THE PERFORMANCE OF STONE MASTIC ASPHALT USING OIL PALM FRUIT ASH MODIFIED BITUMEN AS BINDER

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ABSTRACT

Laboratory experiments have shown that the properties of a 80/100 penetration grade bitumen had improved when modified with an oil palm fruit ash (OPFA). The results of consistency and rheological tests have shown that OPFA-modified bitumen (OPFA-MB) met the requirements for Superpave Performance-Based binder 70–16 and Penetration-Grade binder 60/70, and therefore, it can be classified as binder PG 70–16 and a 60/70 penetration grade bitumen. In addition, several tests such as the Marshall test, indirect tensile modulus resilient (M_R), static uniaxial creep test, wheel tracking test, static-immersion and boiling water test and drain-down test were carried out on stone mastic asphalt (SMA) mixes, both using unmodified- and OPFA-MB. It was observed that presence of OPFA-MB improves the SMA mixes stability, resilient modulus and rut resistance compared to the unmodified one. The use of OPFA-MB also provides a good adhesive to the aggregate. This material is found to be an excellent alternative material for a fiber replacement in SMA mixes.

Keywords: Oil palm fruit ash, stone-mastic asphalt, rheology, rutting, resilient modulus, adhesive.

1. INTRODUCTION

Increasing of traffic volume and vehicle loads has demanding pavement structures which have high strength of surface course. Studied had shown that stone mastic asphalt (SMA) mixtures is more resistant to rutting and increased durability than any other type of hot mix asphalt. (Robert et al.1996).

the stone mastic asphalt (SMA) are composed to have a high proportion of coarse aggregate content typically 70-80%, 6-7% of asphalt content or binder, 8-12% of mineral filler content (Austroads 2001 the high percentage of stone skeleton content results in stone-on-stone contact produces a mixture that is highly resistant to rutting, or permanent deformation. Hence, SMA has clear that the mechanical property is far superior then the conventional hot-mix asphalt (HMA), making it more favorable for application. However, still have one potential construction problem with SMA that is drain-down of the bitumen binder from the aggregate matrix. The modifier is used to make the binder stiff and to prevent drain-down of the bitumen. Beside to prevent drain-down problem, the stiffer bitumen binder will also help to resist rutting at higher temperatures. Yet, one potential problem with using a stiffer binder is thermal cracking (Robert et al. 1996). SMA mixtures have relatively high optimum bitumen content and increased film thickness which tends to reduce the susceptibility to thermal cracking. So it is believed that the negatives of using slightly stiffer bitumen are more than offset by the increased film thickness.

Typically, SMA mixes have polymer-modified bitumen contents the range between 5.5-7.5%. In stead of polymer, in this research Oil Palm Fruit Ash-Modified Bitumen (OPFA-MB) was used as binder. OPFA contents many fibers which able enhances the durability of SMA mix by allowing the use of higher bitumen content. Process to make OPFA-MB will be described prior to explanation about the performance of SMA using OPFA-MB binder.

2. MATERIALS AND RESEARCH METODOLOGY

2.1. Materials

2.1.1. Oil Palm Fruit Ash (OPFA)

Oil Palm Fruit Ash (OPFA) is by-product of palm oil mill, or the ash from burning mesocarp of fruitlets of the palm oil fruits. This by-product has been disposed as waste thus polluting the environment and affecting the health of community surrounding. Physically, OPFA is grayish in colour and become dark with increasing proportions of unburned carbon as shown in Fig. 2.1. The physical properties and chemical composition of OPFA were given in Table 2.1 and 2.2, respectively.

Table 2.1 - Physical Properties of OPFA [Husein]

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

Table 2.2 - Chemical Composition of OPFA [Husein]

Chemical composition	%
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

Figure 2.1 - Oil Palm Fruit Ash after burning (inside is fruitlet of palm oil frui)

As shown in Fig. 2.1, OPFA was originally rough grains with the form of the grain was elongated-flat with maximum grains length 6 mm. to be used as bitumen modifier, OPFA was grained into two grain sizes.. One was very fine which had uniform grains size of 75 µm or 0.075 mm, the other one resulted from sieve analysis using maximum sieve size 300 mm and minimum size 75 µm or 0.075 mm. OPFA with uniform grain size 75 µm denote as Fine-OPFA, and OPFA with maximum grain size 300 µm denote as Coarse-OPFA.

2.1.2. Bitumen

The properties of base bitumen was used in this research were given in Table 2.3.

Table 2.3. - Properties of the base bitumen

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 at 4 reading (°C)	44
Specific Gravity	1.06
Penetration Index	-2.50
Penetration Viscosity Number	-0.43

2.1.3. Aggregate

Materials for coarse and fine aggregate were granite rock types from Malaysian Rock Product (MRP) quarry located in Pontian – Johor Malaysia, while for mineral filler Portland cement class A was used. The gradation of the combined coarse aggregate, fine aggregate and mineral filler for SMA-14 mixtures was shown in Table 2.4.

Table 2.4. - 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

2.2. Research Methodology

2.2.1. Mixing Bitumen with OPFA

Amount of 2.5% to 10% in increments of 2.5% by weight of the bitumen mixed with bitumen at 160°C of mixing temperature, 60 minutes of mixing time, and 800 revolutions per minute (rpm) of stirring mixing speed. The result of mixing between OPFA and bitumen was called OPFA-Modified Bitumen and denote as OPFA-MB. Based on particle size of OPFA and its content to the bitumen, there were four OPFA-MBs with Fine OPFA and four with Coarse OPFA. The four Fine (F)-OPFA-Mb were 2.5% F-OPFA-MB, 5% F-OPFA-MB, 7.5% F-OPFA-MB, 10% F-OPFA-MB, and the four Coarse (C)-OPFA-MB were 2.5% C-OPFA-MB, 5% C-OPFA-MB, 7.5% C-OPFA-MB, 10% C-OPFA-MB.

