EXPERIMENTAL INVESTIGATION OF MARSHALL AND SUPERPAVE MIX DESIGN METHODS FOR RUTTING CRITERIA

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ABSTRACT

Asphalt mix design for tropical high temperature climate regions is challenging, especially, for roads expected to carry heavy truck loads and higher design traffic significantly exceeding 1 million equivalent single axle loads. The main focus, while performing asphalt mix design, in these regions is to ensure that the designed mix is resistant to plastic deformation.

Marshall mix design is still the most commonly used procedure in tropical countries. Serious drawbacks with Marshall mix design procedure are its mode of compaction, which does not simulate the field compaction as well as a poor methodology to identify mixes prone to plastic deformations. To evaluate rutting susceptibility, some studies have recommended extending the original Marshall mix design procedure by supplementing it with a minimum void criterion at refusal density.

This paper reports on an experimental study aimed at evaluating whether the extended Marshall mix design procedures can be reliably used to develop rut resistant asphalt mixes. The Marshall mixes were compared with Superior Performance Asphalt Pavements (Superpave) mix design procedure for secondary compaction and plastic deformation potential. Superpave design procedure was developed in the Strategic Highway Research Program (SHRP) to address drawbacks of the Marshall mix design procedure. Gabbro aggregate with neat (PG64-10) and styrene-butadiene-styrene (SBS) polymer modified bitumen (PG76-10) were used in Marshall mix designs. Various factors influencing the mix design procedures such as a drop in temperature and breaking of aggregates during compaction were studied. It was found that void at refusal density in the extended Marshall design procedure is not a reliable parameter in determining plastic deformation potential of asphalt mixes.

1. INTRODUCTION

The primary causes of rutting in flexible pavements are poorly designed asphalt paving mixture and weak subgrade. Most of the tropical countries and Middle Eastern region witness high temperature, low rainfalls and California Bearing Ratio (CBR) value of more than 25%. Therefore, rutting due to weak subgrade is not expected, provided that pavement structures are designed adequate enough to transfer traffic loads safely to the subgrade. In other words, poorly designed asphalt mixes are expected to be the main cause of rutting in these regions. As a poorly designed asphalt mix experiences plastic deformation under wheel loads, the mix flows and upheaves along the wheel path, resulting in the formation of rut (MS-2 Asphalt Institute, 2014). In fact, one of the main focuses while performing asphalt mix design in hot climates is to ensure that the designed mix is resistant to plastic deformation (Sebaaly et al. 2018, Jitsangiam et al. 2013, Asi 2007).

Asphalt mix design for such tropical high temperature climatic regions is challenging, especially, for roads expected to carry heavy truckloads with higher design traffic significantly exceeding one million equivalent single axle loads (ESAL). Marshall and Superpave are the state of practice mix design procedures in asphalt industry worldwide. The Marshall Mix Design procedure was developed in the 1930s by Bruce Marshall of the Mississippi Highway Department (MS-2 Asphalt Institute 2014). Owing to the simplicity of tests involved in the mix design and quality control during construction and long association of engineers with Marshall mix design, it is still the most commonly used procedure in tropical countries. For higher design traffic (more than 10 million ESAL), the usual process in Marshall mix design is to compact using 75 hammer blows per face (QCS 2014, MS-2 Asphalt Institute 2014, MORTH 2013). The compacted samples are cured at 60^{0}C and then loaded diametrically (ASTM D6927). During loading, the peak load and the corresponding permanent deformation are measured. The peak load is used as an indicator of asphalt mix stability and flow is used as an indicator of asphalt mix resistance to plastic deformation. It has been shown in several studies that these parameters cannot be considered as a reliable indicator of asphalt mix rutting performance. Serious drawbacks with Marshall mix design procedure are a poor methodology to identify mixes which are prone to plastic deformations (Jitsangiam et al. 2013, Asi 2007, Swami et al. 2004) and the mode of compaction, which does not simulate compaction that is achieved in the field (Button et al. 1994).

