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2 **Tire/road noise, texture, and vertical accelerations: Surface**
3 **assessment of an urban road.**

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28 ABSTRACT

29 Pavements are made up of several layers with different mechanical and functional
30 characteristics. The correct design of the surface layer of a road may lead to pavements with
31 better characteristics regarding ride quality and safety, but also pavements that may be used
32 as a measure against noise. The use of low-noise pavements may be an effective measure to
33 reduce the generation of acoustic pollution by road traffic. This work aims to assess some
34 functional characteristics of a rehabilitated urban street, after two months in service
35 conditions. The pavement was fabricated with a gap-graded bituminous mixture type Stone
36 Mastic Asphalt (SMA) with crumb rubber (CR) from end-of-life (EOL) tires. This work
37 studies the acoustic performance of the pavement, as well as other surface characteristics
38 such as the macrotexture depth (MPD) and the unevenness (IRI), establishing the relationship
39 between them and the tire/road noise at different frequencies. Finally, the main vertical
40 acceleration frequencies of the pavement/vehicle system at 50 km/h were also assessed and
41 related to the pavement unevenness and conservation. According to the results, this mixture
42 might be used as a noise mitigation measure within the Action Plans of some urban areas
43 with problems related to noise. The macrotexture depth of the mixture contributes to its
44 acoustic performance at low frequencies; however, its acoustic performance cannot be totally
45 explained from a macrotexture point of view.

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52 **Keywords:**

53 Tire/pavement noise;

54 Action Plans against noise;

55 Surface characteristics;

56 Mean Profile Depth;

57 Vertical accelerations;

58 Stone Mastic Asphalt;

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61 **Highlights:**

62 - Some sections of the pavement with SMA8 stand out for their good acoustic performance

63 - The relationship between macrotexture and tire/pavement noise has been studied

64 - The macrotexture does not entirely explain the good acoustic performance

65 - The acceleration spectrum shape depends on the pavement aging and conservation

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76 **1. Introduction**

77 The development of an environmentally friendly transport system is one of the key goals of
78 modern societies [1]. The road transport of goods and people is essential for the economic
79 activities of any country; however, transport has become a serious threat, causing acoustic
80 pollution in some areas. With the aim of reducing the impact of this type of pollution on
81 population, the European Environmental Noise Directive (END) 2002/49/EC of the European
82 Parliament and Council, relating to the assessment and management of environmental noise
83 was promulgated. The 2017 END revision [2] showed that noise pollution continues to be a
84 major health problem in Europe, as well as in all the modern world, compromising people
85 health [3-5], with problems related to annoyance [6], sleep disorders [7], learning impairment
86 [8, 9] or hypertension ischemic heart disease [10].

87 Prevention of unwanted noise is then mandatory to fulfill with the required Noise Maps and
88 Action Plans against noise [11]. Actions against noise might include the promotion of public
89 transport, the traffic management, the construction of noise barriers and/or the pavement
90 rehabilitation [12].

91 Expensive and not always accepted acoustic barriers are the most widespread solution to
92 mitigate the noise produced by the main sources [13], but also innovative solutions, such as
93 monitoring using a wireless sensor network, are studied [14, 15]. However, one of the best
94 solutions to reduce noise in the surroundings, thus preventing health effects, is to use
95 pavements with improved acoustic features. Gap-graded bituminous mixtures with crumb
96 rubber (CR) may be an effective way to reduce noise, as well as the End-Of-Life (EOL) tires
97 disposal on landfills [16, 17], which is a significant environmental problem because tires are
98 highly durable and non-biodegradable [18]. CR can be incorporated into asphalt mixes by

99 means of the dry or the wet processes. In the dry process CR is used as a portion of the fine
100 aggregate, while in the wet process the CR acts as an asphalt binder modifier [19].

