Performance-based assessment of rutting resistance of asphalt mixes designed for hot climate regions

Original
Performance-based assessment of rutting resistance of asphalt mixes designed for hot climate regions / Sebaaly, Haissam; Riviera, PIER PAOLO; Varma, Sudhir; Maina, James W.; Santagata, Ezio. - In: INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING. - ISSN 1029-8436. - ELETTRONICO. - 23:7(2022), pp. 2448-2459. [10.1080/10298436.2020.1858484]

Publisher:
Taylor&Francis

Published
DOI:10.1080/10298436.2020.1858484

PERFORMANCE-BASED ASSESSMENT OF RUTTING RESISTANCE OF ASPHALT MIXES DESIGNED FOR HOT CLIMATE REGIONS

ABSTRACT

In hot climate regions asphalt mixes can be designed using the classical volumetric approach supplemented by the evaluation of basic mechanical parameters. To minimize the risk of permanent deformation, composition of the mixes can be defined by selecting densely packed aggregates and low binder contents. Despite the effectiveness of such an approach, mix design systems need to be improved by including performance-based tests that focus on the evaluation of the true rutting potential of asphalt mixes. The investigation described in this paper addressed these issues by considering twelve rut-resistant asphalt mixes designed as per the requirements set in the State of Qatar. These mixes, containing neat and polymer-modified binders (PMBs), were subjected to the Hamburg Wheel-Track Test (HWTT), dynamic modulus test and flow number test. Test temperature, specimen conditioning and loading conditions were varied in order to obtain a full description of the response of the mixes in terms of their permanent deformation resistance. It was postulated that the most meaningful results would be obtained from HWTTs carried out in dry conditions, thus avoiding the superposition of the effects derived from rutting with those due to moisture damage. Analysis of experimental data led to tentative requirements set on the results of dry HWTTs that can be introduced in the mix design framework currently adopted in the State of Qatar. Based on the calculation of rank correlation coefficients, it was found that dynamic modulus tests can be employed for the assessment of rutting potential, provided that in the case of mixes containing neat binders, reference is made to the results of tests carried out with no confinement. Furthermore, it was shown that flow number tests can be useful in ranking rut-resistant asphalt mixes containing neat binders and that the best outcomes are achieved by performing the corresponding tests in confined conditions.

Keywords: asphalt mixes, rutting, Hamburg Wheel-Track Test, dynamic modulus, flow number, Marshall stability.

1. Introduction

Rutting in asphalt pavements occurs in the form of surface depressions along the wheel paths. As a result of its origin and underlying mechanisms, it is the most frequent distress recorded by highway agencies in hot climate regions (Kandhal *et al.* 1998, Santagata *et al.* 2011, Isailović *et al.* 2016, Alkaissi 2020). Thus, in these geographical areas the main focus of asphalt mix design is the optimization of resistance to permanent deformation, which becomes of crucial importance especially for infrastructures characterized by heavy truck loads and relevant volumes of commercial traffic (Livneh 1990, Asi 2007, Jitsangiam *et al.* 2013). Furthermore, requirements related to resistance to permanent deformation are also embedded in quality assurance and quality control (QA/QC) systems. In most cases these requirements are set on the results of volumetric characterization tests, while in the more advanced QA/QC systems they can also be expressed with respect to the results of performance-based tests.

The type of rutting that can be controlled through an appropriate formulation of asphalt mixes is the one which derives from the accumulation of non-reversible deformations in the upper bitumen-bound portion of the pavement. As extensively described in the literature, under the effects of repeated traffic loading, these deformations develop in three phases, typically referred to as primary, secondary and tertiary (Eisenmann and Hilmer 1997, Zhou *et al.* 2004, Miljković and Radenberg 2011, Santagata *et al.* 2013, Santagata *et al.* 2015a, Santagata *et al.* 2017a). The primary phase includes early consolidation phenomena that are associated to traffic post-compaction occurring with a non-negligible reduction of the initial voids content of the mixes. The secondary phase takes place at constant volume as a result of shear effects, frequently leading to the formation of lateral surface bulges next to the wheel paths. Finally, the tertiary phase is reached when the asphalt mixes exhibit a rapid increase of non-reversible strains, ultimately leading to failure.

The abovementioned issues related to the optimization of asphalt mixes are relevant for countries located in the hot climate regions, some of which, like the State of Qatar, have road networks that are rapidly expanding as a result of the ongoing socio-economic development (Sadek *et al.* 2014). Furthermore, environmental and loading conditions occurring in asphalt pavements can be extremely challenging. In particular, previous studies have shown that during the summer season pavement temperature in the Gulf region can be as high as 70 °C, with significant strains occurring under loading especially in the surface wearing courses (Al-Abdul Wahhab *et al.* 1997, Siri *et al.* 2017).

To prevent the occurrence of rutting, asphalt mixes in the State of Qatar are designed by adopting densely packed aggregate structures and relatively low bitumen contents (in the range of 3.4 % to 4.4 % by weight of the total mix). These characteristics are guaranteed by satisfying the requirements contained in Qatar Construction Specifications (QCS 2014), which refer to asphalt mixes containing either neat bitumen (belonging to the 60-70 penetration grade) or polymer-modified binders (PMBs) (Qatar Construction Specifications 2014).

As per QCS 2014, design of asphalt mixes in most cases is carried out using the Marshall methodology described in the corresponding Asphalt Institute manual (Asphalt Institute 2014). In such a context, minimum acceptance thresholds are defined for Marshall stability, flow and quotient, which, regardless of their empirical character, have proven to be acceptable indicators of the potential resistance to plastic deformation due to loading of asphalt mixes. A further design criterion included in QCS 2014 refers to the voids content of Marshall specimens compacted with 400 blows per face, which needs to be higher than a minimum acceptance limit to prevent the potential occurrence of bitumen overfilling the aggregate structure, with the consequent risk of bleeding or plastic deformation under loading. This type of requirement focuses on the so-called “refusal density” conditions, which are those that are reached by an asphalt mix when the aggregate structure is compacted to the maximum degree possible and any supplementary compaction effort does not produce any effect. The concept of refusal density has been validated by many years of experience and is included in the technical specifications adopted in several countries characterized by a hot climate (Dachlan *et al.* 1997, Smith and Jones 1998, Rao *et al.* 2007, SSCW 2008).

According to QCS 2014, designers in the State of Qatar have the option of adopting, as an alternative to the classical Marshall mix design method, the more advanced SUPERPAVE procedure (Cominsky *et al.* 1994, Bahia *et al.* 1998, AASHTO 2017a, AASHTO 2017b). In such case, refusal density conditions are assessed by considering specimens compacted with the gyratory shear compactor with a number of gyrations equal to Nmax (variable as a function of design traffic). The corresponding minimum voids content is fixed at 2 % for all asphalt mixes to exclude the possibility of bleeding or plastic flow under traffic. As proven by past investigations, the voids content recorded in these conditions may be considered as an indicator of the rutting resistance potential of asphalt mixes (Anderson *et al.* 2002, Mahmoud *et al.* 2004). However, it should be underlined that gyratory compaction does not simulate rutting failure mechanisms nor can it be conducted at in-service pavement temperatures.

Additional requirements that are included in QCS 2014 for the quality control of SUPERPAVE asphalt mixes refer to the results of performance-based tests that provide an insight into their rutting resistance. In particular, minimum allowable values are fixed for the dynamic modulus (equal to 1,920 MPa at 45 °C, measured at a frequency of 10 Hz with no confining pressure) and for the flow number (equal to 740 at 54.4 °C, measured with an applied deviatoric stress of 600 kPa with no confining pressure).

Regardless of the options given by QCS 2014, most designers prefer to adopt the Marshall mix design procedure and, in any case, usually select design binder contents on the lower side of the specification range. This leads to relatively low values of voids filled with asphalt (VFA), that according to specifications have to be in the 50-75 % range.

Although such a strategy may more easily yield satisfactory values of Marshall parameters and air voids at 400 blows per face, it can be detrimental for the durability of asphalt mixes. Although the experience developed in the use of rut-resistant wearing course mixes in the State of Qatar has been extremely positive, improvements are still needed in their mix design and quality control. Thus, specific studies have been carried out in the recent past by considering the characteristics of commonly employed asphalt mixes and in particular by trying to assess the effectiveness of refusal density parameters (Varma *et al.* 2019), by making use of packing principles derived from Bailey ratios (Horak *et al.* 2019) and by developing a mix design optimization process based on the implementation of artificial neural networks (Sebaaly *et al.* 2018).

This paper is a follow-up to the abovementioned investigations and focuses on the comparative assessment of different test methods employed for the evaluation of the rutting resistance of wearing course mixes, containing both neat bitumen and PMBs, designed as per QCS 2014. In particular, it considers the results obtained using the Hamburg Wheel-Track Test (HWTT) performed in the so-called “dry” conditions as those which are truly representative of rutting resistance (Chaturabong and Bahia 2017a) and thereafter identifies, for other experimental techniques, the preferred testing conditions and the most representative performance indicators. The ultimate goal of the study is to develop a performance-based framework which can enhance the current mix design and QA/QC systems adopted in the State of Qatar for asphalt wearing course mixes. Furthermore, it provides a database of experimental results that can be of use for other researchers that tackle the same issue in countries where pavements are subjected to similar environmental and loading conditions.

