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Rutting and Moisture Damage Evaluation of Warm Mix Asphalt Incorporating POFA Modified Bitumen

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Abstract*: The unwanted disposal Palm Oil Fuel Ash (POFA) can be minimised through its application in road construction. Available literatures have shown that POFA improves the performance of hot mix asphalt (HMA), however, its application in warm mix asphalt (WMA) remains unexplored. This study was carried out to investigate the performance of WMA with POFA modified bitumen. In this study, Five percent POFA and 0.75% Evotherm is blended with 60/70 PEN grade bitumen to produce warm POFA modified bitumen (B3). The B3 binder is subjected Fourier Transform Infrared spectroscopy (FTIR), Atomic Force Microscopy (AFM), and Contact angle measurements to understand the effect of this modification at microstructural level. Also, the binder is used in preparing dense graded asphalt concrete (AC14) at 140/130 ℃ mixing/compaction temperatures rspectively. Mixture performance tests such as Marshall flow and stability, dynamic creep, Asphalt Pavement Analyser (APA), tensile strength ratio, and boiling water tests were used to examine the resistance of B3 binder to rutting and moisture damage. Results from dynamic creep and APA test shows that the WMA mixtures possess 30% improved rutting resistance than the conventional HMA. On the contrary, the WMA sample parade lower resistance to moisture damage by 10% as revealed by the tensile strength ratio test. All the tested samples satisfied the specification limits for AC14 mixture, thus alleviating any concern regarding the moisture damage vulnerability of WMA mixtures.

***Keywords* : Wet Process, Evotherm, Stripping, Atomic force microscopy, Palm oil fuel ash.**

I. INTRODUCTION

Warm mix asphalt (WMA) is a sustainable paving technology that was developed in Europe and now applied all over the world. It is a technology used by the HMA industry to reduce the temperature for mixing, placing, and compaction of asphalt mix. This is achieved by incorporating additives that lowers the bitumen viscosity or expands its volume which in turn helps the aggregates to get completely coated with bitumen at temperatures lower than HMA [1], [2]. WMA technology has been successfully demonstrated on dense-graded mixtures, stone mastic asphalt, as well as mixtures with recycled asphalt pavement (RAP). In fact, it offers potential for essentially any type of mix [3], [4]. Although the main aim of using WMA is to reduce production temperature and emission of greenhouse gas (GHG); there are lots of other direct and indirect benefits as a result. Direct benefits include 30 - 50% reduction in energy (fuel) consumption during asphalt production, reduction in GHG (CO2, CO, NOx and SO2), fumes and odours to the environment. It also reduces the shear resistance (workability) and compaction of the HMA and enhance pavement performance. Some of the indirect benefits of WMA are reduction in short term aging of binders, early opening of the road to traffic, and the workers are given a safer work setting due to the lower emissions during paving. Moreover, WMA can be utilised for longer hauling distance and extended paving season since the cooling rate and gap between paving and ambient temperatures is less, higher fatigue cracking and dynamic modulus rutting parameter than HMA [5]–[9]. Fig. 1 provides a pictorial comparison of HMA and WMA. Moisture damage remains a major concern affecting the performance and durability of flexible pavements thus making water as the number one enemy of our roads. The Infiltration of water into asphalt mixtures results in two failure modes, namely adhesion and cohesion failures. Adhesion failure (stripping) is due to binder film stripping away from the aggregate surface, while cohesion failure is caused by failure within the bitumen. WMA being produced at lower temperature than HMA is more susceptible to adhesion failure at the binder-aggregate interface. A typical stripping failure involves the gradual loss of strength over time, which causes various surface deformations like rutting, corrugation, shoving, ravelling, cracking, etc [10]. To prevent this, anti-stripping agents are normally incorporated during asphalt production. The most commonly used anti-stripping additives are hydrated lime and ordinary portland cement (OPC). Others include fly ash, and liquid anti-stripping agents like amines, di-amines, and liquid polymers. Although contractors prefer using liquid anti stripping agents because it is easy use; many department of transportation (DOT) agencies prefer hydrated lime because of its excellent performance and ease of validating the use of the material.

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However, hydrated lime is relatively expensive when compared with OPC or waste products like fly ash and Palm Oil Fuel Ash (POFA).
Despite the numerous advantages of WMA over HMA, researchers have pointed out that WMA mixtures are more vulnerable to moisture damage than HMA. This is due to incomplete drying of the aggregates which results in having a trapped film of water at the binder-aggregate interface [11]. As such, this research intends to investigate the moisture damage performance POFA modified bitumen in WMA. The study is aimed at determining whether the addition of POFA in bitumen (wet process) will counter the potential adhesive failure WMA. Literatures have shown that POFA modified bitumen provide better aggregate coating and resistance to adhesive failure than the unmodified one. It also reduces temperature susceptibly of the bitumen, rutting, fatigue, and thermal cracking of the mix [12]–[14]. More on the prospects of POFA in asphalt mixtures are discussed below.

