© 2014 IJEDR | Volume 2, Issue 2 | ISSN: 2321-9939

Permanent Deformation of Superpave and Marshall Mix Using SPT Dynamic Modulus Test

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***Abstract*— Construction of pavements evolved and undergone many changes with regards to mix design methods and mix characterization over the years. The Marshall mix design method is currently used in Malaysia to construct hot mix asphalt (HMA) pavements. In this study, the Superpave mix design method was employed to design the HMA mix. Further investigations to evaluate the rutting performance of asphaltic mixtures using both mix design methods were conducted. Rutting is one of the most common pavement distresses in tropical climatic condition. This test was conducted on eight different types of HMA mixtures consisting of two different aggregate gradation of maximum nominal aggregate size of 12.5 and 9.5 mm. The binder used in the HMA mixture is of penetration grade 80-100 and 60-70. The Simple Performance Test (SPT) was used to evaluate rutting on both Superpave and Marshall mixes. Results showed that the Superpave mixtures are more rut resistant compared to Marshall mixtures. This is especially true for Superpave mixtures using binder penetration 60-70. The SPT provides a full characterization of the mix over a broad range of temperatures and loading frequencies, hence this test is highly recommended for evaluation of rutting performance in tropical climatic condition.**

***Index Terms*— Permanent deformation, Simple Performance Test**

I. INTRODUCTION

In Malaysia, asphaltic road dominates the overall surfacing types at 87,626 km of which only 343 km consists of concrete roads [1]. The asphaltic road has been designed using the Marshall mix design method for decades by the Malaysian Public Works Department (PWD) following the JKR/SPJ/2008 standard specification [2]. Until today, these pavements are still in service and have undergone maintenance work annually costing a large amount of money due to premature failure, increase in traffic loads and climatic conditions [3]. In tropical climatic conditions, rutting is prone to occur, hence with the successful implementation of Superpave method in the USA, it is timely to initiate a study or adopt a better mix design system for HMA pavements in Malaysia. Astudy also concluded that the Superpave designed hot-mix asphalt was found to use less binder than the conventional Marshall mixtures of the same design aggregate structure from the same quarry source [4] which agreed with studies conducted by other researchers in Jordan [5] and Taiwan [6]. A study in India also favored the use of Superpave gyratory compactor (SGC) which is capable of achieving a lower air void content than can be achieved by the mechanical Marshall compactor [7]. The Superpave mixtures also exhibit better creep resistance compared to Marshall mixtures in flexible pavement in Pakistan [8] and based on Iraq road specification, the results indicate that Superpave mixes have lower asphalt content [9]. Hence, from the economic point of view, Superpave mixes are better than Marshall mixes.

II. EXPERIMENTAL WORK

In this study, four mixes were designed using the Superpave system and another four were designed based on Marshall method. Figure 1 shows the two different gradations of nominal maximum size 19 mm and 12.5 mm were considered for the mixes. The aggregates were acquired from two different quarry sources which supply aggregates for road construction, representing the central (QS) and southern (QJ) region of Peninsular Malaysia. These aggregates were tested for the source and consensus aggregate properties as required in the Superpave system (Table 1). Two types of binder were selected for the Superpave and Marshall mixes which follows the requirements of the PWD specifications. The mix design matrix for all the mixes is tabulated in Table 2.

