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The Performance Characteristics of Stone Mastic Asphalt Mixtures Using Oil Palm Fruit Ash-Modified Bitumen

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Abstract: This study was conducted to investigate the use of oil palm fruit ash-modified bitumen (OPFA-MB) as a binder in stone-mastic asphalt (SMA) mixtures. The OPFA was used to take advantage of a waste by-product of the palm oil milling industry which could help to reduce environmental pollution. Binder tests such as penetration, softening point, viscosity, storage stability, dynamic shear rheometer (DSR), bending beam rheometer (BBR), and the direct tension test (DTT) were conducted on both unmodified and OPFA-modified bitumens. It was found that the properties of unmodified bitumen improve when OPFA is added. In addition, several asphalt mixture tests, including the Marshall Stability test, indirect tensile modulus resilience test, static uniaxial creep test, wheel tracking test, static-immersion and boiling water test, and drain-down test, were also performed on SMA mixes. The presence of OPFA was observed to enhance the stability, resilient modulus, and rut resistance of SMA mixes compared to the unmodified bitumen. This material was also found to be a good alternative material for fiber replacement in SMA mixes.

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Introduction

In recent years, increased traffic levels, larger and heavier vehicles, new axle designs, and increased tire pressures have added to the already severe demands of load and environment on the highway system, resulting in the need to enhance the properties of existing asphalt material [1, 2]. Previous studies have shown that the use of a stone mastic asphalt or stone matrix asphalt (SMA) mix improves resistance to rutting and also increases pavement durability compared to other types of asphalt mixture [3]. In principle, SMA is a mixture of crushed coarse aggregate, crushed fine aggregate, mineral filler, bitumen, and stabilizing agent. Typically, the stabilizing agents used are fibers and polymers [3].

A typical SMA mix composition includes a high proportion, typically 70-80%, of coarse aggregate, 6-7% bitumen or binder, and 8-12% mineral filler [4]. The high percentage of stone skeleton content results in stone-on-stone contact, which produces a mixture that is highly resistant to rutting [3, 5-6]. SMA also seems to have enhanced durability as a result of the higher bitumen content and lower air void content [7]. Other advantages include high resistance to reflective cracking, slower aging, and reduced traffic noise [8]. For pavements with cracking or raveling, it is suggested that SMA is considered for use as an overlay, because it may reduce severe reflection cracking from underlying cracked pavements due to the flexible mastic [9]. Hence, the mechanical properties of SMA are far superior to conventional asphalt mixtures, making it more favourable for application.

Historically, SMA originated in Germany in the 1970s to provide maximum resistance to rutting caused by studded tyres on European roads [10]. SMA has been used for many years and its usage is forecast to continue to increase in the immediate future, particularly in the USA, Europe, and Japan. This mix is recommended to be used in high stress areas such as climbing lanes, or where excessive axle loads are expected [10]. However, drain-down has been regarded as the main problem with this type of asphalt mixture due to its nature and the high proportion of binder. To prevent this problem, the use of some additives may be essential [11], one being polymer-modified bitumen (PMB) [12].

Typically, SMA mixes consist of PMB and this material may be further stabilized by means of cellulose fibers to prevent excessive binder drain-down [10]. In addition, the presence of fibers increases the toughness and fracture resistance of SMA mixes [13-14]. Also, the stiffer bitumen binder will enhance resistance to rutting, particularly at high temperatures [15]. However, one potential problem with using a stiffer binder is thermal cracking [3]. SMA mixes have relatively high optimum bitumen content and increased film thickness, which tends to reduce susceptibility to thermal cracking. So it is believed that the downsides of using slightly stiffer bitumen are more than offset by the increased film thickness. In addition, the use of PMB in road paving is relatively expensive.

Therefore, because of the escalating cost of materials and energy, and the scarcity of natural resources, it is apparent that there is a necessity for a polymer-modified mixture that can be conveniently prepared from a comparatively inexpensive polymer. Such a mixture would prove indispensable in high performance road construction [16]. The application of solid waste materials is one such alternative for PMBs. A considerable amount of research has been conducted to investigate using alternative materials in SMA mixes. Chiu and Lu [17] conducted a laboratory study of SMA

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mixes using ground tire rubber. They found that no fiber was needed to prevent drain-down when asphalt rubber was used.