2. Materials and methods

2.1 Materials

The experimental investigation described in this paper was carried out by considering twelve different wearing course asphalt mixes (associated to identification numerical codes 1 to 12) which were designed as per QCS 2014 (Marshall method) for different projects in the State of Qatar (Qatar Construction Specifications 2014, Asphalt Institute 2014). The corresponding Job Mix Formulae (JMF) were fully approved for use in construction projects in the State of Qatar. All mixes contained gabbro aggregates of similar origin, stockpiled in the premises of various asphalt production plants. Bituminous binders employed for the preparation of the mixes were those that are admitted for use in the State of Qatar: neat bitumen belonging to the 60-70 penetration grade (mixes 1 to 6) and PMB containing styrene-butadiene-styrene (SBS) and classified as PG76E-10 according to the SUPERPAVE performance grade (PG) system (mixes 7 to 12) (AASHTO 2020, Santagata *et al.* 2020). Neat bitumen was reported in all cases to be of the same origin, whereas PMBs were produced by different manufacturers in the State of Qatar according to undisclosed procedures and recipes. It was also verified that all 60-70 neat binders were classified as PG64S-22.

All the asphalt mixes considered in the investigation were prepared in the laboratory in small batches of approximately 15 kg. Mixing was performed mechanically and was interrupted when a complete dispersion of the binder and homogeneous coating of aggregates were obtained. The mixing temperature was adjusted to take into account the different viscosity of the employed binders. Thus, it was maintained in the 155-160 °C range for 60-70 bitumen and in the 165-170 °C range for PMBs. Prior to compaction, all mixes were short-term aged as per AASHTO R 30-02 guidelines (AASHTO 2019a).

JMF data of the abovementioned asphalt mixes are synthesized in the top part of Tables 1 and 2, which list particle size distribution data (expressed in terms of percent passing for the most significant sieve openings) and binder content values (expressed as a percentage of the total mix). The central part of the two tables contains the volumetric characteristics of Marshall specimens compacted as per ASTM D6926-20 (ASTM 2020) with 75 blows per face, those of specimens compacted to refusal with 400 blows per face, and the experimental results derived from Marshall tests (stability, flow and quotient) carried out as per ASTM D6927-15 on the specimens compacted with 75 blows (ASTM 2015). Whenever applicable, QCS 2014 acceptance limits are also shown for considered characteristics or quantities.

The lower part of Tables 1 and 2 contains the results of the additional volumetric characterization tests carried out on specimens of the asphalt mixes compacted using the gyratory shear compactor at three different levels as per AASHTO R 83 17 (AASHTO 2017d). The first one is associated with a target void content of 7.0 %, which corresponds to the minimum compaction level considered acceptable in the field and consequently employed for mechanical characterization tests. The other two levels are those associated to given values of the number of imposed gyrations, indicated as N_{design} and N_{max}, which correspond to the conditions considered in the SUPERPAVE mix design method for the verification of target mix volumetrics (Cominsky *et al.* 1994).

The experimental data provided in Tables 1 and 2 clearly show that all the considered asphalt mixes (indicated in the following as “60-70 mixes” and “PMB mixes”) are characterized by a similar continuous particle size distribution. However, a distinction can be made depending upon the percent passing the primary control sieve (PCS), that for mixes with a nominal maximum aggregate size (NMAS) of 19 mm corresponds to the sieve with a 4.75 mm opening (with a threshold value of the percent passing equal to 47 %) (AASHTO 2017a). Most of the mixes containing neat bitumen are of the “fine” type (with the only exceptions of mixes 3 and 6), whereas most of the mixes containing PMB are of the “coarse” type (with exception of mixes 8 and 11).

Binder content of the mixes is contained in the QCS 2014 range, with higher values adopted for the PMB mixes (mean value equal to 4.2 %) in comparison to 60-70 mixes (mean value equal to 3.8 %). Such a difference is reflected by lower values of residual voids (v) (5.8 % versus 6.3 %) and VMA (14.9 % versus 15.5 %), and by higher values of VFA (61.0 % versus 59.7 %).

When considering the volumetric characteristics of Marshall specimens compacted with 400 blows per face, quite surprisingly most of the mixes (with the only exception of mix 4) do not meet the acceptance criterion indicated in QCS 2014 (void content greater than 4.0 %). On the contrary, all mixes meet the acceptance criteria defined for Marshall stability, flow and quotient.

As expected, since the mixes were designed with the Marshall procedure, none of them exhibit a void content equal to 4.0 % when compacted with a number of gyrations equal to N_{design}. Absolute deviations from such a condition vary quite significantly, ranging from 0.1 % to 1.7 %, with no identifiable trend or dependency from any other characteristic.

Finally, when considering the state of compaction achieved with a number of gyrations equal to N_{max}, half of the considered mixes violate the SUPERPAVE acceptance criterion (voids content greater than 2.0 %). However, once again such an occurrence is not associated with any specific property of the mixes.

2.2 Methods

All the specimens employed for the performance-based tests described in the following were prepared by means of the gyratory shear compactor in accordance with AASHTO R 83-17 (AASHTO 2017d). Target air voids content was fixed at 7.0 %, with a tolerance of ±0.5 %. Such a value was considered as representative of typical compaction conditions achieved on site for wearing course asphalt mixes in the State of Qatar.

As indicated in the following, performance-based tests carried out on the asphalt mixes during the investigation included the Hamburg Wheel-Track Test (HWTT), the dynamic modulus test and the flow number test. The HWTT is a performance-based test that is gaining a widespread popularity in the pavement engineering international community due to its capability of simulating, in a reduced scale, the repeated loading effects of moving vehicles in actual pavements (Williams and Prowell 1999, Lu and Harvey 2006, Mohammad *et al.* 2015). The dynamic modulus and flow number tests were identified, in the past, among the simple performance tests to be considered for incorporation, along with the volumetric requirements, in the SUPERPAVE mix design method as valuable supplements capable of addressing rutting-related issues (Witczak *et al.* 2002, Witczak 2006, Witczak 2007). Dynamic modulus was recommended as the primary test and flow number was recommended as an optional test.

2.2.1 Hamburg Wheel-Track Tests

In the experimental investigation described in this paper, the HWTT was conducted in accordance with AASHTO T 324-19 (AASHTO 2019b) in “dry” conditions, with no water conditioning of the test specimens, to measure what was considered in the study as the true rutting performance of the asphalt mixes. Nevertheless, tests carried out in “wet” conditions were included in the investigation to collect experimental data that may be compared to other results published in the literature.

The choice of focusing on “dry” HWTTs was made to better simulate the field behaviour of the mixes in the conditions that occur in the State of Qatar, thereby avoiding the superposition of rutting and moisture damage effects that may be misleading when focusing exclusively on the resistance to permanent deformation. In such a context it should be noted that very few studies have been published on the subject of dry HWTTs (Chaturabong and Bahia 2017a, Walubita *et al.* 2018, Dai *et al.* 2020) and that no limits deriving from such an alternative procedure are included in specifications. On the contrary, most of the research works documented in the literature refer to the use of the HWTT carried out in wet conditions, with a multitude of analyses performed for its improvement and validation (Aschenbrener 1995, Izzo and Tahmoressi 1999, Williams and Prowell 1999, Lu and Harvey 2006, Yildirim *et al.* 2007, Mohammad *et al.* 2015, Chaturabonga and Bahia 2017b, Lv *et al.* 2018, Walubita *et al.* 2019a). Moreover, it has been reported that several U.S. Departments of Transportation (DoTs) include wet HWTT acceptance limits in their specifications (Mohammad *et al.* 2015).

Tests were carried out according to the AASHTO test standard by making use of two steel wheels with 203.2 ± 2.0 mm diameter and 47 mm width, subjected to a vertical load of 705 ± 4.5 N. Loads were repeatedly applied across the surface of the cylindrical samples with 52 ± 2 passes per minute. As recommended by Tsai et al. (Tsai *et al.* 2016), rut depth measured at the center of the cylindrical specimens was used in the analysis of test results. Since different responses were expected from the 60-70 and PMB mixes, tests were performed at two different test temperatures to obtain rut depth included in the optimal operation range of the employed displacement transducers. In particular, mixes prepared with 60-70 penetration neat binders (characterized by an upper PG limiting temperature of 64 °C) were tested at 50 ºC, while the mixes containing PMB (with an upper PG limiting temperature of 76 °C) were tested at 55 ºC. These values were referenced from the testing conditions recommended by the Colorado DoT, which however refers to wet HWTTs (Colorado Department of Transportation Specification 2020). In both cases, before the loading phase of the tests, specimens were conditioned (either in air or in water) for 60 minutes at the selected test temperature.

Results of the HWTTs were expressed in terms of the number of loadings required to reach an average rut depth (calculated from two nominally identical specimens) equal to 12.5 mm, or, as an alternative, as the rut depth measured after 20,000 loadings. Once again, these conditions were tentatively defined by referring to the most frequent thresholds indicated (in wet conditions) in the previously mentioned DoT specifications (Mohammad *et al.* 2015).

