

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

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(Article begins on next page)

1 **PERFORMANCE-BASED ASSESSMENT OF RUTTING RESISTANCE** 2 **OF ASPHALT MIXES DESIGNED FOR HOT CLIMATE REGIONS**

3 **ABSTRACT**

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

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

27 **1. Introduction**

28 Rutting in asphalt pavements occurs in the form of surface depressions along the wheel paths.
29 As a result of its origin and underlying mechanisms, it is the most frequent distress recorded
30 by highway agencies in hot climate regions (Kandhal *et al.* 1998, Santagata *et al.* 2011,
31 Isailović *et al.* 2016, Alkaissi 2020). Thus, in these geographical areas the main focus of asphalt
32 mix design is the optimization of resistance to permanent deformation, which becomes of
33 crucial importance especially for infrastructures characterized by heavy truck loads and
34 relevant volumes of commercial traffic (Livneh 1990, Asi 2007, Jitsangiam *et al.* 2013).
35 Furthermore, requirements related to resistance to permanent deformation are also embedded
36 in quality assurance and quality control (QA/QC) systems. In most cases these requirements
37 are set on the results of volumetric characterization tests, while in the more advanced QA/QC
38 systems they can also be expressed with respect to the results of performance-based tests.
39 The type of rutting that can be controlled through an appropriate formulation of asphalt mixes
40 is the one which derives from the accumulation of non-reversible deformations in the upper
41 bitumen-bound portion of the pavement. As extensively described in the literature, under the
42 effects of repeated traffic loading, these deformations develop in three phases, typically
43 referred to as primary, secondary and tertiary (Eisenmann and Hilmer 1997, Zhou *et al.* 2004,
44 Miljković and Radenberg 2011, Santagata *et al.* 2013, Santagata *et al.* 2015a, Santagata *et al.*
45 2017a). The primary phase includes early consolidation phenomena that are associated to
46 traffic post-compaction occurring with a non-negligible reduction of the initial voids content
47 of the mixes. The secondary phase takes place at constant volume as a result of shear effects,
48 frequently leading to the formation of lateral surface bulges next to the wheel paths. Finally,
49 the tertiary phase is reached when the asphalt mixes exhibit a rapid increase of non-reversible
50 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 overflowing 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 N_{max} (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.

123 **2. Materials and methods**

124 **2.1 Materials**

125 The experimental investigation described in this paper was carried out by considering twelve
126 different wearing course asphalt mixes (associated to identification numerical codes 1 to 12)
127 which were designed as per QCS 2014 (Marshall method) for different projects in the State of
128 Qatar (Qatar Construction Specifications 2014, Asphalt Institute 2014). The corresponding Job
129 Mix Formulae (JMF) were fully approved for use in construction projects in the State of Qatar.
130 All mixes contained gabbro aggregates of similar origin, stockpiled in the premises of various
131 asphalt production plants. Bituminous binders employed for the preparation of the mixes were
132 those that are admitted for use in the State of Qatar: neat bitumen belonging to the 60-70
133 penetration grade (mixes 1 to 6) and PMB containing styrene-butadiene-styrene (SBS) and
134 classified as PG76E-10 according to the SUPERPAVE performance grade (PG) system (mixes
135 7 to 12) (AASHTO 2020, Santagata *et al.* 2020). Neat bitumen was reported in all cases to be
136 of the same origin, whereas PMBs were produced by different manufacturers in the State of
137 Qatar according to undisclosed procedures and recipes. It was also verified that all 60-70 neat
138 binders were classified as PG64S-22.

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

146 JMF data of the abovementioned asphalt mixes are synthesized in the top part of Tables 1 and
147 2, which list particle size distribution data (expressed in terms of percent passing for the most

148 significant sieve openings) and binder content values (expressed as a percentage of the total
149 mix). The central part of the two tables contains the volumetric characteristics of Marshall
150 specimens compacted as per ASTM D6926-20 (ASTM 2020) with 75 blows per face, those of
151 specimens compacted to refusal with 400 blows per face, and the experimental results derived
152 from Marshall tests (stability, flow and quotient) carried out as per ASTM D6927-15 on the
153 specimens compacted with 75 blows (ASTM 2015). Whenever applicable, QCS 2014
154 acceptance limits are also shown for considered characteristics or quantities.