To those eight of OPFA-MB, consistency test consist of penetration at 25°C, softening point, and viscosity test at 60°C and 135°C were performed to determine Penetration Index (PI) and Penetration Viscosity Number (PVN), the two parameters to measure temperature susceptibility of binder. In addition of consistency test, rheological tests consist of Dynamic Shear Rheometer (DSR), Bending Beam Rheometer, and, if necessary Direct Tension Tester (DDT) were also performed. The test results will be given and discussed in section 3, Results and Discussion.

2.2.2. Producing and Test of Stone Mastic Asphalt

In this study stone mastic asphalt (SMA)-14 mixtures were designed by using Marshall Mix design according to Malaysian Standard Specification. Marshall Specimens were made in accordance with ASTM D1559. The specimen can then be used for further analysis, and because of the limited compact effort applied in the field of porous asphalt mixtures, the 50 blows per face should be used.

The gradation of the aggregate was given in Table 2.4 was used. All of eight OPFA-MB in addition base bitumen and PG 76-22 were used as binder. Base bitumen and PG 76-22 was used to make comparison and evaluate how far OPFA-MB appropriate to use as binder of SMA since based on the Malaysian Standard Specification, SMA is designed use modified bitumen like PG as binder.

There are two general types of tests that are used to characterize asphalt mixtures namely Physical and Mechanical test (Robert, F.L. et al. 1996), and three groups of tests, namely Fundamental, Simulative, and Empirical tests (Read, J. and Whiteoak, D. 2003). Physical tests include measurement of density, air voids, voids in mineral aggregate, voids filled with bitumen, and aging characteristics. The Mechanical tests include measurement of Marshall Stability and flow, Hveem stability and cohesion, gyratory shear index (GSI), dynamic modulus, resilient modulus, flexural stiffness modulus, indirect tension, creep, and moisture susceptibility. While Fundamental tests include repeated load triaxial test, unconfined static uniaxial creep compression test, repeated load indirect tensile test, and dynamic stiffness and fatigue tests, Simulative tests include wheel tracking test, gyratory compactor, and durability testing, and Empirical test include Marshall test.

In addition to the above tests, storage stability test was also conducted to evaluate the possible separation of OPFA-MB under storage. The test procedure was conducted in accordance with ASTM D5892.. The test procedure was as follows: immediately after the mixing was being finished, OPFA-MB was poured into 25.4 mm by 139.7 mm aluminum tube and was heated to 165°C for 1 and 3 days in the oven. The selection of storage days was based on estimation of road construction delay. At the end of the test period, samples were placed in the freezer at -10°C for 4 hours to solidify the OMB. Upon removing the tube from the freezer, samples were cut into three equal length portions with the spatula and hammer. Softening point ($T_{r\&b}$) test was performed to the top and bottom of the samples. The difference of $T_{r\&b}$ between top and bottom portions was used to evaluate OPFA-MB's stability. The difference of $T_{r\&b}$ should be controlled within 2°C at which point OMB can be properly stored, as practiced by researchers of highway engineering in Taiwan (Chen, J.S. et al 2003).

3. RESULTS AND DISCUSSION

3.1. OPFA-Modified Bitumen (OPFA-MB)

3.1.1 Consistency test results of OPFA-MB

The results of penetration, softening point, viscosity, and specific gravity test, as well as determination of PI and PVN were given in Table 3.1.

Table 3.1. – Consistency test results, PI and PVN values of OPFA-MB

OPFA content	Penetration at 25°C av. 2x5 reading (dmm)	$T_{R\&B}$ avg. 4 reading (°C)	Viscosity 135°C (Pa.s)	Viscosity 60°C (Pa.s)	S.G.	PI	PVN
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0%	87	44	0.4	35.50	1.08	-2.5	-0.43
2.5% F	67	48	0.5	36.30	1.05	-0.80	-0.40
5% F	66	49	0.5	38.00	1.06	-0.60	-0.43
7.5% F	64	50	0.5	39.80	1.08	-0.30	-0.49
10% F	62	51	0.5	41.70	1.10	-0.30	-0.29
2.5% C	60	52	0.4	41.70	1.08	-0.20	-0.85
5% C	62	50	0.4	42.20	1.09	-0.40	-0.84
7.5% C	67	45	0.4	44.70	1.10	-0.80	-0.77
10% C	62	52	0.5	39.80	1.10	-0.10	-0.54

Discussion will be specially given to 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 (Read, J. and Whiteoak, D. 2003). From those limitations of PI value can be drawn a hypothesis that the binder are not susceptible to changes of temperature if it has PI value is close to the average value Table 3.1 column 7 show that the PI value of all OPFA-MB is higher than the PI value of base bitumen, this value shows that all OPFA-MB resist more to the low temperature. Furthermore from the statistical analysis given in Table 3.2, all OPFA-MB have PI test results which have coefficient of confidence 95% close to the average value, and coefficient of determination R-square is above 0.90 as well as coefficient of correlation R is above 0.95, this means that penetration give high distribution to the value of PI, and that the hypothesis is true.