Figure 1 displays typical results which were obtained for 60-70 and PMB mixes. It can be observed that the evolution of rut depth occurs with a progressive change of the rate of deformation, starting from an initial phase of consolidation and reaching a secondary phase of shear flow. This type of trend is consistent with the rutting mechanisms observed in the field, thus indicating that the HWTT is a truly simulative test procedure. However, it should be emphasized that none of the considered asphalt mixes reached tertiary flow conditions when subjected to HWTTs in dry conditions. This is discussed in section 3.3.

2.2.2 Dynamic modulus and flow number tests

The dynamic modulus and flow number tests were performed by making use of the Asphalt Mixture Performance Tester (AMPT) as per the requirements of AASHTO T 378-17 (AASHTO 2017e).

Dynamic modulus represents a fundamental property of asphalt mixes which can be measured over a wide range of frequencies and temperatures. In particular, it corresponds to the norm of the complex modulus that for viscoelastic materials can be assessed by considering the stress-strain relationship under a continuous sinusoidal (haversine) loading. In analytical terms, such a modulus is defined as the ratio between the peak amplitudes of stress and strain. During dynamic modulus tests, the time lag between the stress and strain functions is also evaluated, with the consequent determination of the so-called phase angle. This is an additional viscoelastic parameter that can be meaningful to compare and assess the rutting susceptibility of different asphalt mixes since lower phase angle values indicate a higher resistance to permanent deformation.

For all the considered asphalt mixes, the dynamic modulus test was conducted both in unconfined and confined conditions (with a constant confining pressure of 69 kPa). Tests were carried out at eight different frequencies (20 Hz, 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz, 0.2 Hz, 0.1

Hz) and three temperatures (4 °C and 20 °C for all mixes, with an additional high temperature equal to 40 °C or 45 °C for neat and PMB mixes, respectively).

As discussed in previous research studies, dynamic modulus, along with phase angle, provides insight regarding potential viscoelastic energy dissipation, which has been shown to relate well with rutting performance of asphalt mixes (Witczak *et al.* 2002, , Bhasin *et al.* 2003, Apeagyei 2011). However, for characterization of rutting resistance, instead of considering dynamic modulus values recorded at specific temperatures and frequencies, reference can be made to the five complex modulus rutting indexes (CMRIs) proposed by Dave et al. (Dave *et al.* 2019). These are derived from three characteristic points belonging to the master curves calculated at any relevant temperature as indicated in Equations 1 through 5.

$$\mathrm{CMRI-I} = \frac{\delta_A-\delta_B}{|f_A-f_B|} \qquad [1]$$

$$\mathrm{CMRI-II} = \frac{|E_A^*|-|E_B^*|}{|f_A-f_B|} \qquad [2]$$

$$\mathrm{CMRI-III} = \left|\frac{|E_A^*|-|E_B^*|}{|f_A-f_B|}\right|^2 \qquad [3]$$

$$\mathrm{CMRI-IV} = \frac{|E_C^*|}{\delta\cdot|f_A-f_B|^2} \qquad [4]$$

$$\mathrm{CMRI-V} = \frac{|E_A^*|-|E_B^*|}{(\delta_A-\delta_B)\cdot|f_A-f_B|^2} \qquad [5]$$

where: δA is the peak phase angle, δB is the phase angle corresponding to HWTT loading conditions (frequency of 0.866 Hz), δC is the estimated average phase angle between δA and δB; fA and fB and are the logarithms of the frequencies corresponding to δA and δB, respectively; |E*A|, |E*B| and |E*C| are the dynamic modulus values corresponding to δA, δB and δC, respectively.

The flow number test is a repeated load test in which a haversine load pulse is applied to cylindrical test specimens with rest periods between successive loadings. Accumulated permanent strain and strain rate are measured at each load cycle with the final objective of identifying the number of loadings which correspond to the transition from viscous flow conditions to tertiary flow failure. Previous research has shown that flow number tests provide results that under certain conditions may exhibit a clear relationship with those coming from loaded wheel tests (Walubita *et al.* 2013, Zhang *et al.* 2013, Santagata *et al.* 2015b, Walubita *et al.* 2019b). Furthermore, they can yield rutting-related rankings of asphalt mixes that are consistent with the corresponding rankings of bituminous binders, thus highlighting the benefits of polymer modification (Santagata *et al.* 2015c, Santagata *et al.* 2017b). In such a context, a confining pressure can be applied to test specimens in order to better simulate stress conditions occurring in actual pavements and to avoid premature failure (von Quintus *et al.* 2012).

Flow number tests were carried out, as the dynamic modulus tests, both in unconfined and confined conditions (with a constant confining pressure of 69 kPa). In the first case vertical deviatoric stress was fixed at 600 kPa, whereas in the second case a value of 483 kPa was employed. Tests were performed at the same temperatures adopted for HWTTs: 50 ºC for the 60-70 mixes and 55 ºC for the PMB mixes.

3. Results and analysis

3.1 Hamburg Wheel-Track Tests

As mentioned in section 1, all asphalt mixes included in the investigation were designed to be rut resistant according to the approach embedded in QCS 2014. It was also postulated that the best quantitative indicator of rutting resistance could be derived from HWTTs carried out in dry conditions, with the consequent possibility of avoiding any superposition with stripping induced effects. Nevertheless, HWTTs were also performed in wet conditions in straight accordance with the corresponding AASHTO standard (AASHTO 2019b).

HWTT results are synthesized in Table 3, which lists the rut depth (RD_{dry} and RD_{wet}) reached after 20,000 loading passes. In the case of wet HWTTs, four mixes reached the threshold value of 12.5 mm, so the corresponding number of loading passes is indicated in an additional column. Table 3 also contains the relative rankings (R#$_{dry}$ and R#$_{wet}$) assigned to the mixes belonging to the two groups (60-70 and PMB) based on the recorded RD results. The value of 1 is assigned to the mix with the greatest rut resistance (i.e. with the lowest final RD value), while higher values are progressively associated to those with a lower rut resistance (e.g. ranking 6 given to the mix with highest RD value).

As expected, for all mixes the final RD value recorded in dry conditions was significantly lower than the one measured for test specimens submerged in water. This obviously derives from the fact that in wet HWTTs results represent the superposition of rutting and moisture damage effects, whereas in the dry HWTTs final rut depth depends exclusively upon rutting. In such a context it is not surprising that the average difference between the results obtained in the two conditions (wet versus dry) is lower for the PMB mixes, thus revealing a greater resistance to stripping (i.e. a stronger binder-aggregate adhesion) that is ensured by means of polymer modification.

When focusing on the results derived from dry HWTTs, it can be observed that RD values recorded for the two groups of mixes were contained within relatively narrow ranges: 3.8-5.0 mm for the 60-70 mixes, 1.9-3.6 mm for the PMB mixes. Since it was assumed that all the asphalt mixes were designed to be rut-resistant, it can therefore be postulated that for acceptance purposes maximum admissible RD values of 5.5 mm (at 50 °C) and 4.0 mm (at 55 °C) can be assumed for 60-70 and PMB mixes, respectively. These threshold values, calculated by considering an excess of 10 % with respect to maximum recorded values, will need to be validated and possibly fine-tuned with further investigations.

Although the RD values of the various asphalt mixes belonging to each group are quite similar, rankings can still allow some distinctions to be made. In particular, the mixes characterized by the highest rut resistance were found to be mix 6 (RD equal to 3.8 mm at 50 °C) and mix 8 (RD equal to 1.9 mm at 55 °C) in the 60-70 and PMB group, respectively. However, no clear association can be made between the relative rankings and the composition and volumetrics of the mixes provided in Tables 1 and 2. For example, in the 60-70 group the best rut resistance was exhibited by the mix (number 6) with the lowest value of air voids and VMA in Marshall-compacted specimens (75 blows per face) and the highest value of VFA. Conversely, in the PMB mix these characteristics (i.e. lowest air voids and VMA, highest VFA) were found for the mix with the worst rut resistance (mix number 9). Similar observations can be made when considering Marshall stability. The highest value recorded for the PMB mixes was found for the mix with the lowest rut resistance ranking (mix 9), while in the 60-70 group the lowest stability value was determined from the mix with the highest ranking (mix 6).

The only parameters that seem to somehow match with the rut resistance rankings are the air voids and VFA recorded for Marshall specimens compacted with 400 blows per face. In particular, the 60-70 mixes ranked from 4 to 6 (with RD values greater than 4.7 mm) reached air void values lower than 3 %, with corresponding VFA values greater than 75 %. Likewise, in the PMB group the mix that received the worst ranking (mix number 9) exhibited an air void content of less than 2 %, with a corresponding VFA value above 80 %.

In conclusion, it can be stated that there is no possibility of tailoring rut resistance of asphalt mixes by considering the results of the preliminary volumetric and basic mechanical characterization tests normally included in mix design (Tables 1 and 2). On the contrary, it is necessary to perform the HWTT which is sensitive to the actual packing of the aggregate structure and to its interaction with the bituminous binding matrix.