Al-Hadidy and Qiu [18] found that the presence of waste pyrolysis polypropylene (PP) in SMA reduces temperature susceptibility and subsequently improves the performance of the mix compared to conventional mixes. The use of steel slag in SMA mixes as the coarse portion of the aggregate enhances resistance to moisture damage and permanent deformation [19-20]. Recently, Moghadam et al. [21] found that the use of a small amount of waste polyethylene terephthalate (PET) increases the stiffness modulus of SMA mixes. A pavement straw composite fibre (PSCFs) from agricultural waste straw and modified bentonite was used by Qiang et al. [6] in SMA mixes. The presence of PSCFs improves the fatigue life of SMA mixes.

This study was conducted to investigate the use of different proportions of oil palm fruit ash (OPFA) as a modifier for SMA mixes. OPFA contains many fibers that enhance the durability of SMA mixes by allowing a higher bitumen content to be used. The aim of using OPFA is to find an alternative binder modifier to polymers and other modifiers, and to take advantage of the waste by-product of the palm oil milling industry, which could help reduce environmental pollution. Several binder tests, including penetration, softening point, viscosity, storage stability, dynamic shear rheometer (DSR), bending beam rheometer (BBR), and the direct-tension test (DTT), were conducted to determine the characteristics of unmodified and OPFA-MBs. Meanwhile, the performance of SMA mixed with OPFA-MB was characterized by means of the Marshall Stability test, indirect tensile resilient modulus test, static uniaxial creep test, wheel tracking test, static immersion and boiling water test, and drain-down test.

Experimental Design

Materials

Oil PalmFruit Ash (OPFA)

Oil palm fruit ash (OPFA) is a by-product of palm oil milling, or the ash from burning the mesocarp of the fruitlets. This by-product is currently disposed of as waste, thus polluting the environment and affecting the health of the surrounding community. Physically, OPFA is greyish in colour and becomes dark with increasing proportions of unburned carbon, as shown in Fig. 1. The physical properties and chemical composition of OPFA are given in Table 1 and Table 2, respectively [22]. As shown in Fig. 1, OPFA originates from palm oil milling and consists of rough grains. The grain is elongated-flat in shape with a maximum grain length of 6 mm. Two grain sizes were used in this research. One was very fine with a uniform grain size of 75 μm resulting from grinding the original OPFA and sieving through sieve size 75 μm, and the other resulted from sieve analysis using a maximum sieve size of 300 μm and a minimum size of 75 μm. OPFA with a uniform grain size of 75 μm is known as Fine-OPFA, and OPFA with a maximum grain size of 300 μm is known as Coarse-OPFA.

Fig. 1. Oil Palm Fruit Ash after Burning (Inside is Fruitlet of Palm Oil Fruit).

Table 1. Physical Properties of OPFA [22].

Test	Physical Properties
Fineness – Sp. Surface Area (m^2/kg)	519
Soundness – Le Chatelier Method (mm)	1
Specific Gravity	2.22

Table 2. Chemical Composition of OPFA [22].

Chemical Composition	Percent (%)
Silicon Dioxide (SiO_2)	43.60
Aluminum Oxide (AL_2O_2)	11.40
Ferric Oxide (Fe_2O_3)	4.70
Calcium Oxide (CaO)	8.40
Magnesium Oxide (MgO)	4.80
Sodium Oxide (Na_2O)	0.39
Potassium Oxide (K_2O)	3.50
Sulphur Trioxide (SO_3)	2.80
Loss On Ignition (LOI)	18.00

Bitumen

An 80/100 penetration grade bitumen was used in this study as a control sample. Details of the properties of the base bitumen are given in Table 3. In addition, a PG 76-22 binder was also used to compare with the OPFA-SMA mixture. The use of PMB is recommended for SMA mixes, as mentioned in the Malaysian Public Works Department (PWD) specification [10].

Aggregates

The materials used as coarse and fine aggregates were granite rock types from the Malaysian Rock Product (MRP) quarry located in Pontian, Johor, Malaysia, and Portland cement class A was used as the mineral filler. The gradation of the combined coarse aggregate, fine aggregate, and mineral filler for SMA-14 mixtures is shown in Table 4.

Research Methodology

Table 3. Properties of the Base Bitumen.

Properties	Value
Penetration at 25°C and 100 Gram Load (dmm)	87
Viscosity at 60°C (Pa.s)	35.5
Viscosity at 135°C (Pa.s)	0.4
Softening Point (°C)	44
Specific Gravity (SG)	1.06
Penetration Index (PI)	-2.50
Penetration Viscosity Number (PVN)	-0.43

Table 4. Gradation Limits of Combined Aggregates for SMA-14.