Table 3.2. – Statistical analysis of penetration index (PI)

Sample	Mean of PI	Standard Deviation (σ)	Coeff. of Confidence (%)	Confidence Interval (μ)	R	R-square
F-OFA-MB	-0.74	1.95	95	$-3<\mu<1$	0.99	0.98
C-OPFA-MB	-0.66	2.08	95	$-3<\mu<1$	0.99	0.98

McLeod as quote by Robert et.al gave the limitation of PVN value for bitumen between +0.5 to -2. The lower the PVN values of bitumen, the higher its temperature susceptibility (Robert et al. 1996). PVN values are shown in Table 3.1 column 8 shows that PVN values of Fine-OPFA-MB and 7.5% and 10% of Coarse-OPFA-MB was in between 0 to the average value -0.75. Statistical analysis in Table 3.3 shows that all PVN value of OPFA-MB have coefficient of confidence 95%, however, coefficient of correlation and coefficient of determination of OPFA-MB both for Fine and Coarse OPFA content are below 0.50. This case shows that the relation between penetration value and the PVN value is not so good and the contribution of penetration to the PVN is low.

Table 3.3.- Statistical analysis of penetration-viscosity number (PVN)

Sample	Mean of PI	Standard Deviation (σ)	Coeff. of Confidence (%)	Confidence Interval (μ)	R	R-square
F-OFA-MB	-0.39	0.17	95	-1<μ<0	0.63	0.40
C-OPFA-MB	-0.61	0.52	95	-1<μ<0	0.36	0.13

3.1.2. *Storage stability test*

The results of storage stability test that was indicated by the difference of softening point temperature of top and bottom of the each same samples test for 1 day and 3 days storage are shown in Table 3.4. The sample with different softening point temperature below 2°C was categorized stable and these samples were considered to have compatibility between OPFA and bitumen.

Table 3.4. – Storage stability test results

OPFA-MB	Test duration		OPFA-MB	Test duration	
	1 day (°C)	3 days (°C)		1 day (°C)	3 days (°C)
2.5% Fine	1.50	1.50	2.5% Coarse	0.50	1.00
5% Fine	1.00	1.50	5% Coarse	3.00	3.00
7.5% Fine	1.50	2.00	7.5% Coarse	4.50	4.50
10% Fine	4.00	4.50	10% Coarse	5.00	5.00

From Table 3.4 above can be informed that only eight from sixteen samples or 50% were categorized as stable or OPFA disperse in the bitumen. Those eight samples were 2.5%, 5%, and 7.5% of Fine-OPFA-MB as well as 2.5% and 5% of Coarse OPFA-MB which stable for 1 and 3 days storage.

3.1.3. *Rheology test results of OPFA-MB*

Taking the results of storage stability test and travel load to the Delft University of Technology the Netherlands, where the rheology test was conducted, into consideration, only six OPFA-MBs were tested in the rheology testing. Those six OPFA-MBs were all Fine OIPFA-MB and 2.5% as well as 5% of Coarse OPFA-MB. Superpave specification was used to evaluate the results of rheology test. The results of rheology test of OPFA-MB were given in Table 3.5 for permanent deformation (rutting) and fatigue cracking or DSR testing results, Table 3.6 for thermal cracking or BBR and Table 3.7 for DDT test results.

Table 3.5. - OPFA-MB which reaches the Superpave limitation

Binder	**Rutting Parameter (G*/sin δ) kPa**	**Fatigue Parameter (G* . sin δ) kPa**	**Temperature (°C)**
Un-aged	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 3.6. - The results of Creep Stiffness by BBR test

Binder	**Stiffness at -20°C (MPa)**	**Temperature at which S(t) = 300 MPa occur (°C)**
2.5% Fine OPFA-MB	329	-19
5% Fine OPFA-MB	438	-17
7.5% Fine OPFA-M	426	-17
10% Fine-OPFA-MB	500	-15
2.5% Coarse-OPFA-MB	388	-18
5% Coarse-OPFA-MB	360	-19

Direct tension test (DTT) was conducted at the test temperature -10°C and 0°C, and was performed to the OPFA-MB binder which had larger difference of Stiffness S(t) value than the Superpave specification limitation. Those binders were 5%, 7.5%, and 10% Fine-OPFA-MB..The test results are shown in Table 3.7.

Table 3.7. – DDT test results

Binder	**DDT Strain (%)**		**BBR Stiffness**	**Temperature reach at**
	at 0°C	**at -10°C**	**at -20°C**	**at S(t) = 300 MPa**
5% Fine-OPFA-MB	0.54	0.1	438	-17°C
7.5% F-OPFA-MB	0.47	0.1	426	-17°C
10% F-OPFA-MB	0.44	0.1	500	-15°C

Superpave requirements for failure strain test using DTT is minimum 1%. The test results at temperature -10°C for those four of OPFA-MB showed the strain were only 0.1%. However, those four OPFA-MB reaching the Superpave stiffness limitation 300 MPa at -17°C, for 5% and 7.5% Fine-OPFA-MB, and -15°C for 10% Fine-OPFA-MB respectively.

3.2 The Performance of Stone Mastic Asphalt

The performance of SMA using OPFA-MB binder was characterized by using Marshall Stability test, Indirect Tensile Resilient Modulus test, Determination of Permanent Deformation by using Static Uniaxial Creep test, Wheel Tracking test, Static Immersion and boiling water test, and Drain-down test. Each test result was analyzed by using Student t Distribution and Regression Model. [Scheaffer, R.L. and McClave, J.T].

