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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.

51 The abovementioned issues related to the optimization of asphalt mixes are relevant for

52 countries located in the hot climate regions, some of which, like the State of Qatar, have road

53 networks that are rapidly expanding as a result of the ongoing socio-economic development

54 (Sadek *et al.* 2014). Furthermore, environmental and loading conditions occurring in asphalt

55 pavements can be extremely challenging. In particular, previous studies have shown that during

56 the summer season pavement temperature in the Gulf region can be as high as 70 °C, with

57 significant strains occurring under loading especially in the surface wearing courses (Al-Abdul

58 Wahhab *et al.* 1997, Siri *et al.* 2017).

59 To prevent the occurrence of rutting, asphalt mixes in the State of Qatar are designed by

60 adopting densely packed aggregate structures and relatively low bitumen contents (in the range

61 of 3.4 % to 4.4 % by weight of the total mix). These characteristics are guaranteed by satisfying

62 the requirements contained in Qatar Construction Specifications (QCS 2014), which refer to

63 asphalt mixes containing either neat bitumen (belonging to the 60-70 penetration grade) or

64 polymer-modified binders (PMBs) (Qatar Construction Specifications 2014).

65 As per QCS 2014, design of asphalt mixes in most cases is carried out using the Marshall

66 methodology described in the corresponding Asphalt Institute manual (Asphalt Institute 2014).

67 In such a context, minimum acceptance thresholds are defined for Marshall stability, flow and

68 quotient, which, regardless of their empirical character, have proven to be acceptable indicators

69 of the potential resistance to plastic deformation due to loading of asphalt mixes. A further

70 design criterion included in QCS 2014 refers to the voids content of Marshall specimens

71 compacted with 400 blows per face, which needs to be higher than a minimum acceptance limit

72 to prevent the potential occurrence of bitumen overfilling the aggregate structure, with the

73 consequent risk of bleeding or plastic deformation under loading. This type of requirement

74 focuses on the so-called "refusal density" conditions, which are those that are reached by an

75 asphalt mix when the aggregate structure is compacted to the maximum degree possible and

76 any supplementary compaction effort does not produce any effect. The concept of refusal

77 density has been validated by many years of experience and is included in the technical

78 specifications adopted in several countries characterized by a hot climate (Dachlan *et al.* 1997,

79 Smith and Jones 1998, Rao *et al.* 2007, SSCW 2008).

80 According to QCS 2014, designers in the State of Qatar have the option of adopting, as an

81 alternative to the classical Marshall mix design method, the more advanced SUPERPAVE

82 procedure (Cominsky *et al.* 1994, Bahia *et al.* 1998, AASHTO 2017a, AASHTO 2017b). In

83 such case, refusal density conditions are assessed by considering specimens compacted with

84 the gyratory shear compactor with a number of gyrations equal to Nmax (variable as a function

85 of design traffic). The corresponding minimum voids content is fixed at 2 % for all asphalt

86 mixes to exclude the possibility of bleeding or plastic flow under traffic. As proven by past

87 investigations, the voids content recorded in these conditions may be considered as an indicator

88 of the rutting resistance potential of asphalt mixes (Anderson *et al.* 2002, Mahmoud *et al.*

89 2004). However, it should be underlined that gyratory compaction does not simulate rutting

90 failure mechanisms nor can it be conducted at in-service pavement temperatures.

91 Additional requirements that are included in QCS 2014 for the quality control of SUPERPAVE

92 asphalt mixes refer to the results of performance-based tests that provide an insight into their

93 rutting resistance. In particular, minimum allowable values are fixed for the dynamic modulus

94 (equal to 1,920 MPa at 45 °C, measured at a frequency of 10 Hz with no confining pressure)

95 and for the flow number (equal to 740 at 54.4 °C, measured with an applied deviatoric stress

96 of 600 kPa with no confining pressure).

97 Regardless of the options given by QCS 2014, most designers prefer to adopt the Marshall mix

98 design procedure and, in any case, usually select design binder contents on the lower side of

99 the specification range. This leads to relatively low values of voids filled with asphalt (VFA),

100 that according to specifications have to be in the 50-75 % range.

101　Although such a strategy may more easily yield satisfactory values of Marshall parameters and

102　air voids at 400 blows per face, it can be detrimental for the durability of asphalt mixes.

103　Although the experience developed in the use of rut-resistant wearing course mixes in the State

104　of Qatar has been extremely positive, improvements are still needed in their mix design and

105　quality control. Thus, specific studies have been carried out in the recent past by considering

106　the characteristics of commonly employed asphalt mixes and in particular by trying to assess

107　the effectiveness of refusal density parameters (Varma *et al.* 2019), by making use of packing

108　principles derived from Bailey ratios (Horak *et al.* 2019) and by developing a mix design

109　optimization process based on the implementation of artificial neural networks (Sebaaly *et al.*

110　2018).

111　This paper is a follow-up to the abovementioned investigations and focuses on the comparative

112　assessment of different test methods employed for the evaluation of the rutting resistance of

113　wearing course mixes, containing both neat bitumen and PMBs, designed as per QCS 2014. In

114　particular, it considers the results obtained using the Hamburg Wheel-Track Test (HWTT)

115　performed in the so-called "dry" conditions as those which are truly representative of rutting

116　resistance (Chaturabong and Bahia 2017a) and thereafter identifies, for other experimental

117　techniques, the preferred testing conditions and the most representative performance indicators.