A. *Wet Process*

Rusbintardjo [15] explored the feasibility of using POFA as a bitumen modifier for stone mastic asphalt, 80/100 penetration bitumen was modified with various POFA size and percentage. Consistency test results show that all POFA modified bitumen were not susceptible to temperature variations. Results from rheological test results show that 5% of fine POFA size can resist thermal cracking at -15°C, fatigue cracking at 20°C, and rutting up to 70°C. Furthermore, static immersion test, boiling water and drain-down test result show that POFA modified bitumen provide better aggregate coating and resistance to adhesive failure than the unmodified bitumen. Lastly, its application in SMA-14 results in having higher marshal stability values than the minimum requirement. The study concludes that POFA is feasible to be used as bitumen modifier. Similarly, Hainin et al. [16] studied the influence of POFA on improving the aging resistance of bitumen. Aging of bitumen damages the bitumen-polymer network structure, degrades the modifiers, and change the properties of a binder [17]. The study found that addition of POFA reduces the temperature susceptibility of binders, which in turn increase the rutting resistance of the bitumen. On the contrary, a study by Akbar [18] found that POFA is not suitable in bitumen modification. This is because the addition of 5% POFA to 40-50 PEN bitumen only makes the bitumen to become stiffer through increase in penetration value without improving the softening temperature. Also, rolling thin film oven (RTFO) and pressure ageing vessel (PAV) test results also suggest that the modified binder is susceptible to both short-term and long-term ageing.

B. *Dry Process*

Borhan et al. [19] investigate the mechanical properties of POFA modified asphalt mixtures and were compared with the conventional mixture. Asphalt concrete mixes having different percentages of POFA (0, 1, 3, 5 and 7%) as an additive of the mineral filler were prepared. The samples were characterized using the Marshall stability, resilient modulus, static creep, dynamic creep, and fatigue test. The resilient modulus, Marshall stability values were found to be generally higher than that of the conventional mixture. The presence of POFA also increased the elastic modulus and stiffness of the mix, this is attributed to the pozzolanic cementing property of POFA. Similarly, the fatigue life of the mix was significantly improved at least twice the fatigue life of the control HMA. The replacement of the mineral filler by POFA can reach up to 5% without impairing the performance of the asphalt concrete mix. Similar result was reported by Rusbintardjo et al. [13] where POFA was used as a bitumen modifier (not as filler replacement). This suggest that irrespective of the POFA addition method used, the performance of the mix is improved. In a similar study carried out by Ahmad et al. [20] to investigate the use of POFA as a filler in asphalt pavement, where (0, 3, 5, 7 and 10%) POFA passing 75μm was incorporated into a dense graded ACW20. The samples were analysed using Marshall stability and resilient modulus. Marshall test result indicates that the addition of POFA improves the stability of asphalt mixture. While the best resilient modulus result was obtained at 3% POFA. Thus, the study further proves that POFA can be used as a filler material in asphalt mixes. In the same vein, Marshall and indirect tensile test were used in examining the performance of POFA modified asphalt mixtures. The study found that the mixes have more stability and flow values when compared with the control samples. Also, better indirect tensile strength (ITS) values were observed when 5% POFA was used as filler, this indicates that the mix is capable of resisting fatigue, rutting, and moisture susceptibility more than the unmodified AC14 mix [14]. From the above literatures on POFA modification, it shows that POFA improves the performance of asphalt mixes. Therefore, this research will incorporate it into WMA and its performance will be examined. Another reason why POFA may produce a better performance in WMA is because of its high pozzolanic property. It is this pozzolanic property that made POFA to be used in replacing OPC when producing concrete cement structures. When POFA comes in contact with water and cement, it produces a mixture with more binding property than OPC. This give POFA modified concrete cement to have less water permeability [21], [22]. Since the aggregate in WMA are at incomplete dry state, then POFA may react with the water to increase the binding property of the asphalt to aggregate and reduce the permeability of the asphalt mixture. Finally, reviewing the available literatures on POFA, it shows that the application of POFA in WMA is still missing, thus another knowledge gap has been identified.

Fig. 1. Comparison of fume emitted by WMA and HMA at their respective production temperatures [23].

II. MATERIALS AND METHODS

A. Materials

i. Bitumen

Two types of bitumen B1 and B2 comparable with 60/70 PEN grade bitumen is obtained from Kemaman Bitumen Company (KBC). B1 will serve as control while B2 will be modified with POFA to produce B3, Table 1 presents the properties of the binders. It can be observed that B2 is one grade higher than B1, this is to counter the tendency for increased rutting susceptibility of WMA due to decreasing production temperatures as recommended by Hurley & Prowell [8].