101 A number of relatively recent works have studied the acoustic performance of SMA mixtures,
102 particularly the relationship between tire/pavement noise and the maximum aggregate size
103 [20], texture [21] or the acoustic absorption [22]. On the other hand, the acoustic performance
104 of SMA mixtures has also been studied by Miljković and Radenberg [23] (thin noise-
105 reducing surface from an SMA mixture); Vuye et al. [24] (SMA10 performance regarding a
106 double-layer porous asphalt concrete); Gardziejczyk et al. [25, 26] (acoustic performance of
107 the SMA11 by the statistical pass by method) and Sweczko-Zurek [27] (tire/road noise and
108 the rolling resistance measured in a SMA11 mixture). Recently, Sangiorgi et al. [28] have
109 studied the SMA11 mixtures with CR by means of the CPX methodology, whereas Vazquez
110 et al. [29] have studied the acoustic performance of SMA mixtures with maximum aggregate
111 size of 11 mm and 16 mm, using the CPX method. It can be concluded that there is an
112 interest in knowing the acoustic behavior of the SMA mixtures and its relationship with other
113 pavement features.

114 In addition to the acoustic behavior of pavements, different research groups have studied how
115 the vehicle accelerations are influenced by other functional characteristics of the road surface
116 and its maintenance. Some research works establish correlations between the vehicle
117 accelerations and the pavement roughness [30-33] or obtain more detailed information about
118 the roughness such as the locations of pavement distresses [34]. Recent studies also detect
119 road anomalies (pavement evaluation) by means of the accelerometer sensors of smartphones
120 [35-37]. In all these works the acceleration signal proved to be a valuable tool to describe the
121 functional performance of pavements.

122 In this work, experimental tests are conducted on a SMA bituminous mixture with CR
123 incorporated by the dry process, located in the Malaga city center (urban landscape). The
124 SMA mixes are described in the harmonized standard (EN 13108-5); however, they are not
125 considered in the *General Technical Specifications for Road and Bridge Works* (PG3) from
126 the Spanish Ministry of Public Works. Other bituminous mixtures that are included in the
127 PG3 are the gap-graded BBTM (Béton Bitumineux Très Mince), AC (Asphalt Concrete) or
128 PA (Porous Asphalt). The SMA Project (2010-2013) [38] was carried out in Spain in order to
129 increase the knowledge about the SMA mixtures and to adapt them to the Spanish PG3.

130 This work aims to study the acoustic performance of the SMA8 pavement at 50 km/h, by
131 means of the Close ProXimity method. The additional surface assessment includes the study
132 of the pavement profile by means of its macrotexture depth (MPD), unevenness (IRI),
133 dynamic stiffness and absorption coefficient. The paper establishes the relationship between
134 the texture (macrotexture and unevenness) of the mix and the tire/road noise produced at
135 different frequencies of the tire/pavement noise spectrum. The main vertical acceleration
136 frequencies of the pavement/vehicle system, rolling at 50 km/h, are also characterized. The
137 vertical acceleration frequencies of the SMA8 are also compared to those of other aged
138 bituminous mixtures, with the same maximum aggregate size, which are commonly laid in
139 Spain. Pavement aging increases the tire/pavement noise levels according to some authors
140 [24, 39-41]. This paper also discusses their influence on the vertical accelerations of the
141 pavement/vehicle system. The characteristics monitored in this research paper are related to
142 the comfort of vehicle users and will contribute to design the future pavements safer, quieter
143 and more resource-efficient.

144 2. Measurement methods

145 Preliminary investigations had been made by the LA²IC (Laboratory of Acoustic Applied to
146 Civil Engineering) to develop a methodology for geo-referenced Close ProXimity
147 measurements in order to assess the acoustical performance of asphalt pavements [41]. A
148 TiresonicMk4-LA²IC trailer (Fig.1) assembled using the Pirelli P6000 reference tire was used
149 in the Close ProXimity sound measurements as part of the test vehicle. Two microphones are
150 mounted very close to the test wheel, in order to evaluate exclusively the acoustical
151 performance of the asphalt mixtures. During the measurements the vehicle speed was kept
152 close to the chosen reference speed. After measurements, sound levels were corrected by
153 temperature to the reference temperature of 20 Celsius degrees ($-0.05 \text{ dB(A)} / ^\circ\text{C}$),
154 considering previous research works [42]. Corrections by speed to the reference speed of 50
155 km/h were also accomplished.

156 On the other hand, the longitudinal profile measurements of the street were carried out using
157 the so-called LaserDynamicPG-LA²IC. It is composed by a commercial high-speed profiling
158 laser device installed at the vehicle front (Fig.1). The laser was designed for quality control of
159 the pavement surfaces, and it allowed to measure profiles of the wearing course, as well as
160 vertical accelerations of the front part of the vehicle.