ASTM Sieve Size (mm)	Percentage by Weight Passing Sieve (%)
19.0	100
12.5	100
9.50	72 – 83
4.75	25 – 38
2.36	16 – 24
0.600	12 – 16
0.300	12 -15
0.075	8 -10

Sample preparation

OPFA was mixed in increments of 2.5% by weight (to a maximum of 10%) with bitumen at a mixing temperature of 160°C, a mixing time of 60 minutes and a stirring speed of 800 revolutions per minute (rpm). The mix of OPFA and bitumen was called OPFA-Modified Bitumen (OPFA-MB). Based on the particle size of OPFA and its content in the bitumen, there were four OPFA-MBs with Fine-OPFA and four OPFA-MBs with Coarse-OPFA. The four Fine-OPFA-MBs (hereafter abbreviated as F-OPFA-MB), namely 2.5, 5, 7.5 and 10% of F-OPFA-MBs, and the four Coarse-OPFA-MBs (hereafter abbreviated as C-OPFA-MB), namely 2.5, 5, 7.5 and 10% of C-OPFA-MBs, were used for further study.

Temperature Susceptibility

Temperature susceptibility is the rate at which the consistency of bitumen changes with change in temperature and is a very important property of bitumen [3]. Two different approaches for determining the temperature susceptibility of the bitumen used are penetration index (PI) and penetration-viscosity number (PVN). The PI is determined from bitumen's softening point (Ring and Ball test), its penetration at 25°C, and the assumption that the penetration of bitumen at its softening point temperature is 800; this is referred to as PI (SP/pen). In this study, the Pfeiffer and Van Doormaal Nomograph [23] was used to calculate PI.

McLeod [24] proposed PVN to determine the temperature susceptibility of bitumen. This number is based on penetration at 25°C and viscosity at either 60 or 135°C, which are usually the specification requirements for paving bitumen, thus the data are readily available to calculate the PVN. The following formula is used to calculate PVN:

$$PVN = \frac{L - X}{L - M}(-1.5) \tag{1}$$

where X is the logarithm of viscosity in centistokes measured at 135°C, L is the logarithm of viscosity at 135°C for a PVN of 0.0, and M is the logarithm of viscosity at 135°C for a PVN of -1.5.

The viscosity values of L and M can be calculated from the following equations.

The equation for the line representing a PVN of 0.0 is:

$$\log V = 4.25800 - 0.79670 \log P \tag{2}$$

The equation for the line representing a PVN of -1.5 is:

$$\log V = 3.46289 - 0.61094 \log P \tag{3}$$

where V is the viscosity in centistokes at 135°C (275°F) and P is the penetration at 25°C.

Storage Stability Test

A storage stability test was also conducted to evaluate the possible separation of OPFA-MBs. The test procedure was conducted in accordance with BS EN 13399:2010, BS 2000-517:2010 [25]. The test was conducted as follows: immediately after mixing, the OPFA-MB was poured into a 25.4 mm by 139.7 mm aluminium tube and heated in an oven to 165°C for one and three day time intervals. The selection of storage days was based on an estimation of road construction delay. At the end of the test period, samples were placed in the freezer at -10°C for four hours to solidify the OPFA-MB. Upon removing the tube from the freezer, samples were cut into three equal lengths with a spatula and hammer. The ring and ball softening point ($T_{R\&B}$) test was performed to the top and bottom sample portions. The difference of the $T_{R\&B}$ between the top and bottom portions was used to evaluate the stability of the OPFA-MBs. A binder is considered to be stable if the difference of the $T_{R\&B}$ values is less than or equal to 2.5°C [26-27].

Rheology Tests

Today, the linear viscoelastic rheological properties of bitumen are usually determined using an oscillatory type testing apparatus known as a dynamic shear rheometer (DSR). The DSR is a powerful tool used to determine the elastic, viscoelastic, and viscous properties of bitumen over a wide range of temperatures and frequencies [28-29]. It is done by measuring the complex shear modulus (G^*)[5] and phase angle (δ) of the binders. The test is performed conforming to European Standard Test NEN-EN 14770 [30]. In this study, the DSR test for permanent deformation or rutting was conducted for unaged and RTFO-aged samples and tested at 50, 60, 65, 70 and 75°C, using a large spindle (25 mm) with a gap of 1.0 mm, and stress sweep control. For fatigue cracking, a test was performed at 20, 25, 30, 35 and 40°C. A small spindle (8 mm) with a gap of 2.5 mm and strain sweep control were used. The test was conducted on PAV-aged samples.