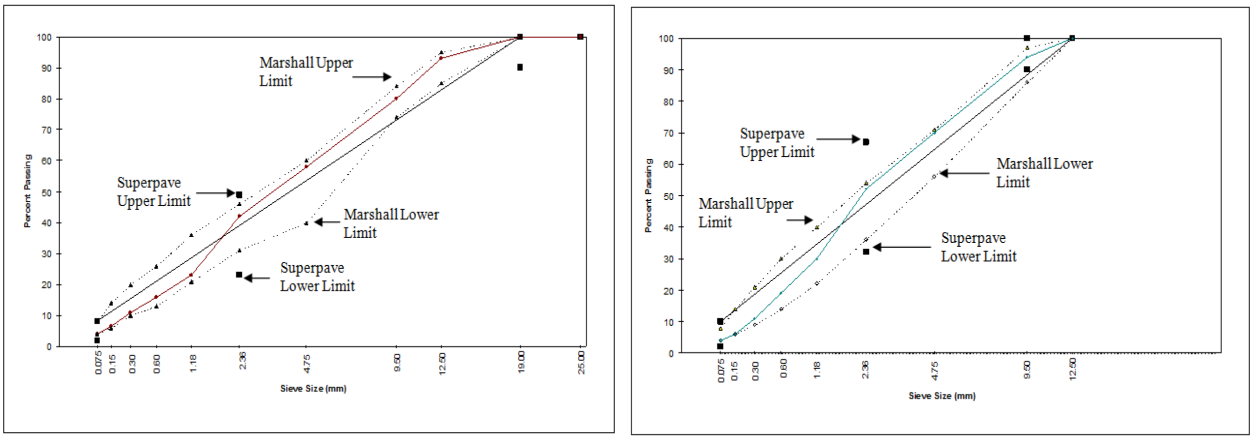

Fig.1 NMAS 12.5mm Aggregate Gradation

Table 1 Summary of Aggregate and Binder Property Tests

	Aggregate Property Tests	QS	QJ	Criteria	Standard
Superpave Aggregate Test					
Consensus	Flakiness* (%)	14.2	16.0	<20%	BS 812
Consensus	Elongation* (%)	16.5	18.0	<20%	BS 812
Consensus	Fine Aggregate Angularity* (%)	52.1	50.4	>45%	AASHTO T33
Consensus	Sand Equivalent Test* (%)	47.6	46.6	>45%	AASHTO 176
Source	Los Angeles Test* (%)	19	22	<45%	AASHTOT96
Source	Soundness Test* (%)	5.9	6.2	<12%	ASTM C88
Source	Deleterious Materials (%)	0.3	0.4	>0.2% to 10%	ASTM C142
Marshall Aggregate Test					
	Aggregate Impact Value (%)	19	22	<30%	BS 812
	Aggregate Crushing Value (%)	21	22	<30%	BS 812
	Ten Percent Fines (kN)	270	140	>100 kN	BS 812
	Water Absorption Test (%)	0.3	0.5	<2%	MS30
Binder Test					
	Binder Tests	PEN 80-100	PEN 60-70	Criteria	Standard
	Penetration @ 25°C (mm)	84	68.3	Conformed	ASTM D5
	Softening Point Test (°C)	43	47	41°C – 51°C	ASTM D36

Note: Aggregate test (*) is also a requirement in the Public Works Department Specifications

Table 2 Test Design Matrix

No.	Factor	Details
1	Aggregate gradation	12.5mm and 9.5 mm NMAS
2	Mix design method	Superpave and PWD Marshall mix design method
3	Aggregate source	Central region (QS); Southern region (QJ)
4	Binder type (PWD specification)	PEN 80/100 (B1); PEN 60/70 (B2)

III. Results and Analysis

The Simple Performance Test (SPT) dynamic modulus was conducted to evaluate rutting potential of HMA mix. The benefit of using the SPT dynamic modulus test is that it is repeatable and non-destructive. The test was conducted at a broad range of temperature and loading frequencies which are applied during testing giving better understanding of the rutting deformation occurring at different conditions. Approximately 6500 g of batch weight was needed to prepare 150 mm in diameter and 165 mm height of the SPT dynamic modulus specimens. After compaction and cooled to room temperature for 24 hours, the specimens were cored and trimmed from the centre of gyratory compacted specimen. Both ends of the specimen were sawed by approximately 5 mm to achieve the final dimensions of the specimen of 100 mm in diameter and 150 mm height. This "ideal" geometry was based on the specimen size and aggregate effect study [10]. The bulk specific gravity and air voids of all the specimens were measured before testing. Geometric properties of each specimen were also determined for criteria acceptance of the test specimen as shown in Table 3. The axial deformations were measured with displacement transducers referenced to gauge points connected to the specimens as shown in the schematic diagram in Figure 2.

Table 3 Criteria for Acceptance of Test Specimens

Criterion Items	Requirements
Size	Size of sample : 100 mm in diameter by 150 mm in height
Coring	Nominal Diameter of sample after coring 100 mm
Diameter	Side of sample after coring : smooth, parallel and free from steps, ridges and grooves
	Standard deviation of six measurements : not greater than 2.5 mm
Ends	Ends of sample after sawing : smooth and perpendicular to the axis
	Tolerance of a cut surface waviness height : 0.05 mm across any diameter
	Angle departing from perpendicular to axis of specimen : not more than 0.5 degrees
Air Void Content	Air Void Content of test Specimen : within 0.5 percent from the target air void content

