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Evaluation on Performance Characteristics of Superpave Asphalt Mix Design under Tropical Climatic Conditions

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Abstract: During the last decade, hot-mix asphalt (HMA) mixture design has undergone major changes with respect to mix design method and mix characterization. Currently in tropical climatic countries, the Marshall mix design method is still used to construct HMA pavements. Therefore, this study was conducted to investigate the performance characteristics of Superpave and Marshall method design HMA mixtures in tropical climatic conditions. Laboratory tests were conducted to evaluate the rutting (permanent deformation) and resilient modulus of different Superpave and Marshall mixes. In addition, dynamic modulus tests by means of the Simple Performance Test (SPT) were also conducted. The relationships between the SPT dynamic modulus test and other performance test results were also examined. It was found that the Superpave-mix design showed far superior performance compared to the Marshall-mix design based on all types of testing in this study. Since the dynamic modulus test provides full characterization of the mix over a broad range of temperatures and loading frequencies, this test is highly recommended for Superpave mixture characterization under tropical climatic conditions.

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***Key words**: Marshall-mix design; Rutting; Superpave-mix design; Simple Performance Test.*

Introduction

Tremendous development in the national infrastructure network over the last decade has led to an increase in road construction throughout Malaysia. Asphaltic roads dominate the overall surfacing types at 87,626 km compared to only 343 km of concrete roads. The other 3,651 km are earth or gravel roads. There are over 16,509 km of federal roads and 104,112 km of state roads [1]. The conventional Marshall-mix design method for hot-mix asphalt (HMA) mixtures has been used for decades by the Malaysian Public Works Department, PWD [2] to construct flexible pavements, following the JKR/SPJ/2008 standard specification. Although these pavements are still in service, a large amount of money is allocated for maintenance work annually due to pavement distress, which sometimes occurs prematurely due to increasing traffic load and wet tropical climatic conditions. Hence it is timely for PWD to initiate a paradigm shift to enhance or adopt a better mix design system for HMA mixtures in Malaysia [3]. Until the early 1990s, the Marshall method was used widely in HMA mixture design. This method does not need expensive equipment and uses a small amount of materials. Although the equipment used in the Marshall method is inexpensive, studies show that the impact compaction is unrealistic compared to gyratory compaction, which simulates the field density about fifty per cent of the time [4].

The Superior Performing Asphalt Pavement (Superpave) was developed in 1993 by the Strategic Highway Research Program (SHRP) and the resulting system contained the following elements; a new grading system for asphalt binder (performance graded (PG) grading system), consensus properties of the aggregate, a new mix design procedure, and a mixture analysis procedure [5]. In recent years, studies have been conducted outside the USA to evaluate the feasibility and performance of Superpave-designed mixtures. For instance, a study was conducted in Taiwan to compare the volumetric and mechanical performance properties of Superpave mixtures and typical Taiwan mixtures (TTM) using the Marshall method [6]. It was found that the binder contents of the Superpave-designed mixtures are lower than the TTM Marshall-designed mixtures, and TTM mixtures exhibit low densification values. In Jordan, a research study proved the superiority of Superpave mixes over Marshall mixes [7]. A study in India showed that the Superpave gyratory compactor (SGC) is capable of achieving a lower air void content than could be achieved by the mechanical Marshall Hammer compactor. The study also found that Superpave mixes have a lower asphalt binder content than Marshall mixes [8].

Khan and Kamal [9] found that Superpave mixtures exhibit better creep resistance compared to Marshall mixtures in flexible pavement in Pakistan. A study was conducted based on the Iraq road specification; the results indicate that the Superpave mixes have a lower asphalt content than Marshall mixes. As a result, Superpave mixes are more economical than Marshall mixes [10]. Jitsangiam et al. [11] investigated the suitability of using the Superpave mix design in Thailand's climatic conditions. It was

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found that the Superpave mixes show far superior performance compared to Marshall mixes based on all types of testing conducted in their study (i.e. resilient modulus test, dynamic creep test, and indirect tensile strength test).

With the successful implementation of the Superpave method worldwide, it is a suitable time for the Malaysian PWD to initiate a paradigm shift to adopt a better mix design system for HMA pavements that suit tropical climate conditions. The primary objective of this study, therefore, is to evaluate the mix properties and performance of both Superpave- and Marshall-designed mixtures using local materials. A comparison between these mixtures was then made using a Simple Performance Test (SPT), dynamic modulus, resilient modulus and wheel tracking tests. However, this study does not consider a low temperature environment because the temperature in Malaysia rarely falls below 30°C in daylight hours and is usually in the range of 35 to 45°C [12].

The research undertaken in this study was divided into three phases. The first phase involved designing the aggregate structures and determining the acceptable parameters for dense-graded mixtures for both mix types. The second and third phases involved using data from phase one to evaluate the above-designed HMA mixtures. Characterization and performance tests were conducted to determine how resistant the above HMA mixes were to permanent deformation. The final phase of the study was to conduct the SPT dynamic modulus tests on all the HMA mixtures. The relationships between the SPT test and other performance test results obtained in the second phase were also examined.

Experimental Design

Phase One: Material Selection and HMA Mixture Design

Binders

As the climatic conditions in Malaysia are fairly consistent throughout the country, the supply of performance graded (PG) asphalt binder in this region is based on higher temperatures. The asphalt binder of Performance Grade (PG) 64 and PG70 are equivalent to Penetration Grade (PEN) 80/100 (B1) and PEN 60/70 (B2) respectively, in accordance with JKR/SPJ/2008-S4. Table 1 shows the properties of the binders used in this study.

Aggregates

Two granite aggregate sources were selected in this study, representing the central and southern parts of Peninsular Malaysia. The granite Quarry Selangor (QS) is located in the central part of Peninsular Malaysia in the vicinity of Kuala Lumpur, and Quarry Johor (QJ) is located in the southern part of Peninsular Malaysia. Aggregate properties were evaluated for compliance with both mix design systems. As stated in JKR/SPJ/2008-S4, only granite aggregates are permissible for use as the asphalt wearing course. Two different gradations with different nominal maximum aggregate size (NMAS) were selected, as shown in Fig. 1 (a and b). To enable a comparison of the volumetric properties and rutting performance to be made between the mixes, the gradations for all mixtures were purposely selected to fall within the upper and lower limits, complying with both Superpave and Marshall grading requirements. A total of 16 mixes were designed, of which eight were Superpave-designed mixes; the remainder were Marshall Mixes.

Marshall mix design

Standard Marshall mix design procedures from JKR/SPJ/2008-S4 were employed to design the HMA mix. For this purpose, 15 specimens of each mix were prepared and compacted to 75 blows per face using the Marshall Hammer. The mixes were compacted directly after mixing and then cooled before being extruded from the mold. The Marshall stability and flow test of each mix type was conducted on compacted Marshall Specimens, as specified in the AASHTO T245 standard. The laboratory measured values were then used for Marshall volumetric analysis. The optimum binder content (OBC) of the mix was estimated corresponding to 4% design air voids. The bulk density, voids-filled with asphalt (VFA), Stability and flow test values were then obtained corresponding to OBC to obtain the values of each mix property and check against the Marshall mix criteria.

Superpave Mix Design

The procedures adopted to develop the Superpave specimens used in this study were in accordance with AASHTO T312 and PP-28-200 procedures. For Superpave-designed mixtures, when blended at OBC, should yield acceptable volumetric properties at 4% air voids based on the established Superpave criteria at the design number of gyrations. The project traffic load chosen in this study was medium to high, which is equivalent to 3 to <30 million ESALs. The Superpave gyratory compactor (SGC) was used to compact the specimens. To achieve the design density of HMA mixtures, a design number of gyrations (N_{des}) of 100 was selected. The compactibility estimation of the mixture was determined at the initial number of gyrations (N_{ini}) after eight gyrations. At 160 gyrations or the maximum number of gyrations (N_{max}), the mixture properties were established as a check to help guard against plastic failure caused by traffic in excess of the design level.

The mix was batched out in appropriate quantities to produce a final mix specimen of approximately 4700 g. A bitumen content of 4% was used for each mix type, starting with the median and at intervals of ±0.5% of the median. Two replicate samples were prepared for each bitumen content. Prior to mixing, aggregates were

Table 1. Binder Properties.