3.2.1 Marshall Stability

Specific gravity and Marshall Stability are shown in Table 3.8. Specific gravity of the specimens is range from 2.3 up to 2.7 with average 2.7. Minimum requirement of Marshall Stability according to Malaysian Standard Specification is 6200N. The results show that all OPFA-MB have Marshall Stability above the minimum specification requirement, and above Marshall stability for base bitumen, but below PG 76-22

Table 3.8. – Specific Gravity and Marshall Stability

Binder	**Specific Gravity**	**Marshall Stability (MPa)**	**Binder**	**Specific Gravity**	**Marshall Stability (MPa)**
Base Bitumen	2.27	7161			
OPFA-MB 2.5%F	2.31	7409	OPFA-MB 2.5%C	2.25	7594
OPFA-MB 5%F	2.27	7471	OPFA-MB 5%C	2.27	7553
OPFA-MB 7.5%F	2.30	7553	OPFA-MB 7.5%C	2.30	7925
OPFA-MB 10%F	2.27	7677	OPFA-MB 10%C	2.27	8049
PG 76 - 22	2.26	8069			

3.2.2. Indirect tensile resilient modulus (M_R) testing

Indirect tensile resilient modulus (M_R) test was conducted in accordance with the ASTM D4132-82, by using three test temperatures 5, 25, and 40°C, two loading frequency 0.5 Hz or 500 ms and 1.0 Hz or 1000 ms, as well as peak loading force 1000 N. The Poisson's ratio of 0.25 was set for test temperature of 5°C and Poison's ratio of 0.40 was set for test temperature 25°C and 40°C. The summary of the test results are showed in Table 3.9.

Resilient modulus is the ratio of stress to resilient strain (as opposed to viscous strain) in an asphalt mixtures sample (Malik, R.B. and Tahar, E.K. 2009). Another meaning of this definition is that if the strain of asphalt mixtures is low, then the asphalt mixture has a high resilient modulus and it is not easily cracked if it loaded. However the results are irregular and do not reflect that the higher of OPFA content also the higher of resilient modulus value. Statistical analysis which was conducted by using student t distribution gives the coefficient of confidence for all test temperatures 80% and 85% as shown in Table 3.10a for lading frequency 500ms and 3.10b for lading frequency 1000ms.

Table 3.9.. – Summary of indirect tensile Resilient Modulus (M_R) test results

Average M_R value (MPa) for each test temperature; peak loading force 1000N						
Binder	**Loading frequency 500ms**			**Loading frequency 1000ms**		
	5°C	**25°C**	**40°C**	**5°C**	**25°C**	**40°C**
Base Bitumen	8114	1755	441	7671	1443	324
OPFA-MB 2.5% F	6842	2897	460	6198	2674	397
OPFA-MB 5% F	8233	2711	317	6713	2442	267
OPFA-MB 7.5% F	6884	2939	340	6422	2426	267
OPFA-MB 10% F	7469	3401	364	7042	3136	362
OPFA-MB 2.5% C	5913	2711	198	5841	2281	156
OPFA-MB 5% C	5496	2743	418	5057	2513	345
OPFA-MB 7.5% C	6738	2840	439	6519	2734	415
OPFA-MB 10% C	6627	3112	504	5347	2822	446
PG 76 - 22	4901	2027	440	3815	1860	386

Table 3.10a -: Statistic of resilient modulus using loading frequency 500ms

Loading Frequency 500ms	**Mean of Avg. M_R**	**Standard Dev. (σ)**	**Coef of Confi-dence (%)**	**Confidence Interval (μ)**	**R Square R^2**	**R**
Test temperature 5°C						
F-OPFA-MB	5363	4974	80	$2080<\mu<8646$	0.1294	0.36
C-OPFA-MB	4239	4094	80	$1537<\mu<6942$	0.5055	0.71
Test temperature 25°C						
F-OPFA-MB	1958	2130	85	$290<\mu<3625$	0.7984	0.89
C-OPFA-MB	1918	1895	80	$668<\mu<3170$	0.6258	0.79
Test temperature 40°C						
F-OPFA-MB	275	276	85	$59<\mu<491$	0.6133	0.78
C-OPFA-MB	286	347	80	$57<\mu<515$	0.9462	0.97

Table 3.10b. - Statistic of resilient modulus using loading frequency 1000ms

Loading Frequency 500ms	**Mean of Avg. M_R**	**Standard Dev. (σ)**	**Coef of Confi-dence (%)**	**Confidence Interval (μ)**	**R Square (R^2)**	**R**
Test temperature 5°C						
F-OPFA-MB	4864	4500	80	$1893<\mu<7834$	0.6941	0.83
C-OPFA-MB	3797	3947	85	$707<\mu<6887$	0.6513	0.81
Test temperature 25°C						
F-OPFA-MB	1732	1983	85	$179<\mu<3284$	0.6745	0.82
C-OPFA-MB	1744	1742	80	$595<\mu<2894$	0.8085	0.90
Test temperature 40°C						
F-OPFA-MB	231	237	85	$46<\mu<416$	0.1850	0.43
C-OPFA-MB	250	320	80	$39<\mu<461$	0.9938	1.00

Coefficient of correlation R and coefficient of determination R^2 of nine samples of twelve samples or 75% of the samples is strong and fit. Anyhow if it is compared to the resilient modulus of PG 76-22 binder, resilient modulus of all OPFA-MB binder are higher

3.2.3. Determination of Permanent Deformation by using Static Uniaxial Creep test

The test was conducted by referring to the ASTM C1252.. Static loading stress 200 kPa was applied at temperature 40°C. The results of rutting and strain form creep test are shown in Table 3.11.