The bending beam rheometer (BBR) is used to measure the stiffness of a binder at low temperatures. The test uses engineering

[5] Many authors use G^* to mean $|G^*|$ and refer to the magnitude as the 'complex modulus'.

beam theory to measure the stiffness of a small bitumen beam sample under a creep load. Two parameters are evaluated with the BBR, namely creep stiffness, which is a measure of how bitumen resists constant loading, and the *m*-value, which is a measure of how bitumen stiffness changes as loads are applied. The test was performed based on European Standard Test NEN-EN 14771 [31]. Finally, the direct tension test (DTT) was used to measure the low temperature ultimate tensile strain of the binders, typically in the range of 0 to -20°C.

Stone Mastic Asphalt-14 (SMA-14) Mixes

In this study, stone mastic asphalt-14 (SMA-14) mixes were designed using the Marshall Mix design, based on the Malaysian PWD Specification [10]. The Marshall Specimens were prepared in accordance with ASTM D1559 [32], using 50 blows per face compaction standard. The Malaysian Specification of 75 compaction blows was 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 gradation of the aggregate used is given in Table 4. Five different bitumen contents, namely 5, 5.5, 6, 6.5 and 7% (by weight of aggregates) were used to determine the optimum bitumen content (OBC). Three samples were prepared for each binder contents. The Marshall Stability and specific gravity test were then conducted on each sample. The specific gravity of the sample was used to determine the void content of the mix (VMA) of SMA mixes. The OBC was found to be around 5.8% from the mix design used for the SMA-14 mixtures. After obtaining the OBC, laboratory tests were carried out on SMA-14 specimens using both F-OPFA-MBs and C-OPFA-MBs, control bitumen, and PG 76-22 binder. Several performance tests conducted on SMA mixes are discussed in the following sections.

Indirect Tensile Resilient Modulus Test

The indirect tensile test to determine the resilient modulus of bituminous mixtures was performed in accordance with ASTM D4123–82 [33]. The specimens used in this study were Marshall Specimens, which have an average height of 70 mm and an average diameter of 101.6 mm. The test was conducted at 5, 25, and 40℃ (±1°C) at a loading frequency of 0.5 and 1 Hz for each test temperature and a load duration of 0.1 second. The test was conducted by applying compressive loads with a haversine waveform. The load was applied vertically in the vertical diametral plane of a cylindrical specimen. The resulting horizontal deformation of the specimen was measured and an assumed Poisson’s ratio was used to calculate the resilient modulus. For a test temperature of 5°C, the Poisson’s ratio was assumed to be 0.25, and for 25 and 40°C, the Poisson’s ratio was assumed to be 0.40 [30]. The values for the vertical and horizontal deformation were measured by linear variable differential transducer (LVDT). The total resilient modulus was calculated using the total recoverable deformation, which includes both the instantaneous recoverable and the time-dependent continuing recoverable deformation during the unloading and rest period portion of one cycle.

Static Uniaxial Creep Test

The static uniaxial creep test was the simplest method of assessing the resistance to permanent deformation or rutting. The Marshall specimen was used in the static uniaxial creep test. Its dimensions were similar to those of the specimen used in the indirect tensile resilient modulus test. The test was conducted in accordance with the Texas Department of Transportation Standard Test, TxDOT Designation Tex-231-F [34]. The specimen was placed in a controlled temperature chamber maintained at a test temperature of 40°C for three to five hours prior to the start of the test. The specimen was then mounted on a compression head and the temperature was maintained at 40°C. Three cycles of a 125 lb (556 N) square wave preload were applied at one-minute intervals followed by a one-minute rest period for each cycle. This was to allow the loading plates to achieve more uniform contact with the specimen. A 125 lb (556 N) load was then applied to the specimen for one hour. At the end of one hour the load was removed, allowing the specimen to rebound for ten minutes. During the entire loading and unloading time, the applied load was monitored and recorded, resulting in vertical deformation for each LVDT. The average deformation for each specimen was calculated by averaging the readings from the two LVDT. The average deformation values were converted to strain using the ratio of permanent deformation to thickness of the specimen.

Wheel Tracking Test

Permanent deformation or rutting was also tested using the Wessex dry wheel tracking test machine. A wheel tracking machine was preheated without any sample present at a 50°C test temperature for approximately two hours. A contact pressure of 4.60 kg/cm^2 (460 kPa) and total wheel load of 18.40 kg (0.18 kN) was applied to the 300 mm × 300 mm × 50 mm slab specimens. The test used type A of the test procedure, according to the WESSEX BS EN 12697 manual: the abort depth was 15 mm, the center of the specimen was subjected to 1,000 wheel passes or cycles, and each point was taken after 25 seconds, thus the test was conducted for about 40 minutes. The results were expressed as the rutting depth occurring on the sample at the end of 1,000 cycles or when the abort depth was reached.

