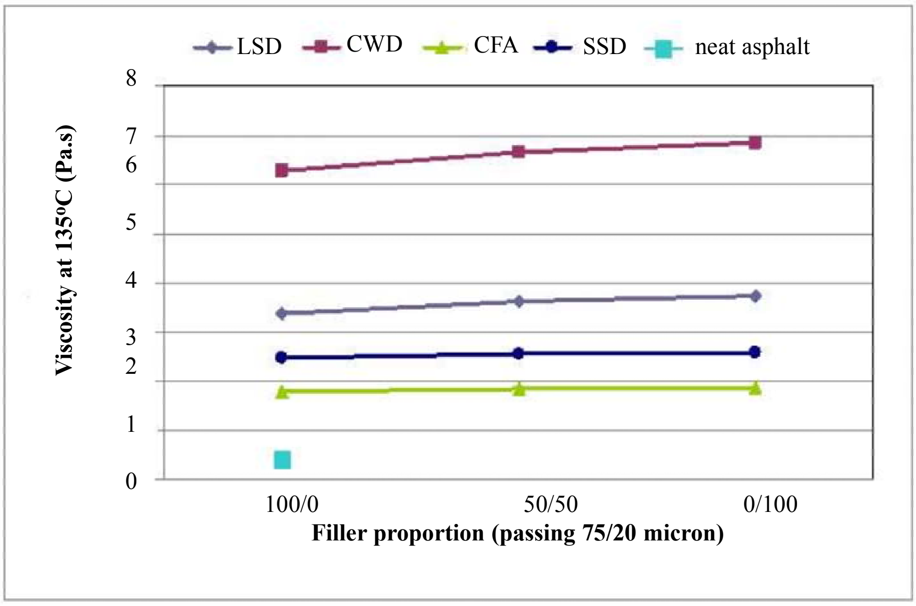

Figure 14. Viscosity of Mastics @ 135°C

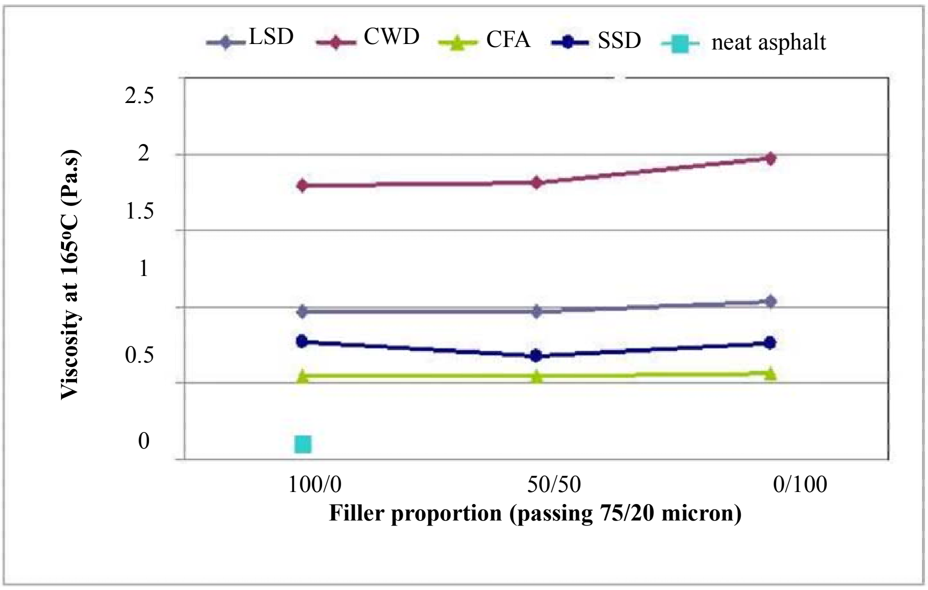

Figure 15. Viscosity of mastics @ 165°C

filler particle size. The smaller the particle size was, the higher the viscosity. Its performance in terms of softening point, viscosity, and penetration for filler mastic was far superior to the neat asphalt. In terms of filler type, it was observed from Figs. 14 and 15 that CWD filler-asphalt mastic had the most stiffening effects, LSD ranked second, SSD ranked third, and CFA filler had the least regardless of the filler particle size. In terms of particle size, a general trend was observed in that the viscosity of mastics increased as the filler particle size decreased at both temperatures (135°C and 165°C).