Table 3.11. - Creep test results

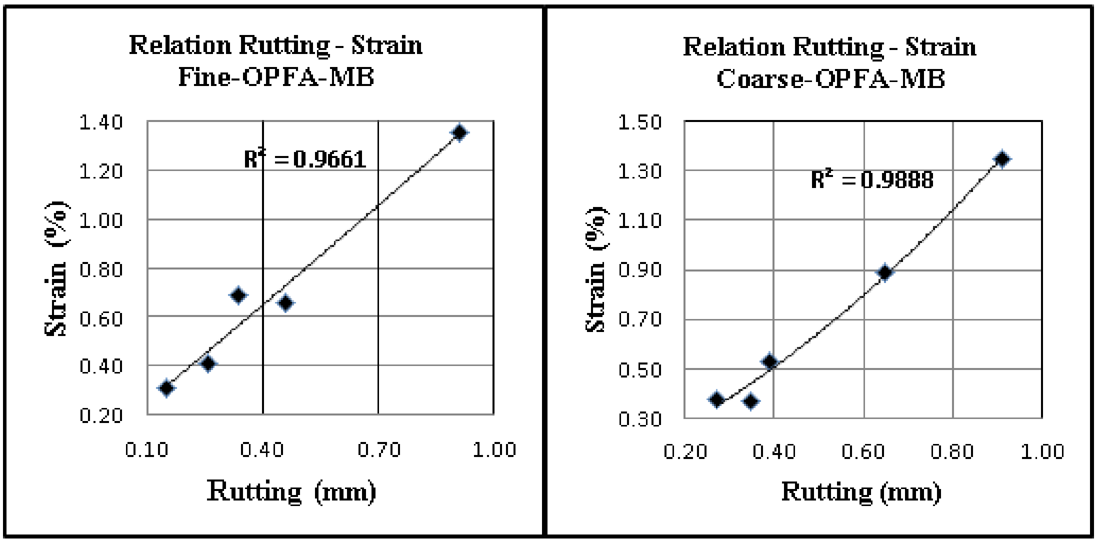
Binder	**Strain (%)**			**Permanent Deformation (mm)**		
	Test 1	**Test 2**	**Avg.**	**Test 1**	**Test 2**	**Avg**
Base Bitumen	0.54	2.15	**1.35**	0.36	1.45	**0.91**
OPFA-MB 2.5% F	0.71	0.10	**0.41**	0.45	0.07	**0.26**
OPFA-MB 5% F	0.56	0.82	**0.69**	0.42	0.26	**0.34**
OPFA-MB 7.5% F	0.31	0.12	**0.22**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

As shown in Table 3.11 by adding OPFA to the bitumen binder, permanent deformation and strain decrease significantly. However, the decrease of permanent deformation and strain is not in the way stated by the hypothesis that the increase of OPFA content the lower of permanent deformation and strain value will be. The test results show the opposite results, the increasing of OPFA content, the greater of the permanent and strain value. But to the PG 76-22 binder the test results show the logical result, the permanent deformation and strain of PG 76-22 binder is smaller than of OPFA-MB binder. This is shows that PG 76-22 binder is stronger than OPFA-MB binder.

The relation between permanent deformation and strain is statistically explained and calculated by using Equation 3.1. [Scheaffer, R.L and McClave, J.T.]. While it regression model given in Fig. 3.1.

$$R = \frac{n\sum XiYi - (\sum Xi)(\sum Yi)}{\sqrt{\{n\sum Xi^2 - (\sum Xi)^2\}\{n\sum Yi^2 - (\sum Yi)^2\}}} \qquad \text{eq. 3.1}$$

where *R* is coefficient of correlation, *Xi* is summation of average rutting, *Yi* is summation of average strain and *n* is a number of data. Strain and permanent deformation or rutting is two parameters that have relation each other. If strain low, rutting will also low. The test of static uniaxial creep resulted strain and rutting which statistically justify that relation. In Fig. 3.1 show the relation have coefficient of correlation R = 0.9829 and coefficient of determination R^2 = 0.9661 for fine-OPFA-MB, and R = 0.9944 and R^2 = 0.9888 for coarse-OPFA-MB. The statistical analysis shows that the relation of strain-rutting is fit.



Gambar 3.1. Regression model for strain-rutting relation

Separately, the test results of both strain and rutting statistically also shown that OPFA content in the binder has significantly the strain and rutting of the SMA mixture. Regression model of rutting is given in Fig. 3.2 and 3.3 show that rutting have R = 0.9247 and R^2 = 0.8556 (fine-OPFA-MB), as well as R = 0.9252 and R^2 = 0.8562 (coarse-OPFA-MB). Meanwhile, regression model for strain is R = 0.8550; R^2 = 0.7320 (fine-OPFA-MB), and R = 0.9503; R^2 = 0.9036 (coarse-OPFA-MB). Those figures show that even though the results of permanent deformation and strain spread and did not follow the hypothesis, but the relationship between OPFA content and permanent deformation as well as strain is strong and significant.