3.2 Dynamic modulus tests

Dynamic modulus values measured at individual temperatures in both unconfined and confined conditions were shifted to develop master curves at the reference temperature of 20 °C by referring to the analytical expression given in Equation 6 (AASHTO 2017c).

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\cdot\log f_r}} \qquad [6]$$

where δ, α, β and γ are fitting parameters, and f_r is the reduced frequency.

Results obtained from the construction of master curves are displayed in Figures 2 and 3, which show the dynamic modulus and phase angle of the two groups of mixes (60-70 and PMB) as a function of reduced frequency. Values of the fitting parameters included in Equation 6 are listed in Table 4.

When analyzing the data displayed in the dynamic modulus and phase angle master curves, significant differences were found, as expected, between 60-70 and PMB mixes in the low frequency range which is representative of high temperature and slow loading conditions that are meaningful with respect to rutting. In particular, the PMB mixes exhibited higher stiffness and lower phase angles, thus indicating a higher resistance to accumulation of permanent deformation. For both groups of mixes, differences were also recorded between data obtained from tests carried out in unconfined and confined conditions. As expected, in the presence of lateral confinement all mixes exhibited a a stiffer and more elastic response under loading.

A significant difference between the two groups of mixes was recorded in terms of their variability. All 60-70 mixes had a very similar behaviour, with dynamic modulus and phase angle data points very close to each other (with the only exception of mix number 5). On the contrary, the PMB mixes exhibited widely different values of both viscoelastic parameters. Such an outcome can be explained by considering the fact that the PMBs employed in the investigation differed in composition, while all the 60-70 neat binders came from the same source.

It should be mentioned that QCS 2014 includes an acceptance requirement for the dynamic modulus of asphalt mixes designed according to the SUPERPAVE method. In particular, when measured at 45 °C and a loading frequency of 10 Hz, such a parameter is required to be greater than 1,920 MPa. By considering the experimental data recorded during the investigation, this condition was not met by any of the 60-70 mixes that yielded an average value of 1,387 MPa. On the contrary, the PMB mixes satisfied the requirement, exhibiting an average value of the dynamic modulus equal to 2,184 MPa.

To better assess the potential rutting resistance of the asphalt mixes as described by dynamic modulus test results, the previously mentioned CMRIs were evaluated for the two groups at the same temperatures employed for the HWTTs: 50 °C for the 60-70 mixes and 55 °C for the PMB mixes. The outcomes of these calculations, carried out by employing Equations 1 through 5, are shown in Tables 5 and 6, which refer to unconfined and confined tests, respectively. Both tables also contain the relative rankings (R#I through R#V) associated with the CMRI values, assigned to the mixes with the same criterion employed for the ranking based on HWTT results (i.e. giving rankings 1 and 6 to the mixes with the highest and lowest rut resistance, respectively).

Results listed in Tables 4 and 5 indicate that the rankings associated to the various CMRIs varied significantly and were also sensitive to the confinement adopted during testing. However, conclusions can be drawn from their analysis only by considering their relationship with the rankings previously assigned based on HWTT tests carried out in dry conditions. This is discussed in section 3.4.

3.3 Flow number tests

Results of flow number tests carried out on the two groups of mixes (at 50 °C for 60-70 mixes and at 55 °C for PMB mixes) are given Table 7, which also contains the rankings ($R\#_{FN-U}$ and $R\#_{FN-C}$) associated to each mix.

As in the case of the dynamic modulus tests, it can be observed that PMB mixes exhibited a greater resistance to permanent deformation than 60-70 mixes. Notwithstanding the fact that the tests on the PMB mixes were performed at a higher temperature (55 °C versus 50 °C), they led to significantly higher flow number values. Moreover, as expected, for both groups of mixes a non-negligible increase of the flow number was observed when applying a confining pressure during repeated loading. These outcomes are consistent with previous research works that highlighted the non-linear response of asphalt mixes in the conditions that are imposed during flow number tests (Santagata *et al.* 2017a).

Relative rankings coming from flow number tests were also sensitive to confinement conditions. However, as for the CMRIs derived from dynamic modulus tests, further comments can be made only by considering their relationship with the rankings previously assigned based on HWTT tests carried out in dry conditions. This is discussed in section 3.4.

According to QCS 2014, SUPERPAVE mixes should exhibit a flow number greater than 740 at 54.4 °C with an applied deviatoric stress of 600 kPa and with no confining pressure. By referring to the results listed in Table 6, it can be observed that all PMB mixes (except for mix 10) satisfied such a requirement. On the contrary, the 60-70 mixes exhibited flow number values at 50 °C that were all below 700 and therefore certainly violate the abovementioned requirement at a higher temperature.

3.4 Comparative evaluation of different test methods

Since all the asphalt mixes considered in the investigation were designed to be rut-resistant, to compare the different test methods employed during the investigation, a relationship was not sought between the individual test results. Rather, the analysis focused on the degree of similarity between the relative rankings derived from each test procedure. In statistical terms, this corresponds to the calculation of the so-called Spearman's rank correlation coefficient (ρ) that assesses how well the relationship between two variables can be described using a monotonic function. Values of ρ can vary between -1 and 1, with a value of 0 corresponding to no correlation. Values close to 1 are indicative of a good correlation, with similar rankings being associated with the two considered procedures. On the contrary, values close to -1 indicate strongly dissimilar rankings, with fully opposed information provided by the two compared procedures.

Since it was assumed that the most representative evaluation of rutting resistance stems from dry HWTTs, ρ was calculated by comparing its rankings to those associated with all the other procedures employed in the investigation. The results of such an evaluation are synthesized in Table 8.

When considering the rankings coming from HWTTs carried out in wet conditions, as expected their degree of correlation to true rutting resistance ranking was found to be weak in the case of 60-70 mixes that are characterized by non-negligible stripping effects (ρ equal to 0.200). However, the degree of correlation between the rankings associated with dry and wet HWTTs increased significantly in the case of PMB mixes (ρ equal to 0.771) since these are less prone to moisture damage.

The different CMRIs that are extracted from dynamic modulus master curves are characterized by a non-uniform degree of correlation that changes as a function of confining conditions and of the type of binder. Thus, selection of the most appropriate CMRI needs to be based on the combined analysis of all the considered cases. When analyzing the data listed in Table 8, it can be observed that the highest ρ values were recorded for parameters CMRI-III, CMRI-IV and CMRI-V derived from the tests carried out in the absence of any confinement (ρ values comprised between 0.829 and 0.943). In such a context it is interesting to note that the degree of correlation of the rankings of these parameters decreases significantly when considering results coming from dynamic modulus tests carried with lateral confinement in the case of 60-70 mixes (with negative ρ values comprised between -0.200 and -0.314), whereas it remains almost constant for the PMB mixes (ρ in the 0.886-0.943 range). Such an outcome is consistent with the viscoelastic and non-linear characteristics of the considered mixes. The PMB mixes are stiffer and therefore their response under loading at smaller strains is less affected by confinement; on the contrary, the less stiff 60-70 mixes are more affected by lateral confining pressure. As a consequence, the application of a confinement pressure tends to mask the specific rutting resistance properties of the individual 60-70 mixes, preventing their assessment with respect to the reference dry HWTT.

Finally, ρ values associated with the flow number tests clearly indicate that for 60-70 mixes a better degree of correlation is achieved by performing the tests in confined conditions (ρ equal to 0.771). This is consistent with physical expectations and in line with recommendations coming from previous research (Santagata *et al.* 2017a). However, these observations do not apply to the case of the PMB mixes since it was found that the corresponding test results, regardless of the confinement conditions imposed during repeated loading, yielded rankings that are in contrast with those of dry HWTTs (with negative ρ values). This outcome suggests that the standard flow number test may not be adequate to discriminate between the rutting resistance of asphalt mixes characterized by a densely packed aggregate structure and by the presence of stiff elastic binders. Thus, the use of the flow number test may be beneficial when comparing the results to a minimum threshold value for acceptance purposes, while it is not recommended when trying to fine-tune the composition of a rut-resistant mix.

4. Summary and conclusions

The experimental investigation described in this paper focused on the use of different testing techniques for the assessment of the rutting resistance of wearing course asphalt mixes employed in the State of Qatar. These included mixes containing both neat 60-70 penetration bitumen and several PMBs. They were all designed to be rut resistant as per the requirements of QCS 2014 (Marshall method) and it was assumed that their most representative evaluation could be performed by making use of HWTTs carried out in dry conditions.

The experimental results suggest that the mix design and QA/QC framework currently adopted in the State of Qatar may be supplemented by requirements set on the results of dry HWTTs.

In particular, threshold values of the final rut depth measured after 20,000 loading passes may be set at 5.5 mm for 60-70 mixes (tested at 50°C) and at 4.0 mm for PMB mixes (tested at 55°C). Moreover, adjustments may be made to current specifications since it appears that the minimum admissible value of 4.0 % air voids measured on Marshall specimens compacted with 400 blows per face may be too high.