Marshall Stability Test

The Marshall test, developed by the United States Corps of Engineers in the 1940s, is the most widely used test to measure the strength of asphalt mixtures. The test was conducted in accordance with ASTM D1559 [32].

Static Immersion and Boiling Water Test

The static immersion test measures the adhesiveness of bitumen. 300 g of coarse SMA-14 aggregate was coated with base bitumen, PG 76-22, and all OPFA-MB binders. The binder content was 6.8% by weight of aggregate. The coated aggregate was then immersed in distilled water at 25°C for 48 hours. The sample was then observed through water to estimate the percentage of total visible area of aggregate which remained coated above or below 95%. This test

Table 5. Consistency Test Results, PI and PVN Values of OPFA-MBs

OPFA	Content (%)	Pen (dmm)	$T_{R\&B}$ (°C)	Viscosity (Pa.s)		S.G.	PI	PVN
				135 °C	60 °C			
Fine	0	87	44	0.4	35.50	1.08	-2.5	-0.43
	2.5	67	48	0.5	36.30	1.05	-0.80	-0.40
	5	66	49	0.5	38.00	1.06	-0.60	-0.43
	7.5	64	50	0.5	39.80	1.08	-0.30	-0.49
	10	62	51	0.5	41.70	1.10	-0.30	-0.29
Coarse	2.5	60	52	0.4	41.70	1.08	-0.20	-0.85
	5	62	50	0.4	42.20	1.09	-0.40	-0.84
	7.5	67	45	0.4	44.70	1.10	-0.80	-0.77
	10	62	52	0.5	39.80	1.10	-0.10	-0.54

Table 6. Storage Stability Test Results.

OPFA-MB	Content (%)	1 day (°C)	3 days (°C)
Fine	2.5	1.50	1.50
	5	1.00	1.50
	7.5	1.50	2.0
	10	4.00	4.50
Coarse	2.5	0.50	1.00
	5	3.00	3.00
	7.5	4.50	4.50
	10	5.00	5.00

method did not involve any strength testing. A boiling water test was conducted in accordance with ASTM D3625 [35], where loose asphalt mixture was added to boiling water. ASTM D3625 specifies a 10-minute boiling period. In the same manner as the static immersion test, the percentage of the total visible area of aggregate that retained its original coating after boiling was estimated as above or below 95%.

Drain-down Test

A drain-down test was conducted on all SMA-14 mixtures to measure the percentage of bitumen drained from the mixture. A sample of SMA-14 mixture was placed into a standard cylindrical wire basket. The basket was constructed using standard 6.3 mm sieve cloth, as specified in AASHTO M92. The test was conducted in accordance with AASHTO T 425.

Results and Discussion

OPFA-Modified Bitumen (OPFA-MB)

Consistency Test Results of OPFA-MB

The results of the penetration, softening point, viscosity, and specific gravity tests, as well as the determination of PI and PVN, are given in Table 5. The discussion will specifically focus on the PI and PVN, the two parameters of temperature susceptibility. The value of PI ranges from around -3 for highly temperature susceptible bitumen to +7 for highly blown low-temperature susceptible bitumen [36]. From these limitations of PI value, the hypothesis can be drawn that the binder is not susceptible to changes in temperature if it has a PI value close to the average value. Table 5 shows that the PI values of all OPFA-MBs are higher than that of the base binder. This indicates that the OPFA-MB shows better resistance at low temperatures. The PVN values for bitumen are normally between +0.5 and -2.0 with a good range between +1 and -1 [28]. The lower the PVN value of bitumen, the higher its susceptibility to temperature [37]. The PVN values for all F-OPFA-MBs and 7.5 and 10% C-OPFA-MBs were between 0 and the average value of -0.75.

Storage Stability Test

The results of the storage stability test, which were indicated by the difference in softening point temperature of the top and bottom portions of each sample after one day and three days' storage, are shown in Table 6. The sample with a softening point temperature below 2.5°C was categorized as stable, and these samples were considered to have compatibility between OPFA and bitumen. This table shows that only eight of the sixteen samples, or 50%, were categorized as stable, or that the OPFA was uniformly dispersed in the bitumen. These eight samples were 2.5, 5, and 7.5% F-OPFA-MBs and 2.5% C-OPFA-MBs, which were stable for one and three days of storage. The OPFA does not dissolve in bitumen due to the fact that the OPFA has higher specific gravity values compared to the specific gravity values of bitumen.