4.4 Penetration and Softening Point Tests

The penetration tests of neat asphalt and mastics were conducted according to ASTM D5 which is the standard test method for the penetration of asphalt. Figure 16 shows that the penetration decreased with a reduction in filler particle size, regardless of filler type. The smaller the particle size, the lower the penetration was. In terms of filler type, CWD filler mastic scored the lowest penetration, LSD ranked second, SSD third, and CFA filler mastic ranked fourth.

The softening point was used to evaluate high temperature properties of neat asphalt binder and mastics

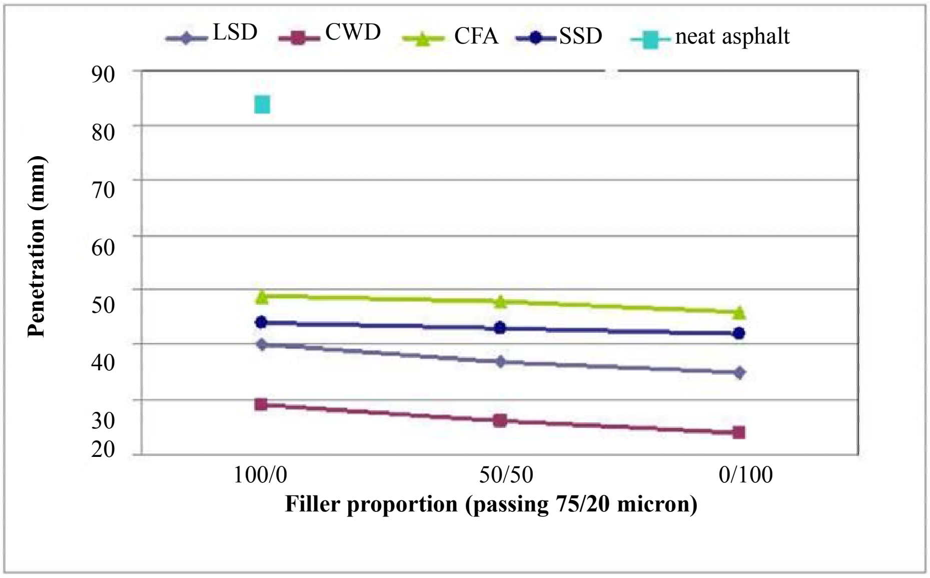

Figure 16. Penetration of neat asphalt and mastics

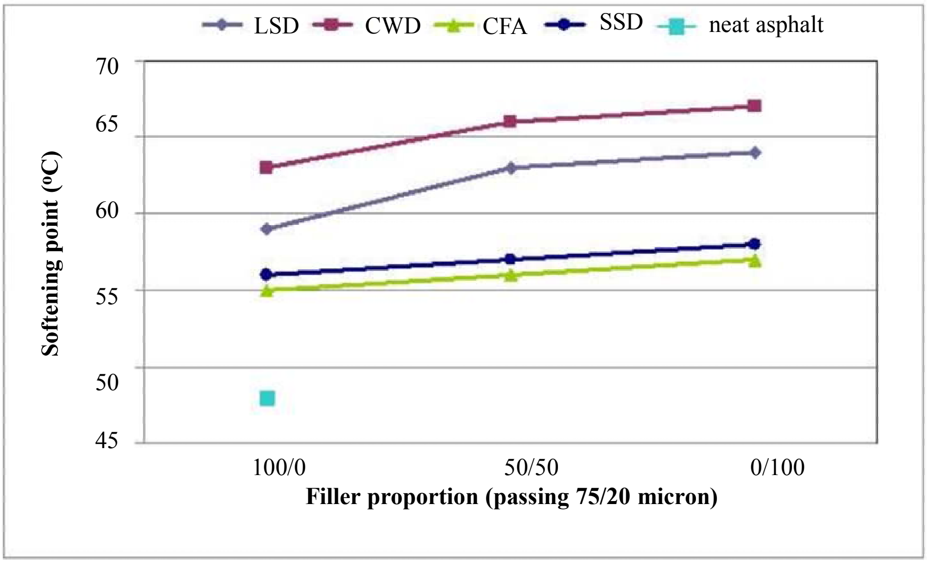

Figure 17. Softening point of neat asphalt and mastics

using the ring-and ball apparatus (ASTM D36). The stiffening power is used in Germany to qualify mineral fillers for use in pavements. The Germans use a range of stiffening power to determine acceptable mineral fillers at 10-20°C (Harris *et al*. 1998). Mastics that exceed 20°C would be considered too stiff and the mineral fillers would be disqualified to avoid laying crack-susceptible pavement.