Table 1: The bitumen properties

Binder Type	Property						
	Penetration (dmm)	Softening Point (°C)	Viscosity (cP) at		G*/sin δ > 1 kPa	Ductility (cm)	Elastic Recovery (%)
			135°C	165°C			
B1	63	50	700	200	70 °C	119	14
B2	68	64	1400	400	76 °C	77	34

Table 2: Chemical composition of POFA [24]

Composition	Silicon Dioxide	Aluminum Oxide (Al2O2)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Ferric Oxide (Fe_2O3)	Potassium Oxide (K2)	Sulphur Trioxide (SO3)	Sodium Oxide (Na_2O)
Value (%)	43.6	11.4	8.4	4.8	4.7	3.5	2.8	0.4

ii. Palm oil fuel ash

POFA is a by-product of palm oil mill or the ash from burning mesocarp of fruitlets of the palm oil fruits. The black waste material was obtained from Alaf palm oil mill Johor, Malaysia. The material was oven dried at 100℃ for 24 hours before grinding in the Los Angeles abrasion machine (LAAV) to obtain finer particle sizes. Fig. 2 shows a picture of the POFA used for the study while Table 2 presents the chemical composition of the material.

Fig. 2. Palm oil fuel ash

iii. Evotherm

Evotherm warm mix additive produced by Ingevity from USA will be used in reducing the asphalt production temperature, it is a brown oily liquid that is partially soluble in water. Fig. 3 displayed the Evotherm additive.

Fig. 3. Evotherm warm mix additive

iv. Aggregate

Fresh granite aggregate was obtained from Hanson quarry Johor, Malaysia. The aggregates were sieved to obtain a dense graded gradation with the nominal maximum aggregate size of 14 mm. The aggregate gradation and the proposed mix gradation are shown in Table 3. Although the Malaysian Public Works Department (PWD) specification recommends replacing the mineral filler with 2% hydrated lime or ordinary portland cement (OPC) as anti-stripping agent, this research will not add any of the above additives. This is because moisture damage evaluation of the POFA modified bitumen is part of what the study aimed to achieve.

Table 3: Gradation limit for dense graded asphalt concrete mix (AC14)

BS Sieve Size (mm)	Gradation limit (%)	Selected Mix Gradation (%)
20.0	100	100
14.0	90 - 100	95
10.0	76 - 86	81
5.0	50 - 62	56
3.35	40 - 54	47
1.18	18 - 34	26
0.425	12 - 24	18
0.150	6 - 14	10
0.075	4 - 8	6

B. Binder Preparation

Five percent POFA (addition by weight of bitumen) is blended with B2 at 160 °C for one hour using high shear mixer at 4000 rpm. At the end of one hour, 0.75% Evotherm chemical is added to the blend at 160 °C for five minutes. The size and amount of POFA was selected based on the recommendations of Rusbintardjo et al. [13], while the optimum Evotherm dosage was determined after conducting trial and error at 0.3 – 0.75% recommended by the Evotherm manufacturer.

The produced binder (B3) is subjected to physical, rheological, and microstructural tests to evaluate and compare its properties with that of B1.

C. Mixture Preparation

HMA samples were produced using B1 bitumen at 165℃ and 145℃ mixing and compaction temperatures respectively, this conventional mixture will serve as the control sample. The asphalt production temperature used were determined from the viscosity-temperature graph. As for the WMA, the warm POFA modified binder (B3) was used to prepare asphalt mixture using Marshall mix design. The sample were mixed at 140 ℃ and compacted 130 ℃.

D. Tests

In this research microstructural tests were first conducted on the binders to compare the morphology of B3 and B1. This will help in having a better understanding of the mixture test results. They include Fourier Transform Infrared (FTIR), Atomic Force Microscopy (AFM), and contact angle. Mixture test conducted on compacted samples include, Marshall test, dynamic creep, asphalt pavement analyser (APA) for rutting. Furthermore, boiling water test, tensile strength ratio test, and APA-moisture damage test were carried out to examine moisture susceptibility of the WMA. The tests were conducted in accordance with the Malaysian PWD specification, American Society for Testing and Materials (ASTM), and American Association of State Highway and Transportation Officials (AASHTO) manuals.

i. Fourier Transform Infrared

FTIR is an analytical technique used to identify polymeric, organic and inorganic compounds present in a material. Chemical changes in B1 and B3 were investigated using Attenuated Total Reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy. In this study, the bitumen sample is placed on the ATR prism, an infra-red light with 4000 to 500 cm wavelength is passed to the bitumen sample. The amount of energy absorbed by the bitumen at various wavelength is recorded by a computer which transforms it into peaks and is presented as plots of intensity against wavenumber. Figure 4 presents the ATR-FTIR equipment used for the study.