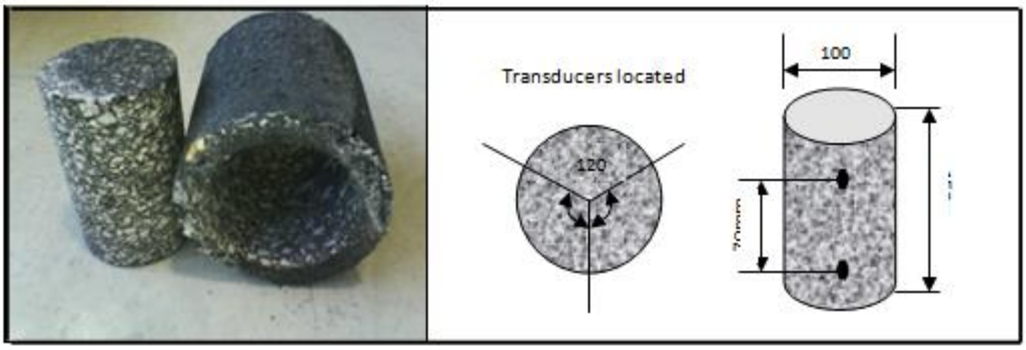

Fig.2 Cored and Trimmed SPT Specimen

The SPT dynamic modulus test procedures follow the test protocols described in NCHRP in Project 9-19, Superpave Support and Performance Models Management [11]. Three Linear Variable Displacement Transducers (LVDT), were placed at 120 degrees on the specimen surface to capture full range accumulation of the compressive permanent deformation. A continuous uniaxial sinusoidal (haversine) compressive stress at a specified test frequency is applied to the unconfined cylindrical test specimen in a cyclic manner. The dynamic load was properly adjusted during the tests to keep the strain level between 75 to 125 microstrain. The strain level should be checked after completion of the test, otherwise the dynamic pulse load is increased or decreased to adjust the strain to be within the limits. In order to develop master curves for all the mixtures, each specimen was tested at six different temperatures and six frequencies for each test temperature. Prior to testing, the specimens must be placed in the testing chamber until the effective temperature, contact stress and confining pressure were achieved. It is also important to ensure the specimens were placed in the centre under the loading platens as shown in the schematic diagram in Figure 3.

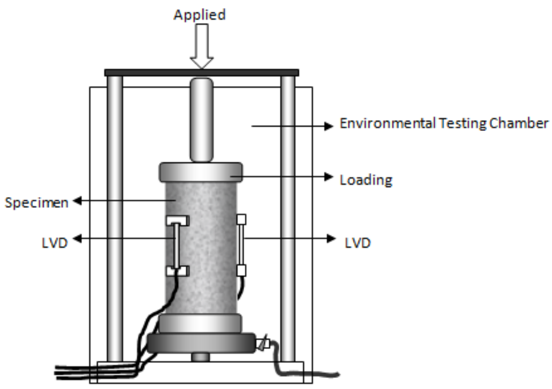

Fig. 3 Schematic Diagram of SPT Dynamic Modulus Test Setup

To begin the test, the LVDTs were zeroed, and minimal contact load was applied to specimen. A sinusoidal compressive load was applied on the specimen in a cyclic manner. Calculations performed is divided into four steps to determine the loading stress (σ_o), recoverable strain (ε_o), dynamic modulus ($|E^*|$) and finally the phase angle (ϕ). The associated equations are as listed follows:

Loading stress applied to specimen :

$$\sigma_o = \frac{P}{A} \qquad (1)$$

The recoverable axial strain from individual strain gauges :

$$\varepsilon_o = \frac{\Delta}{GL} \qquad (2)$$

Dynamic modulus for each LVDT :

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \qquad (3)$$

Phase angle for each LVDT :

$$\phi = \frac{t_i}{t_p}(360) \qquad (4)$$

Where
σ_o = stress
P = average load amplitude
A = area of specimen
ε_o = strain, Δ = average deformation amplitude
GL = gauge length
ϕ = phase angle
t_i = average time lag between a cycle of stress and strain
t_p = average time for a stress cycle

To determine susceptibility of these mixes to rutting deformation at high temperature, stiffer layer is desired to resist the permanent deformation. Figure 4 shows the dynamic modulus master curves constructed for QS and QJ mixtures using the principle of time-temperature superposition. The master curves were shifted to simulate environmental conditions and to compare the dynamic modulus of different mixtures across testing temperatures and frequencies. The dynamic modulus test results showed that the dynamic modulus of HMA was dependent on both the loading rate and test temperature. Mixtures were stiffer at a low temperature and high frequency and the dynamic modulus values were lowest at the combination of the highest temperature and lowest frequency.