Type	PEN 80-100 (B1)	PEN 60-70 (B2)	Criteria
Penetration at 25°C (0.1 mm)	84	68	
Ring & Ball Softening Point (°C)	43	42	48-56
Rotational Viscosity (original)	0.35 Pa-s	0.45 Pa-s	3 Pa-s Max.
Rotational Viscosity (RTFO)	0.6 Pa-s	0.7 Pa-s	3 Pa-s Max

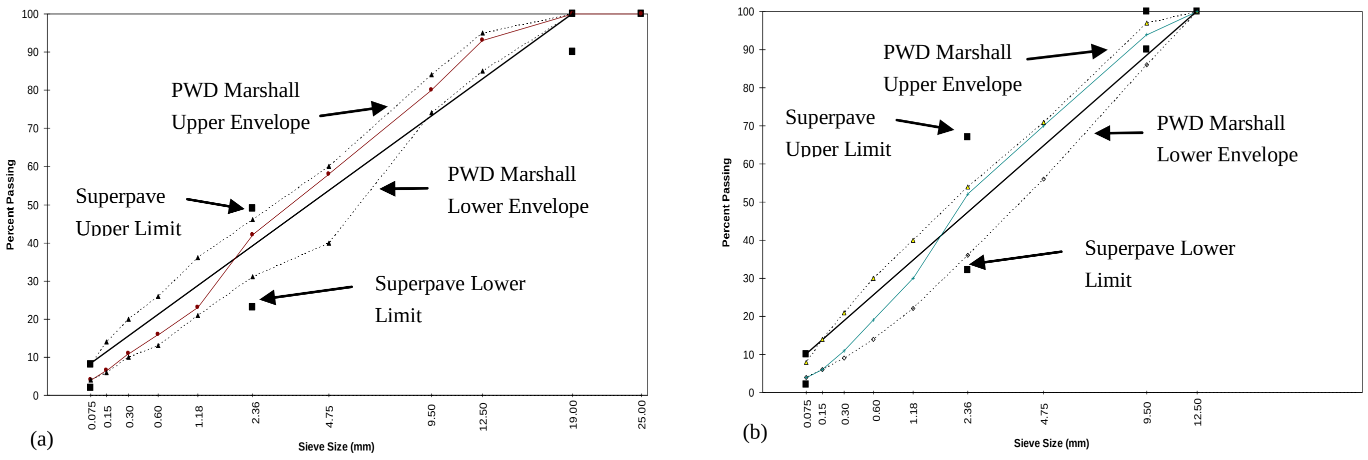

Fig. 1. NMAS (a) 12.4 mm and (b) 9.5 mm Gradations.

heated in an oven set approximately 15°C higher than the mixing temperature for approximately four hours to achieve a uniform temperature. The binder was also heated to mixing temperature to enable a homogenous coating of binder and aggregate in the mixing process. The resulting HMA mix was then placed in a flat pan and conditioned for another two hours at the compaction temperature. Mixing temperatures for B1 and B2 binders were chosen at 150 and 165°C, while the compaction temperatures were 140°C (B1) and 150°C (B2) respectively.

Short-term aging simulates field conditions during mixing and placement, which allows for absorption of the asphalt binder into the aggregate pores. The mix was stirred occasionally in the oven to prevent uneven heating and exposure during the short-term aging process. The SGC mold was also preheated to compaction temperature before compacting the short-term aged mixture at N_{des}. A consolidation pressure of 600 kPa with a speed of 30 rpm was applied to compact the specimen at a 1.25° angle of gyration using the SGC. The dimension of each compacted specimen was 150 mm in diameter with a height of within 110 ±5 mm, depending on the weight of the mixture. The height and number of gyrations was recorded until the compaction process terminated as specified.

The volumetric properties of the HMA mix were calculated based on G_{mb} and G_{mm} to determine the air voids content of the specimens. A water displacement method that conformed to ASTM D2726 was conducted to determine the G_{mb} of the compacted specimens. The minimum loose mix weight required for G_{mm} based on NMAS 12.5 mm and 9.5 mm to be 1500 and 1000 g respectively. The volumetric evaluation consists of voids in the mineral aggregate (VMA), VFA and air voids. The dust proportion is also one of the major components in determining the stability and durability of HMA. The OBC is established at 4% air voids from graphs plotted between the volumetric properties and binder content. The volumetric property data were compared to the Superpave volumetric mixture design requirements. Once the OBC was selected, an additional two specimens were fabricated and compacted to N_{max} at the OBC. The process to determine G_{mb} and G_{mm} was repeated again to ensure that N_{max} did not exceed 98%.

Phase Two: HMA Mixture Performance and Characterization

Wheel Tracking Test

The dry wheel tracking test was conducted using a Wessex wheel tracking device where a mold was fabricated to hold the SGC rut specimen. The height of the SGC rut mold follows exactly the original slab mold of the Wessex wheel tracking device. This is to avoid any inaccuracy during the rutting test. Approximately 3,700 g of Superpave or Marshall mix was compacted to 7 ± 0.5% air voids to make a cylindrical specimen with a diameter of 150 mm and a final height of 65 mm. This was accomplished by putting a given amount of mixture in the SGC mould and compacting to the specified height. The specimens were left to cool at room temperature for 24 hours after compaction. The air void content was also determined before conducting the test in order to meet test requirements. The specimens were then trimmed and paired to fit in the wheel tracking mold. Care was taken to make sure that the specimens fitted exactly into the mold. The rut test was conducted at 60°C, since initial tests at 40°C showed negligible rut depths. Prior to testing, the specimens were conditioned for at least four hours at test temperature. The specimens were subjected to simulated trafficking with a simple harmonic motion by applying 525 N load for one hour.

Dynamic Creep Test

The dynamic creep test is an unconfined test conducted using a Universal Testing Machine (IPC UTM-5) that applies repeated pulsed uniaxial stress on a specimen. The test was performed according to the protocol developed by NCHRP-9-19 Superpave Models, Draft Test Method W2 (*7*). The results of the dynamic creep test are useful to analyze the densification of pavement at the early stage of the rutting test, the characteristics of pavement under load repetition, and also the susceptibility of the HMA mix to permanent deformation. The test was performed at 40°C and pre-loaded for 120 seconds at 10 kPa as the conditioning stress to ensure that the platen was loaded flat on the specimen. The temperature inside the controlled chamber was brought to the desired level and specimens were conditioned for approximately two hours to achieve a uniform temperature before commencement of the test. The deviator stress during each loading pulse was 200 kPa and the pulse width duration was 0.1 s with a rest period of 0.9 s. The test was conducted until the maximum axial strain limit reached 10,000 micro-strains or until 3,600 cycles, whichever occurred first. The resulting axial deformations were measured in the axial direction using Linear Variable Differential Transducers (LVDTs). The accumulated strain was recorded after each load cycle.

Indirect Tensile Resilient Modulus Test

The indirect tensile resilient modulus test was conducted to evaluate rutting at 40°C using the IPC UTM-5 machine, in accordance with ASTM 4123. The specimens were subjected to a cyclic load with a sinusoidal wave shape, and the test sequence consisted of five conditioning pulses followed by five loading pulses, when data was collected. The load was applied for a period of 0.1 seconds with a rest period of 0.9 seconds. The horizontal and vertical deformations were measured by means of extensometers and LVDTs respectively. A pulse repetition time of 1000 ms was chosen for high trafficked volume roads and 3000 ms for low trafficked volume roads, based on the previous study done by Tayfur et al. [13]. The horizontal and vertical deformation of the sample was measured by extensometers and LVDTs respectively.

Phase Three: Simple Performance Test to Predict Pavement Performance

Simple Performance Test (SPT)

The SPT dynamic modulus test procedure follows the test protocols described in NCHRP Project 9-19, Superpave Support and Performance Models Management [14]. The conditioning procedures are similar to modified Lottman test specimens. However, extra care should be taken to avoid detachment of the glued LVDT gauge holders from the specimen. The dynamic modulus of conditioned (E_{wet}) and unconditioned (E_{dry}) values were obtained from the tests conducted at six different frequencies by applying a sinusoidal compressive load on the specimen in a cyclic manner. The test was conducted at 25°C on each specimen with loading frequencies of 25, 10, 5, 1, 0.5 and 0.1 Hz. The dynamic stress applied is 100 kPa and it is important to attain axial strains between 75 to 150 microstrains throughout the testing process. Prior to testing, the specimens must be placed in the testing chamber until the effective temperature and contact stress are achieved. It is also important to ensure the specimens are placed in the center under the loading platens.