Fig. 4. ATR-FTIR equipment

ii. Atomic Force Microscopy

Theoretically, the adhesion rate between bitumen and aggregate in a mixture depends on the surface roughness of the bitumen to stick and coat the aggregates [25]. AFM test was conducted to examine the changes occurring due to the addition of POFA. The test will provide information relating to the binders increase in stiffness, adhesion, and other features at nano scale. More details on the process of conducting this test is reported in the work of Al-Rawashdeh & Sargand [26], and Hussein [27].

iii. Contact angle

One of the main concerns relating to the durability of WMA is its potential for moisture induced bond failure. This is primarily due to the lower mixing temperatures involved which ends up trapping a thin water layer at the aggregate – bitumen interface. It is the presence of water either contained within the aggregate particle or external to the bitumen coated particle is most likely the main reason for failures at this crucial interface [28], [29]. The addition of POFA or Evotherm additive can affect the bonding of a bitumen, as such sessile drop technique is used to forecast the adhesion characteristics of the binders [30]. The test was conducted by a dropping 2mm of distilled water on a bitumen coated glass plate, the angle formed by the distilled water on the bitumen surface is calculated using video contact measuring device (VCA optima) [31], [32]. Fig. 5 shows the contact angle measuring process.

(a) (b) (c) (d)

Fig. 5. Contact angle measurement process

iv. Marshall Test

Mix design is the design of bituminous mixture in order to achieve adequate binder content for durability, adequate stability to support traffic load, sufficient air voids, and sufficient workability to placement of the mix. Marshall samples were prepared by heating 1200g of combined gradation of coarse, fine and mineral filler aggregate in the oven at 165℃ mixing temperature, the heated aggregates were dry mixed for 5 seconds before a pre-heated B1 binder is added. The aggregate and the bituminous material were thoroughly mixed for 60 s. Four specimens were prepared for each bitumen content between 4.0% to 6.0% at increments of 0.5 percent. The asphalt mix is then transferred into a pre-heated mould and compacted at 75 blow per face using a Marshall compactor [33], [34]. The compacted sample is removed from the mould after it has sufficiently cooled to room temperature, and testing is completed within 24 hours from sample prepation to testing. Tests conducted here include determination of the bulk specific gravity, stability and flow in accordance with ASTM D 2726 and ASTM D 1559 specifications respectively. After completion of the test, specific gravity and void analysis were carried out to determine the air void percentage in compacted mix (VIM), voids filled with bitumen (VFB), and so on [35], [36]. As for the, WMA, the samples were produced were mixed and compacted at 140℃ and 130℃ respectively. The production temperature was selected based on the manufacturer's recommendation and practiced by Hamzah et al. and Xie et al. [37], [38].

v. Dynamic creep

Dynamic creep test is used to establish the resistance of HMA and WMA samples to permanent deformation by cyclic compression test.

The test was carried out using Universal Material Testing Apparatus shown in Fig. 6 in accordance with the British Standards procedures [39]. At the end of the test, the strain (%) and displacement (mm) versus load cycles graph is generated, and the creep stiffness modulus is calculated based on the strain and deformation data produced.

Fig. 6. Dynamic creep test set-up

vi. Asphalt pavement analyzer for Rutting

APA test for rutting covers the determination of a mixtures' susceptibility to permanent deformation under dynamic load application. The test tries to reveal the rut depth on a sample after repetitive traffic load application. In this test, gyratory compacted samples having 6 to 8% air void content were produced. The samples were conditioning in the APA machine at 60°C for four hours prior to testing. During testing, 8000 cycle of APA load and pressure is applied and the total deformation on each sample is recorded by the computer system attached to the machine. The APA test set-up is depicted in Fig. 7.

Fig. 7. APA test set-up

vii. Boiling water

Boiling water test is used to rapidly assess the loss of adhesion in paving mixture through visual inspection of the percentage of stripped aggregates after immersion in boiling water. In this test, an uncompacted bituminous mixture is first prepared and heated in distilled water for 10 mins, the amount of bitumen coating retained on the aggregates is visually observed and rated as above or above 95% coating retained. For the sake of comparison, a similar amount of fresh bituminous coated sample is placed into a separate glass beaker covered with unheated distilled water for 10 min, the water is then decanted, and the mixture is emptied onto a white towel in accordance with ASTM D3625/D3625M manual.

viii. Tensile strength ratio (TSR)

Tensile strength test is the most widely used test employed by paving agencies to determine the moisture susceptibility of asphalt mixtures. In simple terms, the test measures the ratio of diametric strength of a cylindrical sample after moisture conditioning to that before moisture conditioning. This test was employed to determine whether the incorporation of POFA can counter the moisture susceptibility of WMA. For this research, the TSR test was conducted according to ASTM 4867/D4867M-09 guidelines.