161

162 Fig. 1. Semi-anechoic chamber of the TiresonicMk4-LA²IC (rolling on the SMA8 pavement)
163 and a detail of the Laser profiler at the front part of the vehicle.

164 The geo-referenced registration of the test data was possible because of the synchronized
165 measurements of the pavement profile (and the vertical acceleration), the sound and the GPS
166 coordinates. An encoder was assembled on the right rear wheel to give precision on the
167 distance measured [17].

168 The Mean Profile Depth (MPD) and the International Roughness Index (IRI) were calculated
169 from the longitudinal profile measurements. MPD is a measure of the macrotexture depth
170 (texture wavelength varying from 0.5 mm to 50 mm) of the pavement. On the other hand, IRI
171 is a parameter related to unevenness of the road (texture wavelength varying from 500 mm to
172 100 m) and an indicator of the ride quality.

173 The dynamic stiffness and the acoustic absorption of the mixture were also measured. The
174 former by means of a shaker and an impedance head and the latter using an absorption tube.
175 More details of the measurement techniques are given elsewhere [43].

176 3 Test track section

177 The test track section is located in Málaga city center. This section is a six-lane street that
 178 connects the port and the city Hall. Due to its location, the studied pavement supports high
 179 traffic levels (average daily traffic > 35000).

180 For this pilot section, we designed a bituminous mixture SMA with 8 mm as maximum
 181 aggregate size (SMA8), with CR from EOL tires (dry process) and laid in a 2.5cm thickness
 182 layer (Fig.2). The proportion of CR added was 0.5% of the total weight of the mixture and its
 183 maximum size was 0.63 mm. The composition of the mixture and its physical and mechanical
 184 properties are shown in Table 1 and Table 2, respectively.

185 Table 1: Composition of the SMA8 employed in the rehabilitation of the test track section

Material	Size (mm)	% in the asphalt mix
Limestone	5/8	67.1
Limestone	0/4	19.7
CO ₃ Ca	< 0.063	7.0
Bitumen 50/70	-	5.7
CR from EOL	<0.63	0.5

186 Table 2: Characterization of the SMA8 employed in the rehabilitation of the test track section

Characteristic	Value	Standard
Maximum density (kg/m ³)	2505.7	EN 12697-5 (Method A)
Bulk density (kg/m ³)	2382.3	EN 12697-6 (Method B) Compaction: 50x50 blows
Air voids content (%)	4.9	EN 12697-8
Voids in the mineral aggregate (%)	18.0	EN 12697-8
Voids filled with bitumen (%)	72.6	EN 12697-8
Marshall stability (kN)	9.8	EN 12697-34 Compaction: 50x50 blows
Marshall deformation (mm)	2.1	EN 12697-34
Binder drainage (%)	0.2	EN 12697-18
Water sensitivity (%)	95.3	EN 12697-12 (Method A)