118　The ultimate goal of the study is to develop a performance-based framework which can

119　enhance the current mix design and QA/QC systems adopted in the State of Qatar for asphalt

120　wearing course mixes. Furthermore, it provides a database of experimental results that can be

121　of use for other researchers that tackle the same issue in countries where pavements are

122　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).

173   Binder content of the mixes is contained in the QCS 2014 range, with higher values adopted

174   for the PMB mixes (mean value equal to 4.2 %) in comparison to 60-70 mixes (mean value

175   equal to 3.8 %). Such a difference is reflected by lower values of residual voids (v) (5.8 %

176   versus 6.3 %) and VMA (14.9 % versus 15.5 %), and by higher values of VFA (61.0 % versus

177   59.7 %).

178   When considering the volumetric characteristics of Marshall specimens compacted with 400

179   blows per face, quite surprisingly most of the mixes (with the only exception of mix 4) do not

180   meet the acceptance criterion indicated in QCS 2014 (void content greater than 4.0 %). On the

181   contrary, all mixes meet the acceptance criteria defined for Marshall stability, flow and

182   quotient.

183   As expected, since the mixes were designed with the Marshall procedure, none of them exhibit

184   a void content equal to 4.0 % when compacted with a number of gyrations equal to N_{design}.

185   Absolute deviations from such a condition vary quite significantly, ranging from 0.1 % to 1.7

186   %, with no identifiable trend or dependency from any other characteristic.

187   Finally, when considering the state of compaction achieved with a number of gyrations equal

188   to N_{max}, half of the considered mixes violate the SUPERPAVE acceptance criterion (voids

189   content greater than 2.0 %). However, once again such an occurrence is not associated with

190   any specific property of the mixes.

191   *2.2 Methods*

192   All the specimens employed for the performance-based tests described in the following were

193   prepared by means of the gyratory shear compactor in accordance with AASHTO R 83-17

194   (AASHTO 2017d). Target air voids content was fixed at 7.0 %, with a tolerance of ±0.5 %.

195   Such a value was considered as representative of typical compaction conditions achieved on

196   site for wearing course asphalt mixes in the State of Qatar.

197   As indicated in the following, performance-based tests carried out on the asphalt mixes during

198 the investigation included the Hamburg Wheel-Track Test (HWTT), the dynamic modulus test

199 and the flow number test. The HWTT is a performance-based test that is gaining a widespread

200 popularity in the pavement engineering international community due to its capability of

201 simulating, in a reduced scale, the repeated loading effects of moving vehicles in actual

202 pavements (Williams and Prowell 1999, Lu and Harvey 2006, Mohammad *et al.* 2015). The

203 dynamic modulus and flow number tests were identified, in the past, among the simple

204 performance tests to be considered for incorporation, along with the volumetric requirements,

205 in the SUPERPAVE mix design method as valuable supplements capable of addressing rutting-

206 related issues (Witczak *et al.* 2002, Witczak 2006, Witczak 2007). Dynamic modulus was

207 recommended as the primary test and flow number was recommended as an optional test.

208 *2.2.1   Hamburg Wheel-Track Tests*

209 In the experimental investigation described in this paper, the HWTT was conducted in

210 accordance with AASHTO T 324-19 (AASHTO 2019b) in "dry" conditions, with no water

211 conditioning of the test specimens, to measure what was considered in the study as the true

212 rutting performance of the asphalt mixes. Nevertheless, tests carried out in "wet" conditions

213 were included in the investigation to collect experimental data that may be compared to other

214 results published in the literature.

215 The choice of focusing on "dry" HWTTs was made to better simulate the field behaviour of

216 the mixes in the conditions that occur in the State of Qatar, thereby avoiding the superposition

217 of rutting and moisture damage effects that may be misleading when focusing exclusively on

218 the resistance to permanent deformation. In such a context it should be noted that very few

219 studies have been published on the subject of dry HWTTs (Chaturabong and Bahia 2017a,

220 Walubita *et al.* 2018, Dai *et al.* 2020) and that no limits deriving from such an alternative

221 procedure are included in specifications. On the contrary, most of the research works

222 documented in the literature refer to the use of the HWTT carried out in wet conditions, with a

223 multitude of analyses performed for its improvement and validation (Aschenbrener 1995, Izzo

224 and Tahmoressi 1999, Williams and Prowell 1999, Lu and Harvey 2006, Yildirim *et al.* 2007,

225 Mohammad *et al.* 2015, Chaturabonga and Bahia 2017b, Lv *et al.* 2018, Walubita *et al.* 2019a).

226 Moreover, it has been reported that several U.S. Departments of Transportation (DoTs) include

227 wet HWTT acceptance limits in their specifications (Mohammad *et al.* 2015).

228 Tests were carried out according to the AASHTO test standard by making use of two steel

229 wheels with 203.2 ± 2.0 mm diameter and 47 mm width, subjected to a vertical load of 705 ±

230 4.5 N. Loads were repeatedly applied across the surface of the cylindrical samples with 52 ± 2

231 passes per minute. As recommended by Tsai et al. (Tsai *et al.* 2016), rut depth measured at the

232 center of the cylindrical specimens was used in the analysis of test results. Since different

233 responses were expected from the 60-70 and PMB mixes, tests were performed at two different

234 test temperatures to obtain rut depth included in the optimal operation range of the employed

235 displacement transducers. In particular, mixes prepared with 60-70 penetration neat binders

236 (characterized by an upper PG limiting temperature of 64 °C) were tested at 50 ⁰C, while the

237 mixes containing PMB (with an upper PG limiting temperature of 76 °C) were tested at 55 ⁰C.