Rheological Properties of OPFA-MB

Taking into consideration the results of the storage stability test and travel load to the Delft University of Technology of the Netherlands, where the rheology test was conducted, only six OPFA-MBs were tested for rheological properties (six OPFA-MBs were all F-OPFA-MBs and 2.5 and 5% C-OPFA-MBs). The Superpave specification was then used to evaluate the rheology test results in terms of resistance to rutting and fatigue cracking. To measure rutting, the DSR test was conducted on unaged and RTFO-aged binder. The test was also conducted on PAV-aged binder to measure fatigue cracking. Table 7 shows the OPFA-MBs, which reach the Superpave limitations. The finding shows that OPFA added to bitumen at certain percentages has an influence on the binder durability in terms of rutting and fatigue cracking.

The stiffness of OPFA-MBs or the resistance to thermal cracking was observed by means of the BBR test, and the test was performed at temperatures of -30 and -20°C. Besides stiffness (S_t), the BBR

Table 7. OPFA-MB which Reaches the Superpave Limitation.

Binder	Rutting Parameter (G*/sin δ) kPa	Fatigue Parameter (G*×sin δ) kPa	Temperature (°C)
Unaged	G*/sin δ = 1 (7.5% F-OPFA-MB)		65
RTFO Aged	G*/sin δ = 2.3 (5% F-OPFA-MB)		70
PAV Aged		G*.sin δ = 5005 (2.5% F-OPFA-MB)	20

Table 8. The Results of Creep Stiffness by BBR Test.

OPFA-MB	Content (%)	Stiffness at -20 °C (MPa)	Temperature at which *S*(*t*) = 300 MPa Occur (°C)
Fine	2.5	329	-19
	5.0	438	-17
	7.5	426	-17
	10.0	500	-15
Coarse	2.5	388	-18
	5.0	360	-19

Table 9. DDT Test Results

Binder	Content (%)	DDT Strain (%)		BBR Stiffness at -20°C	Temperature Reach at S(t) = 300 MPa (°C)
		0°C	10°C		
F-OPFA-MB	2.5	0.46	0.1	441	-16
	5.0	0.54	0.1	438	-17
	7.5	0.47	0.1	426	-17
	10.0	0.44	0.1	500	-15

test also measures *m*-value. The *m*-value indicates the rate of change in the stiffness. The test results are shown in Table 8. Superpave specifications require a maximum limitation of 300 MPa for stiffness and a minimum of 0.300 for *m*-value. At -30°C, all OPFA-MBs fulfilled the Superpave requirements, but at -20°C, none of the OPFA-MBs met the requirements; however, the minimum *m*-value requirement of 0.300 was fulfilled by all OPFA-MBs. These results require further study or analysis to determine whether the OPFA-MBs are still resistant to thermal cracking at -20°C.

The DTT test was later conducted at -10 and 0°C on the OPFA-MB binders, which showed a larger difference in stiffness values than the Superpave limitation. These binders were 2.5, 5, 7.5, and 10% F-OPFA-MBs. The finding is shown in Table 9. The Superpave requirement for the failure strain test using DTT is a minimum of 1%. The test results at a temperature of -10°C for those OPFA-MBs showed that the strain was only 0.1%. However, they reach the Superpave stiffness limitation of 300 MPa at -16°C for 2.5%, -17°C for 5% and 7.5% F-OPFA-MB and -15°C for 10% F-OPFA-MB.

The Performance Characteristics of SMA-14 Mixes

Marshall Stability

The specific gravity and Marshall Stability test results are shown in Table 10. The specific gravity of the specimens ranges from 2.25 up to 2.30, with an average of 2.27. The minimum requirement of Marshall Stability, according to Malaysian PWD Specifications [10], is 6200 N. It is observed that all OPFA-MB binders have Marshall Stability values above the minimum requirement and above the value of the control sample, but lower than PG 76-22 binder. This finding indicates that the OPFA-MBs have a high load-withstanding strength compared to the conventional asphalt mixture.

Table 10. Specific Gravity and Marshall Stability Values.

Binder	Type	Content (%)	SG	Marshall Stability (N)
Control	-	0	2.27	7161
PG 76-22	-	0	2.26	8069
OPFA-MB	Fine	2.5	2.31	7409
		5	2.27	7471
		7.5	2.30	7553
		10	2.27	7677
	Coarse	2.5	2.25	7594
		5	2.27	7553
		7.5	2.30	7925
		10	2.27	8049

Indirect Tensile Resilient Modulus Testing

A summary of the indirect tensile resilient modulus test results is shown in Table 11. The resilient modulus is the ratio of stress to resilient strain (as opposed to viscous strain) in an asphalt mixture sample [38]. However, the results are irregular and do not reflect the fact that the higher the OPFA content was, the higher the resilient modulus value was. When compared to the resilient modulus of PG 76-22 binder, the resilient modulus values of all OPFA-MB binders were higher and this shows that they are not easily cracked when exposed to the load.