187

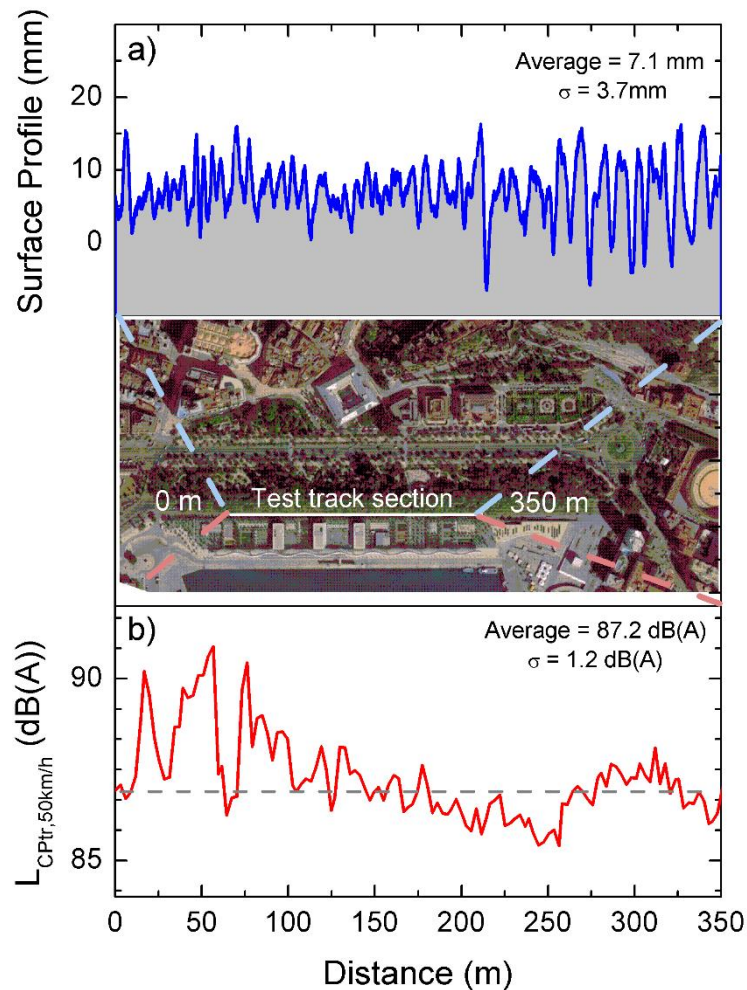
188 Fig. 2: Paving operations with mixture SMA8 in Málaga and a detail of its macrotexture.

189 4. Analysis of measurements and discussion

190 Field measurements were conducted two months after paving operations. The test results
191 presented in this section allow to characterize some of the surface properties of a bituminous
192 mixture type SMA with a maximum aggregate size of 8 mm and CR added by the dry
193 process.

194 4.1. Surface assessment: Close ProXimity sound levels and its relationship with MPD and IRI

195 Continuous tire/pavement sound levels were assessed by means of the Close ProXimity
196 method and related to the pavement profile over a distance of 350 m. Figure 3 shows the
197 pavement profile and the continuous tire/pavement sound levels corrected by the vehicle
198 speed and by the pavement temperature ($L_{CPtr, 50 \text{ km/h}}$).



199

200 Fig. 3. (a) Surface profile of the SMA8 pavement and (b) continuous tire/pavement sound

201 levels corrected by the speed and the temperature.

202 As it is shown in Fig.3, there is no clear relationship between the pavement profile and the

203 tire/pavement sound levels. However, the homogeneity of the pavement profile along the

204 studied section should be highlighted. Despite of this, the tire/pavement sound levels depend

205 significantly on the specific section in which they are measured. More specifically, the L_{CPtr} ,206 50 km/h levels between 20 m and 100 m distance are the highest, as it is shown in Fig.3b, with

207 values above 90 dB(A). On the other hand, there are other sections where sound levels are

208 considerably lower: between 85 dB(A) and 86 dB(A). The arithmetic average of the

209 measured sound levels in the middle of the 350 m road segment was 87.2 dB(A). This CPX

210 value is lower than the 90.6 dB(A) reported by Miljkovic and Radenberg [23] in a SMA8