Results and Discussion

Volumetric Properties of Marshall and Superpave Mixes

Table 2. Volumetric Properties of PWD Marshall Mixtures.

Quarry QS					
Parameter	12.5-QS-B1	12.5-QS-B2	9.5-QS-B1	9.5-QS-B2	PWD Criterion
OBC (%)	5.6	5.9	6.1	6.2	-
Stability (kN)	10.2	10.1	10.2	11.0	>8 kN
Flow (mm)	3.5	3.5	3.2	3.3	2-4 mm
VMA (%)	16.2	16.8	17.2	17.5	-
VFA (%)	75	75	75	77	70-80
Quarry QJ					
Parameter	12.5-QJ-B1	12.5-QJ-B2	9.5-QJ-B1	9.5-QJ-B2	PWD Criterion
OBC (%)	5.4	5.4	6.0	5.9	-
Stability (kN)	13.2	13.1	9.7	12.3	>8 kN
Flow (mm)	2.8	3.5	3.2	3.2	2-4 mm
VMA (%)	14.9	14.8	16.4	15.9	-
VFA (%)	79	80	75.8	80	70-80

Table 3. Volumetric Properties of Superpave Mixtures.

Quarry QS					
Mix Design Properties	12.5-QS-B1	12.5-QS-B2	9.5-QS-B1	9.5-QS-B2	Criterion
OBC (%)	5.1	5.3	5.4	5.7	-
Air Voids (%)	4.0	4.0	4.0	4.0	-
VMA (%)	14.9	15.8	15.7	16.5	14.0* min
VFA (%)	73.1	74.4	74.6	75.7	65-75**
Dust Proportion	0.8	0.8	0.8	0.7	0.6-1.2
Quarry QJ					
Mix Design Properties	12.5-QJ-B1	12.5-QJ-B2	9.5-QJ-B1	9.5-QJ-B2	Criterion
OBC (%)	5.5	5.5	6.4	6.3	-
Air Voids (%)	4.0	4.0	4.0	4.0	-
VMA (%)	16.0	16.0	17.6	17.4	14.0* min
VFA (%)	74.9	75.0	76.5	77	65-75**
Dust Proportion	0.8	0.8	0.7	0.7	0.6-1.2

Note: B1- asphalt binder penetration grade 80/100; B2- asphalt binder penetration grade 60/70; (*) For 9.5 mm (3/8”) nominal maximum size mixtures, the specified minimum VMA is 15.0; (**) For design traffic levels 3-30 million ESALs, (9.5 mm) 3/8” nominal maximum size mixtures, the specified VFA range shall be 65-76 per cent.

Table 2 shows the design parameters to determine OBC for Marshall prepared specimens for QS and QJ mixes. The OBC for QS mixtures ranges from 5.6 to 6.2%, and 5.4 to 6.0% for QJ mixtures. Higher OBC and VMA values are expected for NMAS 9.5 mm mixes due to the finer gradation of the mix compared to the 12.5 mm gradation. The surface area of aggregate in the finer mix is higher and hence needs more binder to coat the aggregate. The stability and flow results show that the values are within the specified limits of the Marshall requirements of a durable mix.

Meanwhile, Table 3 summarizes the volumetric properties of the design mixtures corresponding to OBC of the mix along with the Superpave mix design criteria. For QS mixtures, the results show that the mixture properties satisfy all the criteria set by the Superpave system. The OBC of QS mixes range from 5.1 to 5.7%. The OBC of the NMAS 9.5-QS mixtures is slightly higher compared to the NMAS 12.5-QS mix. This can be explained by the higher surface area in NMAS 9.5 mixtures, where more binder is needed to coat the finer aggregates. The OBC of QJ mixes ranged from 5.5 to 6.4%. The results show that 12.5-QJ mixtures meet the requirements of the Superpave criteria except for the 9.5-QJ mixtures, which satisfy all except the VFA criteria. For 9.5-QJ mixes, the dust proportion seems to be on the lower side of the criteria range, which resulted in the high OBC and high VFA values in the mix.

For QS mixes, there is a significant difference in OBC between the Marshall and Superpave mixes. The OBC for both 9.5-QS and 12.5-QS Superpave mix is approximately 0.6% less than the QS-Marshall mix of the same gradation. The minimum VMA requirement is an indication that the minimum permissible binder should be incorporated into the mix to ensure durability and also exhibit lower values for the QS Superpave mixes. Interestingly, the results for QJ mixes show a reverse trend. The difference in OBC is almost negligible in that the OBC for QJ Marshall mixes are only approximately 0.2% lower than the QJ Superpave mix. This phenomenon could possibly be contributed by the QJ aggregate properties. QJ aggregates have a higher aggregate impact value compared to QS aggregates, which indicates that QJ aggregates are weaker. The method of compaction effort using the SGC compactor could contribute to this phenomenon, which reduces the VMA, thus decreasing the binder content of the mix.

The HMA mix design of Marshall and Superpave mixtures shows that the aggregate quality and source both have an effect on the mix design results. The results from the QS mixtures were in good agreement with previous studies, which show that Superpave mixtures utilize less OBC compared to Marshall mixtures [6-8, 10]. Although QJ mixes do not show the same trend, further investigation to determine the mixture performance is important to identify the superiority of these mixtures with respect to permanent deformation and the characterization tests in phase two of this study.

Rutting Resistance

Fig. 2 shows that the rutting values of the Superpave mixtures vary from 0.8 mm to 3.0 mm compared to the Marshall mixtures which have high rutting values ranging from 4.1 mm to 6.5 mm. This obviously indicates the high resistance of Superpave mixtures compared to Marshall mixtures. In addition, the results also show that NMAS 9.5 mm grading for a particular mixture has lower rutting values compared to NMAS 12.5 mm mixtures. Asphalt binder type also contributed to the rutting resistance. In this study, HMA with asphalt binder type B2 exhibited better rutting resistance than asphalt binder type B1.

In Fig. 3, the wheel tracking rates for both Marshall and Superpave mixes were compared. According to Faustino et al. [15], two parameters are considered in a wheel tracking test to ensure that the performance of materials is correctly assessed. The wheel tracking rate is measured as the primary measure of the resistance to permanent deformation and the maximum rut depth is a secondary measure. This is important because different mixtures may deform differently, and some mixtures may rut excessively in the early stages of the rutting test compared to the latter part of the test. In this study, the results show that different types of aggregate

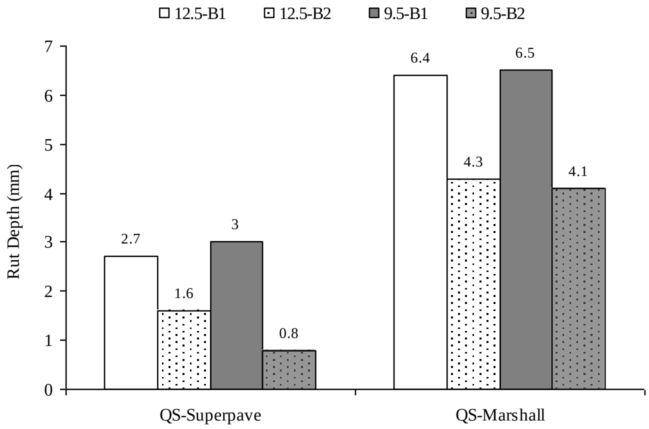

Fig. 2. Comparison between Superpave and Marshall Mixtures.