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

164 The experimental data provided in Tables 1 and 2 clearly show that all the considered asphalt
165 mixes (indicated in the following as “60-70 mixes” and “PMB mixes”) are characterized by a
166 similar continuous particle size distribution. However, a distinction can be made depending
167 upon the percent passing the primary control sieve (PCS), that for mixes with a nominal
168 maximum aggregate size (NMAS) of 19 mm corresponds to the sieve with a 4.75 mm opening
169 (with a threshold value of the percent passing equal to 47 %) (AASHTO 2017a). Most of the
170 mixes containing neat bitumen are of the “fine” type (with the only exceptions of mixes 3 and
171 6), whereas most of the mixes containing PMB are of the “coarse” type (with exception of
172 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 $705 \pm$
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 °C, while the
237 mixes containing PMB (with an upper PG limiting temperature of 76 °C) were tested at 55 °C.
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, Apeageyi
 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.

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

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

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

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

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

286 where: δ_A is the peak phase angle, δ_B is the phase angle corresponding to HWTT loading
 287 conditions (frequency of 0.866 Hz), δ_C is the estimated average phase angle between δ_A and
 288 δ_B ; f_A and f_B and are the logarithms of the frequencies corresponding to δ_A and δ_B ,
 289 respectively; $|E^*A|$, $|E^*B|$ and $|E^*C|$ are the dynamic modulus values corresponding to
 290 δ_A , δ_B and δ_C , 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 °C for the
308 60-70 mixes and 55 °C 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
$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma \cdot \log f_r}} \quad [6]$$

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.

520 **References**

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

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

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

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

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

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

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

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

542 Al-Abdul Wahhab, H.I., Asi, I.M., Al-Dubabe, I.A., and Farhat Ali M., 1997. Development of
543 performance-based bitumen specifications for the Gulf countries. *Construction and Building Materials*,
544 11(1), 15-22. 10.1016/S0950-0618(97)00002-0.

545 Alkaissi, Z.A., 2020. Effect of high temperature and traffic loading on rutting performance of flexible
546 pavement. *Journal of King Saud University - Engineering Sciences*, 32(1), 1-4.
547 10.1016/j.jksues.2018.04.005.

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

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

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

555 Asi, I.M., 2007. Performance evaluation of SUPERPAVE and Marshall asphalt mix designs to suite
556 Jordan climatic and traffic condition. *Construction and Building Materials*, 21(8), 1732-1740.
557 10.1016/j.conbuildmat.2006.05.036.

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

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

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

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

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

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

572 Chaturabong, P., and Bahia, H.U., 2017b. The evaluation of relative effect of moisture in Hamburg
573 wheel tracking test. *Construction and Building Materials*. 153, 337-345.
574 0.1016/j.conbuildmat.2017.07.133.

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

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

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

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

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

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

592 Horak, E., Maina, J., Myburgh, P., and Sebaaly, H., 2019. Monitoring permeability potential of hot mix
593 asphalt via binary aggregate packing principles correlated with Bailey ratios and porosity principles.
594 *Journal of the South African Institution of Civil Engineering*, 61(3), 32-44. 10.17159/2309-
595 8775/2019/v61n3a4.

596 Isailović, I., Wistuba, M.P., and Cannone Falchetto, A., 2016. Permanent deformation of hot mix
597 asphalt under compression and tension. *Proceedings of 6th Eurasphalt & Eurobitume Congress*.
598 10.14311/EE.2016.401.

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

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

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

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

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

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

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

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

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

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

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

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

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

628 Santagata, E., Baglieri, O., Dalmazzo, D., and Tsantilis, L., 2013. Evaluation of the anti-rutting potential
629 of polymer-modified binders by means of creep-recovery shear tests. *Materials and Structures*, 46(10),
630 1673-1682. 10.1617/s11527-012-0006-0.