238 These values were referenced from the testing conditions recommended by the Colorado DoT,

239 which however refers to wet HWTTs (Colorado Department of Transportation Specification

240 2020). In both cases, before the loading phase of the tests, specimens were conditioned (either

241 in air or in water) for 60 minutes at the selected test temperature.

242 Results of the HWTTs were expressed in terms of the number of loadings required to reach an

243 average rut depth (calculated from two nominally identical specimens) equal to 12.5 mm, or,

244 as an alternative, as the rut depth measured after 20,000 loadings. Once again, these conditions

245 were tentatively defined by referring to the most frequent thresholds indicated (in wet

246 conditions) in the previously mentioned DoT specifications (Mohammad *et al.* 2015).

247 Figure 1 displays typical results which were obtained for 60-70 and PMB mixes. It can be

248 observed that the evolution of rut depth occurs with a progressive change of the rate of

249 deformation, starting from an initial phase of consolidation and reaching a secondary phase of

250 shear flow. This type of trend is consistent with the rutting mechanisms observed in the field,

251 thus indicating that the HWTT is a truly simulative test procedure. However, it should be

252 emphasized that none of the considered asphalt mixes reached tertiary flow conditions when

253 subjected to HWTTs in dry conditions. This is discussed in section 3.3.

254 *2.2.2   Dynamic modulus and flow number tests*

255 The dynamic modulus and flow number tests were performed by making use of the Asphalt

256 Mixture Performance Tester (AMPT) as per the requirements of AASHTO T 378-17

257 (AASHTO 2017e).

258 Dynamic modulus represents a fundamental property of asphalt mixes which can be measured

259 over a wide range of frequencies and temperatures. In particular, it corresponds to the norm of

260 the complex modulus that for viscoelastic materials can be assessed by considering the stress-

261 strain relationship under a continuous sinusoidal (haversine) loading. In analytical terms, such

262 a modulus is defined as the ratio between the peak amplitudes of stress and strain. During

263 dynamic modulus tests, the time lag between the stress and strain functions is also evaluated,

264 with the consequent determination of the so-called phase angle. This is an additional

265 viscoelastic parameter that can be meaningful to compare and assess the rutting susceptibility

266 of different asphalt mixes since lower phase angle values indicate a higher resistance to

267 permanent deformation.

268 For all the considered asphalt mixes, the dynamic modulus test was conducted both in

269 unconfined and confined conditions (with a constant confining pressure of 69 kPa). Tests were

270 carried out at eight different frequencies (20 Hz, 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz, 0.2 Hz, 0.1

271 Hz) and three temperatures (4 °C and 20 °C for all mixes, with an additional high temperature

272 equal to 40 °C or 45 °C for neat and PMB mixes, respectively).

273 As discussed in previous research studies, dynamic modulus, along with phase angle, provides

274 insight regarding potential viscoelastic energy dissipation, which has been shown to relate well

275 with rutting performance of asphalt mixes (Witczak *et al.* 2002, , Bhasin *et al.* 2003, Apeagyei

276 2011). However, for characterization of rutting resistance, instead of considering dynamic

277 modulus values recorded at specific temperatures and frequencies, reference can be made to

278 the five complex modulus rutting indexes (CMRIs) proposed by Dave et al. (Dave *et al.* 2019).

279 These are derived from three characteristic points belonging to the master curves calculated at

280 any relevant temperature as indicated in Equations 1 through 5.

281 $$\text{CMRI} - \text{I} = \frac{\delta_A - \delta_B}{|f_A - f_B|} \qquad [1]$$

282 $$\text{CMRI} - \text{II} = \frac{|E_A^*| - |E_B^*|}{|f_A - f_B|} \qquad [2]$$

283 $$\text{CMRI} - \text{III} = \left| \frac{|E_A^*| - |E_B^*|}{|f_A - f_B|} \right|^2 \qquad [3]$$

284 $$\text{CMRI} - \text{IV} = \frac{|E_C^*|}{\delta \cdot |f_A - f_B|^2} \qquad [4]$$

285 $$\text{CMRI} - \text{V} = \frac{|E_A^*| - |E_B^*|}{(\delta_A - \delta_B) \cdot |f_A - f_B|^2} \qquad [5]$$

286 where: δA is the peak phase angle, δB is the phase angle corresponding to HWTT loading

287 conditions (frequency of 0.866 Hz), δC is the estimated average phase angle between δA and

288 δB; fA and fB and are the logarithms of the frequencies corresponding to δA and δB,

289 respectively; │E*A│, │E*B│ and │E*C│ are the dynamic modulus values corresponding to

290 δA, δB and δC, respectively.