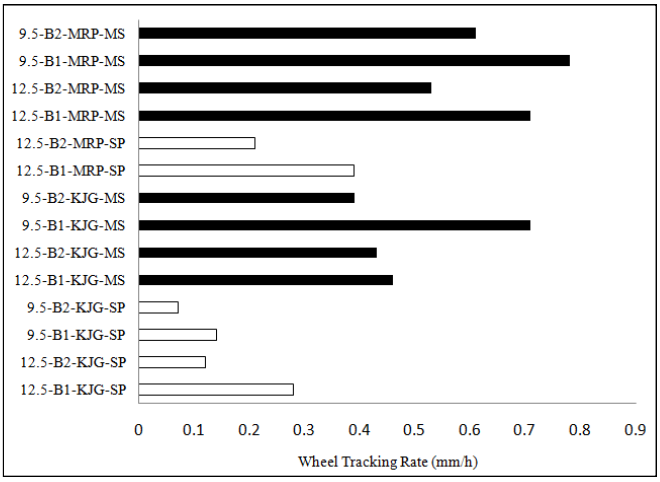

Fig. 3. Wheel Tracking Rates of Mixes

gradation do not give a huge difference on the wheel tracking rate. However on the other hand, different types of binder and mix design method show variability in the results of wheel tracking rate. It can be seen that the Superpave mixes have a lower wheel tracking rate compared to Marshall-designed mixes.

An independent *t*-test analysis was also conducted to compare statistically the superiority of the mix design method used to design the HMA mix. The null hypothesis is that the mean rutting resistance of Superpave-designed HMA mixes and Marshall-designed mixes is equal (H_0: $\mu_{Superpave} = \mu_{Marshall}$). From Table 4, The Levene's test for equality of variances shows that the population variance is equal and *t*-value is considered to test for the null hypothesis. The results showed that the p-value is 0.000, less than 0.05, hence the null hypothesis is rejected. This indicates that the Superpave- designed mixtures are least resistant to rutting compared to Marshall-designed mixtures.

Dynamic Creep

The dynamic creep curves of all mixtures were obtained and are depicted in Fig. 4 (a and b). The accumulated strain is recorded at each load cycle, and in this test, termination occurred when the load cycle reached 3,600 or 10,000 microstrains. As the loading period is required to terminate at 3,600 cycles, tests showed that not all

Table 4. Independent Samples t-test for Rutting of HMA

			Rutting (Superpave vs. Marshall)	
			Equal Variances Assumed	Equal Variances Not Assumed
Levene's Test for Equality of Variances	F		0.579	
	Significant		0.461	
t-test for Equality of Means	t		-5.159	-5.336
	df		12	11.904
	Sig. (2-tailed)		0.000	0.000
	Mean Difference		-3.76250	-3.76250
	Std. Error Difference		0.72931	0.70511
	95% Confidence Interval of the Mean	Lower	-5.35154	-5.30018
		Upper	-2.17346	-2.22484

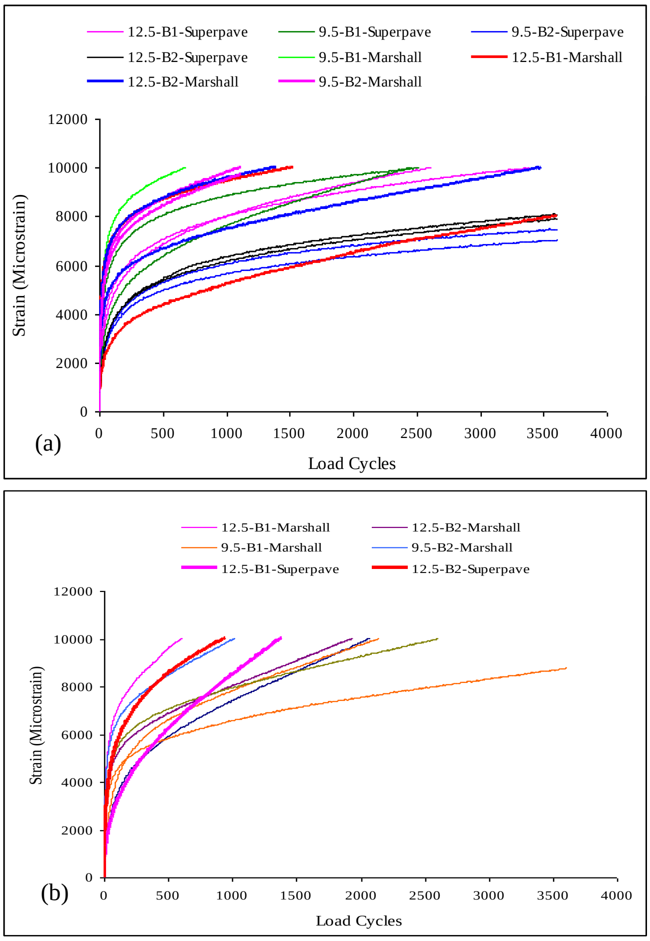

Fig. 4. Dynamic Creep Curves for (a) QS and (b) QJ HMA Mixes.

specimens failed before reaching the maximum number of cycles. The tests were conducted on mixes which met the Superpave and Marshall mix design requirements. Therefore, no test was conducted for the 9.5 mm NMAS Superpave mix. Under 3,600 load cycles, all axial strains exhibit a curve relationship with load cycles in the log strain versus log load cycles plot.

Fig. 5 demonstrates the two linear fittings from the dynamic creep

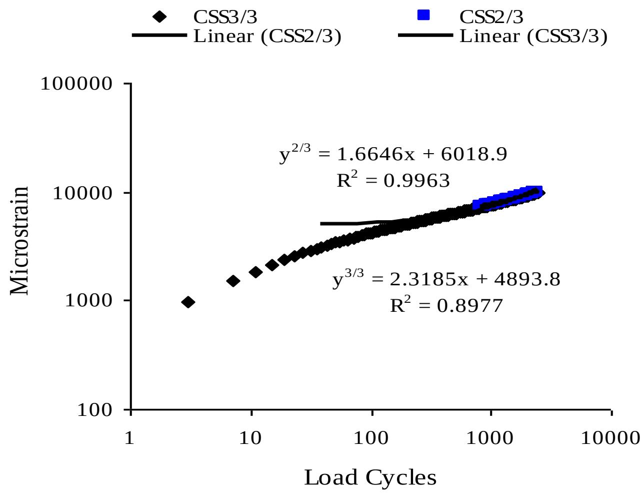

Fig. 5. Intercept of Two-fittings.

curve results in a logarithmic plot known as the Creep Strain Slope (CSS). The relationship coefficient is small when this curve is linearly fitted [16]. Hence, this plot is divided into two segments to enable analysis of the densification, characteristics under load repetition, and the susceptibility of the mix to permanent deformation. A linear relationship for all mixtures was found between axial strain and load cycle after 1,200 cycles. The last two thirds of the dynamic creep curve in the log-log plot can be used to evaluate the development of permanent deformation of the mixes. Table 5 tabulates the two linear fitting relationships for all mixes.

From the dynamic creep curve, permanent deformation at the densification stage can roughly be denoted at the initial axial strain from the intercept of the fitted linear equation. A larger intercept denotes a higher initial permanent deformation. The compaction method is related to the initial permanent deformation of the specimen and is not caused by the load cycles. Table 6 shows the initial permanent deformation between the SGC compacted and Marshall compacted specimens. All Superpave-designed mixtures show a lower intercept, which indicates lower initial permanent deformation at the densification stage compared to the Marshall mix. The least deformed mix at the initial densification stage is 12.5-QS-B2-SP (153.5), and the most susceptible mix to deformation at the densification stage is the 12.5-B1-QS-Marshall (7160.5) mix.

Since the initial permanent deformation is not affected by the load cycle but is due to the densification of the compacted specimen in the laboratory, characterizing the permanent deformation must be examined on the other two thirds of the linear dynamic creep curve. CSS can be used to characterize the permanent deformation susceptibility of the mixes under load repetitions. The mix is less resistant to permanent deformation when the CSS is greater. Mixture susceptibility to permanent deformation with respect to CSS is also tabulated in Table 6.

In general, QJ mixtures exhibit larger CSS values compared to QS mixtures. The CSS values are notably largest for 12.5-QJ-B1-Marshall mix, followed by the 12.5-QJ-B1 mix. The lowest CSS values are for 12.5-QS-B2-Marshall mix, 9.5-QS-B2-Marshall, 9.5-QSB2- SP, and 12.5-QS-B2-SP. This in general indicates that QS mixtures are more resistant to permanent

Table 5. Fitted Linear Relationship of the Dynamic Creep Curve.