631 Santagata, E., Baglieri, O., Alam, M., and Dalmazzo, D., 2015a. A novel procedure for the evaluation
632 of anti-rutting potential of asphalt binders. *International Journal of Pavement Engineering*, 16(4), 287-
633 296. 10.1080/10298436.2014.942859.

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

637 Santagata, E., Baglieri, O., Alam, M., and Riviera, P.P., 2015c. Evaluation of rutting properties of
638 bituminous binders by means of Single Shear Creep-Recovery (SSCR) tests and correlation with
639 mixture performance. *Proceedings of the 8th RILEM International Symposium on Testing and*
640 *Characterization of Sustainable and Innovative Bituminous Materials*, RILEM Bookseries 11, 745-756.
641 10.1007/978-94-017-7342-3_60.

642 Santagata, E., Baglieri, O., Riviera, P.P., Lanotte, M., and Alam, M., 2017a. Influence of lateral
643 confining pressure on flow number tests. *Proceedings of the 10th International Conference on the*
644 *Bearing Capacity of Roads, Railways and Airfields*, BCRRA, 237-242. 10.1201/9781315100333-
645 35.2017.

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

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

653 Sebaaly, H., Varma, S., and Maina, J., 2018. Optimizing asphalt mix design process using artificial
654 neural network and genetic algorithm. *Construction and Building Materials*, 168, 660–670.
655 10.1016/j.conbuildmat.2018.02.118.

656 Sirin, O., Paul, D.K., Kassem, E., and Ohiduzzaman, M., 2017. Effect of aging on asphalt binders in
657 the State of Qatar: a Case Study. *Road Materials and Pavement Design*, 18, 165-184.
658 10.1080/14680629.2017.1389094.

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

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

663 Tsai, B.W., Coleri, E., Harvey J.T., and Monismith, C.L., 2016. Evaluation of AASHTO T 324
664 Hamburg-Wheel Track device test. *Construction and Building Materials*, 114, 248-260.
665 10.1016/j.conbuildmat.2016.03.171.

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

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

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

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

677 Walubita, L.F., Faruk, A.N.M., Zhang, J., Komba, J.J., Alrashyda, E.I., and G.S. Simate, G.S., 2019a.
678 The Hamburg Rutting Test (HWTT) alternative data analysis methods and HMA screening
679 criteria. *International Journal of Pavement Research and Technology*, 12, 110-116.
680 10.1007/s42947-019-0014-3.

681 Walubita, L.F., Fuentes, L., Lee, S.I., Dawd, I., and Mahmoud, E., 2019b. Comparative evaluation of
682 five HMA rutting-related laboratory test methods relative to field performance data: DM, FN, RLPD,
683 SPST, and HWTT. *Construction and Building Materials*, 215, 737-753.
684 0.1016/j.conbuildmat.2019.04.250.

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

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

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

691 Witczak, M.W., 2007. Specification criteria for Simple Performance Tests for rutting, *NCHRP Report*
692 *580*.

693 Yildirim, Y., Jayawickrama, P.W., Hossain, M.S., Alhabshi, A., Yildirim, C., Smit, A.F., and Little D.,
694 2007. Hamburg Wheel Tracking database analysis, Report 0-1707-7.

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

698 Zhou, F., Scullion, T., and Sun, L., 2004. Verification and modeling of three-stage permanent
699 deformation behavior of asphalt mixes. *Journal of Transportation Engineering*, 130(4), 486-494.
700 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	-

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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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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}	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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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

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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#									
		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

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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

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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