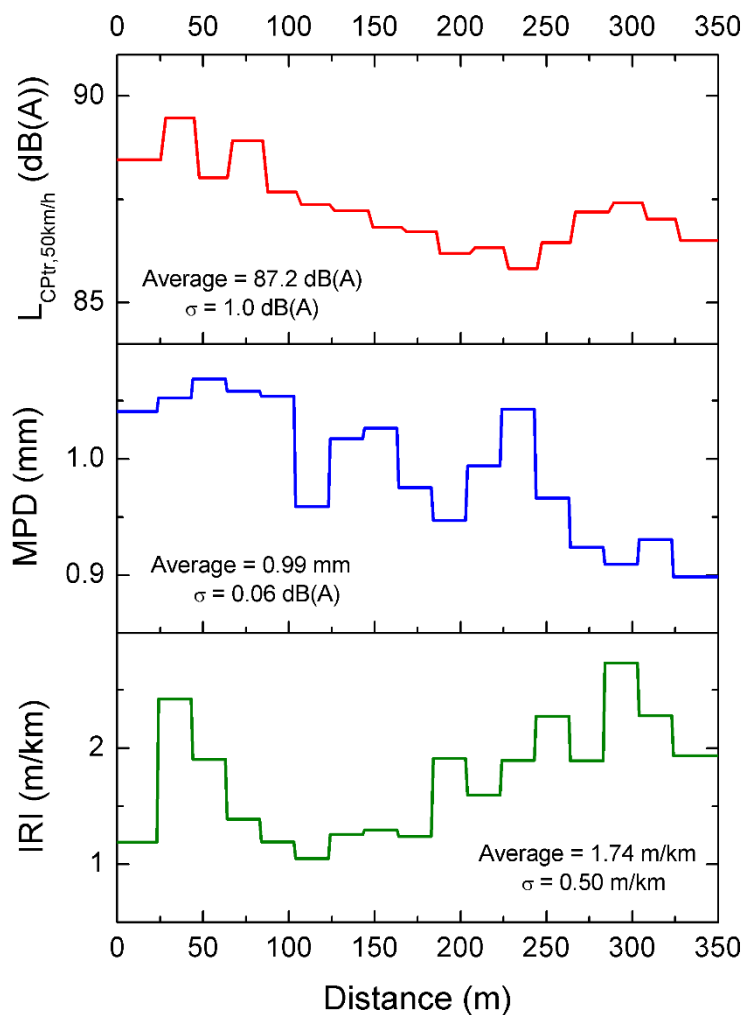
211 mixture without CR. However, differences might be due to the aging of the mixtures when
212 tested, since they studied the SMA8 mixture within the first three years of service. The
213 acoustic aging of rubberized and non-rubberized SMA bituminous mixtures has been
214 reported by other research papers [26, 40]. On the other hand, the values measured agree with
215 those reported by Sangiorgi et al. [28] at 50 km/h driving speed for a SMA8 mixture without
216 CR (86.3 dB(A) and 88.4 dB(A) after nine and fifteen months in service conditions,
217 respectively).

218 The average tire pavement sound levels presented in this paper were also lower than those
219 measured by Vazquez et al. [29] at 50 km/h in other pavements with higher maximum
220 aggregate size but without CR: SMA11 (88.1 dB(A)) and SMA16 (88.9 dB(A)). These results
221 confirm the dependence between the tire/pavement noise and the maximum aggregate size of
222 the wearing courses.

223 After the speed and temperature corrections the SMA8 section has an excellent noise
224 reduction level according to the LA²IC accreditation methodology [29]; According to this
225 methodology, the achieved reduction is about 3 dB(A) (compared with a conventional
226 bituminous mixture type Asphalt Concrete AC16, after eight years in service conditions).
227 However, the reasons for the difference in terms of noise levels in the same pavement (Fig.3)
228 throughout the section should be sought in the texture characteristics of the studied pavement.

229 In this work, the pavement texture was studied by means of the macrotexture depth (MPD)
230 and the unevenness (IRI). Figure 4 compares the tire/pavement sound levels and the MPD/IRI
231 values. Arithmetic average values are shown in this figure every 20 m intervals (sub-
232 sections), in order to facilitate the analysis. The results show that in this studied section there
233 is not a clear relationship between the tire/pavement sound levels and the unevenness. Higher
234 IRI values do not lead to high sound levels. This observation agrees with the work of Liao et

235 al. [44], although, a stronger relationship between the IRI and $L_{CPtr, 50km/h}$ levels was observed
 236 by Vazquez and Paje [45] in other BBTM type gap-graded pavements. On the other hand, the
 237 MPD might influence the tire/pavement sound levels: the highest $L_{CPtr, 50km/h}$ values are
 238 related to larger MPD values in the first 100 m of the test section. However, there are other
 239 sections between 200 m and 250 m where relatively high MPD values coincide with the
 240 lowest tire/pavement sound levels recorded.