ix. Asphalt pavement analyzer for moisture damage

APA test for moisture damage covers the determination of a mixtures' susceptibility to moisture damage under repetitive traffic loading. In this test, gyratory compacted samples were partially saturated with distilled water by applying a vacuum pressure of 70 kPa for seven minutes. The vacuum pressure is removed and the sample is left submerged in the water for another five minutes. Bulk specific gravity of the sample is determined using ASTM D2726 procedure and the volume of water absorbed is calculated by subtracting the mass of saturated surface-dry sample prior to vacuum saturation from the mass of saturated surface-dry sample after saturation. After saturating the samples to 55 – 80% degree of saturation, the samples are conditioned in water bath for 24 hours at 60°C. The test is conducted in the APA machine in the presence of hot water maintained at 60°C until 8000 cycles is achieved. The average rut depth at the end of 8000 cycles is recorded by the computer system attached.

III. RESULTS AND DISCUSSION

This section presents the binder and mixture properties of the POFA modified bitumen in WMA. The results will be compared with that of the control B1 bitumen to determine the effect of the additive. Table 4 present the consistency test result conducted on the warm POFA modified binder. It shows that B3 displayed decrease in penetration and ductility values by 55% and 80% respectively, while softening point, viscosity and elastic recovery significantly increased. The outcome of these tests suggests that POFA modification thickens the bitumen. Microstructural examination presented in Fig. 8, 9, and 10 reveals that the average contact angle increased from 93 to 101°. This indicates that the addition of 5% POFA slightly enhance the adhesion property of the binder by 9%. The FTIR revealed a structure that is similar to the B1, while AFM average roughness value for B1 and B2 are 4.496 and 4.686 nm respectively.

Table 4: Physical and rheological properties of B1 and B3

Binder Type	Penetration (dmm)	Softening Point (°C)	Viscosity (mPa.s) at		Ductility (cm)	Elastic recovery (%)
			135°C	165°C		
B1	63	50	700	200	119	14
B3	28	64	1970	500	23	34

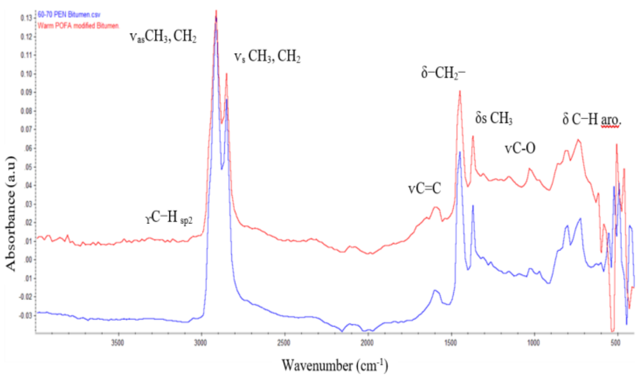
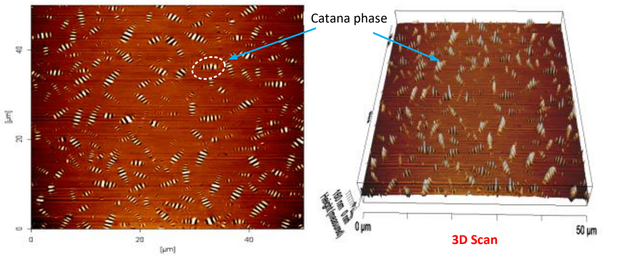
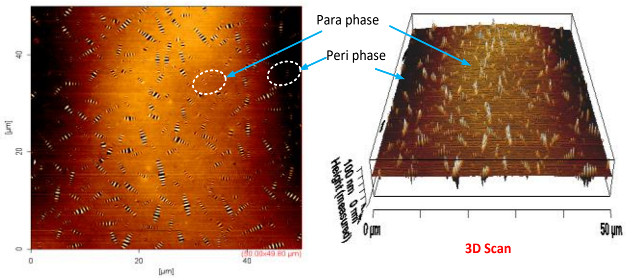


Fig. 8. FTIR result

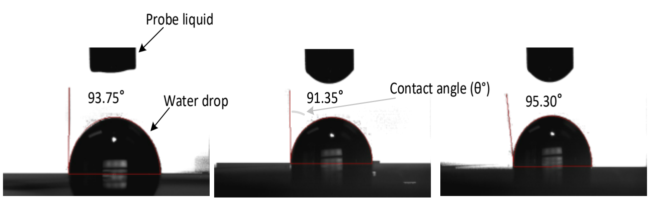


(a)

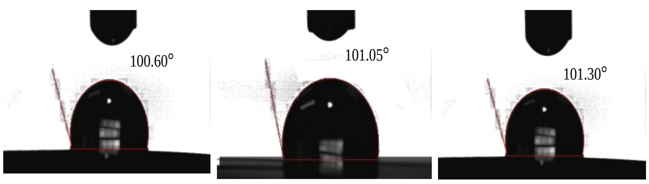


(b)