Regarding the other testing techniques, it was observed that their results and the consequent rankings are sensitive to several factors that need to be taken into account. HWTTs performed on specimens submerged in water may lead to misleading results since they depend upon the occurrence of stripping effects especially in the case of 60-70 mixes. Dynamic modulus tests can be meaningful for the assessment of the rutting potential of the asphalt mixes and the fine-tuning of their composition when considering three different indexes (CMRI-III, CMRI-IV and CMRI-V). However, in the case of 60-70 mixes, it may be more appropriate to refer to the results of unconfined dynamic modulus tests to prevent the occurrence of the masking effects of confining pressure that tend to uniform the response under loading of different mixes. Flow number tests can also be extremely useful in ranking 60-70 mixes and the best outcomes are achieved by performing the corresponding tests in confined conditions. However, these tests fail to capture the differences between similar rut-resistant mixes containing PMBs. Finally, it should be underlined that the acceptance thresholds currently indicated in QCS 2014 for dynamic modulus and flow number test results seem to be appropriate for PMB mixes, while they are probably too severe for 60-70 mixes.

The conclusions drawn from this investigation will need to be supported by further studies which should possibly include the evaluation of different types of asphalt mixes and of test specimens cored from pavement wearing courses. Furthermore, a validation of the proposed acceptance limits is necessary and will require the monitoring of pavement sections subjected to actual vehicle loading.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

AASHTO, 2017a. *AASHTO M 323-17, Standard specification for Superpave volumetric mix design*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2017b. *AASHTO R 35-17, Standard practice for Superpave volumetric design for asphalt mixtures*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2017c. *AASHTO R 84-17, Standard practice for developing dynamic modulus master curves for asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT)*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2017d. *AASHTO R 83-17, Standard practice for preparation of cylindrical performance test specimens using the Superpave Gyratory Compactor (SGC)*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2017e. *AASHTO T 378-17, Standard Method of test for determining the dynamic modulus and flow number for asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT)*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2019a. *AASHTO R 30-02, Standard practice for mixture conditioning of Hot-Mix Asphalt (HMA)*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2019b. *AASHTO T 324-19, Standard method of test for Hamburg Wheel-Track Testing of compacted Hot Mix Asphalt (HMA)*. Washington, DC: American Association of State and Highway Official.

AASHTO, 2020. *AASHTO M 332-20, Standard specification for Performance-Graded asphalt binder using Multiple Stress Creep Recovery (MSCR) test*. Washington, DC: American Association of State and Highway Official.

Al-Abdul Wahhab, H.I., Asi, I.M., Al-Dubabe, I.A., and Farhat Ali M., 1997. Development of performance-based bitumen specifications for the Gulf countries. *Construction and Building Materials*, 11(1), 15-22. 10.1016/S0950-0618(97)00002-0.

Alkaissi, Z.A., 2020. Effect of high temperature and traffic loading on rutting performance of flexible pavement. *Journal of King Saud University - Engineering Sciences*, 32(1), 1-4. 10.1016/j.jksues.2018.04.005.

Anderson, R., Turner, P., Peterson, R., and Mallick, R., 2002. Relationship of Superpave gyratory compaction properties to HMA rutting behavior, *NCHRP Report 478*, Transportation Research Board, Washington, DC.

Apeagyei, A.K., 2011. Rutting as a function of dynamic modulus and gradation. *Journal of Materials in Civil Engineering*, 23(9), 1302-1310. 10.1061/(ASCE)MT.1943-5533.0000309.

Aschenbrener, T., 1995. Evaluation of Hamburg wheel-tracking device to predict moisture damage in hot mix asphalt. *Transportation Research Record*, 1492, 193–201.

Asi, I.M., 2007. Performance evaluation of SUPERPAVE and Marshall asphalt mix designs to suite Jordan climatic and traffic condition. *Construction and Building Materials*, 21(8), 1732-1740. 10.1016/j.conbuildmat.2006.05.036.

Asphalt Institute, 2014. *MS-2 Asphalt Mix Design Methods*, 7th Edition, Asphalt Institute Manual Series.

ASTM, 2020. *ASTM D6926-20, Standard practice for preparation of asphalt mixture specimens using Marshall apparatus*. West Conshohocken, PA: ASTM International.

ASTM, 2015. *ASTM D6927-15, Standard test method for Marshall stability and flow of asphalt mixtures*. West Conshohocken, PA: ASTM International.

Bahia, H., Friemel, T., Peterson, P., Russell, J., and Poehnelt, B., 1998. Optimization of constructability and resistance to traffic: a new design approach for HMA using the Superpave compactor. *Journal of the Association of Asphalt Paving Technologists*, 67, 189-232.

Bhasin, A., Button, J.W., and Chowdhury, A., 2003. Evaluation of simple performance tests on HMA mixtures from the South Central United States, *Report 9-558-1*, Texas Department of Transportation.

Chaturabong, P., and Bahia, H.U., 2017a. Mechanisms of asphalt mixture rutting in the dry Hamburg Wheel Tracking test and the potential to be alternative test in measuring rutting resistance. *Construction and Building Materials*, 146, 175-182. 10.1016/j.conbuildmat.2017.04.080.

Chaturabong, P., and Bahia, H.U., 2017b. The evaluation of relative effect of moisture in Hamburg wheel tracking test. *Construction and Building Materials*. 153, 337-345. 0.1016/j.conbuildmat.2017.07.133.

Colorado Department of Transportation, 2020. Hamburg Wheel-Track Testing of Compacted Bituminous Mixtures, *CP-L 5112-20*, Colorado Department of Transportation Specification.

Cominsky, R.J., Huber, G.A., Kennedy, T.W., and Anderson, M., 1994. SHRP-A-407: The SUPERPAVE mix design manual for new construction and overlays, Strategic Highway Research Program.

Dachlan, A.T., Zamhari, K.A., Sterling, A.B., and Toole, T, 1997. Improved Indonesian procedure for asphalt mix design. *Proceedings of the 2nd Conference of Eastern Asia Society for Transportation Studies*.

Dai, X., Jia, Y., Wang, S., and Gao, Y., 2020. Evaluation of the rutting performance of the field specimen using the Hamburg Wheel-Tracking test and dynamic modulus test. *Advances in Civil Engineering.* 10.1155/2020/9525179.

Dave, E.V., Sias, J.E., and Nemati, R., 2019. Layer coefficients for New Hampshire Department of Transportation pavement design, *Report FHWA-NH-RD-26962N*, New Hampshire Department of Transportation.

Eisenmann, J., and Hilmer, A., 1987. Influence of wheel load and inflation pressure on the rutting effect at asphalt-pavements – experiments and theoretical investigations. *Proceedings of Sixth International Conference on the Structural Design of Asphalt Pavements*.

Horak, E., Maina, J., Myburgh, P., and Sebaaly, H., 2019. Monitoring permeability potential of hot mix asphalt via binary aggregate packing principles correlated with Bailey ratios and porosity principles. *Journal of the South African Institution of Civil Engineering*, 61(3), 32-44. 10.17159/2309-8775/2019/v61n3a4.

Isailović, I., Wistuba, M.P., and Cannone Falchetto, A., 2016. Permanent deformation of hot mix asphalt under compression and tension. *Proceedings of 6th Eurasphalt & Eurobitume Congress*. 10.14311/EE.2016.401.

Izzo, R.P., and Tahmoressi, M., 1999. Use of the Hamburg Wheel-Tracking device for evaluating moisture susceptibility of hot-mix asphalt. *Transportation Research Record*, 1681(1), 76-85.

Jitsangiam, P., Chindaprasirt, P., and Nikraz, H., 2013. An evaluation of the suitability of SUPERPAVE and Marshall asphalt mix designs as they relate to Thailand's climatic conditions. *Construction and Building Materials*, 40, 961-970. 10.1016/j.conbuildmat.2012.11.011.

Kandhal, P.S., Mallick, R.B., and Brown, E.R., 1998. Hot mix asphalt for intersections in hot climates, *NCAT Report No. 98-06*, National Center for Asphalt Technology, Auburn, AL, USA.

Livneh, M., 1990. Asphalt mix design for hot climate regions. *Australian Road Research*, 20(2).

Lu, Q., and Harvey, J.T., 2006. Evaluation of Hamburg Wheel-Tracking device test with laboratory and field performance data. *Transportation Research Record*, 1970, 25-44. 10.3141/1970-05.

Lv, Q., Huang, W., Bahia, H.U., Tang, N., Zhu, T., 2018. Three-stage damage evolution of asphalt mixture in the Wet Hamburg wheel tracking device test using X-Ray computed tomography. *Journal of Materials in Civil Engineering*, 30(7). 10.1061/(ASCE)MT.1943-5533.0002355.

Mahmoud, A., and Bahia, H., 2004. Using gyratory compactor to measure mechanical stability of asphalt mixtures, Wisconsin Highway Research Program WHRP 05-02.

Miljković, M., and Radenberg, M., 2011. Rutting mechanisms and advanced laboratory testing of asphalt mixtures resistance against permanent deformation. *Facta Universitatis-Series: Architecture and Civil Engineering*, 9(3), 407-417. 10.2298/FUACE1103407M.