Mastics that test below 10°C would not be stiffened enough. These would be susceptible to excessive drain-down, bleeding, shoving, and rutting. The stiffening power of mastics can be expressed using (2) as follows:

$$\Delta T = T_2 - T_1 \quad (2)$$

where ΔT (°C) denotes the stiffening power of the mastic. The subscripts 1 and 2 present softening point of neat asphalt and the mastic, respectively. Table 10 indicates that the stiffening power of mastics is in the range of 7-19°C.

The CWD mastics had the highest stiffening power and were the stiffest mastics, while limestone ranked second, SSD third, and CFA had the least stiffening power regardless of filler particle size.

On the other hand, a general trend was observed in that the fine filler particle size mastics showed the stiffest mastics, regardless of filler type. Figure 17 shows the softening point increases with decrease in particle size. The smaller the particle size, the higher the softening point was.

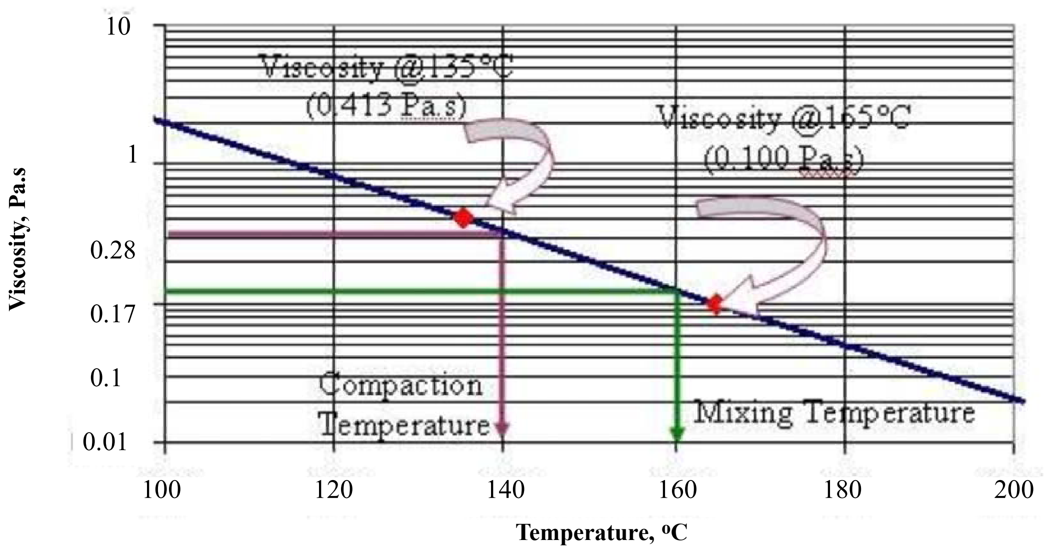

Figure 18. Viscosity - temperature relationships for asphalt binder

5. Mix Design

The Marshall Mix Design procedure (ASTM D 1559) was followed in performing the mix designs. Locally available materials that met the normal SMA specifications were used to produce the reference mix. The OAC for SMA mixtures is usually selected to produce 4% air voids and a drain-down of less than 0.3%. The mixing and compaction temperatures were obtained from viscosity-temperature relationships developed for neat asphalt corresponding to the mixing and compaction viscosities of 0.17 and 0.28 Pa.s, respectively. The mixing and compaction temperature was observed to be 160°C and 140°C for neat asphalt as depicted in Fig. 18.

OAC was calculated as per the Asphalt Institute MS-2 series by taking the average asphalt content corresponding to 4% air voids, maximum stability, and maximum bulk density, and was checked for other parameters. The air voids in the design were kept at 4% as per the requirements of specifications.