Static Uniaxial Creep Test

The results of the rutting and strain form creep test are shown in Table 12. As shown in the table, by adding OPFA to the binder, permanent deformation and strain decrease significantly. However,

Table 11. The Indirect Tensile Resilient Modulus Test Results.

Average M_R Value (MPa) for each Test Temperature; Peak Loading Force 1000 N								
Binder	Type	Content (%)	Loading Frequency 500 ms			Loading Frequency 1000 ms		
			5℃	25°C	40°C	5℃	25°C	40°C
Control	-	0	8114	1755	441	7671	1443	324
PG 76-22	-	0	4901	2027	440	3815	1860	386
OPFA-MB	Fine	2.5	6842	2897	460	6198	2674	397
		5	8233	2711	317	6713	2442	267
		7.5	6884	2939	340	6422	2426	267
		10	7469	3401	364	7042	3136	362
	Coarse	2.5	5913	2711	198	5841	2281	156
		5	5496	2743	418	5057	2513	345
		7.5	6738	2840	439	6519	2734	415
		10	6627	3112	504	5347	2822	446

Table 12. Creep Test Results.

Binder	Type	Content (%)	Strain (%)			Deformation (mm)		
			Test 1	Test 2	Avg.	Test 1	Test 2	Avg.
Control	-	0	0.54	2.15	1.35	0.36	1.45	0.91
PG 76 - 22	-	0	0.27	0.55	0.41	0.19	0.39	0.29
OPFA-MB	Fine	2.5	0.71	0.10	0.41	0.45	0.07	0.26
		5	0.56	0.82	0.69	0.42	0.26	0.34
		7.5	0.31	0.12	0.22	0.22	0.09	0.15
		10	0.97	0.35	0.66	0.66	0.25	0.46
	Coarse	2.5	0.16	0.59	0.38	0.12	0.42	0.27
		5	0.14	0.60	0.37	0.10	0.60	0.35
		7.5	0.54	0.52	0.53	0.40	0.38	0.39
		10	0.54	1.24	0.89	0.40	0.90	0.65

Table 13. The Results of the Wheel Tracking Test.

Binder	Type	Content (%)	Sample Thickness (mm)	Rut Depth (mm)
Control	-	0	55	6.6
PG 76 - 22	-	0	60	1.8
OPFA-MB	Fine	2.5	56	4.4
		5	55	4.2
		7.5	55	4.2
		10	59	4.4
	Coarse	2.5	61	5.9
		5	62	5.2
		7.5	60	4.6
		10	60	5.2

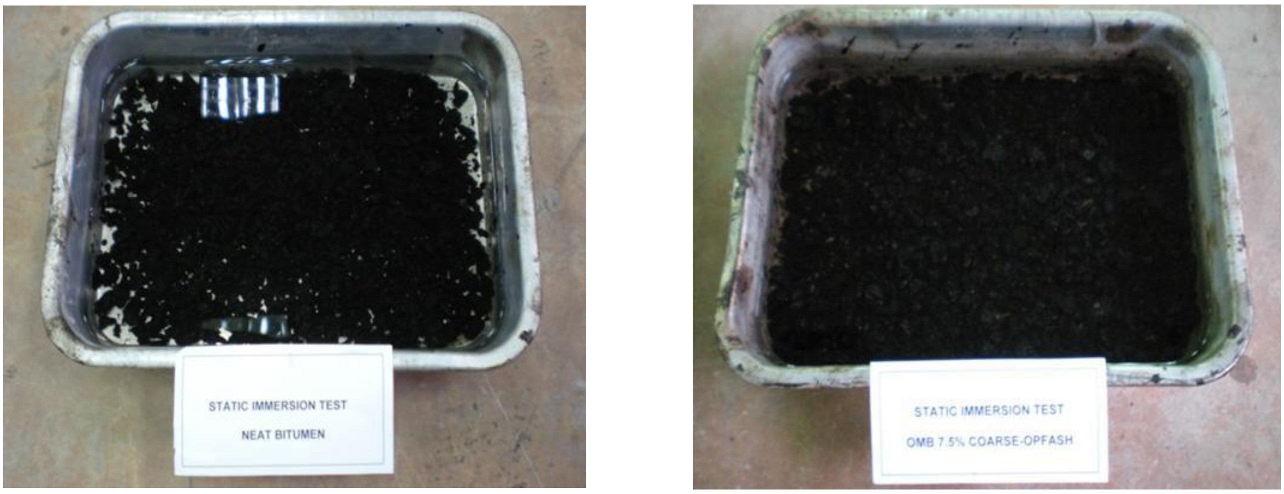
the hypothesis states that the greater the OPFA content is, the lower the permanent deformation and strain value will be. The test results show the opposite, i.e. that the greater the OPFA content is, the greater the permanent and strain value will be; but the test results are logical for the PG 76-22 binder: the permanent deformation and strain of PG 76-22 binder is smaller than that of OPFA-MB binders. This indicates that SMA mixed with PG 76-22 binder is stronger than SMA mixed with OPFA-MB.