2. EXTENDED MARSHALL MIX DESIGN

Ideally, the desired mix-design-parameter to determine rutting susceptibility of asphalt mixes during the mix design process should be able to account the densification of asphalt layer under in-service traffic loading. Understanding the changes in volumetric properties, mainly, air void of asphalt mix during construction and service life of the pavement, have been of interest to researchers. Researchers have studied different asphalt mix design methods to evaluate the ability of laboratory compaction to predict mix resistance to permanent deformation (Button et al. 1994, Izzo 1999). Permanent deformation in asphalt mixes is typically divided into three zones, in which the tertiary zone is the stage when asphalt mix exhibits permanent deformation at increasing rates with an increase in cyclic loading, demarking rutting failure. In tertiary compaction zone, the air void in asphalt mix is typically less than 2%. At low air voids, 2% - 2.75%, the bitumen in asphalt mix starts to behave as a lubricant rather than a binder (McDaniel and Levenberg 2013, Miomir and Radenberg 2011). The traditional Marshall mix design parameter, flow value that is measured during Marshall mix design, does not represent the change in air void which is experienced by asphalt mix in the secondary and tertiary compactions stages. Some studies recommend extending the original Marshall mix design procedure by introducing an additional compaction effort to resemble the densified state of asphalt at the end of service life (Dachlan et al. 1997, Smith and Jones 1998, Rao et al. 2007). Various agencies have incorporated this extended Marshall mix design by supplementing their design specification with a minimum void criterion at refusal density (QCS 2014, SSCW 2008, BS 598-104:2005). The refusal density is a measure of air void at compaction beyond which the air void is asymptotic. Asphalt mixes at this air void are expected to represent the in-situ condition at the end of the pavement service life. The convenient and popular method to impart this refusal compaction density is through additional Marshall hammer blows. Most countries still use the concept of refusal density to cross-check their asphalt mix designs. In Asia Pacific Region (200 blows per face), Indian Subcontinent (200 / 300 per face), and Middle East (BS 598-104:2005 or 400 / 500 / 600 blows per face) (Read 2016). However, the approach is often questioned on its ability to achieve refusal density (Kandhal et al. 2010). Marshall hammer blows are typically imparted at 64 ± 4 blows per minute (ASTM D6926), which means that increasing the number of blows directly increases the duration of compaction. Increase in compaction time may result in substantial dropping in the asphalt mix temperature during compaction. Compacting asphalt mix at temperatures significantly below the compaction temperature may indicate false resistance of mix to densification. Furthermore, the repeated hammering of low-temperature asphalt mix may lead to the breaking of aggregates. Similar concepts correlated to 300 gyrations with Gyratory compactor or with an option to directly use the Gyratory tests were used in South Africa in the recent past (SABITA Interim Guidelines 2001, SABITA Manual 24 2005) but were withdrawn upon the release of SABITA Manual 35 / TRH 8 (2018).

Superpave mix design procedure was developed in the Strategic Highway Research Program (SHRP). Superpave mix design offers several advantages over the Marshall mix design procedure, such as measurement of height and estimation of density during compaction. In the Superpave mix design, compaction is achieved through gyrations. Researchers have shown that gyratory based asphalt mix compaction in laboratory simulates field much better compare to compaction using Marshall hammer. Based on the concept of refusal density in Marshall mix design, maximum gyration (Nmax) was proposed in SHRP to estimated refusal density. In Superpave, the size of the sample is 6 inches diameter, which in comparison to 4 inches diameter in Marshall mix design is expected to lose lesser temperature during compaction. As Marshall mix design method has several deficiencies, it is in the best interest of the transportation agencies that are using it to investigate whether refusal density criteria is conducive in designing rut resistance asphalt mixes.

3. STUDY OBJECTIVES

The first objective of the study was to measure and compare air voids at Marshal refusal density and Superpave maximum gyrations for asphalt mixtures commonly used in the State of Qatar. This is important to determine the worthiness of Marshall refusal density test in evaluating rutting resistance of asphalt mixtures. The second objective was to measure and compare the temperature of asphalt mix samples after the end of Marshall and Superpave compactions at refusal densities. This is required to understand alteration in the test environment during compaction. The third objective was to measure and compare the change in gradation after refusal compactions. This is important to determine whether the achieved refusal density is a result of a change in air void due to breaking of aggregates or due to restructuring during compaction.