Mohammad, L.N., Elseifi, M.A., Raghavendra, A., and Ye, M., 2015. Hamburg Wheel-Track test equipment requirements and improvements to AASHTO T 324, *NCHRP Web-Only Document 219*.

QCS 2014, 2014. Qatar Construction Specifications. State of Qatar.

Rao, S.K., Das, J.K, and Chowdhury, P., 2007. Asphalt mix design - Refusal density approach for heavily trafficked roads. *Journal of the Indian Roads Congress*, 68(1), 53-64.

Sadek, H., Masad, E., Sirin, O., Al-Khalid, H., Sadek, M., and Little, D., 2014. Implementation of mechanistic-empirical pavement analysis in the State of Qatar. *International Journal of Pavement Engineering*, 15(6), 495-511. 10.1080/10298436.2013.837164.

Santagata, E., Riviera, P.P., and Dalmazzo, D., 2011. Rutting behaviour of wearing course mixtures in severe temperature and loading conditions. *Proceedings of the 5th International Conference Bituminous Mixtures and Pavements*, 541-550.

Santagata, E., Baglieri, O., Dalmazzo, D., and Tsantilis, L., 2013. Evaluation of the anti-rutting potential of polymer-modified binders by means of creep-recovery shear tests. *Materials and Structures*, 46(10), 1673-1682. 10.1617/s11527-012-0006-0.

Santagata, E., Baglieri, O., Alam, M., and Dalmazzo, D., 2015a. A novel procedure for the evaluation of anti-rutting potential of asphalt binders. *International Journal of Pavement Engineering*, 16(4), 287-296. 10.1080/10298436.2014.942859.

Santagata, E., Baglieri, O., Alam, M., Lanotte, M., and Riviera, P.P., 2015b. Evaluation of rutting resistance of rubberized gap-graded asphalt mixtures. *Proceedings of the 6th International Conference Bituminous Mixtures and Pavements*, 407-412.

Santagata, E., Baglieri, O., Alam, M., and Riviera, P.P., 2015c. Evaluation of rutting properties of bituminous binders by means of Single Shear Creep-Recovery (SSCR) tests and correlation with mixture performance. *Proceedings of the 8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials*, RILEM Bookseries 11, 745-756. 10.1007/978-94-017-7342-3_60.

Santagata, E., Baglieri, O., Riviera, P.P., Lanotte, M., and Alam, M., 2017a. Influence of lateral confining pressure on flow number tests. *Proceedings of the 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, BCRRA, 237-242. 10.1201/9781315100333-35.2017.

Santagata, E., Baglieri, O., Riviera, P.P., and Alam, M., 2017b. Correlating creep properties of bituminous binders with anti-rutting performance of corresponding mixtures. *International Journal of Pavement Research and Technology*, 10(1), 38-44. 10.1016/j.ijprt.2016.11.008.

Santagata, E., Yeganeh, S., Idris, O.E.M., Ali, M.H.M.M., and Al-Emadi, K.M.I, 2020. Test procedures for advanced characterization of bituminous binders employed for pavement construction in Public Works Authority road projects - State of Qatar. *Proceedings of the International Conference on Civil Infrastructure and Construction* (CIC 2020), 502-511. 10.29117/cic.2020.0063.

Sebaaly, H., Varma, S., and Maina, J., 2018. Optimizing asphalt mix design process using artificial neural network and genetic algorithm. *Construction and Building Materials*, 168, 660–670. 10.1016/j.conbuildmat.2018.02.118.

Sirin, O., Paul, D.K., Kassem, E., and Ohiduzzaman, M., 2017. Effect of aging on asphalt binders in the State of Qatar: a Case Study. *Road Materials and Pavement Design*, 18, 165-184. 10.1080/14680629.2017.1389094.

Smith, H.R., and Jones, C.R., 1998. Bituminous surfacings for heavily trafficked roads in tropical climates. *Proceedings of the Institution of Civil Engineers: Transport*, 129(1), 28-33.

SSCW 2008, 2008. Standard Specifications for Construction Works. Ministry of Works, Kingdom of Bahrain.

Tsai, B.W., Coleri, E., Harvey J.T., and Monismith, C.L., 2016. Evaluation of AASHTO T 324 Hamburg-Wheel Track device test. *Construction and Building Materials*, 114, 248-260. 10.1016/j.conbuildmat.2016.03.171.

Varma, S., Sebaaly, H., Maina, J., and Al Ghbani, A., 2019. Experimental investigation of Marshall and SUPERPAVE mix design methods for rutting criteria. *Proceedings of the Annual Southern African Transport Conference*.

von Quintus, H., Mallela, J., Bonaquist, R., Schwartz, C., and Carvalho, R., 2012. Calibration of rutting model for structural and mix design, *NCHRP Report 719*.

L.F. Walubita, L.F., Zhang, J., Alvarez, A.E., and Hu, X., 2013. Exploring the flow number (FN) index as a means to characterise the HMA permanent deformation response under FN testing. *Journal of the South African Institution of Civil Engineering*, 55(3), 103-112.

Walubita, L.F., Nyamuhokya, T.P., Naik, B., Holleran, I., and Dessouky, S., 2018. Sensitivity analysis and validation of the simple punching shear test (SPST) for screening HMA mixes. *Construction and Building Materials*, 169, 205-214. 10.1016/j.conbuildmat.2018.02.198.

Walubita, L.F., Faruk, A.N.M., Zhang, J., Komba, J.J., Alrashydah, E.I., and G.S. Simate, G.S., 2019a. The Hamburg Rutting Test (HWTT) alternative data analysis methods and HMA screening criteria. *International Journal of Pavement Research and Technology*, 12, 110-116. 10.1007/s42947-019-0014-3.

Walubita, L.F., Fuentes, L., Lee, S.I., Dawd, I., and Mahmoud, E., 2019b. Comparative evaluation of five HMA rutting-related laboratory test methods relative to field performance data: DM, FN, RLPD, SPST, and HWTT. *Construction and Building Materials*, 215, 737-753. 0.1016/j.conbuildmat.2019.04.250.

Williams, R.C., and Prowell, B.D., 1999. Comparison of laboratory wheel-tracking test results with Wes Track performance. *Transportation Research Record*, 1681, 121-128. 10.3141/1681-15.

Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus H. 2002. Simple Performance Test for Superpave Mix Design, *NCHRP Report 465*.

Witczak, M.W., 2006. Simple Performance Tests: summary of recommended methods and database, *NCHRP Report 547*.

Witczak, M.W., 2007. Specification criteria for Simple Performance Tests for rutting, *NCHRP Report 580*.

Yildirim, Y., Jayawickrama, P.W., Hossain, M.S., Alhabshi, A., Yildirim, C., Smit, A.F., and Little D., 2007. Hamburg Wheel Tracking database analysis, Report 0-1707-7.

Zhang, J., Alvarez, A.E., Lee, S.I., Torres, A., and Walubita, L.F., 2013. Comparison of flow number, dynamic modulus, and repeated load tests for evaluation of HMA permanent deformation. Construction and Building Materials, 44, 391-398. j.conbuildmat.2013.03.013.

Zhou, F., Scullion, T., and Sun, L., 2004. Verification and modeling of three-stage permanent deformation behavior of asphalt mixes. *Journal of Transportation Engineering*, 130(4), 486-494. 10.1061/(ASCE)0733-947X(2004)130:4(486).

Table 1. Mix design results for asphalt mixes containing neat 60-70 bitumen

Sieve Size	**Mix-1**	**Mix-2**	**Mix-3**	**Mix-4**	**Mix-5**	**Mix-6**	**QCS 2014**
	Passing (%)						
19.0	100	100	100	100	100	100	86-100
12.5	80	83	83	79	83	83	69-87
4.75	50	52	44	50	49	44	40-60
2.36	31	35	32	35	36	31	25-45
0.075	3.7	4.2	4.5	3.8	4.0	4.1	2-8
Binder content (%)	3.9	3.8	3.4	3.6	3.9	4.1	3.4-4.4
Marshall-compacted specimens							
v (%) at 75 blows	6.2	6.5	6.4	6.5	6.7	5.2	5.0-8.0
VMA (%) at 75 blows	15.8	15.9	14.7	15.5	16.5	14.6	≥ 14.0
VFA (%) at 75 blows	60.8	59.1	56.5	58.1	59.4	64.4	50-75
Stability (kN)	13.5	13.1	12.2	14.4	14.5	12.1	≥ 11.5
Flow (mm)	2.9	2.9	2.5	2.4	3.0	2.6	2-4
Marshall quotient (kN/mm)	4.7	4.5	4.9	5.9	4.9	4.7	≥ 4.75
v (%) at 400 blows	2.7	2.5	3.9	4.2	2.2	3.4	≥ 4.0
VMA (%) at 400 blows	11.0	10.4	10.6	11.3	10.2	11.8	-
VFA (%) at 400 blows	75.6	76.2	63.4	63.1	78.3	70.9	-
Gyratory-compacted specimens							
VMA (%) at v = 7%	15.0	14.5	13.4	13.9	14.6	15.1	-
VFA (%) at v = 7%	53.0	52.2	48.3	49.8	51.8	53.6	-
v (%) at N_{design}=125	4.1	4.9	2.5	4.4	3.5	3.6	4.0
VMA (%) at N_{design}=125	12.3	12.6	9.3	11.6	11.3	12.0	-
VFA (%) at N_{design}=125	66.6	61.4	72.8	61.6	69.1	70.0	-
v (%) at N_{max}=205	3.6	4.2	1.5	3.3	1.9	2.2	≥ 2.0
VMA (%) at N_{max}=205	12.1	12.0	8.3	10.6	9.8	10.7	-
VFA (%) at N_{max}=205	67.8	64.9	82.5	68.3	81.0	79.6	-