Fig. 9. AFM scan (a) B1 (b) B3



(a)



(b)

Fig. 10. Contact angle result for (a) B1 (b) B3

A. Marshall

Marshall test result produced with B1 is presented in Fig. 11. The figure displays plots of Marshall stability, flow, void in total mix (VTM), void filled with bitumen, stiffness and density against 4 – 6% range of bitumen content. These plots were used in selecting the optimum bitumen content in accordance with the Malaysian PWD specification for unmodified bitumen. The mean OBC is determined by averaging five optimum bitumen contents obtained from the curves. An OBC of 5.2% by weight of aggregate was obtained. Verification samples were also prepared using the obtained OBC to ensure that the desired mix design parameters were met. The same OBC of 5.2% is used to produce the WMA samples using the warm POFA modified bitumen (B2) as recommended by the National Centre for Asphalt Technology (NCAT) [8]. Table 5 presents a combined summary of the Marshall results for HMA and WMA samples. One of the important parameters in Marshall test is the stability, it is the maximum stress (load) a mixture can resist before failure. While flow represents the corresponding maximum strain (deformation) of the mixture at the maximum stress. The stability results show that the WMA asphalt mixture possess lower stability than the HMA. This is due to the reduction in asphalt production temperature thereby decreasing its load carrying capacity by four percent. Similar trend was observed in the flow values. Despite this reduction, the values are well above the minimum stability requirement set by the Malaysian PWD. In the same vein, a decrease in mixture stiffness was observed on the WMA mixtures compared to the HMA mixtures. An unexpected result was observed in the amount of air void present in the WMA, the air void percentage was found to be below the recommended 3-5%, the lack of sufficient air voids may induce rutting/bleeding during the pavement in service life.

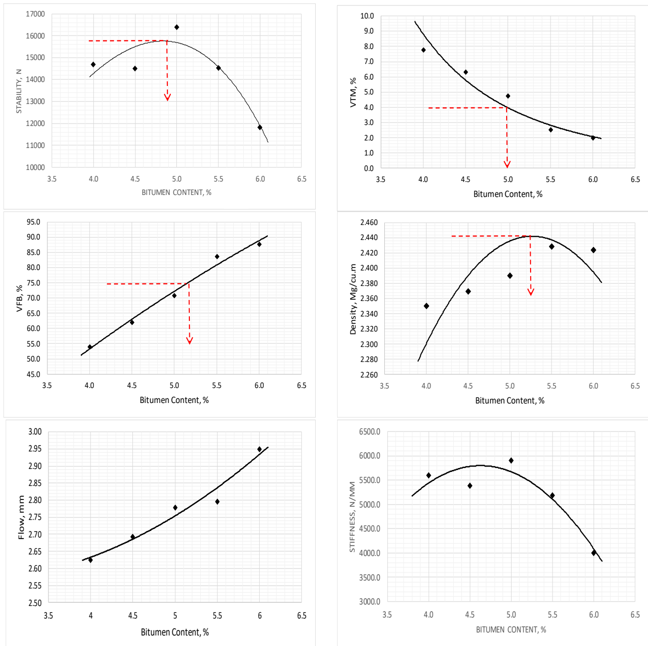


Fig. 11: HMA Marshall test results

Table 5: Summary of Marshall Test result for HMA and WMA

Parameter	Values		Malaysian Specification:	
	HMA	WMA	Unmodified Bitumen	Polymer Modified Bitumen
Bitumen content (%)	5.2	5.2	4.0 – 6.0	4.5 – 6.5
Stability (N)	15,200	14,640	> 8,000	> 13000

Flow (mm)	2.9	4.25	2.0 – 4.0	2.0 – 5.0
Stiffness (N/mm)	5,240	3,445	> 2,000	> 2,600
VTM (%)	4.10	2.60	3.0 – 5.0	3.0 – 5.0
VFB (%)	77	75	70 – 80	70 – 80

B. Dynamic Creep

The most significant result obtained from the creep test is the strain or rate of permanent deformation due repetitive load application. Fig. 12 explains the cumulative axial strain curves expressed as a function of the number of load applications (cycles) conducted at 40 °C and 300 kPa stress level. The result shows that the strain gradually develops with increasing number of load repetitions. Also, it can be seen that the HMA parade a higher strain than the WMA mixture. This indicates that POFA modification improved the deformation resistance of the bitumen. The above finding is further confirmed by the ultimate permanent strain on the samples at 3600 cycle, where the HMA and WMA mixtures have permanent strain of 0.67%, and 0.50%. This indicates that the mixture with POFA modified bitumen is the less susceptible to rutting failure as compared with the conventional HMA mixture. This improvement is credited to the creep stiffness modulus (CSM) values of the samples where lower CSM resulted in higher strain percentage. The CSM of HMA and WMA were found to be 446 and 513 Mpa respectively. Similar relationship between CSM and rutting resistance was reported by Azahar et al. [40]. Although, this test can be used to rank or check the suitability of a given mixture, it does not allow making a quantitative prediction of rutting in the field to be made [39]. Thus, this study proceeds by conducting APA-rutting test to quantify the rutting resistance of WMA mixtures.