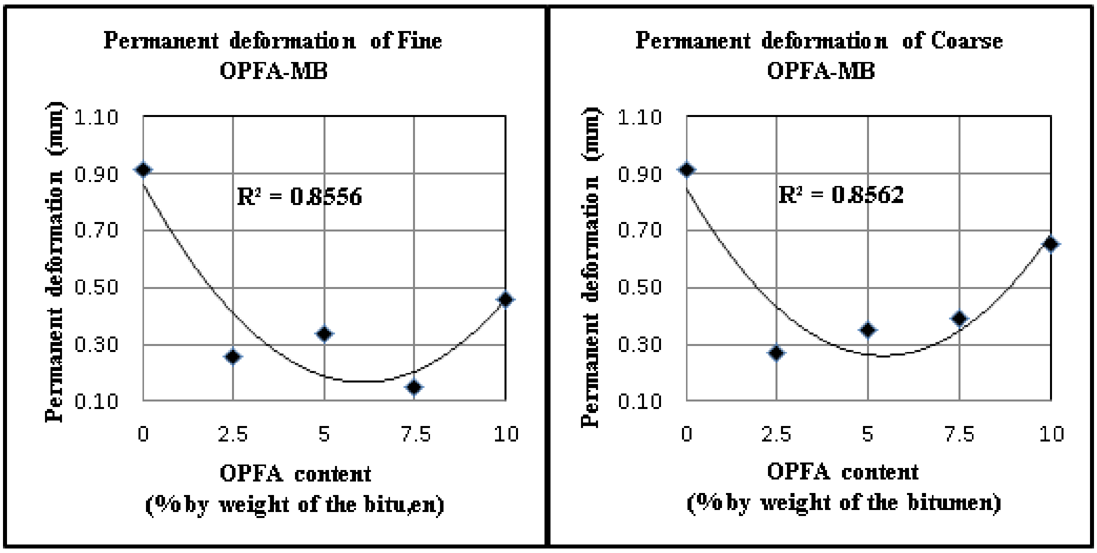


Figure 3.2. – Regression model for Permanent Deformation

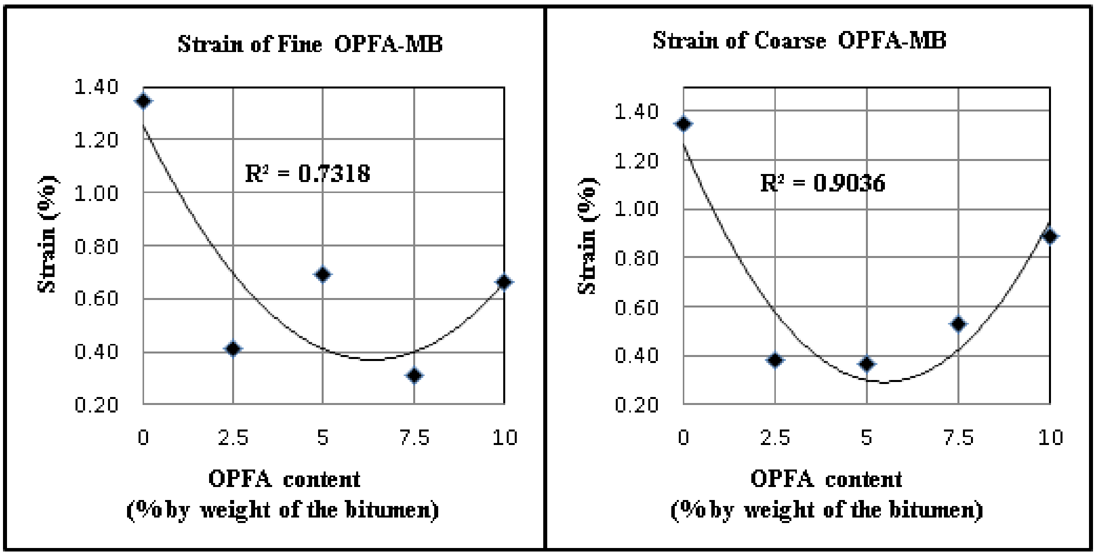


Figure 3.3.. – Regression model of Strain

3.2.4. Wheel Tracking test

Permanent deformation or rutting was also measured by using the wheel tracking test. Test was conducted by using Wessex Wheel Tracker and carried out at temperature 50°C, with 18.4 kg of load and 1000 cycles. Summary of test results are given in Table 3.12.

Table 3.12: - The results of Wheel Tracking test

Binder	Specific Gravity	Sample thickness (mm)	Number of cycles	Rut depth (mm)
Base bitumen	2.19	55	1000	6.6
OPFA-MB 2.5% F	2.17	56	1000	4.4
OPFA-MB 5% F	2.19	55	1000	4.2
OPFA-MB 7.5% F	2.18	55	1000	4.2
OPFA-MB 10% F	2.24	59	1000	4.4
PG 76 - 22	2.18	60	1000	1.8
OPFA-MB 2.5% C	2.23	61	1000	5.9
OPFA-MB 5% C	2.24	62	1000	5.2
OPFA-MB 7.5% C	2.17	60	1000	4.6
OPFA-MB 10% C	2.19	60	1000	5.2

The relation between sample thickness and rut depth is analyzed by using Equation 3.1. It is found that the relation of both parameter is very weak as shown by the coefficient of correlation R which is only 0.2514. However, rut depth of both Fine-OPFA-MB and Coarse-OPFA-MB show logical results in relation to OPFA content. The higher percentage of OPFA content the lower of rut depth value except for 10% Fine OPFA-MB and 7.5% Coarse OPFA-MB. The value of coefficient of deformation R^2 is 0.8271 and 0.9796 for Fine and Coarse OPFA-MB respectively and the coefficient of correlation R is 0.9095 for Fine OPFA-MB and 0.9697 for Coarse OPFA-MB as shown in Figure 3.4 regression model for Fine and Coarse OPFA-MB,

The value of coefficient of determination, R-square, and coefficient of correlation, R, show the significant influence of the OPFA content to the OPFA-MB binder to the rut depth of the SMA-14 mixtures. Compared to the SMA-14 mixture using base bitumen binder, all SMA-14 using OPFA-MB binder have lower rut depth value even though they are higher than rut depth of SMA-14 using PG 76-22 binder.