5.1 Sample Preparation

Cylindrical specimens of 101.6 x 63.4 mm were prepared with asphalt contents ranging from 5 to 7% with an increment of 0.5%. Three specimens were prepared for each binder content. Twelve mix designs were prepared namely, LSD100/0, LSD50/50, LSD0/100, CWD100/0, CWD50/50, CWD0/100, CFA100/0, CFA 50/50, CFA 0/100, SSD100/0, SSD 50/50, and SSD 0/100, representing the four types of mineral fillers with three different filler proportions. These designs were prepared with the same blend of coarse and fine aggregates to keep aggregate angularities and mineralogical characteristics constant. The only variable in the mixtures was the filler proportion of 100/0, 50/50, and 0/100 (passing 75 microns/passing 20 microns by the total weight of aggregate).

Twelve Marshall mix designs were performed to determine the OAC of the SMA mixtures. Four sets of 45 specimens (4 types of filler x 3 filler proportions x 15 specimens for each mix design) + 4 sets of 15 loose specimens (4 types of filler x 1 specimen at each asphalt content (total 5 specimens) x 3 filler particle size proportions) for calculating the theoretical maximum density, a total of 240 specimens were prepared for the four selected mineral filler type and three level of filler proportions to determine the OAC. The fiber content was fixed at 0.3% of the total mix for all the mixes. Laboratory specimens were prepared using fifty blows of the Marshall hammer per side. Seventy five compaction blows were not used since they would tend to break down the aggregate more and would not result in a significant increase in density over that provided by 50 blows. The temperatures for mixing and compaction were designated at 160ºC and 140ºC.

5.2 Determination of Optimum Asphalt Content

OAC was calculated as per the Asphalt Institute's method by taking the average asphalt content corresponding to 4% air voids, maximum stability, and maximum bulk density, and then was checked for other parameters (Asphalt Institute, 1993). The OAC obtained for the LSD, CWD, CFA, and SSD mixtures were 5.81%, 5.89%, 5.91% for LSD; 5.87%, 5.80%, 5.76% for CWD; 5.78%, 5.66%, 5.64% for CFA and, 5.84%, 5.87%, 6.09% for SSD by weight of the mixture.

The OAC obtained for particle sizes smaller than 20 microns for limestone and SSD filler was higher than that obtained for particle sizes smaller than 75 microns, which indicates that the OAC increased as the particle size decreased.