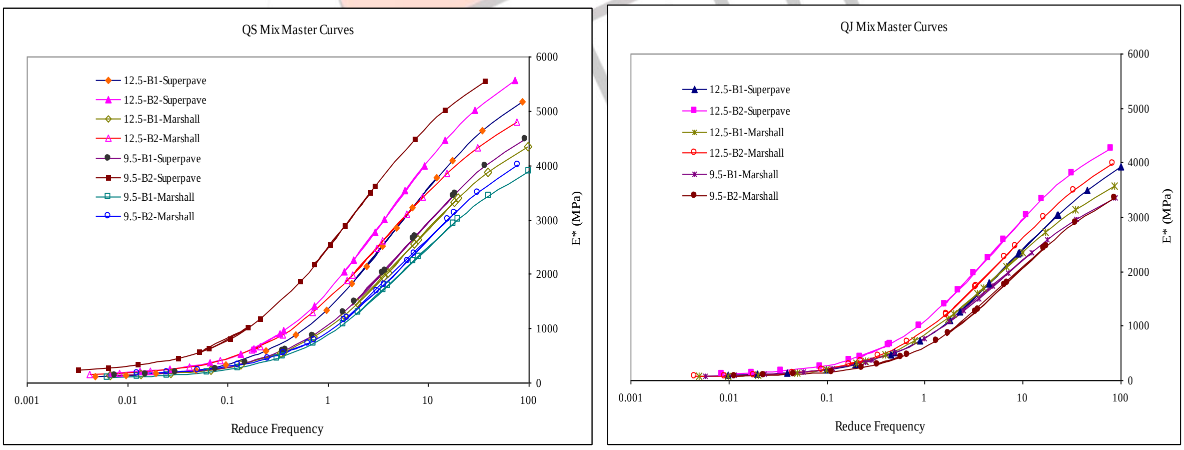

Fig. 4 Dynamic Modulus Master Curve for QS and QJ HMA Mixtures

Results from the SPT dynamic modulus test can be used to rank different HMA mixes. A comparison to rank the different mixtures was established from modular ratio [12]. The modular ratio (R) can be calculated as follows:

$$R = \frac{E^*_{mix}}{E^*_{Reference}} \qquad (5)$$

where, R = modular ratio

E^*_{mix} = Dynamic Modulus value for given mixture
$E^*_{Reference}$ = Dynamic Modulus value for reference mixture.

Results tabulated in Tables 4 and Table 5 show the HMA mixture modular ratio ranking at 40°C and 50°C at three different loading frequencies (20Hz, 10Hz and 0.5Hz). The 12.5-B1-QJ-Marshall mix was used as the reference mixture to calculate modular ratio. At higher temperatures, the most significant permanent deformation that occurred on pavement is rutting. The HMA mix must be stiff enough to withstand rutting and the best HMA mix is the one with the highest E* values. Again, results do not show many variations at different loading frequencies. As shown in Figure 5, it is noticeable that the least susceptible against permanent deformation are QS-Superpave mixes, specifically 9.5-B2-QS-SP followed by 12.5-B2-QS-SP. In addition, results also revealed that the mixture utilising B2 binder type is stiffer and is more resistant to rutting at high temperatures than the mix with B1 binder. It can be concluded that with regards to mix design methods, Superpave-designed mixtures are more resistant to permanent deformation than the Marshall-designed mixtures.