4. APPROACH AND LABORATORY TESTING PROGRAM

In this study, the most commonly used 400 blows per each face is used to determine the refusal density of Marshall mix design and commonly used Superpave Nmax of 205 is used as a maximum number of gyrations. In Marshall mix design, minimum 3% air void after refusal compaction is considered sufficient to identify mixtures as rut resistant (QCS

2014). In Superpave mix design, minimum 2% air void after a maximum number of gyrations is considered sufficient to identify mixtures as rut resistant (MS-2 Asphalt Institute 2014). For both the design methods, irrespective of the binder type, in all available literature and state-of-practice, the number of compaction cycles and air void criteria at the refusal compaction are fixed. Refusal compaction of 400 blows (total 800 blows considering 400 blows on each side of the sample) compare to 75 blows at the design level and maximum gyrations of 205 compare to 125 gyrations at the design level, increase the compaction time by 10.7 and 1.6 times respectively. Increase in compaction time results in substantial dropping in the asphalt mix temperature during compaction. This drop in temperature would depend on the size of the test sample and thermal resistivity of the mixture and binder type. Since this drop in temperature and the resulting change in stiffness would be different for different mixtures a fix refusal density specification cannot be used. Compacting asphalt mix at temperatures significantly below the compaction temperature may indicate false resistance of the mix to densification. In fact, rutting potential of two asphalt mixtures intended to experience the same infield environmental conditions should be evaluated at the same laboratory test conditions. Therefore, to study the appropriateness of Marshall refusal density test, loss in temperature during compaction were measured for different mixtures. Therefore, the hypothesis in the study is that the drop in temperature during the Marshall refusal density test does not inhibit the test in achieving refusal density.

The mixtures in this study are produced using two binders PG 64-10 and PG 76-10 and crushed gabbro aggregate. The PG 64-10 is an unmodified binder and PG 76-10 is SBS modified binder. The heat retention is dependent on the property of constituents of asphalt mix. Aggregates with lower densities can be expected to cool down faster. Therefore, to simplify the test matrix, the type of aggregate was kept the same for all the mixes in this study. The aggregate and binder properties of the mixtures used in the study are shown in Table 1 and Table 2 respectively. Out of the 8 mixtures in Table 1, the first four mixtures were produced using PG 64-10 and the rest four mixtures were produced PG 76-10. For each mix, four replicates were compacted using Marshall as per ASTM D 6927 2015 and three replicates were compacted using Superpave, as per AASHTO R 83 2017.

Table 1: Aggregate properties of the mixtures used in the study

Aggregate Property	Asphalt Mixture Number							
	1	2	3	4	5	6	7	8
Combined aggregate specific gravity	2.852	2.886	2.882	2.874	2.887	2.895	2.857	2.897
Two or more fractured faces, %	100	100	100	100	100	100	100	100
Flat and elongated particles, %	0	0	0	0	0	0	0	0
Los Angeles abrasion, %	16	13	14	15	13	12	16	11
Aggregate Crushing Value, %	14	10	12	13	11	10	13	10

Table 2: Binder properties of the mixtures used in the study

Binder Property	PG grade	
	PG 64-10	PG 76-10
Specific gravity	1.030	1.032
Penetration (0.1 mm) at 25^{0}C	66	52
Softening point ring & ball, ^{0}C	47.6	62
Rotational viscosity, 176^{0}C	0.09	0.48
Rotational viscosity, 135^{0}C	0.44	2.51
Rotational viscosity, 120^{0}C	0.95	4.10
Rotational viscosity, 100^{0}C	4.10	6.32

5. ANALYSIS AND DISCUSSION

The temperature measured at the beginning and at the end of compaction for all the PG 64-10 and PG76-10 mixtures are shown in Table 3. The temperature of compaction for PG 64-10 and PG 76-10 mixtures were obtained from corresponding rotational viscosity range of 0.28±0.03 Pas and 1.4±0.1 Pas respectively, measured at 20 rpm with spindle no 27. In Marshall refusal-density-compaction, temperatures were measured both after 400 blows on face one and after additional 400 blows on face two. It can be seen from Table 3 that Marshall samples lost almost 50% of their initial temperature for the 400 blows test (i.e. 400 blows per face). The average drop in temperature for the PG 64-10 and PG 76-10 mixtures compacted using Marshall was 73.8^{0}C and 76.8^{0}C respectively. When the same mixtures were compacted in Superpave gyratory compactor using the same compaction temperatures (within the range corresponding to viscosity tolerance), the average drop in temperature for the PG 64-10 and PG 76-10 mixtures was 34.4^{0}C and 41.1^{0}C respectively. From the results, it can be observed that irrespective of the compaction type, the drop in temperature for SBS modified asphalt mixtures were higher compared to unmodified asphalt mixtures.