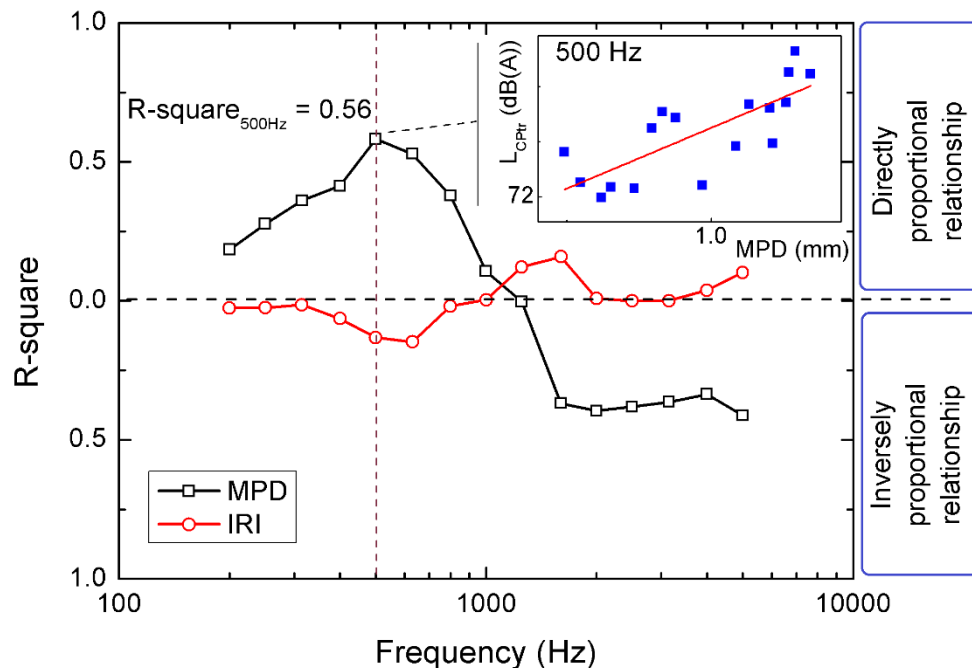


241

242 Fig. 4. Averaged $L_{CPtr, 50km/h}$ levels, MPD and IRI values each sub-section of 20 m length.

243 In order to further study the relationships between MPD, IRI and the $L_{CPtr, 50 km/h}$ noise levels,
 244 the adjustment between the one-third-octave band frequency of the tire/pavement noise and
 245 the MPD/IRI values of each sub-section was analyzed. The R-square coefficient at every

246 frequency band of the tire/pavement sound spectrum is shown in Fig.5. The R-square is
 247 defined as a positive number; however, this figure also shows the positive/negative slope of
 248 the adjustment. When the magnitudes are directly proportional, they are depicted in the upper
 249 half of the chart, whereas if there is an inversely proportional relationship they are depicted in
 250 the lower half.



251

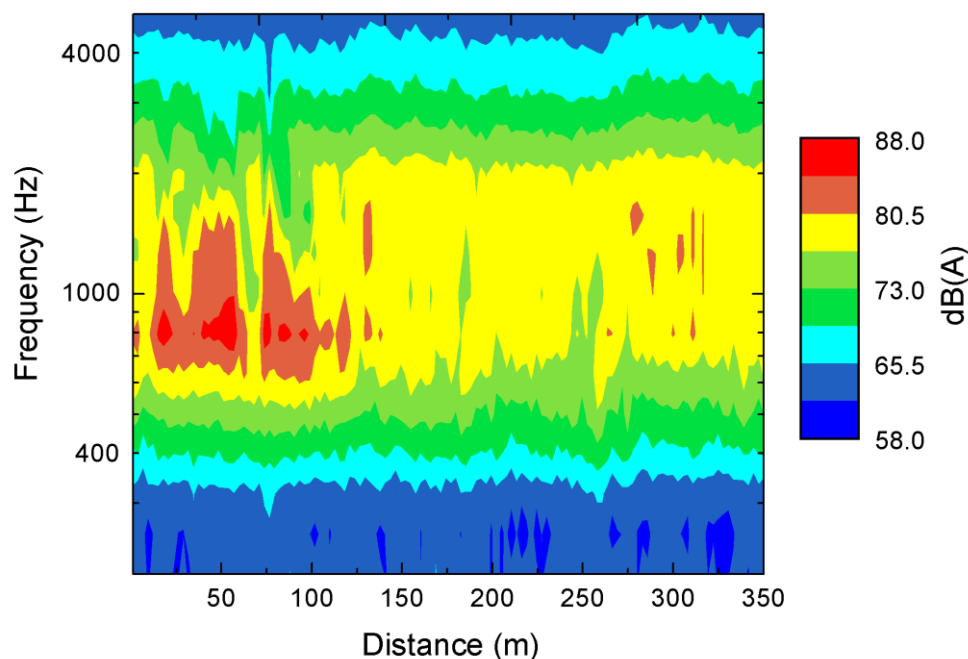
252 Fig. 5. R-square values between IRI/MPD and $L_{CPtr, 50km/h}$. A detail of a linear fitting between
 253 MPD and $L_{CPtr, 50km/h}$ at the frequency of 500 Hz is included.