Table 2. Mix design results for asphalt mixes containing PMB

Sieve Size	**Mix-7**	**Mix-8**	**Mix-9**	**Mix-10**	**Mix-11**	**Mix-12**	**QCS 2014**
	Passing (%)						
19.0	100	100	100	100	100	100	86-100
12.5	88	83	79	81	83	80	69-87
4.75	46	47	45	46	49	44	40-60
2.36	29	31	30	31	33	30	25-45
0.075	4.8	4.6	4.4	4.6	4.4	4.3	2-8
Binder content (%)	4.3	4.1	4.1	4.0	4.3	4.3	3.4-4.4
Marshall-compacted specimens							
v (%) at 75 blows	6.1	6.0	5.2	5.9	6.0	5.7	5.0-8.0
VMA (%) at 75 blows	15.3	14.4	14.2	14.8	15.7	15.0	≥ 14.0
VFA (%) at 75 blows	60.1	58.3	63.4	60.1	61.8	62.0	50-75
Stability (kN)	17.1	16.4	19.3	17.0	18.7	17.3	≥ 11.5
Flow (mm)	2.9	3.0	2.8	3.2	2.8	3.2	2-4
Marshall quotient (kN/mm)	5.9	5.4	6.9	5.3	6.7	5.4	≥ 4.75
v (%) at 400 blows	2.7	3.2	1.9	2.8	2.3	2.5	≥ 4.0
VMA (%) at 400 blows	11.8	11.8	10.5	11.3	11.3	11.5	-
VFA (%) at 400 blows	75.7	73.0	82.2	75.0	79.5	78.2	-
Gyratory-compacted specimens							
VMA (%) at v = 7%	15.6	15.3	15.2	15.1	15.6	15.6	-
VFA (%) at v = 7%	55.0	54.4	53.9	53.5	55.1	55.1	-
v (%) at N_{design}=125	4.1	3.5	2.3	5.0	2.9	2.3	4.0
VMA (%) at N_{design}=125	12.9	12.1	10.9	13.3	11.8	11.3	-
VFA (%) at N_{design}=125	68.4	71.3	78.6	62.2	75.7	79.8	-
v (%) at N_{max}=205	2.9	1.9	1.5	3.8	1.6	1.4	≥ 2.0
VMA (%) at N_{max}=205	11.9	10.9	10.1	12.2	10.6	10.5	-
VFA (%) at N_{max}=205	75.4	80.1	85.6	68.9	85.3	86.4	-

Table 3. Results and corresponding rutting resistance rankings of the asphalt mixes determined from HWTTs

Mix	Binder	T (°C)	Dry WHTT		Wet HWTT		
			RD_{dry}	$\text{R\#}_{\text{dry}}$	RD_{wet}	Cycles	$\text{R\#}_{\text{wet}}$
Mix-1	60-70	50	4.7	4	7.8	-	1
Mix-2			5.0	6	12.5	12,300	5
Mix-3			4.3	3	12.5	17,200	3
Mix-4			3.9	2	12.5	12,000	6
Mix-5			4.8	5	12.5	14,900	4
Mix-6			3.8	1	8.8	-	2
Mix-7	PMB	55	2.2	2	3.0	-	1
Mix-8			1.9	1	3.6	-	2
Mix-9			3.6	6	4.4	-	4
Mix-10			2.9	5	12.0	-	6
Mix-11			2.4	4	5.3	-	5
Mix-12			2.3	3	3.8	-	3

Table 4. Master curve fitting parameters of the asphalt mixes (at 20 °C)

Mix	**Binder**	**Unconfined tests**				**Confined tests**			
		δ	**α**	**β**	**γ**	**δ**	**α**	**β**	**γ**
Mix-1	60-70	-2.185	6.996	1.633	0.256	-2.240	6.836	1.825	0.276
Mix-2		-2.319	6.933	1.869	0.278	-2.258	6.934	1.770	0.256
Mix-3		-2.280	6.898	1.786	0.266	-2.256	6.923	1.771	0.254
Mix-4		-2.221	6.870	1.758	0.266	-2.246	6.823	1.898	0.272
Mix-5		-2.228	6.751	2.053	0.275	-2.215	6.773	2.086	0.253
Mix-6		-2.462	7.066	1.863	0.281	-2.469	7.061	1.835	0.259
Mix-7	PMB	-2.270	6.955	1.885	0.237	-2.178	6.803	1.889	0.227
Mix-8		-2.156	6.859	2.026	0.265	-2.187	6.786	2.041	0.251
Mix-9		-0.376	4.974	1.566	0.291	-0.407	5.186	1.385	0.237
Mix-10		-2.141	6.737	1.759	0.273	-1.968	6.907	1.441	0.195
Mix-11		-2.333	6.884	2.090	0.370	-2.346	6.880	2.125	0.344
Mix-12		-2.256	6.874	2.155	0.272	-2.206	6.876	2.054	0.242

Table 5. CMRIs and corresponding rutting resistance rankings of the asphalt mixes determined from dynamic modulus master curves (unconfined tests)

Mix	**Binder**	**CMRIs (I-V) and corresponding R#**									
		I	**$R\#_{I}$**	**II**	**$R\#_{II}$**	**III**	**$R\#_{III}$**	**IV**	**$R\#_{IV}$**	**V**	**$R\#_{V}$**
Mix-1	60-70 (50 °C)	2.77	6	570.0	6	451.2	4	16.1	4	129.1	3
Mix-2		2.80	4	592.0	3	435.9	5	14.8	5	114.8	5
Mix-3		3.04	1	592.0	4	470.5	3	17.4	3	123.1	4
Mix-4		2.92	3	725.3	1	818.4	1	27.7	1	316.2	1
Mix-5		2.80	5	588.7	5	323.4	6	9.1	6	63.5	6
Mix-6		3.00	2	607.8	2	504.6	2	18.1	2	139.4	2
Mix-7	PMB (55 °C)	1.63	5	636.0	4	724.3	2	41.0	2	505.6	2
Mix-8		1.54	6	870.8	1	1,063.4	1	60.1	1	843.9	1
Mix-9		3.64	2	522.7	5	380.7	5	13.7	5	76.2	5
Mix-10		3.89	1	456.5	6	276.2	6	7.4	6	43.0	6
Mix-11		2.58	4	649.5	3	536.0	4	21.1	4	171.6	4
Mix-12		3.44	3	750.4	2	700.5	3	31.4	3	190.0	3

Table 6. CMRIs and corresponding rutting resistance rankings of the asphalt mixes determined from dynamic modulus master curves (confined tests)

Mix	**Binder**	**CMRIs (I-V) and corresponding R#**									
		I	**R#$_{I}$**	**II**	**R#$_{II}$**	**III**	**R#$_{III}$**	**IV**	**R#$_{IV}$**	**V**	**R#$_{V}$**
Mix-1	60-70 (50°C)	2.53	3	605.1	5	452.5	6	15.9	6	133.6	6
Mix-2		2.41	5	662.4	3	521.6	3	20.5	3	170.3	3
Mix-3		2.94	1	639.4	4	505.1	4	19.9	4	135.8	5
Mix-4		2.03	6	683.4	2	541.0	2	20.6	2	210.7	2
Mix-5		2.51	4	833.2	1	940.4	1	36.0	1	422.3	1
Mix-6		2.82	2	588.9	6	488.9	5	19.5	5	144.2	4
Mix-7	PMB (55°C)	0.72	6	655.9	4	1,320.0	2	148.3	1	3,698.1	1
Mix-8		0.91	5	701.2	3	1,354.7	1	126.2	2	2,871.8	2
Mix-9		3.03	2	568.6	5	416.5	5	18.5	5	100.8	5
Mix-10		4.15	1	509.2	6	308.1	6	11.3	6	44.9	6
Mix-11		2.24	4	740.4	2	814.6	4	48.2	4	400.4	4
Mix-12		2.41	3	801.8	1	1,176.8	3	91.6	3	716.2	3

Table 7. Results and corresponding rutting resistance rankings of the asphalt mixes determined from flow number tests

Mix	Binder	T (°C)	Unconfined		Confined	
			FN	**$R\#_{FN-U}$**	**FN**	**$R\#_{FN-C}$**
Mix-1	60-70	50	327	6	1,110	4
Mix-2			459	3	890	5
Mix-3			374	5	1,713	2
Mix-4			653	1	1,996	1
Mix-5			379	4	583	6
Mix-6			459	2	1,379	3
Mix-7	PMB	55	2,394	3	3,471	5
Mix-8			1,884	4	3,492	4
Mix-9			6,091	1	14,790	1
Mix-10			725	6	8,531	3
Mix-11			3,813	2	12,572	2
Mix-12			1,812	5	2,434	6