Comparison of aggregate gradation before and after refusal density compaction is shown in Table 4. The variations in gradation for all the mixtures at all the sieve sizes were less than 2%, which is acceptable considering the tolerance of the test itself. Therefore, for comparison, only the percent of aggregate passing sieve size 0.075mm is presented. Both in Marshall and Superpave, increase in the percent of aggregate passing 0.075mm was observed for all the mixtures after compaction. However, the difference between the percent of material passing 0.075 mm obtain from asphalt samples compacted using Marshall and gyratory compactors were all less than 0.2%. This indicates that, even if any breaking of aggregates happened during the refusal density compaction, it is expected to be similar for Marshall and gyratory compactors. Therefore, any difference in air void between Marshall and Superpave compacted refusal density cannot be due to the breaking of aggregate during compaction. However, it is worth mentioning that, as the aggregate used in the study is crushed Gabbro, the result should be in general associated to good quality aggregates.

Air void after the Marshall refusal density compaction of 400 blows per face (hereafter referred to as 400 blows) and Superpave maximum gyratory compaction are compared for unmodified and modified asphalt mixtures in Figure 1 and Figure 2, respectively. It can be seen from the figures that for unmodified asphalt mixtures both the Marshall and Superpave mix designs produced similar air voids at the end of compaction. The maximum absolute difference in the air void was 0.5% and the average absolute difference was 0.2%. Whereas, for SBS modified asphalt mixtures, the difference in the air voids of Marshall and Superpave samples were observed at the end of compaction.

In fact, for all the modified mixtures, air voids in Marshall 400 blows compacted samples were higher compared to Superpave Nmax 205 gyrations samples. This difference in air void for the modified asphalt mixtures can be understood from the viscosity and drop in temperature presented in Table 2 and Table 3 respectively. Viscosity for both PG 64-10 and PG 76-10 drops as the temperature drops. For PG 76-10, the relationship between viscosity and temperature is close to linear, R^2 value of 0.95. Whereas, for PG 64-10, the relationship is non-linear, with viscosity increasing exponentially as the temperature decreases, the R^2 value of 0.97. The viscosity of unmodified asphalt is less than 1 Pas at 120^{0}C and just over 4 Pas at 100^{0}C. Therefore, the unmodified asphalt mix was workable even at temperatures closer to 100^{0}C. Lower viscosity and gradual change in viscosity over temperatures greater than 120^{o}C explains why the two compaction methods could achieve similar refusal density. Compared to unmodified asphalt the viscosity of modified asphalt is significantly higher at all the temperatures. At 100^{o}C, the viscosity of modified asphalt reached more than 6 Pas. Unlike the exponential increase in viscosity in unmodified asphalt, the increase in viscosity in modified asphalt is linear, which lead to a greater influence of the change in temperature over compaction even at temperatures greater than 120^{o}C. Therefore, lower densification of modified asphalt mixture was observed in Marshall compaction compared to the unmodified asphalt mixture.

Table 3: Temperatures measured before and after refusal density compaction

Mix Type	HMA Mix Number	Temperature (^{o}C) *Marshall Compactor*			Temperature (^{o}C) *Gyratory Compactor*	
		Before Compaction	After 400 Blows	After 800 Blows	Before Compaction	After Nmax
19.0mm NMAS PG 64-10 unmodified	HMA-1	143.2	87.0	68.6	142.9	103.5
	HMA-2	142.9	87.6	72.0	144.5	116.5
	HMA-3	143.9	80.6	66.9	144.0	108.0
	HMA-4	143.0	83.1	70.2	143.5	109.4
19.0mm NMAS PG 76-10 SBS modified	HMA-5	151.2	86.6	71.3	150.7	108.6
	HMA-6	151.4	86.6	70.8	150.7	108.3
	HMA-7	151.6	90.0	80.3	150.3	111.9
	HMA-8	151.5	89.4	76.2	150.7	109.4

Table 4: Percent passing 0.075mm sieve size, measured before and after refusal density compaction

Mix Type	HMA Mix	% Passing 0.075mm as per JMF	% Passing 0.075mm after 800 Blows	% Passing 0.075mm after Nmax
19.0mm NMAS PG 64-10 unmodified	HMA-1	4.2	5.1	5.2
	HMA-2	3.8	4.9	5.0
	HMA-3	4.0	5.1	5.3
	HMA-4	4.1	4.7	4.8
19.0mm NMAS PG 76-10 SBS modified	HMA-5	4.8	5.4	5.5
	HMA-6	4.4	4.9	4.8
	HMA-7	4.4	5.1	5.0
	HMA-8	4.3	4.9	5.0