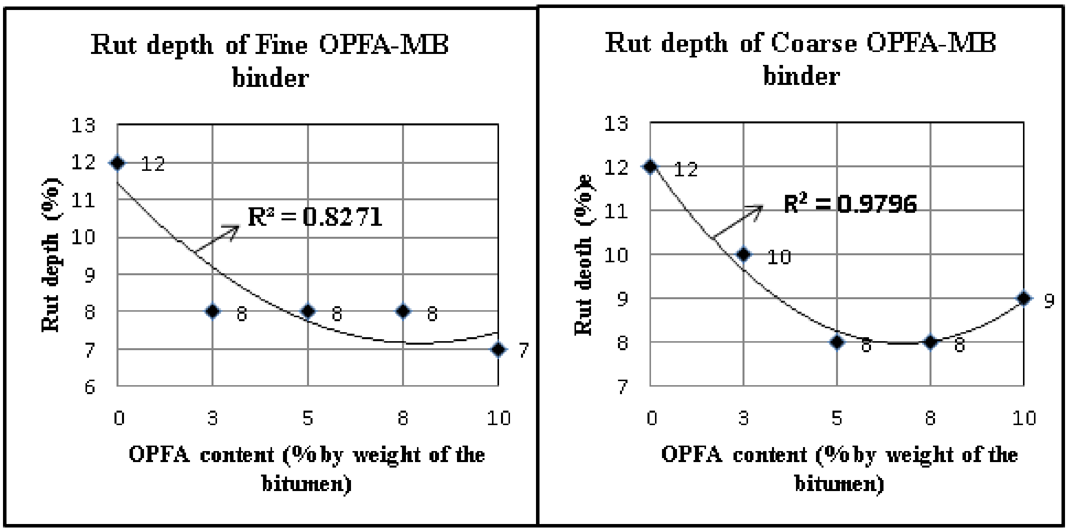
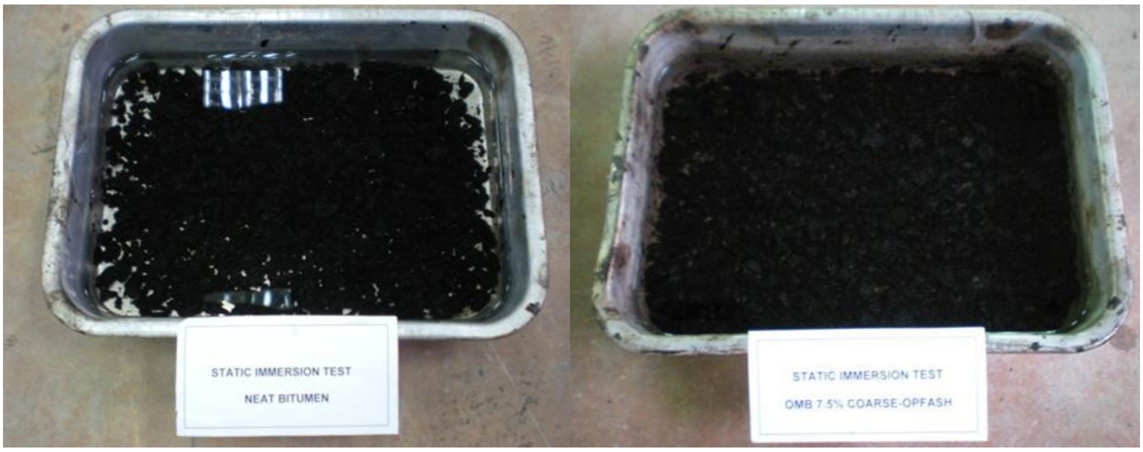


Figure 3.4 - Regression model of wheel tracking test for Fine & Coarse-OPFA-MB binder

3.2.5. Static Immersion and boiling water test

The results of static immersion test show that either un-compacted SMA-14 mixture using base bitumen or OPFA-MB binder possessed good adhesion. After 48 hours immersed into distillation water at temperature 25°C, the percentage of the aggregate in the mixtures using base bitumen and OMB binder remained coated was 100% as shown in Fig. 3.5a and 3.5b.



(a) (b)

Figure 3.5 - Static-immersion test of base bitumen (a) and 7.5% C-OPFA-MB (b) (after 48 hours)

In boiling water test the similar result is found as the one of static immersion test. The test results show that the base bitumen was slightly loose from the aggregate but there were more than 95% still coated aggregate. OPFA-MB binders still remained coated after observation. Fig. 3.6 shows the results of boiling water test for 2.5% Fine and Coarse OPFA-MB. The test results of static-immersion and boiling water showed that bitumen modified with OPFA had a good adhesiveness.

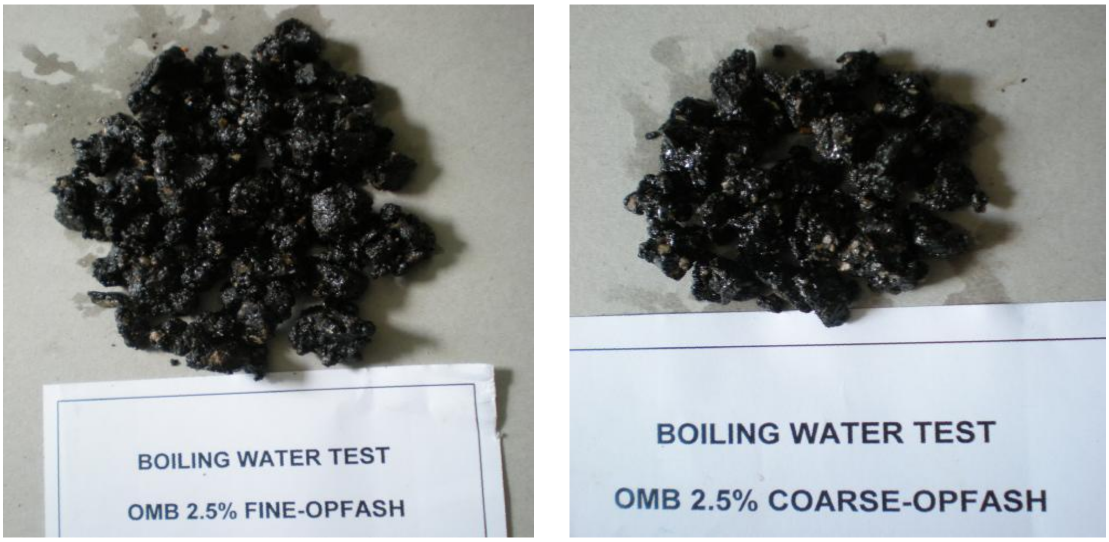


Figure 3.6. - Observe boiling water test for 2.5% F-OPFA-MB (left) and for 2.5% C-OPFA-MB (right)

3.2.6. Drain-down test

Malaysian Standard Specification for Road Works [19] requires the maximum binder drain-down from the loose mix is 0.3% at the test temperature. The test results of drain-down are shown in Table 3.13 and regression model of the statistical analysis is given in Fig. 3.7..