291 The flow number test is a repeated load test in which a haversine load pulse is applied to

292 cylindrical test specimens with rest periods between successive loadings. Accumulated

293 permanent strain and strain rate are measured at each load cycle with the final objective of

294   identifying the number of loadings which correspond to the transition from viscous flow

295   conditions to tertiary flow failure. Previous research has shown that flow number tests provide

296   results that under certain conditions may exhibit a clear relationship with those coming from

297   loaded wheel tests (Walubita *et al.* 2013, Zhang *et al.* 2013, Santagata *et al.* 2015b, Walubita

298   *et al.* 2019b). Furthermore, they can yield rutting-related rankings of asphalt mixes that are

299   consistent with the corresponding rankings of bituminous binders, thus highlighting the

300   benefits of polymer modification (Santagata *et al.* 2015c, Santagata *et al.* 2017b). In such a

301   context, a confining pressure can be applied to test specimens in order to better simulate stress

302   conditions occurring in actual pavements and to avoid premature failure (von Quintus *et al.*

303   2012).

304   Flow number tests were carried out, as the dynamic modulus tests, both in unconfined and

305   confined conditions (with a constant confining pressure of 69 kPa). In the first case vertical

306   deviatoric stress was fixed at 600 kPa, whereas in the second case a value of 483 kPa was

307   employed. Tests were performed at the same temperatures adopted for HWTTs: 50 ⁰C for the

308   60-70 mixes and 55 ⁰C for the PMB mixes.

309   **3. Results and analysis**

310   *3.1 Hamburg Wheel-Track Tests*

311   As mentioned in section 1, all asphalt mixes included in the investigation were designed to be

312   rut resistant according to the approach embedded in QCS 2014. It was also postulated that the

313   best quantitative indicator of rutting resistance could be derived from HWTTs carried out in

314   dry conditions, with the consequent possibility of avoiding any superposition with stripping

315   induced effects. Nevertheless, HWTTs were also performed in wet conditions in straight

316   accordance with the corresponding AASHTO standard (AASHTO 2019b).

317   HWTT results are synthesized in Table 3, which lists the rut depth (RD_{dry} and RD_{wet}) reached

318   after 20,000 loading passes. In the case of wet HWTTs, four mixes reached the threshold value

319   of 12.5 mm, so the corresponding number of loading passes is indicated in an additional

320   column. Table 3 also contains the relative rankings (R#$_{dry}$ and R#$_{wet}$) assigned to the mixes

321   belonging to the two groups (60-70 and PMB) based on the recorded RD results. The value of

322   1 is assigned to the mix with the greatest rut resistance (i.e. with the lowest final RD value),

323   while higher values are progressively associated to those with a lower rut resistance (e.g.

324   ranking 6 given to the mix with highest RD value).

325   As expected, for all mixes the final RD value recorded in dry conditions was significantly lower

326   than the one measured for test specimens submerged in water. This obviously derives from the

327   fact that in wet HWTTs results represent the superposition of rutting and moisture damage

328   effects, whereas in the dry HWTTs final rut depth depends exclusively upon rutting. In such a

329   context it is not surprising that the average difference between the results obtained in the two

330   conditions (wet versus dry) is lower for the PMB mixes, thus revealing a greater resistance to

331   stripping (i.e. a stronger binder-aggregate adhesion) that is ensured by means of polymer

332   modification.

333   When focusing on the results derived from dry HWTTs, it can be observed that RD values

334   recorded for the two groups of mixes were contained within relatively narrow ranges: 3.8-5.0

335   mm for the 60-70 mixes, 1.9-3.6 mm for the PMB mixes. Since it was assumed that all the

336   asphalt mixes were designed to be rut-resistant, it can therefore be postulated that for

337   acceptance purposes maximum admissible RD values of 5.5 mm (at 50 °C) and 4.0 mm (at 55

338   °C) can be assumed for 60-70 and PMB mixes, respectively. These threshold values, calculated

339   by considering an excess of 10 % with respect to maximum recorded values, will need to be

340   validated and possibly fine-tuned with further investigations.

341   Although the RD values of the various asphalt mixes belonging to each group are quite similar,

342   rankings can still allow some distinctions to be made. In particular, the mixes characterized by

343   the highest rut resistance were found to be mix 6 (RD equal to 3.8 mm at 50 °C) and mix 8 (RD

344 equal to 1.9 mm at 55 °C) in the 60-70 and PMB group, respectively. However, no clear

345 association can be made between the relative rankings and the composition and volumetrics of

346 the mixes provided in Tables 1 and 2. For example, in the 60-70 group the best rut resistance

347 was exhibited by the mix (number 6) with the lowest value of air voids and VMA in Marshall-

348 compacted specimens (75 blows per face) and the highest value of VFA. Conversely, in the

349 PMB mix these characteristics (i.e. lowest air voids and VMA, highest VFA) were found for

350 the mix with the worst rut resistance (mix number 9). Similar observations can be made when

351 considering Marshall stability. The highest value recorded for the PMB mixes was found for

352 the mix with the lowest rut resistance ranking (mix 9), while in the 60-70 group the lowest

353 stability value was determined from the mix with the highest ranking (mix 6).

354 The only parameters that seem to somehow match with the rut resistance rankings are the air

355 voids and VFA recorded for Marshall specimens compacted with 400 blows per face. In

356 particular, the 60-70 mixes ranked from 4 to 6 (with RD values greater than 4.7 mm) reached

357 air void values lower than 3 %, with corresponding VFA values greater than 75 %. Likewise,

358 in the PMB group the mix that received the worst ranking (mix number 9) exhibited an air void

359 content of less than 2 %, with a corresponding VFA value above 80 %.