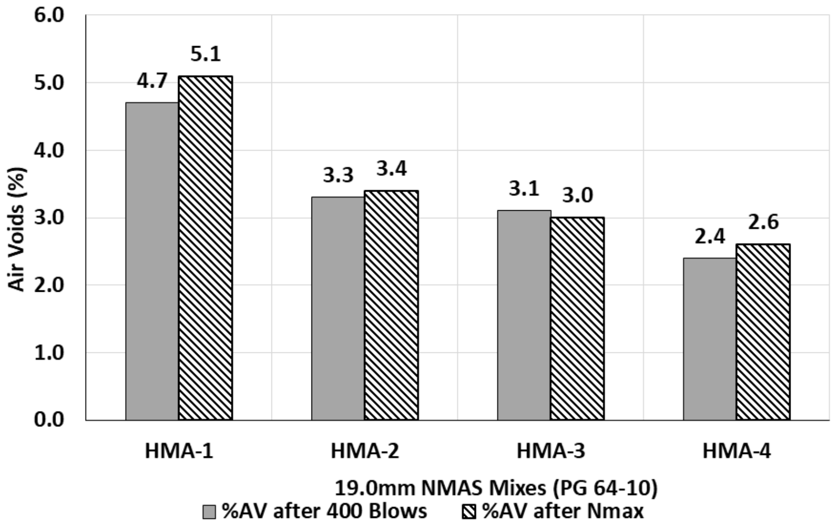

Figure 1: Air void for unmodified PG 64-10 asphalt mixtures after 400 blows Marshall refusal density and Nmax 205 Superpave gyrations

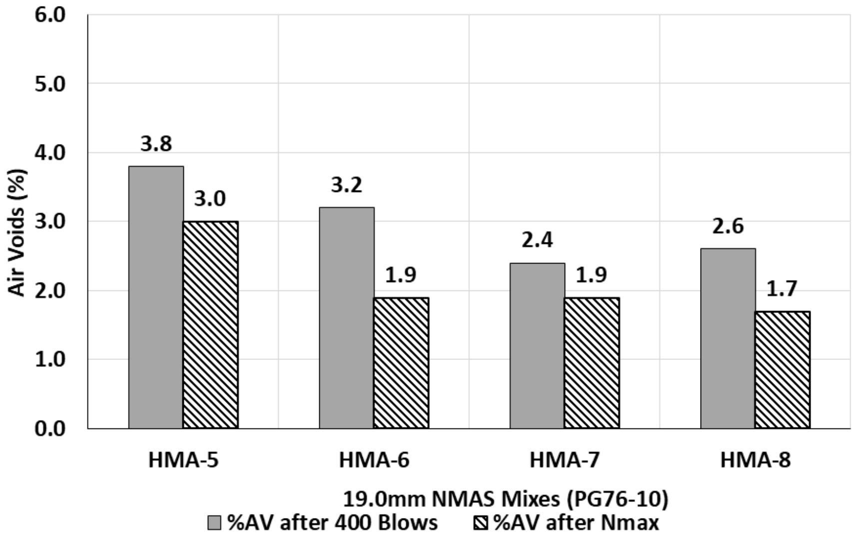

Figure 2: Air void for SBS modified PG76-10 asphalt mixtures after 400 blows Marshall refusal density and Nmax 205 Superpave gyrations

6. CONCLUSIONS

Both, refusal density obtained using Marshall compaction at 400 blows and density at Nmax 205 Superpave gyrations can be used as a mix design criterion to identify rut resistance mixtures for unmodified PG 64-10 asphalt. However, for SBS modified PG 76-10 asphalt mixtures, refusal density obtained from the Marshall compaction and density at Nmax Superpave gyrations are significantly different. Modified mixtures show higher air voids after Marshall refusal compaction, which can be misleading, as it gives a false impression that the mixtures are resistant to densification and therefore will not rut. In addition, when the same mixtures are compacted using Nmax gyrations they may fail the minimum air void requirement (≥2%) in Superpave for Nmax. Therefore, it is recommended to use Superpave Nmax gyratory compaction criteria for identifying rut resistance mixtures during asphalt mix design. Furthermore, it was observed that breaking of aggregate is not a concern in Marshall refusal density test, whereas, drop in temperature during compaction makes the test unfit for assessment of mixtures, especially, with modified binders.

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