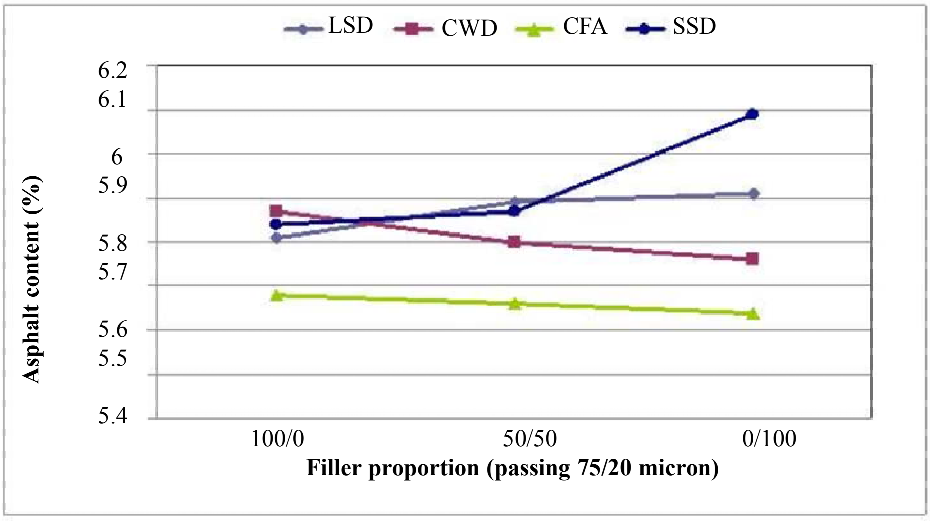

Figure 19. Asphalt content vs filler type

Table 12. Asphalt mixture properties

Material	OAC %	Bulk Sp.gr.	% VTM	% VMA	% VFA	Stability (KN)	Flow (0.025mm)	MQ KN/mm	Resilient Modulus (MPa)
LSD(100/0)	5.81	2.316	3.51	16.47	78.38	7.64	4.10	1.86	3600.00
LSD(50/50)	5.89	2.304	3.92	16.93	76.96	7.82	4.71	1.66	3672.00
LSD(0/100)	5.91	2.314	3.42	16.63	78.88	7.20	4.67	1.54	3568.00
CWD(100/0)	5.87	2.309	3.12	16.23	80.08	7.63	3.85	1.98	3679.00
CWD(50/50)	5.80	2.311	3.08	16.03	80.31	8.54	4.14	2.06	3785.00
CWD(0/100)	5.76	2.316	3.24	15.87	80.64	7.76	3.79	2.05	3627.00
CFA(100/0)	5.68	2.316	3.96	16.68	76.71	7.03	4.06	1.73	3140.00
CFA(50/50)	5.66	2.333	3.49	16.06	77.73	7.76	4.88	1.59	3152.00
CFA(0/100)	5.64	2.338	3.12	15.85	79.75	6.62	5.35	1.24	3075.00
SSD(100/0)	5.84	2.372	3.30	16.67	79.74	9.32	3.58	2.60	3437.00
SSD(50/50)	5.87	2.361	3.77	17.03	79.13	9.52	3.42	2.78	3583.00
SSD(0/100)	6.09	2.362	3.37	17.22	80.22	9.73	3.48	2.80	3453.00

M.Q = Marshall Quotient = Stability/Flow, Sp.gr. of asphalt cement = 1.0295,
Sp.gr. of Coarse Aggregate (Granite) = 2.63, Sp.gr. of Fine Aggregate (Granite) = 2.58
VTM: Voids in Total Mix; VMA: Viods in Mineral Aggregate; VFA: Voids in Filled with Asphalt

On the other hand, the OAC was slightly lower for CWD and CFA fillers, which indicates that the OAC decreased as the particle size decreased, as shown in Fig. 19.

5.3 Marshall Stability and Flow Tests

Marshall stability and flow tests were carried out on compacted specimens at various asphalt cement contents based on ASTM D1559. The summary of mix properties is shown in Table 12. Figure 20 indicates that the Marshall stability of mixtures prepared with steel slag filler with proportions of 100/0, 50/50, and 0/100 were 9.32, 9.52 and 9.73 KN, respectively. Corresponding flow values were 3.58, 3.42, and 3.48 mm as depicted in Fig. 21. This shows that the SSD filler had the highest stability and the lowest flow, although it is within the permissible limit of 2-4 mm. The other mixtures had approximately equal stability and flow values. In terms of filler particle size, the stability increased up to a 50/50 proportion, then started to decrease for CWA, LSD, and CFA mixtures, while for SSD the stability continue to increase beyond the 50/50 proportion.

One property that is sometimes used to characterize asphalt mixtures is the Marshall Stiffness Index, or the Marshall Quotient (MQ) (Roberts *et al.* 1996),