Mix Type	Fitted Linear Relationship for Dynamic Creep Curve	R^2	Linear Relationship for 2/3 Dynamic Creep Curve	R^2
QS Marshall Mixtures				
12.5-B1	$y_{3/3}$ = 2.2014x + 7159.2	0.7184	$y_{2/3}$ = 1.2224x + 8203.2	0.9918
12.5-B2	$y_{3/3}$ = 2.5360x + 7035.2	0.7080	$y_{2/3}$ = 1.4198x + 8118.8	0.9877
9.5-B1	$y_{3/3}$ = 5.8238x + 6771.5	0.6772	$y_{2/3}$ = 2.3066x + 8476.8	0.9934
9.5-B2	$y_{3/3}$ = 3.6911x + 6472.3	0.7551	$y_{2/3}$ = 2.2016x + 7627.6	0.9940
QS Superpave Mixtures				
12.5-B1	$y_{3/3}$ = 1.2915x + 6251.9	0.8073	$y_{2/3}$ = 0.9061x + 7147.5	0.9715
12.5-B2	$y_{3/3}$ = 1.0186x + 4753.6	0.8104	$y_{2/3}$ = 0.6138x + 5776.5	0.9897
9.5-B1	$y_{3/3}$ = 3.6911x + 6472.3	0.7551	$y_{2/3}$ = 0.7768x + 8131.8	0.9861
9.5-B2	$y_{3/3}$ = 0.8526x + 4436.4	0.7555	$y_{2/3}$ = 0.4855x + 5362.8	0.9865
QJ Marshall Mixtures				
12.5-B1	$y_{3/3}$ = 3.1655x + 3934.6	0.9318	$y_{2/3}$ = 2.4717x + 4937.3	0.9992
12.5-B2	$y_{3/3}$ = 2.6004x + 5288.2	0.9212	$y_{2/3}$ = 2.1341x + 5911.2	0.9997
QJ Superpave Mixtures				
12.5-B1	$y_{3/3}$ = 5.4257x + 3073.8	0.9546	$y_{2/3}$ = 4.2916x + 4179.6	0.9546
12.5-B2	$y_{3/3}$ = 5.9991x + 5136.6	0.8464	$y_{2/3}$ = 3.7566x + 6619.9	0.9881

$y_{3/3}$ denotes strain under the load cycles ranging from 0 to 3,600 (i.e. full load cycle)

$y_{2/3}$ denotes strain under the load cycles ranging from 1,200 to 3,600 (i.e. two thirds load cycle)

Table 6. Summary of the Dynamic Creep Test Results.

Mix Type			Ultimate Strain	Permanent Deformation	Creep Stiffness	Intercept	CSS	SCSM
QS Quarry	Marshall	12.5-B1	9013.5	0.59	22.3	5383.9	0.24	1780.8
		12.5-B2	10018.4	0.66	19.7	7097.2	0.13	2286.6
		9.5-B1	10061.0	0.60	19.7	6306.1	0.19	2066.3
		9.5-B2	10023.0	0.65	19.9	6618.7	0.15	2040.0
	Superpave	12.5-B1	9495.0	0.63	21.0	5517.8	0.23	1474.6
		12.5-B2	7902.5	0.53	25.0	4753.6	0.19	1974.3
		9.5-B1	10018.7	0.66	19.6	4898.8	0.29	1099.5
		9.5-B2	7239.8	0.48	27.3	4561.0	0.17	2485.7
QJ Quarry	Marshall	12.5-B1	10031.7	0.66	19.7	6113.5	0.48	1468.4
		12.5-B2	10060.0	0.66	19.6	6007.0	0.21	1716.0
		9.5-B1	9395.1	0.61	21.2	5000.1	0.27	1292.7
		9.5-B2	10012.7	0.65	19.7	6024.3	0.22	1411.2
	Superpave	12.5-B1	10044.4	0.65	19.6	3073.8	0.46	771.0
		12.5-B2	10062.3	0.65	19.6	4606.0	0.29	1156.1
		9.5-B1	x	x	x	x	x	x
		9.5-B2	x	x	x	x	x	x

Note: CSS-characterize under load repetition; Intercept – densification part; x – not available ; SCSM – significantly reflects susceptibility of mix to permanent deformation

deformation than QJ mixtures. However, the actual permanent deformation of the mix cannot be correctly calculated at the transient modulus because the initial axial strain occurred during the densification process at the initial stage. Therefore, at the stable development stage of the dynamic creep test, the information in the last two thirds of the curve is used to calculate the secant creep stiffness modulus (SCSM). Hence, it reflects the susceptibility of mixes to permanent deformation. Fig. 6 shows a strong correlation between the CSS and SCSM. The relationship coefficient of the fitted curve R^2 is 0.84. It is apparent that the CSS decreases with an increase in SCSM. Therefore, enhancing SCSM will minimize the susceptibility of a mixture to permanent deformation.

Resilient Modulus

The indirect tensile resilient modulus test was conducted at two temperatures: 25 and 40°C. At 25°C, the resilient modulus is an indication of the mixture's resistance to fatigue, whereas the resilient modulus at 40°C indicates the mixture's resistance to rutting. The resilient modulus values are higher for QS Superpave-designed mixtures compared to Marshall-designed mixtures when tested at 25°C. The results from Fig. 7a show that as the pulse repetition period during loading time decreases, the resilient modulus values also decrease. From the graph, the 9.5-B2-SP mix shows the least susceptibility to fatigue, with the highest resilient modulus values of 3721 MPa, followed by

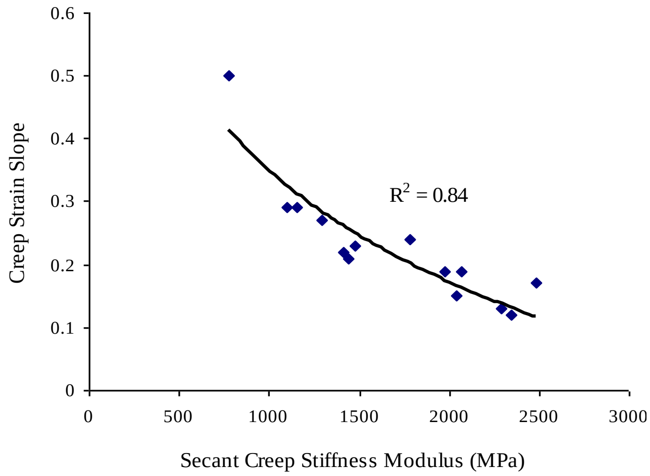

Fig. 6. Relationship between CSS and SCSM.

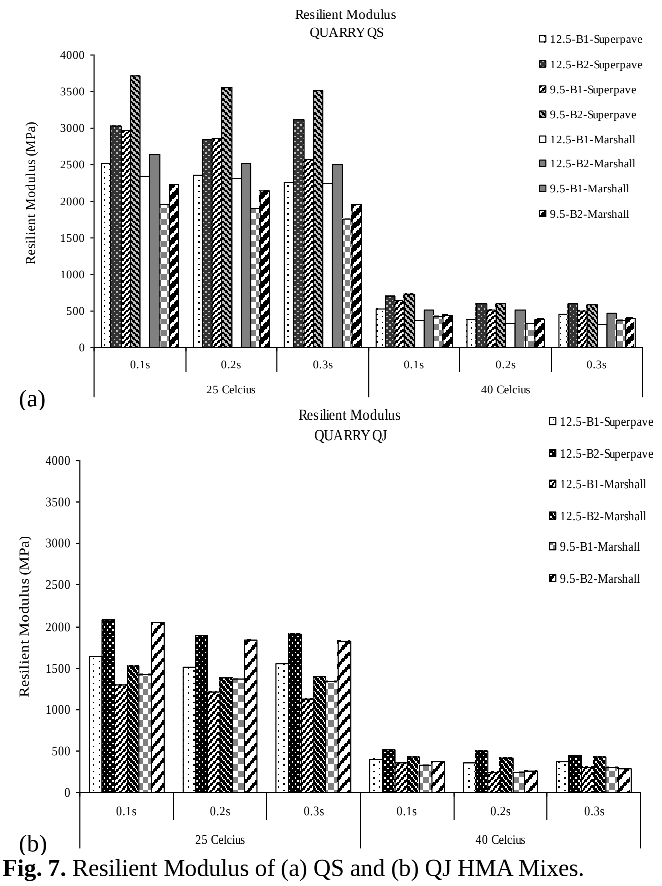

Fig. 7. Resilient Modulus of (a) QS and (b) QJ HMA Mixes.