Table 3.13: - The drain-down test results

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

Drain-down of both base bitumen and all of OPFA-MB as well as PG 76-22 binder fulfilled the required specification. The percentage of the OPFA-MB binder which is drained-off from the basket is lower than that of base bitumen. Regression model also showed that the OPFA content in the bitumen significantly influence the adhesion of the OPFA-MB binder. The results of the drain-down test strengthening the results of static immersion and boiling water test, that OPFA-MB binder has good adhesion to the aggregate.

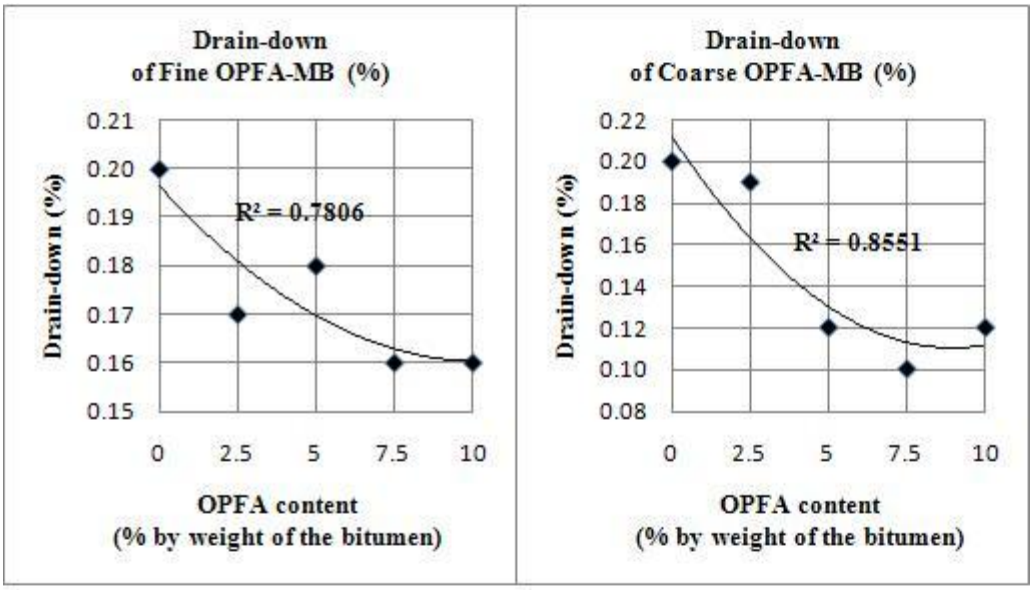


Figure 3.7. - Regression model of drain-down test results

3.2.7. Scoring of the overall test results

From the overall test results and analysis above, by using score of the test results it can be made conclusions the OPFA content which is most feasible to be used as a bitumen modifier. The result of scoring as shown in Table 3.14, 5% Fine-OPFA is in first rank followed by 7.5% Fine-OPFA in second rank, and the next in sequence is 2.5% Fine-OPFA, 7.5% Coarse OPFA, and 10% Coarse OPFA in the third rank, and 2.5% Coarse OPFA and 5% Coarse OPFA in fourth rank. The scoring result suggest that 5% Fine-OPFA and 7.5% Fine-OPFA is the most feasible to be used as bitumen modifier.

Table 3.14. - Scoring of the overall test results

Type of OPFA-MB	**Test number**							**Score**	**Rank**
	1	**2**	**3**	**4**	**5**	**6**	**7**		
2.5% Fine	-	√	-	-	-	-	-	1	-
5% Fine	√	-	√	√	-	√	-	4	1
7.5% Fine	-	-	-	√	√	√	-	3	2
10% Fine	-	-	√	-	-	-	-	1	-
2.5%Coarse	-	-	-	-	-	-	-	0	-
5% Coarse	-	-	-	-	-	-	-	0	-
7.5%Coarse	-	-	-	-	-	-	√	1	-
10%Coarse	-	-	-	√	-	-	-	1	-

Note:1.Resistant to high temperature rutting; 2. Resistant to intermediate temperature fatigue cracking; 3. Resistant to low temperature thermal cracking; 4. Marshall stability; 5. resilient modulus; 6. Creep test; 7. Wheel tracking rutting test; 8. Adhesion test.

4. CONCLUSIONS

From the results as obtained in this study, the following conclusions can be drawn.

1. OPFA-MB can resist rutting at high pavement temperature 70°C, intermediate pavement temperature fatigue cracking at 20°C, and low pavement temperature thermal cracking at -15°C.

2. Using 5% Fine-OPFA-MB as binder, stone mastic asphalt (SMA-14) mixtures, exhibit have resistance to high temperature rutting, resistance to low temperature thermal cracking, the Marshall stability exceed the minimum specification requirement, and also can minimize strain, which in turn it can minimize permanent deformation or rutting.

3. OPFA–MB also exhibits a good adhesion to the aggregate.

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