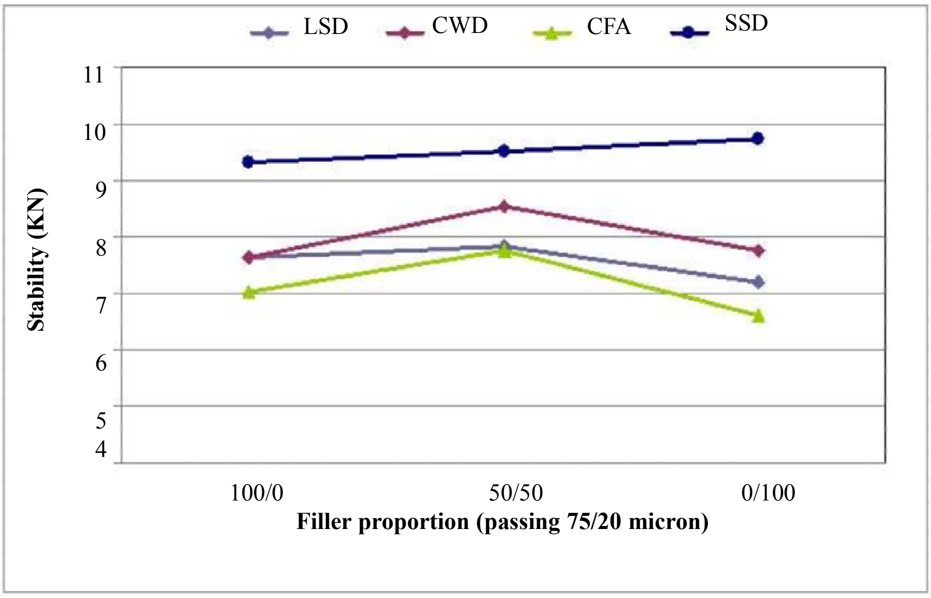

Figure 20. Stability vs filler type

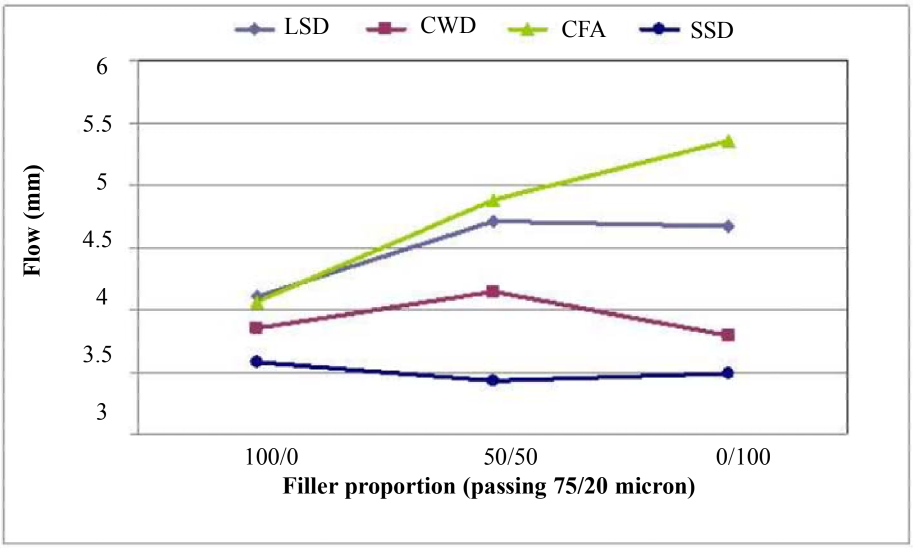

Figure 21. Flow vs filler type

which is the level of Marshall stability divided by the flow. This is an empirical stiffness value and is used to evaluate the quality of asphalt mixtures. MQ (KN/mm) can be used as a measure of the material's resistance to permanent deformation in service. A higher value of MQ indicates a stiffer mixture and, hence, indicates that the mixture is likely to have more resistant to permanent deformation. As shown in Fig. 22, the MQ for ceramic waste and steel slag filler mixtures were higher than the MQ of the reference filler, which indicates a stiffer mixture and that the mixture is more resistant to permanent deformation. Simultaneously, the MQ values of CFA mixtures were the same as the reference filler regardless of filler particle size. In terms of filler particle size, the MQ values decreased by decreasing filler particle size for LSD and CFA mixtures and increased by decreasing filler particle size for CWA and SSD mixtures.

5.4. Indirect Tensile Stiffness Modulus (ITSM) Test

Resilient modulus (MR) is a relative measure of mixture stiffness and load distribution ability; higher MR values lead to stiffer mixtures with higher load distribution ability. The MR was determined from tests on cylindrical specimens for each mixture at designed bitumen contents in the indirect tension mode. The frequency of load application used was 1 Hz, with a load duration of 0.1 seconds to represent field conditions and a resting period of 0.9 seconds.