360 In conclusion, it can be stated that there is no possibility of tailoring rut resistance of asphalt

361 mixes by considering the results of the preliminary volumetric and basic mechanical

362 characterization tests normally included in mix design (Tables 1 and 2). On the contrary, it is

363 necessary to perform the HWTT which is sensitive to the actual packing of the aggregate

364 structure and to its interaction with the bituminous binding matrix.

365 *3.2 Dynamic modulus tests*

366 Dynamic modulus values measured at individual temperatures in both unconfined and confined

367 conditions were shifted to develop master curves at the reference temperature of 20 °C by

368 referring to the analytical expression given in Equation 6 (AASHTO 2017c).

369 $$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma \cdot \log f_r}} \qquad [6]$$

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

371 Results obtained from the construction of master curves are displayed in Figures 2 and 3, which

372 show the dynamic modulus and phase angle of the two groups of mixes (60-70 and PMB) as a

373 function of reduced frequency. Values of the fitting parameters included in Equation 6 are

374 listed in Table 4.

375 When analyzing the data displayed in the dynamic modulus and phase angle master curves,

376 significant differences were found, as expected, between 60-70 and PMB mixes in the low

377 frequency range which is representative of high temperature and slow loading conditions that

378 are meaningful with respect to rutting. In particular, the PMB mixes exhibited higher stiffness

379 and lower phase angles, thus indicating a higher resistance to accumulation of permanent

380 deformation. For both groups of mixes, differences were also recorded between data obtained

381 from tests carried out in unconfined and confined conditions. As expected, in the presence of

382 lateral confinement all mixes exhibited a a stiffer and more elastic response under loading.

383 A significant difference between the two groups of mixes was recorded in terms of their

384 variability. All 60-70 mixes had a very similar behaviour, with dynamic modulus and phase

385 angle data points very close to each other (with the only exception of mix number 5). On the

386 contrary, the PMB mixes exhibited widely different values of both viscoelastic parameters.

387 Such an outcome can be explained by considering the fact that the PMBs employed in the

388 investigation differed in composition, while all the 60-70 neat binders came from the same

389 source.

390 It should be mentioned that QCS 2014 includes an acceptance requirement for the dynamic

391 modulus of asphalt mixes designed according to the SUPERPAVE method. In particular, when

392 measured at 45 °C and a loading frequency of 10 Hz, such a parameter is required to be greater

393 than 1,920 MPa. By considering the experimental data recorded during the investigation, this

394   condition was not met by any of the 60-70 mixes that yielded an average value of 1,387 MPa.

395   On the contrary, the PMB mixes satisfied the requirement, exhibiting an average value of the

396   dynamic modulus equal to 2,184 MPa.

397   To better assess the potential rutting resistance of the asphalt mixes as described by dynamic

398   modulus test results, the previously mentioned CMRIs were evaluated for the two groups at

399   the same temperatures employed for the HWTTs: 50 °C for the 60-70 mixes and 55 °C for the

400   PMB mixes. The outcomes of these calculations, carried out by employing Equations 1 through

401   5, are shown in Tables 5 and 6, which refer to unconfined and confined tests, respectively. Both

402   tables also contain the relative rankings (R#I through R#V) associated with the CMRI values,

403   assigned to the mixes with the same criterion employed for the ranking based on HWTT results

404   (i.e. giving rankings 1 and 6 to the mixes with the highest and lowest rut resistance,

405   respectively).

406   Results listed in Tables 4 and 5 indicate that the rankings associated to the various CMRIs

407   varied significantly and were also sensitive to the confinement adopted during testing.

408   However, conclusions can be drawn from their analysis only by considering their relationship

409   with the rankings previously assigned based on HWTT tests carried out in dry conditions. This

410   is discussed in section 3.4.

411   *3.3 Flow number tests*

412   Results of flow number tests carried out on the two groups of mixes (at 50 °C for 60-70 mixes

413   and at 55 °C for PMB mixes) are given Table 7, which also contains the rankings (R#$_{FN-U}$ and

414   R#$_{FN-C}$) associated to each mix.

415   As in the case of the dynamic modulus tests, it can be observed that PMB mixes exhibited a

416   greater resistance to permanent deformation than 60-70 mixes. Notwithstanding the fact that

417   the tests on the PMB mixes were performed at a higher temperature (55 °C versus 50 °C), they

418   led to significantly higher flow number values. Moreover, as expected, for both groups of mixes

419   a non-negligible increase of the flow number was observed when applying a confining pressure

420   during repeated loading. These outcomes are consistent with previous research works that

421   highlighted the non-linear response of asphalt mixes in the conditions that are imposed during

422   flow number tests (Santagata *et al.* 2017a).

423   Relative rankings coming from flow number tests were also sensitive to confinement

424   conditions. However, as for the CMRIs derived from dynamic modulus tests, further comments

425   can be made only by considering their relationship with the rankings previously assigned based

426   on HWTT tests carried out in dry conditions. This is discussed in section 3.4.

427   According to QCS 2014, SUPERPAVE mixes should exhibit a flow number greater than 740

428   at 54.4 °C with an applied deviatoric stress of 600 kPa and with no confining pressure. By

429   referring to the results listed in Table 6, it can be observed that all PMB mixes (except for mix

430   10) satisfied such a requirement. On the contrary, the 60-70 mixes exhibited flow number

431   values at 50 °C that were all below 700 and therefore certainly violate the abovementioned

432   requirement at a higher temperature.