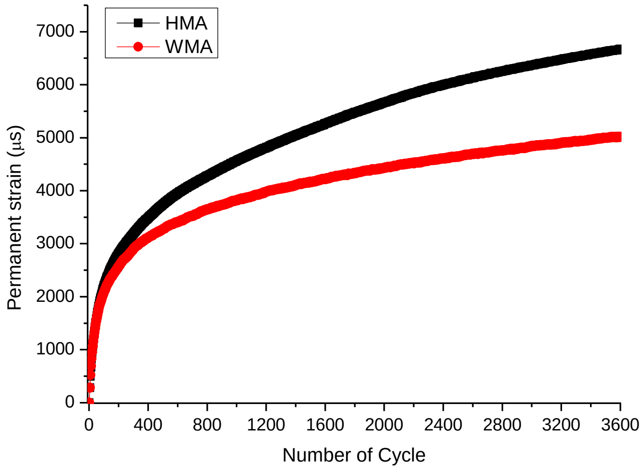


Fig. 12. Scatter plot of strain versus number of cycles @ 40°C

C. APA – Rutting

Rut depth values obtained after the completion of 8000 cycles of loading is presented in Fig. 13. It shows that the WMA mixture showcased an improved rutting resistance than the conventional HMA. Although reduction of production temperature of WMA might increase the rutting potential, but the presence of POFA may tend to negate this to some extent. Nevertheless, the rut depth values are by far below the 7mm rut depth criteria of South Dakota Department of Transportation SDDOT at 8000 cycles. It is surprising that POFA was found to enhance rutting resistance as against its intended purpose of serving as anti-stripping agent. This finding is supported with the microstructural results from Ooi and Ismail [41] where POFA modification was found to improve the thermal resistance.

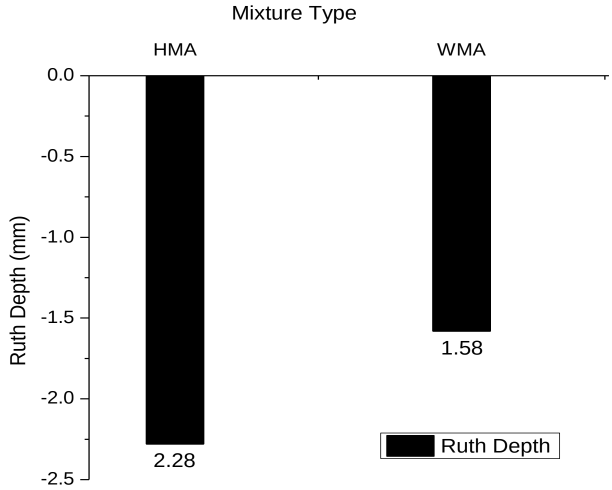


Fig. 13. HMA and WMA Ruth depth at 8000 cycles

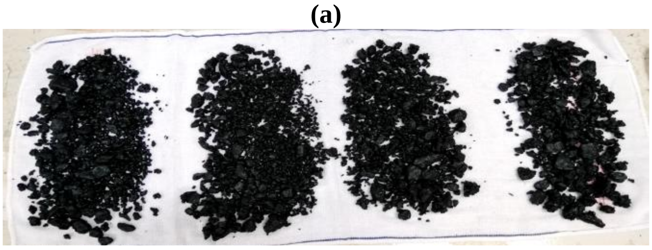
D. Boiling Water

Fig. 14 present the boiling water test result conducted to ascertain the stripping resistance of the mixture. Analyzing the images shows that only the HMA parade minor loss in aggregate coating, but the percentage loss is insignificant to be considered as stripping failure potential of the mix.

On the other hand, the WMA mixture retained 100% of the bitumen coating insinuating that the sample is not susceptible to stripping failure. Based on this test's rating criteria of above or below 95% coating retained, all the tested mixtures were found to be above 95% coating retained. Although this test provides a rapid evaluation of the stripping potential of bituminous mixtures, no significant difference is observed between the tested HMA and WMA samples. Hence, the need for further evaluation before the moisture damage characteristics of warm POFA modified mixture can be clearly understood.