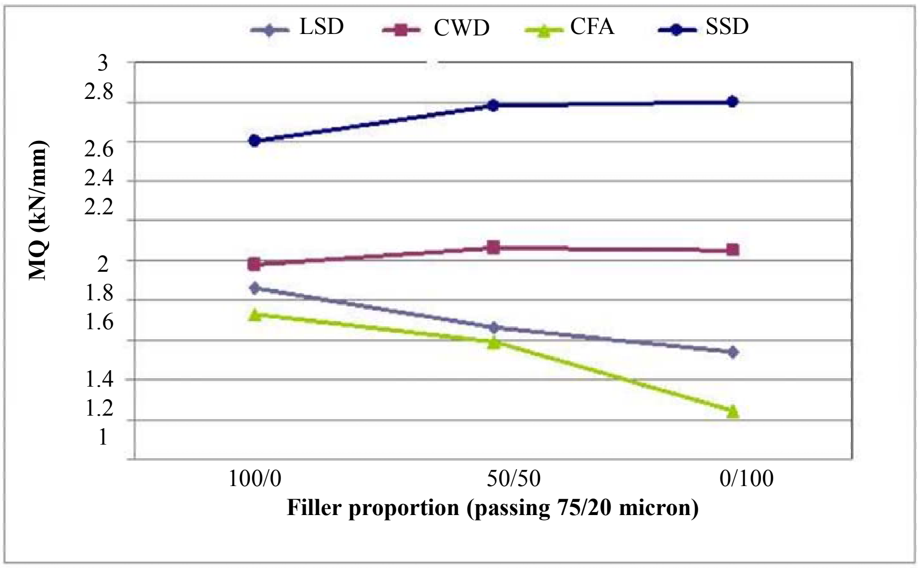

Figure 22. MQ vs filler type

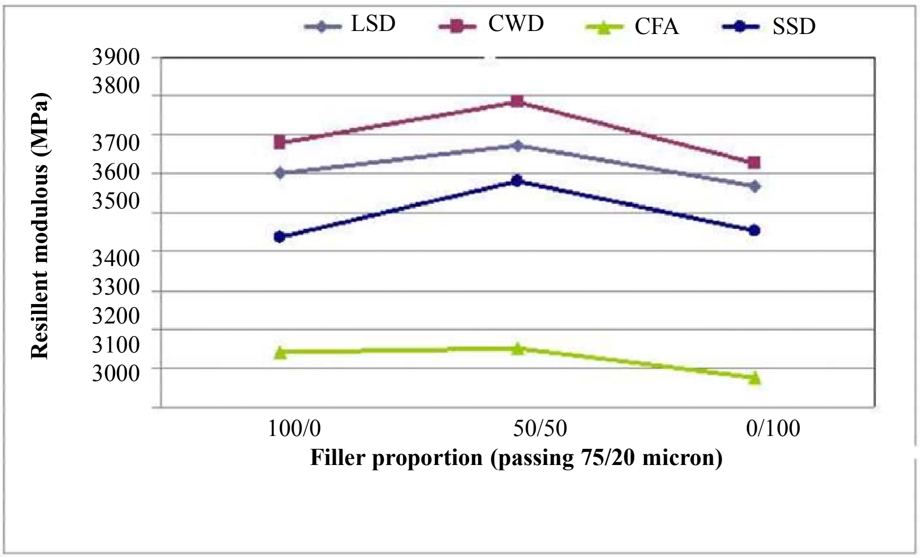

Figure 23. Resilient modulus vs filler type and combination

A constant test temperature was maintained using an environmental air chamber. Each specimen was placed inside the chamber at the set temperature for two hours before testing. All 180 specimens (4 types of filler x 3 filler proportions x 15 specimens at OAC) were subjected to this test at a temperature of 25ºC. The test was carried out using material testing apparatus (MATTA) in accordance with ASTM D4123. The results of the resilient modulus test in mega pascal (MPa) are presented in Fig. 23 and Table 12 for direct comparison between the three different filler mixtures and the reference mixture of LSD filler.

Figure 23 shows that the resilient modulus values of mixtures containing CWA were higher while the resilient modulus values of paving mixtures containing CFA and SSD filler were slightly lower regardless of the filler particle size as compared to paving mixtures of LSD filler. A general trend was observed: regardless of the filler type, the resilient modulus of SMA mixtures increased up to a 50/50 filler proportion. It started to decrease as the filler particle size decreased.

6. Results and Discussion

6.1 Filler/Asphalt Mastic

Test results indicate that penetration decreased with reduction of filler particle size. The smaller the particle size, the lower the penetration was. The viscosity increased with a decrease in filler particle size. The smaller the particle size, the higher the viscosity was. Additionally, the softening point increased with a decrease in particle size; that is, the smaller the particle size the higher the softening point.