433   *3.4 Comparative evaluation of different test methods*

434   Since all the asphalt mixes considered in the investigation were designed to be rut-resistant, to

435   compare the different test methods employed during the investigation, a relationship was not

436   sought between the individual test results. Rather, the analysis focused on the degree of

437   similarity between the relative rankings derived from each test procedure. In statistical terms,

438   this corresponds to the calculation of the so-called Spearman's rank correlation coefficient (ρ)

439   that assesses how well the relationship between two variables can be described using a

440   monotonic function. Values of ρ can vary between -1 and 1, with a value of 0 corresponding to

441   no correlation. Values close to 1 are indicative of a good correlation, with similar rankings

442   being associated with the two considered procedures. On the contrary, values close to -1

443   indicate strongly dissimilar rankings, with fully opposed information provided by the two

444   compared procedures.

445   Since it was assumed that the most representative evaluation of rutting resistance stems from

446   dry HWTTs, ρ was calculated by comparing its rankings to those associated with all the other

447   procedures employed in the investigation. The results of such an evaluation are synthesized in

448   Table 8.

449   When considering the rankings coming from HWTTs carried out in wet conditions, as expected

450   their degree of correlation to true rutting resistance ranking was found to be weak in the case

451   of 60-70 mixes that are characterized by non-negligible stripping effects (ρ equal to 0.200).

452   However, the degree of correlation between the rankings associated with dry and wet HWTTs

453   increased significantly in the case of PMB mixes (ρ equal to 0.771) since these are less prone

454   to moisture damage.

455   The different CMRIs that are extracted from dynamic modulus master curves are characterized

456   by a non-uniform degree of correlation that changes as a function of confining conditions and

457   of the type of binder. Thus, selection of the most appropriate CMRI needs to be based on the

458   combined analysis of all the considered cases. When analyzing the data listed in Table 8, it can

459   be observed that the highest ρ values were recorded for parameters CMRI-III, CMRI-IV and

460   CMRI-V derived from the tests carried out in the absence of any confinement (ρ values

461   comprised between 0.829 and 0.943). In such a context it is interesting to note that the degree

462   of correlation of the rankings of these parameters decreases significantly when considering

463   results coming from dynamic modulus tests carried with lateral confinement in the case of 60-

464   70 mixes (with negative ρ values comprised between -0.200 and -0.314), whereas it remains

465   almost constant for the PMB mixes (ρ in the 0.886-0.943 range). Such an outcome is consistent

466   with the viscoelastic and non-linear characteristics of the considered mixes. The PMB mixes

467   are stiffer and therefore their response under loading at smaller strains is less affected by

468   confinement; on the contrary, the less stiff 60-70 mixes are more affected by lateral confining

469   pressure. As a consequence, the application of a confinement pressure tends to mask the

470   specific rutting resistance properties of the individual 60-70 mixes, preventing their assessment

471   with respect to the reference dry HWTT.

472   Finally, ρ values associated with the flow number tests clearly indicate that for 60-70 mixes a

473   better degree of correlation is achieved by performing the tests in confined conditions (ρ equal

474   to 0.771). This is consistent with physical expectations and in line with recommendations

475   coming from previous research (Santagata *et al.* 2017a). However, these observations do not

476   apply to the case of the PMB mixes since it was found that the corresponding test results,

477   regardless of the confinement conditions imposed during repeated loading, yielded rankings

478   that are in contrast with those of dry HWTTs (with negative ρ values). This outcome suggests

479   that the standard flow number test may not be adequate to discriminate between the rutting

480   resistance of asphalt mixes characterized by a densely packed aggregate structure and by the

481   presence of stiff elastic binders. Thus, the use of the flow number test may be beneficial when

482   comparing the results to a minimum threshold value for acceptance purposes, while it is not

483   recommended when trying to fine-tune the composition of a rut-resistant mix.

484   **4. Summary and conclusions**

485   The experimental investigation described in this paper focused on the use of different testing

486   techniques for the assessment of the rutting resistance of wearing course asphalt mixes

487   employed in the State of Qatar. These included mixes containing both neat 60-70 penetration

488   bitumen and several PMBs. They were all designed to be rut resistant as per the requirements

489   of QCS 2014 (Marshall method) and it was assumed that their most representative evaluation

490   could be performed by making use of HWTTs carried out in dry conditions.

491   The experimental results suggest that the mix design and QA/QC framework currently adopted

492   in the State of Qatar may be supplemented by requirements set on the results of dry HWTTs.

493 In particular, threshold values of the final rut depth measured after 20,000 loading passes may

494 be set at 5.5 mm for 60-70 mixes (tested at 50°C) and at 4.0 mm for PMB mixes (tested at

495 55°C). Moreover, adjustments may be made to current specifications since it appears that the

496 minimum admissible value of 4.0 % air voids measured on Marshall specimens compacted

497 with 400 blows per face may be too high.