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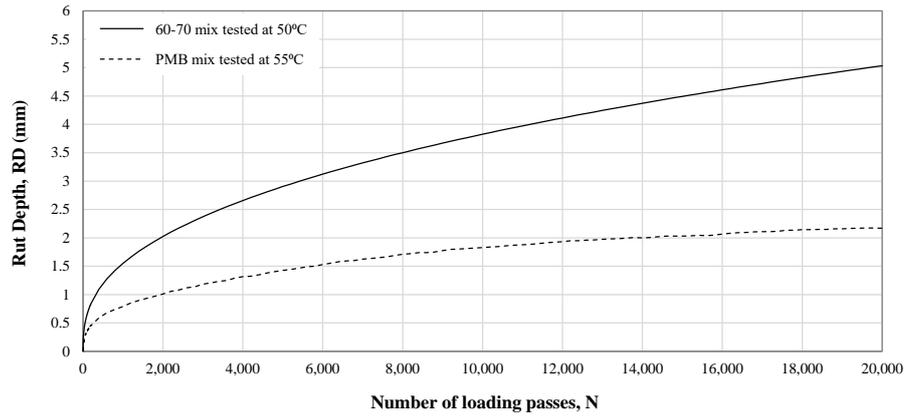


Figure 1. Typical results obtained from dry HWTTs

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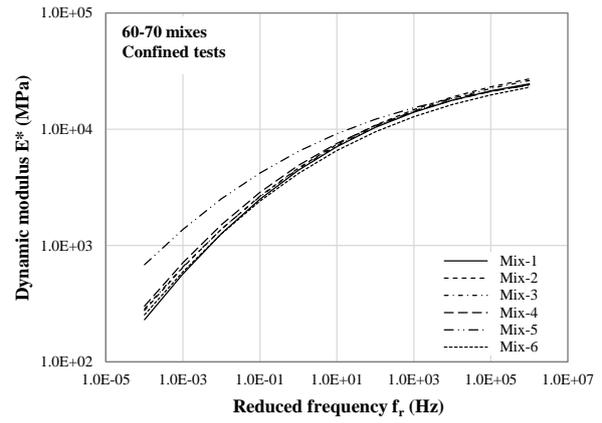
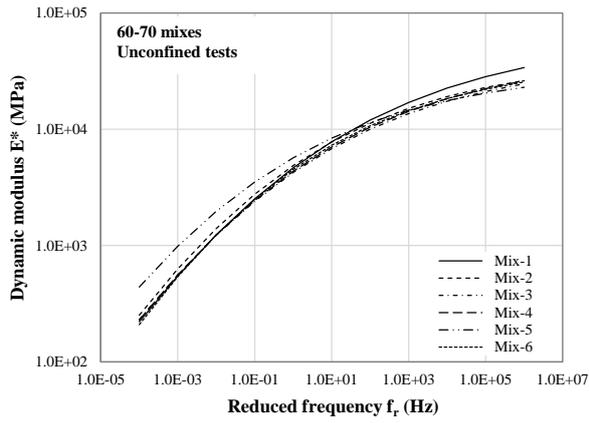
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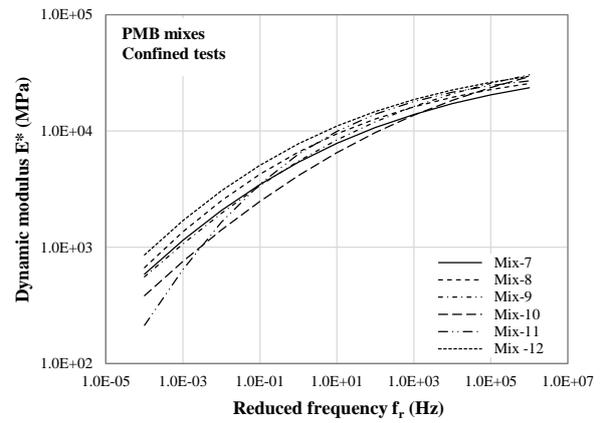
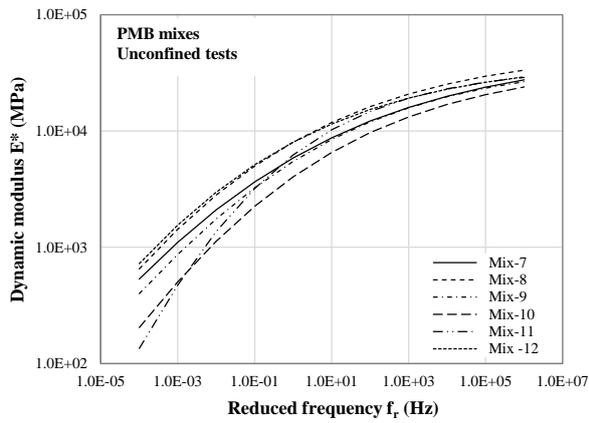