12.5-B2-SP, 9.5-B1-SP, 12.5-B1-SP, 12.5-B2-Marshall, 12.5-B1-Marshall, 9.5-B2-Marshall, and 9.5-B1-Marshall.

As temperature increases, the difference in resilient modulus is more notable, with a decline in stiffness at 40°C. At higher temperatures, almost all Superpave mixtures showed a higher resilient modulus value compared to Marshall mixtures. The difference in the resilient modulus values at higher temperatures indicates that Superpave mixtures are less susceptible to rutting than Marshall mixtures. At a pulse repetition period of 0.1 s in the resilient modulus test, the results show that the most resistant to rutting is 9.5-B2-SP, with the highest resilient modulus value of 728

Table 7. Independent Samples t-test for Resilient Modulus of HMA.

		Rutting (Superpave vs. Marshall) Equal Variances Assumed	Rutting (Superpave vs. Marshall) Equal Variances Not Assumed
Levene's Test for Equality of Variances	F	38.049	
	Significant	0.000	
t-test for Equality of Means	t	2.691	2.892
	df	82	77.571
	Sig. (2-tailed)	0.009	0.005
	Mean Difference	563.07	563.07
	Std. Error Difference	209.287	194.72
	95% Confidence Interval of the Mean Lower	146.75	175.38
	95% Confidence Interval of the Mean Upper	979.40	950.77

MPa, followed by 12.5-B2-SP, 9.5-B1-SP, 12.5-B1-SP, 12.5-B2-Marshall, 9.5-B2-Marshall, 9.5-B1-Marshall, and 12.5-B1-Marshall.

With regards to the binder types used, mixtures with binder type B2 are stiffer and exhibit the highest resilient modulus values for both Marshall and Superpave mixtures. It was estimated that the average resilient modulus values of Superpave mixtures are 30% higher when tested at 25°C, and approximately 32% higher at 40°C compared to Marshall mixtures. In general, the resilient modulus results for QJ mixtures are lower compared to QS mixtures at similar test temperatures, as shown in Fig. 7b.

An independent *t*-test analysis was also conducted to compare Superpave and Marshall Mixtures to evaluate HMA mix stiffness. The null hypothesis is that the stiffness of Superpave-designed HMA mixes and Marshall-designed mixes is equal (H_o: $\mu_{Superpave} = \mu_{Marshall}$). From Table 7, the Levene's test for equality of variances shows that the population variance is equal and the *t*-value is considered to test for the null hypothesis. The results show that the two-tailed significance level is 0.009, hence the null hypothesis is rejected. This indicates that the mean difference between the Superpave-designed mixes and Marshall-designed mixes is significant.

SPT Dynamic Modulus Test

A decrease in the dynamic modulus values was evident for conditioned specimens compared to unconditioned specimens. This is an indication of deterioration in asphalt-aggregate interaction due to moisture infiltrating within the specimen. The master curves plotted for conditioned and unconditioned QS and QJ mixes for all mix design types are shown in Fig. 8 (a and b). With regards to mix design method, the results show that Superpave-designed mixtures have higher dynamic modulus values at all temperatures and frequency conditions compared to the PWD Marshall-designed mixtures of the same mix group. It was also noted that higher dynamic modulus values are obvious for B2 binder type mixtures compared to mixtures utilising binder type B1, and QS mixtures

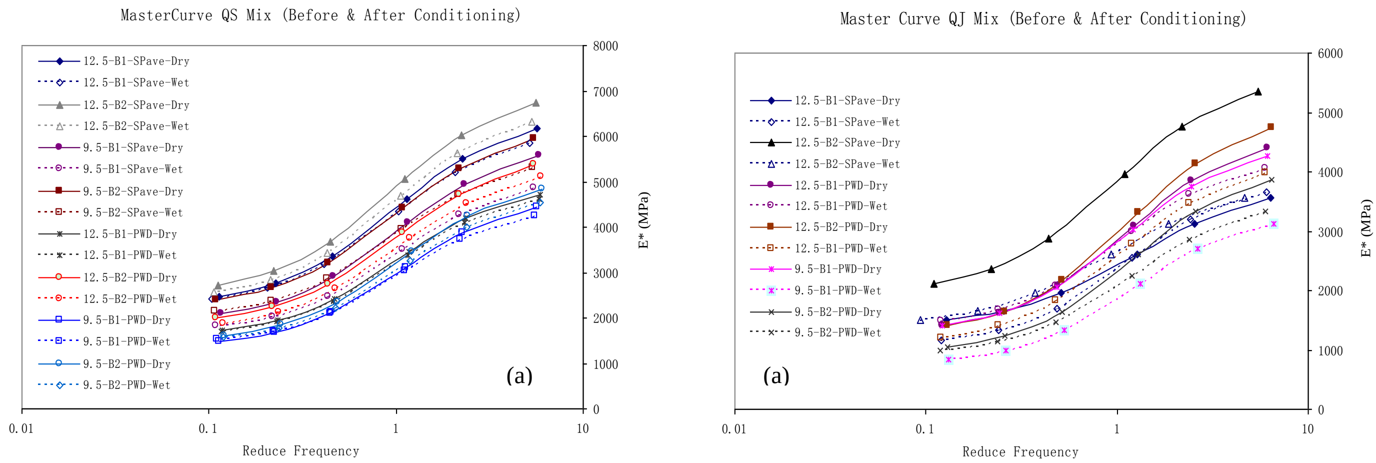

Fig. 8. SPT Dynamic Modulus before and after Conditioning for (a) QS Mix and (b) QJ Mix.

exhibited higher dynamic modulus values compared to QJ mixes.

A *t*-test statistical analysis was also assessed to determine the effectiveness of the SPT dynamic modulus test to differentiate between the conditioned and unconditioned response of the mix (H_o: μ_{dry} E* = μ_{wet} E*). The results of the analyses show that the *p*-values = 0.00 for both PWD and Superpave. The results showed that the p-value is 0.000, less than 0.05, hence the null hypothesis is rejected. This indicates that there is significant effect when the HMA mixtures are conditioned which results in the reduction of stiffness of the mix.

Relationships between the SPT Dynamic Modulus and Other Performance Tests

Relationship between Wheel Tracking and SPT Dynamic Modulus

The permanent deformation or rutting characteristics of HMA mixtures can be characterized by using the results from the dynamic modulus test performed at high temperatures. The dynamic modulus test correlates well with the rutting performance of HMA mixtures, and this is evidenced in a study conducted by Witczak et al. [17], which shows that there is a strong relationship with field rutting performance for permanent deformation. According to Harman [18], stiffness using the dynamic modulus test is the parameter chosen from the NCHRP 9-19 Project as well as from the American Association of State Highway and Transportation Officials AASHTO 2002 design guide.

In this study, the performance of the dynamic modulus, *E**, was evaluated as the rutting indicator at different loading frequencies. The relationship was established with the hypothesis that the stiffness of HMA from the dynamic modulus test could be used to evaluate rutting at high temperatures. The rut stiffness factor, $E^*/\sin\varphi$, values were plotted against rutting for QS and QJ mixtures to determine the best correlations with laboratory rutting at 40, 45 and 50^{o}C and at 5, 2, 1 and 0.5 Hz loading time. The choice of temperature and loading time must be appropriate, because rutting is expected to occur at higher temperatures and/or lower loading times. Fig. 9 shows the correlation plots for the rut stiffness factor at different temperatures and frequencies versus rut depth for all QS and QJ mixtures.