Table 4 Modular Ratio (R) Ranking @ 40°C and 50°C

Mix Design	**NMAS**	**E* @20 Hz**	**R**	**E*@10 Hz**	**R**	**E*@0.5 Hz**	**R**
Modular Ratio ® Ranking @ 40°C							
QS-SP	12.5-B1	6099	1.18^{12}	4943	1.18^{12}	1968	1.21^{11}
	12.5-B2	6500	1.25^{14}	5318	1.27^{14}	2174	1.33^{13}
	9.5-B1	5379	1.04^{10}	4342	1.03^{10}	1625	0.99^{9}
	9.5-B2	6418	1.24^{13}	5247	1.25^{13}	2278	1.39^{14}
QS-Marshall	12.5-B1*	5183	1.00^{9}	4191	1.00^{9}	1628	1.00^{10}
	12.5-B2	5647	1.09^{11}	4626	1.10^{11}	1995	1.22^{12}
	9.5-B1	4707	0.91^{5}	3671	0.87^{4}	1331	0.81^{6}
	9.5-B2	4845	0.93^{6}	3791	0.90^{6}	1266	0.77^{5}
QJ-SP	12.5-B1	4645	0.89^{4}	3723	0.88^{5}	1396	0.85^{7}
	12.5-B2	5027	0.97^{8}	4024	0.96^{8}	1451	0.89^{8}
QJ-Marshall	12.5-B1	4371	0.82^{3}	3443	0.82^{3}	1184	0.73^{3}
	12.5-B2	4929	0.95^{7}	3857	0.92^{7}	1235	0.76^{4}
	9.5-B1	4058	0.78^{1}	3162	0.75^{1}	1090	0.67^{2}
	9.5-B2	4141	0.79^{2}	3184	0.76^{2}	929	0.57^{1}
Modular Ratio ® Ranking @ 50°C							
QS-SP	12.5-B1	2013	1.11^{3}	1333	1.09^{5}	307	1.00^{6}
	12.5-B2	2380	1.31^{2}	1654	1.35^{2}	410	1.34^{2}
	9.5-B1	1975	1.09^{4}	1341	1.10^{4}	350	1.14^{4}
	9.5-B2	2725	1.50^{1}	1986	1.63^{1}	587	1.92^{1}
QS-Marshall	12.5-B1*	1813	1.00^{7}	1220	1.00^{7}	306	1.00^{7}
	12.5-B2	1945	1.07^{5}	1374	1.13^{3}	386	1.26^{3}
	9.5-B1	1580	0.87^{11}	1068	0.87^{10}	300	0.98^{8}
	9.5-B2	1920	1.06^{6}	1310	1.07^{6}	320	1.04^{5}
QJ-SP	12.5-B1	1713	0.94^{9}	1157	0.95^{9}	270	0.88^{10}
	12.5-B2	1782	0.98^{8}	1184	0.97^{8}	272	0.89^{9}
QJ-Marshall	12.5-B1	1282	0.71^{13}	807	0.66^{14}	166	0.54^{13}
	12.5-B2	1594	0.88^{10}	1022	0.84^{11}	204	0.67^{12}
	9.5-B1	1257	0.69^{14}	822	0.67^{13}	204	0.67^{12}
	9.5-B2	1455	0.80^{12}	936	0.76^{12}	211	0.69^{11}

Note: Bold Subscript in R denotes ranking of HMA mix

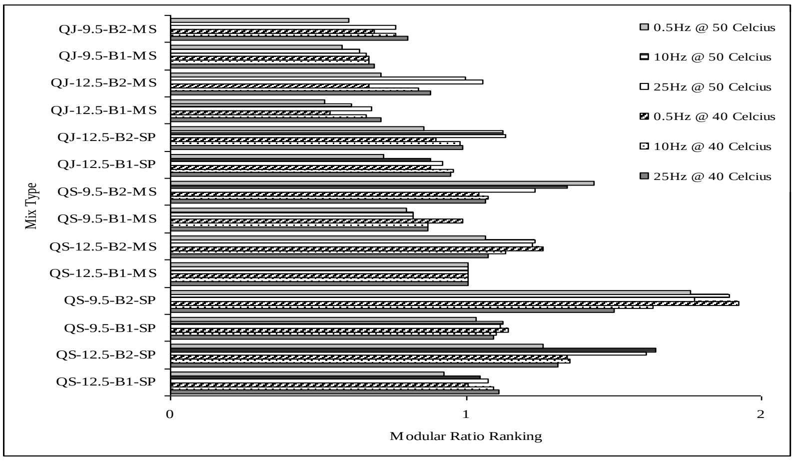

Fig. 5 HMA Mix Type Ranking at 40°C and 50°C

IV. Conclusion

The findings in this study showed that the Superpave designed mixes showed better resistant to permanent deformation compared to Marshall designed mix. Results have provided significant findings on the rutting pavement performance of Marshall and Superpave mixtures based on the SPT dynamic modulus test at high temperature of 40°C and 50°C and ranked from modular ratio (R). This is also evident when the Superpave designed mixes using binder of PEN 60-70 (B2) gave better resistant to deformation compared to the conventional PEN 80-100 binder. The local material also satisfies the Superpave consensus and source aggregate properties criteria and is therefore suitable for use in the Superpave system. Hence, Superpave-designed mixes are more superior and least susceptible to permanent deformation compared to Marshall-designed mixes.

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