Wheel Tracking Test

Table 13 shows the permanent deformation or rutting results obtained using a Wessex wheel tracker test. The higher the percentage of OPFA content is, the lower the rut depth value is, except for 10% F-OPFA-MB and 7.5% C-OPFA-MB. Compared to the SMA-14 mixture using base bitumen binder, all SMA-14 using OPFA-MB binder have a lower rut depth value, even though they are higher than the rut depth of SMA-14 using PG 76-22 binder.

Static Immersion and Boiling Water Test

The results of the static immersion test show that both uncompacted SMA-14 mixtures using base and OPFA-MB binder possessed good adhesion. After 48 hours immersed in distilled water at a temperature of 25°C, 100% of the aggregate in the mixtures using base bitumen and 7.5% C-OPFA-MB binder remained coated, as shown in Fig. 2 (a and b). Only two binders are shown here for brevity, as similar observations were made for other mixes. In the boiling water test, the results show that the control binder became slightly loose from the aggregate, but more than 95% was still coated. Also, it was observed that OPFA-MB binders still remained coated in SMA-14 mixes. Fig. 3 shows the results of the boiling water test for 2.5% F-OPFA-MB and C-OPFA-MBS. For brevity, the results for other mixes were all similar in shape; therefore, the results will only be presented for these two binders with the understanding that the commentary applies to all mixes. The results of the static immersion and boiling water tests show that bitumen



(a) (b)

Fig. 2. Static-immersion Test of Base Bitumen (a) and 7.5% C-OPFA-MB (b) (after 48 Hours).

(a) (b)

Fig. 3. Observed Boiling Water Test for (a) 2.5% F-OPFA-MB and (b) 2.5% C-OPFA-MB.

Table 14: The Drain-down Test Results.

Binder	Type	Content (%)	Drain-down (%)		
			Test 1	Test 2	Average
Control	-	0	0.18	0.22	0.20
PG 76 -22	-	0	0.10	0.15	0.13
OPFA-MB	Fine	2.5	0.16	0.18	0.17
		5	0.28	0.07	0.18
		7.5	0.19	0.13	0.16
		10	0.02	0.30	0.16
	Coarse	2.5	0.10	0.37	0.19
		5	0.10	0.14	0.12
		7.5	0.17	0.02	0.10
		10	0.12	0.11	0.12

modified with OPFA has good adhesiveness when mixed with SMA-14.

Drain-down test

The Malaysian PWD specification requires the maximum binder drain-down from the loose mix to be 0.3% at the test temperature [10]. The drain-down test results are shown in Table 14. The drain-down results for base bitumen, OPFA-MBs, and PG 76-22 fulfilled the required specification. The percentage of OPFA-MB binder which is drained off from the basket is lower than that for the control sample. The results of the drain-down test strengthen the finding from the static immersion and boiling water tests, showing that the presence of OPFA-MB improves the binder adhesion to the aggregates.

Conclusions

Based on the limited tests conducted in this study, several conclusions were drawn:

- Based on the PI and PVN results, adding OPFA to the bitumen improves the temperature susceptibility of bitumen.
- Only 50% of OPFA-MBs show that OPFA cannot be dissolved into bitumen, but other tests show that its presence strengthens the properties of bitumen. The OPFA does not dissolve in bitumen due to the fact that it has higher specific gravity values compared to bitumen.
- The findings show that OPFA added to bitumen at certain percentages improves binder durability in terms of rutting and fatigue cracking at high and low temperatures, respectively. In addition, the use of OPFA-MB in SMA-14 mixes improves the resistance to low temperature cracking, improves the Marshall Stability value, and minimizes rutting at high temperatures compared to SMA-14 mixed with conventional bitumen. However, the use of PG 76-22 binder results in a stronger mixture compared to SMA-14 mixed with OPFA-MB.
- The presence of OPFA-MB improves binder adhesion to the aggregates in SMA-14.

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