The results from the graphs show that a correlation exists between rut stiffness ratio and rutting from the laboratory wheel tracking test. All correlations were found to be significant at α = 0.01. From these figures, the same trend is observed for specimens tested at 40 and 45 ^{o}C. A strong correlation was found between rut depth and rut stiffness factor at 5 Hz loading frequency, a moderate correlation at 2 and 1 Hz loading frequency, and a low correlation was found as loading frequency decreases to 0.5 Hz. However, the relationship between rut depth and rut stiffness factor at 50^{o}C shows that strong correlations exists at 5, 2 and 1 Hz loading frequencies. The correlation is moderate at 0.5 Hz. A study conducted by Witczak [19] selected a loading frequency of 5 Hz and 54.4^{o}C testing temperature as the rutting factor. Nevertheless, the results in this study show that loading frequencies of 5, 2 and 1 Hz and 50^{o}C test temperature can be considered as the rutting factor for Malaysian climatic conditions.

A higher E* value and a lower phase angle value represents a mixture that is more stiff and rut resistant. Therefore, the higher the rutting factor value the better the mixture will perform against rutting. Interestingly, both dynamic modulus and rut stiffness factor values followed similar trends when plotted against individual mixtures, as presented in Fig. 10. The results show that QS mixtures have higher rut stiffness factor values compared to QJ mixtures. This obviously shows that QS mixtures are more rut resistant than QJ mixtures. These results also agree with the results obtained from the laboratory wheel tracking rutting test. However, the most significant rut resistant mix is 9.5-QS-B2 Superpave. It is also noticeable that all mixtures using B2 binder are less susceptible to rutting compared to those using B1.

Relationship between Dynamic Creep and SPT Dynamic Modulus

The results obtained from the dynamic creep test and SPT dynamic modulus test were analysed to determine any possible correlation between the two tests. The secant creep stiffness modulus (SCSM) from the dynamic creep test reflects the susceptibility of mixes to permanent deformation. For the SPT dynamic modulus test, the rut factor ($E^*/\sin\varphi$) is an indication of the rut resistance of HMA mixes.

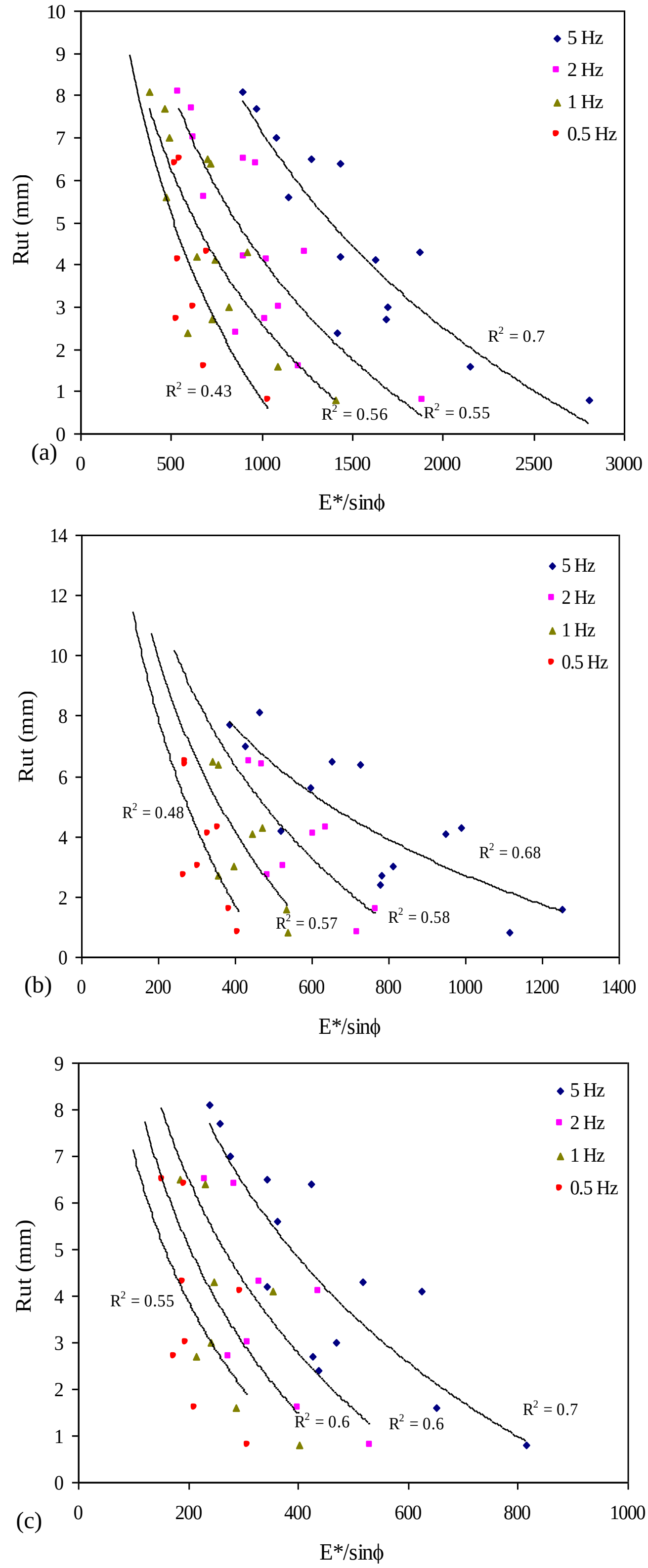

Fig. 9. Rut depth versus rut stiffness at (a) 40, (b) 45 and (c) 50°C

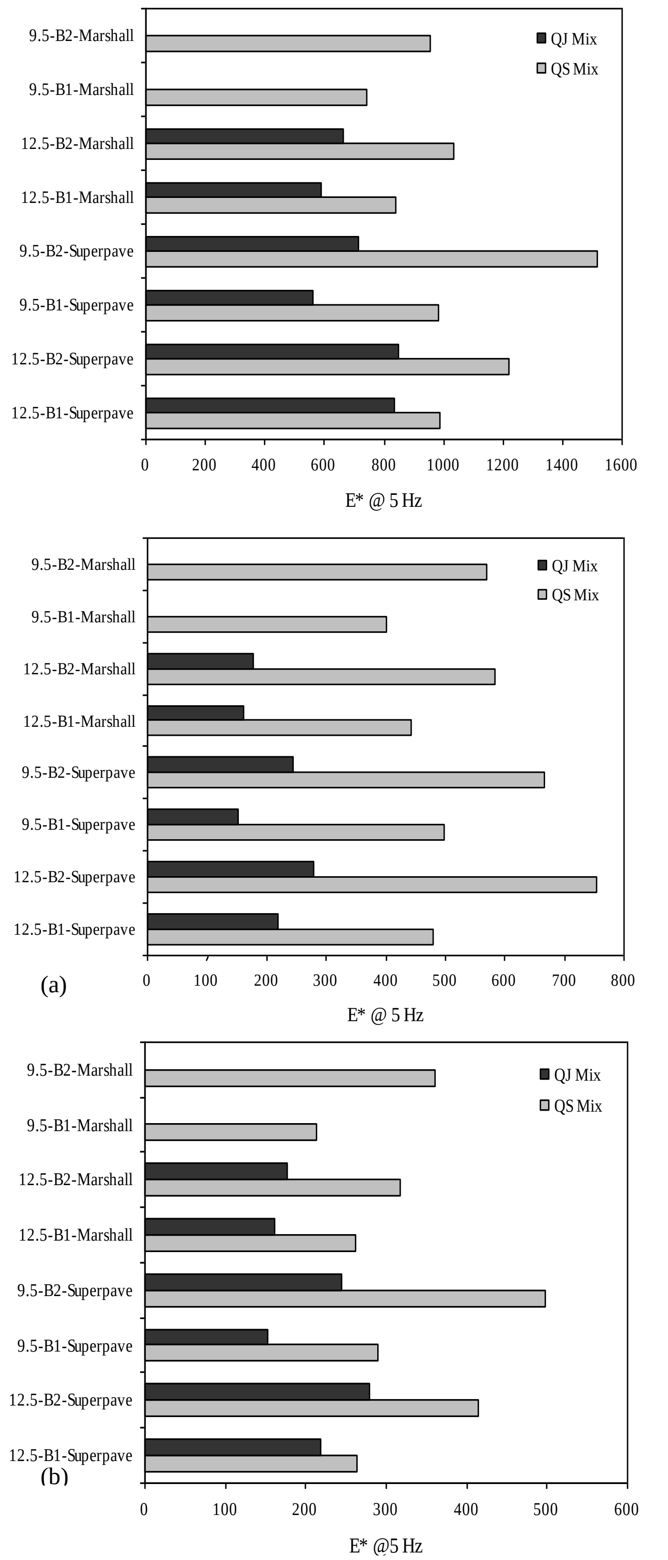

Fig .10. E* at Temperatures of (a) 40, (b) 45 and (c) 50°C and 5 Hz Frequency

In Fig. 11, the linear regression line shows a moderate correlation between the SCSM and the SPT dynamic modulus rut factor, with a coefficient of determination, R^2, of 0.6. This indicates that the SPT dynamic modulus test is a fairly reliable test to determine the susceptibility of mixes to permanent deformation. In the dynamic creep test, the ability of mixes to resist permanent deformation can also be characterized from the creep stiffness values. The results from Fig. 12 show a moderate correlation between the SPT dynamic modulus and creep stiffness. The coefficient of determination, R^2 value from the relationship is 0.6.