498 Regarding the other testing techniques, it was observed that their results and the consequent

499 rankings are sensitive to several factors that need to be taken into account. HWTTs performed

500 on specimens submerged in water may lead to misleading results since they depend upon the

501 occurrence of stripping effects especially in the case of 60-70 mixes. Dynamic modulus tests

502 can be meaningful for the assessment of the rutting potential of the asphalt mixes and the fine-

503 tuning of their composition when considering three different indexes (CMRI-III, CMRI-IV and

504 CMRI-V). However, in the case of 60-70 mixes, it may be more appropriate to refer to the

505 results of unconfined dynamic modulus tests to prevent the occurrence of the masking effects

506 of confining pressure that tend to uniform the response under loading of different mixes. Flow

507 number tests can also be extremely useful in ranking 60-70 mixes and the best outcomes are

508 achieved by performing the corresponding tests in confined conditions. However, these tests

509 fail to capture the differences between similar rut-resistant mixes containing PMBs. Finally, it

510 should be underlined that the acceptance thresholds currently indicated in QCS 2014 for

511 dynamic modulus and flow number test results seem to be appropriate for PMB mixes, while

512 they are probably too severe for 60-70 mixes.

513 The conclusions drawn from this investigation will need to be supported by further studies

514 which should possibly include the evaluation of different types of asphalt mixes and of test

515 specimens cored from pavement wearing courses. Furthermore, a validation of the proposed

516 acceptance limits is necessary and will require the monitoring of pavement sections subjected

517 to actual vehicle loading.

518 **Disclosure statement**

519 No potential conflict of interest was reported by the authors.

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701   **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	-

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704   **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	-

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

Mix	Binder	T (°C)	Dry WHTT		Wet HWTT		
			RD_{dry}	$R\#_{dry}$	RD_{wet}	Cycles	$R\#_{wet}$
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

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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

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

Mix	Binder (T)	CMRIs (I-V) and corresponding R#									
		I	R#$_{I}$	II	R#$_{II}$	III	R#$_{III}$	IV	R#$_{IV}$	V	R#$_{V}$
Mix-1		2.77	6	570.0	6	451.2	4	16.1	4	129.1	3
Mix-2	60-70	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	(50 °C)	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		1.63	5	636.0	4	724.3	2	41.0	2	505.6	2
Mix-8	PMB	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	(55 °C)	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

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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#									
	(T)	I	R#$_I$	II	R#$_{II}$	III	R#$_{III}$	IV	R#$_{IV}$	V	R#$_V$
Mix-1	60-70	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	(50°C)	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	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	(55°C)	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

722 **Table 7.** Results and corresponding rutting resistance rankings of the asphalt mixes
723 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

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726 **Table 8.** Rank correlation coefficients calculated for all test procedures with respect to the
727 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

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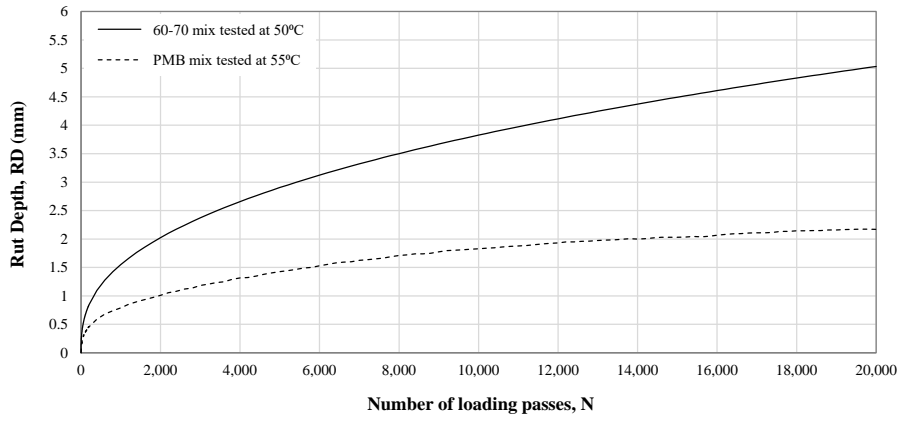
Figure 1. Typical results obtained from dry HWTTs