Table 8. Rank correlation coefficients calculated for all test procedures with respect to the dry HWTT

	Tests without		**Tests with**	
	60-70	**PMB**	**60-70**	**PMB**
HWTT_{wet}	-	-	0.200	0.771
CMRI-I	0.600	-0.886	0.314	-0.829
CMRI-II	0.543	0.771	-0.486	0.486
CMRI-III	0.886	0.943	-0.314	0.943
CMRI-IV	0.886	0.943	-0.314	0.886
CMRI-V	0.829	0.943	-0.200	0.886
FN	0.429	-0.257	0.771	-0.714

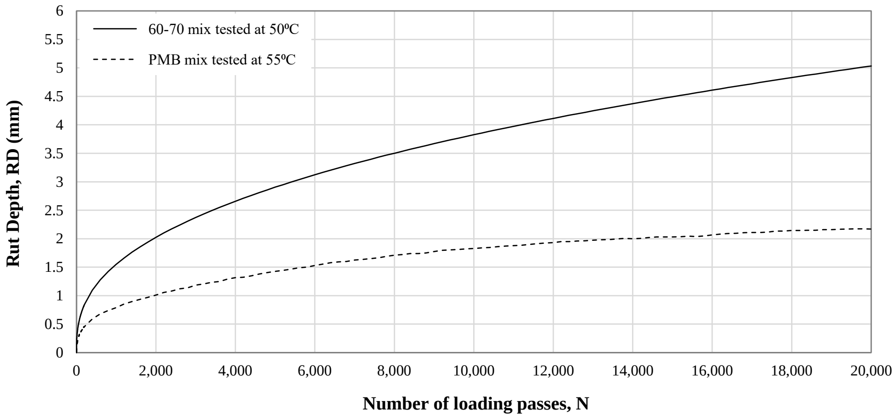

Figure 1. Typical results obtained from dry HWTTs

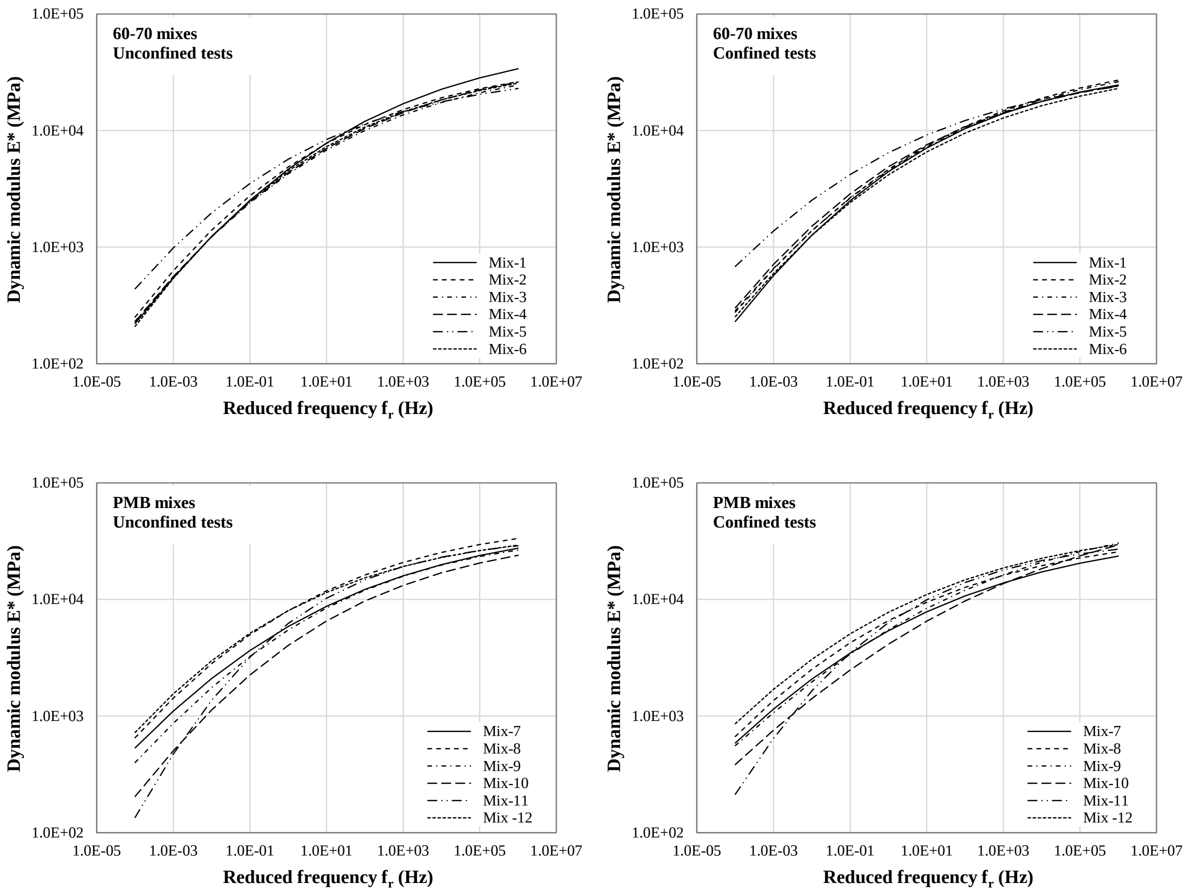

Figure 2. Complex modulus master curves of the asphalt mixes (at 20 °C)

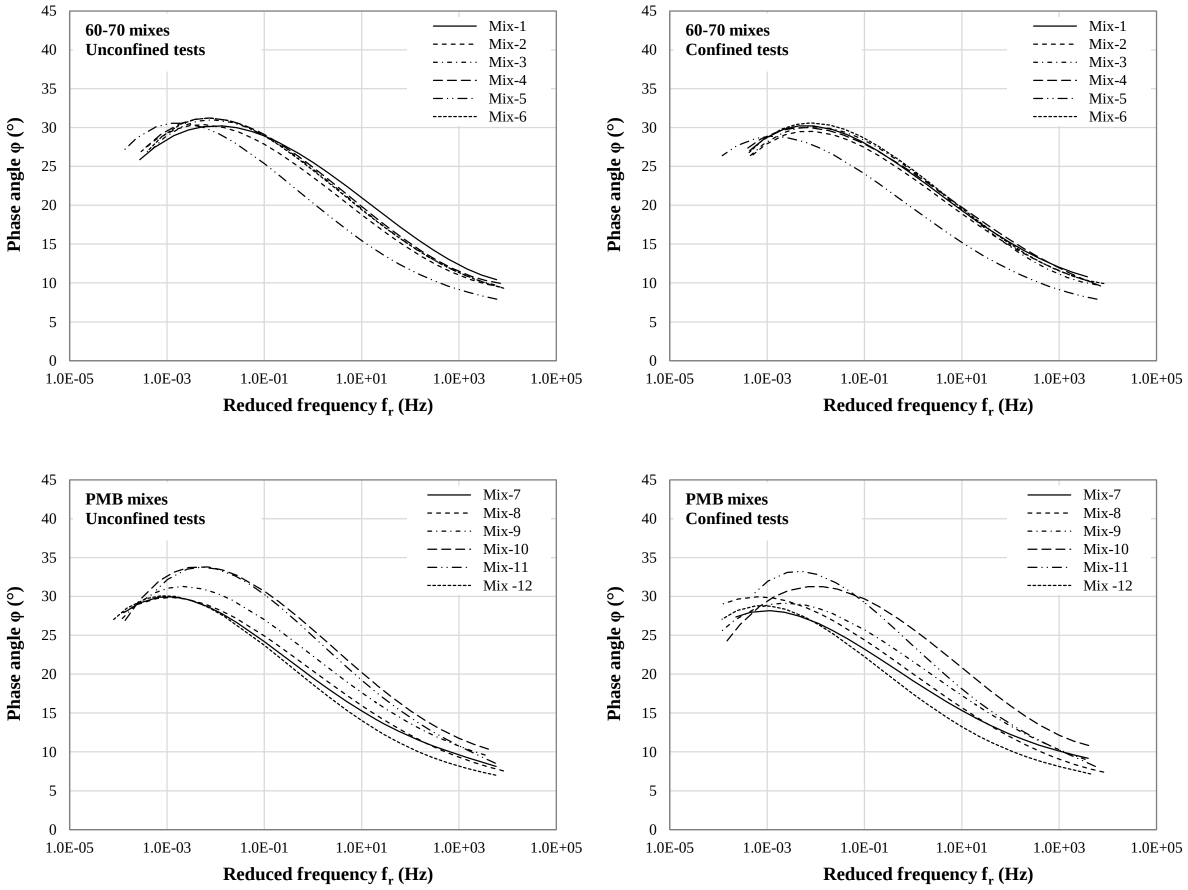

Figure 3. Phase angle master curves of the asphalt mixes (at 20 °C)