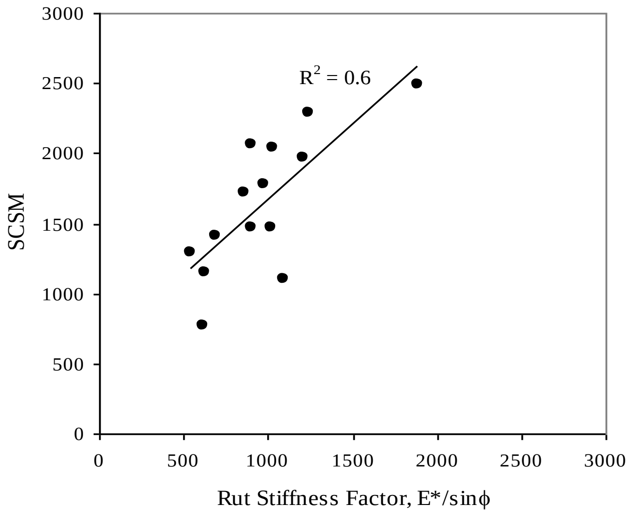

Fig. 11. Relationship between SCSM and Rut Stiffness Factor.

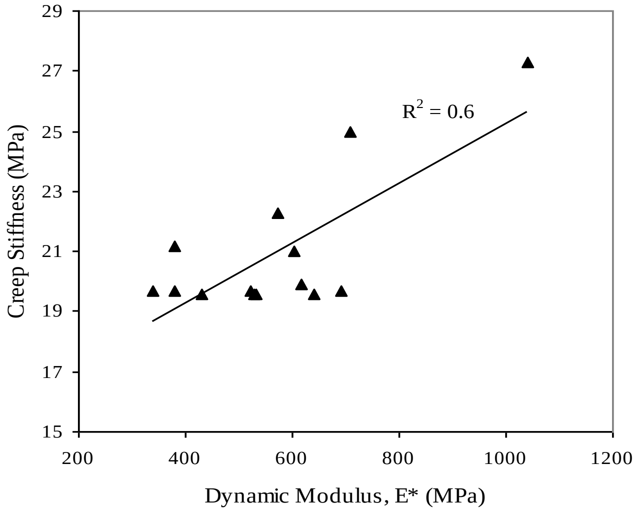

Fig. 12. Relationship between CSS and Dynamic Modulus.

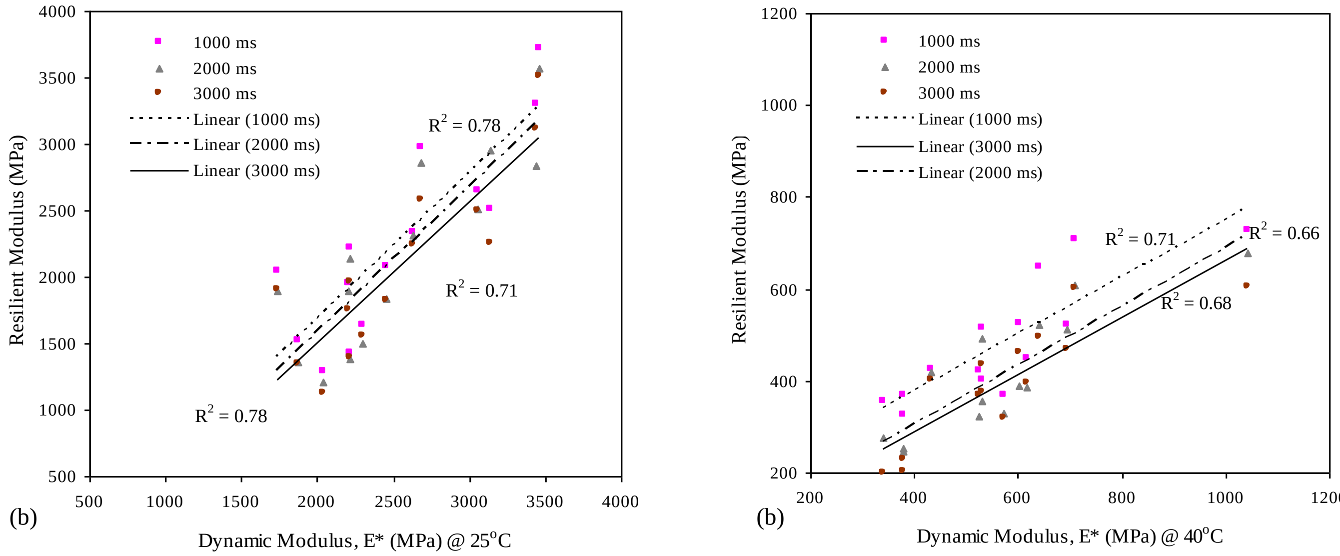

Fig. 13. Resilient Modulus Versus Dynamic Modulus at (a) 25 and (b) 40°C.

Relationship between Resilient Modulus and SPT Dynamic Modulus

Currently, the resilient modulus test results are incorporated in AASHTO pavement design guidelines. However, it has been reported that the complex dynamic modulus is currently being evaluated to replace the resilient modulus for HMA characterizing in NCHRP 1-37A [20]. The results obtained from the resilient modulus test and SPT dynamic modulus test were analysed to determine any possible correlation between the two tests. In the resilient modulus test, the loading time used to perform the test is 100 ms, which is equivalent to 10 rad/s angular frequency. The angular frequency is converted to frequency by division of 2π, and the computed frequency is 1.6 Hz. Hence, for comparison purposes, 2 Hz were selected from the dynamic modulus test. The correlations also considered the three different pulse repetition periods of 1000, 2000, and 3000 ms applied for each resilient modulus test specimen.

The results show a good correlation between the dynamic modulus and resilient modulus with R^2 values ranging from 0.71 to 0.78 for tests carried out at 25°C. Meanwhile, the R^2 values ranged from 0.66 to 0.71 at 40°C. The relationship between the two variables is illustrated in Fig. 13. Since the dynamic modulus test provides full characterization of the mix over a broad range of temperatures and loading frequencies, the dynamic modulus test is a better test, as it provides better characterization of HMA, and can replace the resilient modulus test. This finding was in good agreement with the previous study done by Loulizi et al. [21].

Conclusions

Based on the experimental results obtained, the following conclusions were drawn:

- The local material satisfies the Superpave consensus and source aggregate properties criteria and is therefore suitable for use in the Superpave system.
- Superpave-designed mixtures are more superior and least susceptible to permanent deformation compared to Marshall-designed mixtures based on pavement performance

tests.

- The SPT dynamic modulus test has the potential to replace the resilient modulus test, wheel tracking test, dynamic creep test to evaluate rutting deformation. Rutting can be better performed using the SPT dynamic modulus test and most of the correlations between these tests are moderate to strong which indicates that the SPT dynamic modulus test is viable and reliable in predicting rutting performance. As such, a large amount of specimen fabrication can be minimised to be used for different testing methods. Therefore, the dynamic modulus test is highly recommended for Superpave mixture characterization under tropical climatic conditions since this test provides full characterization of the mix over a broad range of temperatures and loading frequencies.

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