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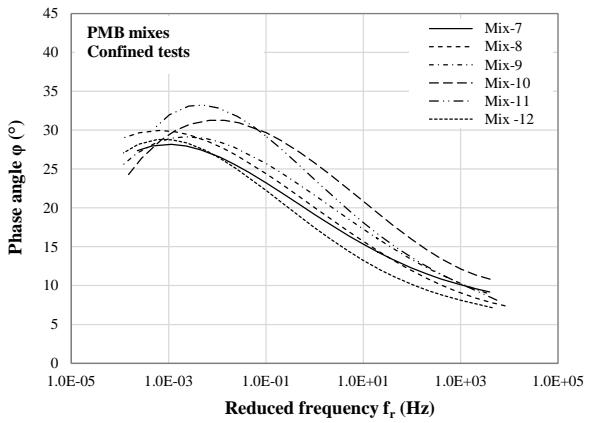
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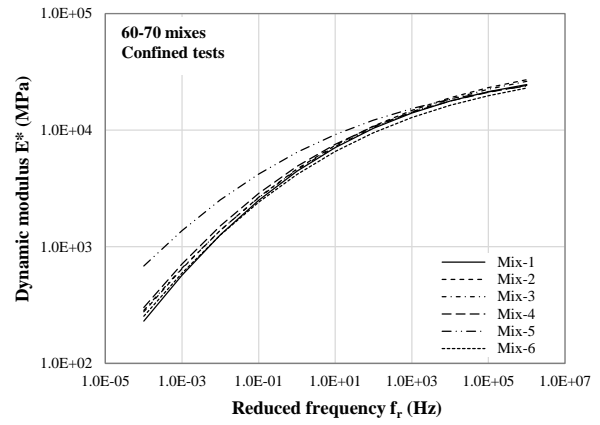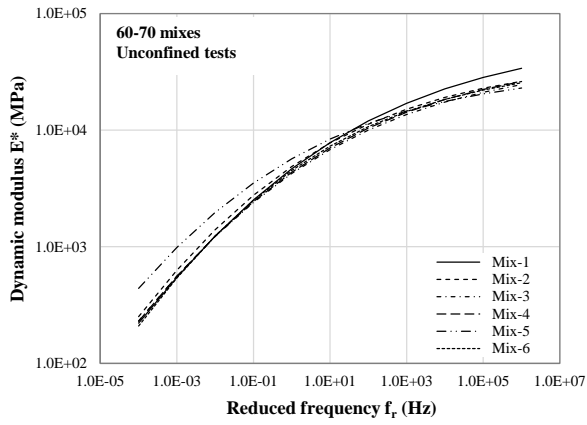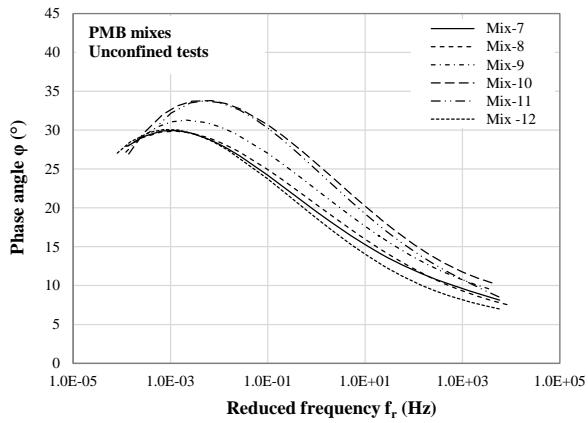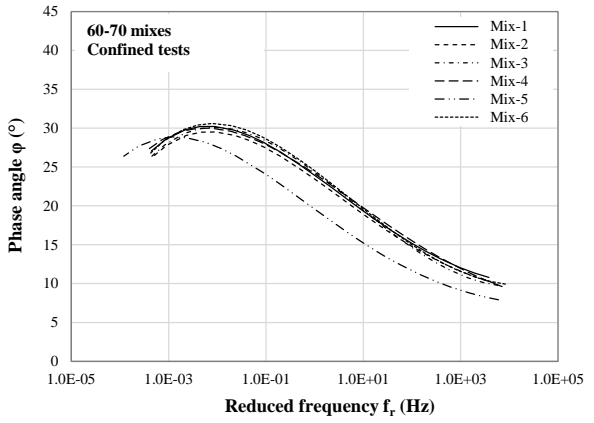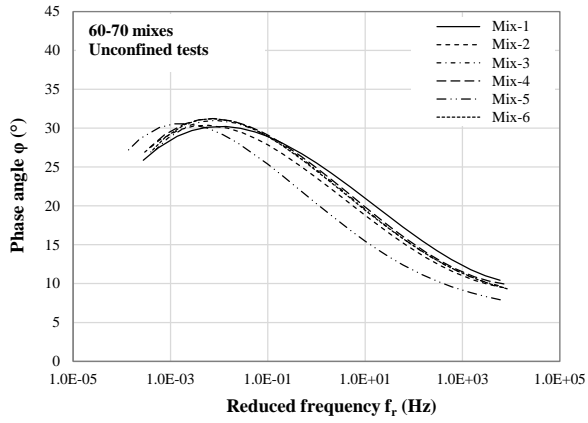

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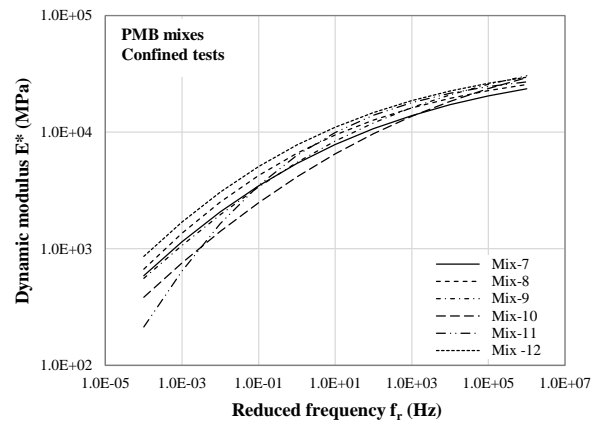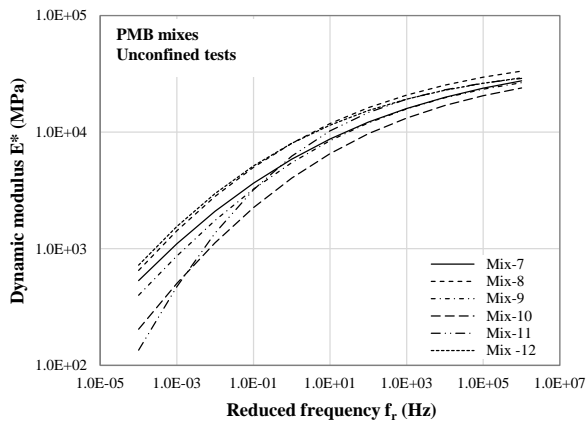
751 **Figure 2.** Complex modulus master curves of the asphalt mixes (at 20 °C)

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

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