Unheated 1 2 3

(a)



Unheated 1 2 3

(b)

Fig. 14. Boiling water test stripping measurement (a) HMA (b) WMA

E. Modified Lottman Test

Fig. 15 presents the indirect tensile test results of the unconditioned subsets (dry) and the moisture conditioned subset (wet), it can be seen that the moisture conditioned subset has lower ITS than the dry subset, this is due to the influx of water into the sample during the 24-hour conditioning process at 60 ℃ thereby weakening the adhesion/cohesion bond of the sample consequently leading to a reduction in the St values. The WMA samples parade a lower St values when compared to the HMA mixture, this can be attributed to the high stiffness of the binder [40]. Moreover, the average St values of each subset were used to calculate the TSR percentage, it shows that the HMA and WMA samples possess 95% and 85% resistance to moisture damage. Higher TSR values imply better resistance to moisture damage [38]. Although both mixtures satisfied the AASHTO T283 minimum requirement of 80%, the HMA sample performs better than the WMA. Thus, POFA modification does not improve the adhesion performance of the binder. The poor performance of B3 can be attributed to the binder being too stiff, as observed from its penetration value of 28mm and ductility of 23cm, thus the mixture is more likely to fail in cohesion.

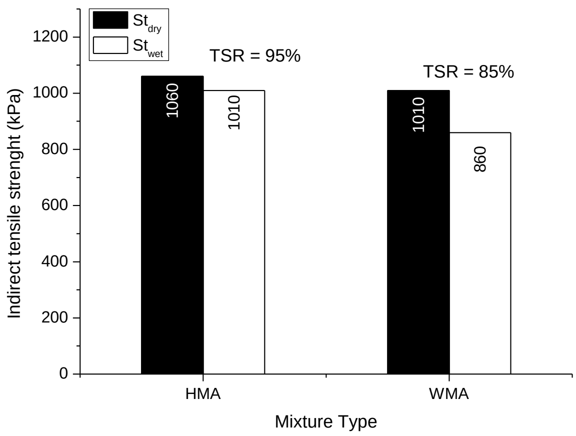


Fig. 15. ITS and TSR results

F. APA Moisture damage

APA-moisture damage test assumes a worst-case scenario of stripping and rutting failures occurring simultaneously under traffic loading and the result is presented in Fig. 16. It shows that the samples deformation increases with increasing number of cycles up to 8000 cycles, the HMA samples displayed lower increase in deformation as compared to the WMA. The total deformation at the completion of 8000 cycles was 3.74 mm for HMA while the WMA samples parade a slightly higher rut depth of 3.78mm. This shows that the lower mixing and compaction temperature does not significantly affect the moisture damage performance of the mixture.

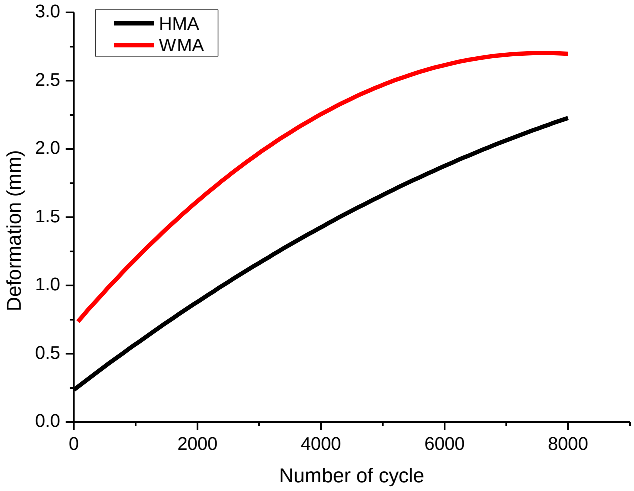


Fig. 16: APA-moisture damage of HMA and WMA.

IV. CONCLUSION

This study evaluates the mixture performance of warm POFA modified bitumen in AC14. The outcome of the binder test conducted shows that penetration and ductility values were significantly reduced, while viscosity was increased by 40%. Contact angle measurement conducted on the binder revealed that POFA addition improved the adhesion property of the WMA by 9%. However, this improvement was not sufficient to improve the mixture performance of the binder in WMA. Marshall test revealed that the WMA have lower resistance to load deformation compared to the HMA but were found to satisfy the Malaysian PWD specification limit for asphalt concrete AC14. T

he result shows that the WMA mixture is not susceptible to stripping failure and adhesion. Surprisingly, warm POFA modified binder mixture displays excellent rutting resistance than its initial purpose of serving as anti-stripping agent for WMA. This led to the conclusion that POFA modified bitumen can be successfully applied in WMA without compromising the mechanical performance of the mix. This study has contributed in having an idea of how POFA modified bitumen will perform in WMA. Also, the 25℃ reduction in mixing and compaction temperature amounts significant reduction in the amount of GHG emissions to the environment as well as significant monetary savings to the paving contractors.

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