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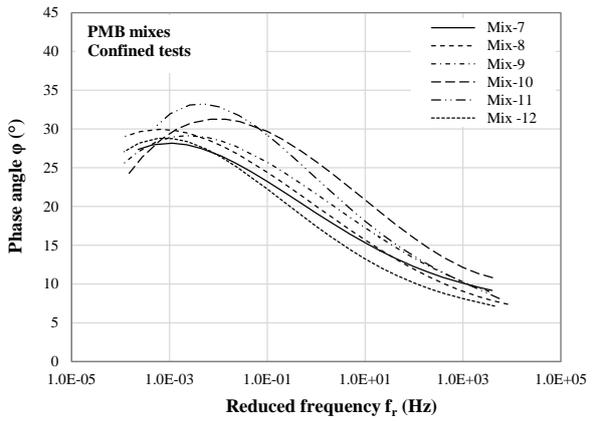
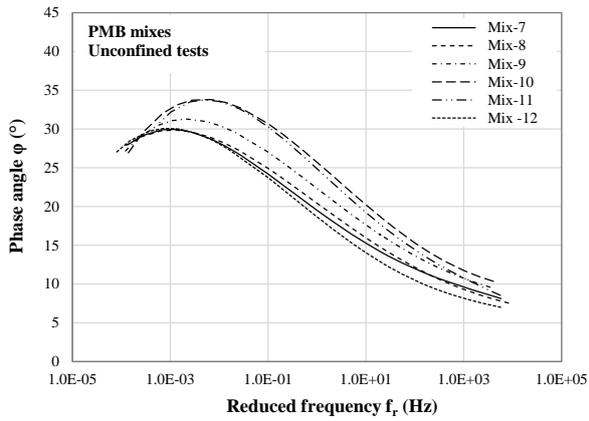
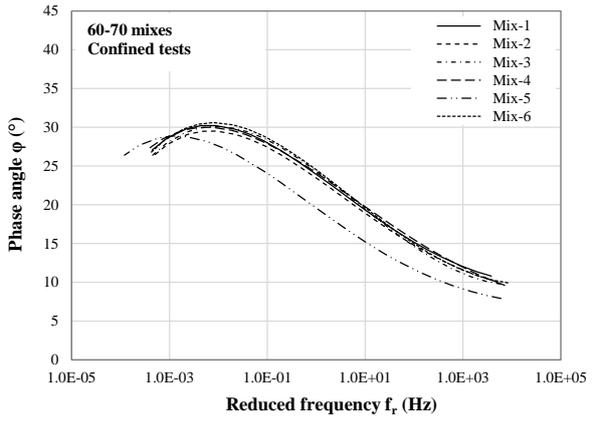
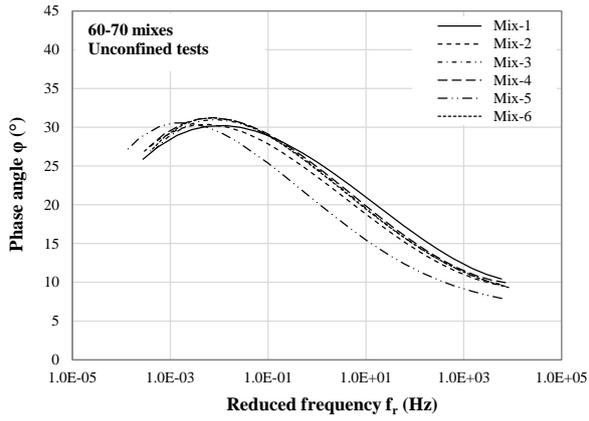


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Figure 2. Complex modulus master curves of the asphalt mixes (at 20 °C)



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