Resulting data indicated that an increase in stiffness due to the addition of filler was represented by an increase in softening point and viscosity as well as a decrease in penetration. The stiffening effects of different filler types and sizes varied greatly. The performance for the filler/asphalt mastic in terms of softening point, viscosity, and penetration was better than the neat asphalt. The best performer among those fillers was the CWA, with a 50/50 filler proportion.

6.2 Mix Design

6.2.1 Optimum Asphalt Content (OAC)

The OAC for CWA and CFA decreased with a decrease in particle size. This phenomenon can be explained by the fact that less asphalt binder is needed with filler of a smaller particle size to form the same amount of mastic to lubricate the aggregate. Less film thickness is thereby needed to coat the aggregate.

Also, this decrease may be due to the increase in the interfacial area per unit volume of mineral fillers as the filler's particle size decreases. Based on the workability of the HMA mixtures, the smaller the filler's particle size, the less asphalt is needed to compact the mixtures to the required air voids. Hence, the "extender" function of the filler commonly has been observed for the mixtures in this study.

On the other hand, the OAC for limestone and steel slag filler increases with a decrease in particle size. The SSD had the highest OAC as the particle size decreased and a higher absorption ability than the other fillers due to its porous nature. This increases asphalt binder demand.

6.2.2 Marshall Stability and Flow

The Marshall stability indicates that the SSD filler had the highest stability and the lowest flow, although it was within the permissible limit of 2-4 mm. This may be attributed to the inherent physical properties of SSD that allow it to mix in order to produce HMA with high stability and the asphalt binder coats the steel slag that prevents hydration of the calcium and magnesium oxide. This advantage may result in an increase of volumetric stability for asphalt mixture with the steel slag filler. The other mixtures had approximately equal stability and flow values. The MQ for CWD and SSD fillers were higher than the MQ of the reference filler which indicates a stiffer mixture and, hence, indicates that the mixture likely is more resistant to permanent deformation. On the other hand, the MQ values of CFA were almost the same as the reference filler.

6.2.3 Resilient Modulus

A general trend was observed in the resilient modulus of mixtures with 50/50 filler particle size proportions. That proportion scored the highest resilient value regardless of filler type. In terms of filler type, the results in Table 12 and Fig. 23 clearly show the superiority of CWD filler mixtures as demonstrated by higher resilient modulus value as compared to the LSD control mixture.

7. Conclusions

The main objective of this study was to facilitate decisions concerning the effectiveness of using new filler types which are byproducts of other industries. The various experimental fillers possessed different particle sizes and were expected to improve the engineering properties of paving mixtures, thereby enhancing pavement performance. The reported improvement in the engineering properties of the paving mixtures containing CWD, CFA, and SSD can be attributed to the bonding and cementation properties of the fillers. These properties tend to increase the viscosity of the filler-asphalt mastic and the texture of the filler particles which consequently increases the frictional resistance among the aggregate particles, increasing the stability of the mix.

From the investigations conducted in this study using different types of fillers with different particle sizes, it can be concluded that

1. Filler type and particle size directly affect the engineering properties of the asphalt mixtures.

2. In addition to filling the voids, the fillers' components interact with the binder present in the mix, potentially making it stiff and brittle. The change in mix properties is strongly related to the properties of the filler.

3. The major finding of this study is that CWD and SSD used as filler were found to be effective in improving the Marshall stability, resilient modulus, and Marshall stiffness index, as compared to LSD filler. CFA had the lowest OAC. It did little to improve the Marshall Stability or resilient modulus value as compared with to reference filler.

4. The results of the laboratory tests show that CWD and SSD fillers improve the overall mixture properties of asphalt. The use of these special fillers improves pavement performance, thus reducing the maintenance and rehabilitation costs of the pavement.
5. It can be concluded that utilization of industrial wastes and byproducts in SMA results in the

improvement of the engineering properties and a reduction in the OAC. The reduction in OAC would result in significant cost saving.

Acknowledgment

The work reported herein was completed as part of an on-going PhD research project entitled Effect of Mineral Fillers Type and Particle Size on the Properties of Mastic and Performance of Stone Mastic Asphalt Pavements.

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