254 According to Fig.5 there is no clear relationship between the IRI and the tire/pavement sound
 255 levels measured in the mixture SMA8 because the corresponding R-square values are lower
 256 than 0.2 at any frequency. This result contrasts with the relationship found elsewhere in other
 257 gap-graded bituminous mixtures [45]. Nevertheless, the unevenness may not be related to the
 258 mixture type, but to the construction process and/or the pavement deterioration, since the
 259 unevenness is composed by higher pavement wavelengths. Figure 5 also shows the
 260 significant influence of the macrotexture depth (MPD) on the tire/pavement noise at different
 261 frequencies. larger MPD values of the studied mixture SMA8 are related to lower

262 tire/pavement noise at frequencies higher than 1 kHz. This could be explained because the
263 MPD reduces noise at these high-order frequencies due to a lower dispersion of the sound
264 [17]. On the other hand, larger MPD values are related to higher tire/pavement sound levels
265 at frequencies up to 800 Hz. These results agree with the existing literature [46, 47]. The
266 maximum R-square value between MPD and $L_{CPtr, 50km/h}$ is 0.56 and it is found at 500 Hz (see
267 detail in Fig.5). However, a stronger relationship between MPD and low frequencies of $L_{CPtr,}$
268 $50km/h$ was expected in this test track section, because the tire/pavement noise at low
269 frequencies is generally related to impact and vibration generation mechanisms, and
270 consequently, to the macrotexture. The results included in Fig.5 suggest that the
271 tire/pavement sound levels at low frequencies might be affected by other mechanisms in this
272 mixture, because the MPD cannot totally explain these values by itself. This behavior at low
273 frequencies is also not due to the character of the surface texture, that is expressed by the
274 parameter c [41]. This parameter c was calculated as the ratio between the average MPD and
275 the Root Mean Square (RMS) of MPD data measured throughout the test track section.
276 Values of c up to 0.95 are characteristics of negative textures, whereas c values from 1.05
277 define the positive textures. According to previous works, positive texture would increase the
278 mechanical generation of tire/pavement noise, whilst negative texture would reduce its
279 generation/propagation [48]. In the SMA8 the parameter c was established around 1.00, so the
280 pavement texture is considered as neutral.

281 There are some sections of the studied pavement with high MPD values according to Fig.4,
282 particularly in the first 100 m of the tested road segment. The differences in MPD values may
283 influence the tire/pavement sound spectrum. The influence of large MPD values on the
284 pavement acoustics is reflected in Fig.6, where the frequency spectrum map ($L_{CPtr, 50km/h}$) of
285 the test section is shown. At sections with larger MPD values (in the first 100 m) the
286 frequency spectrum mapping, (obtained for a driving speed of 50 km/h) shows higher noise

287 values between 600 Hz and 1600 Hz, and lower noise values between 1600 Hz and 2500 Hz.
 288 The lower noise values could be explained by the dispersion of the sound, as it was said
 289 before, but the higher sound emissions between 600 Hz and 1600 Hz are not only related to
 290 the macrotexture depth (MPD). Possibly, the reason of these higher noise values is within the
 291 pavement texture; other parameters, such as the dominant texture wavelengths, could explain
 292 these values in the pavement type SMA8. On the other hand, the sections around 150 m and
 293 225 m from the starting point of the test, also present large MPD values (see Fig.4), but the
 294 sound spectrum in Fig.6 indicates that the MPD of these sections does not dominate the
 295 acoustic behavior of the pavement.



296

297 Fig. 6. Sound frequency spectrum map ($L_{CPtr, 50km/h}$) of the test section.

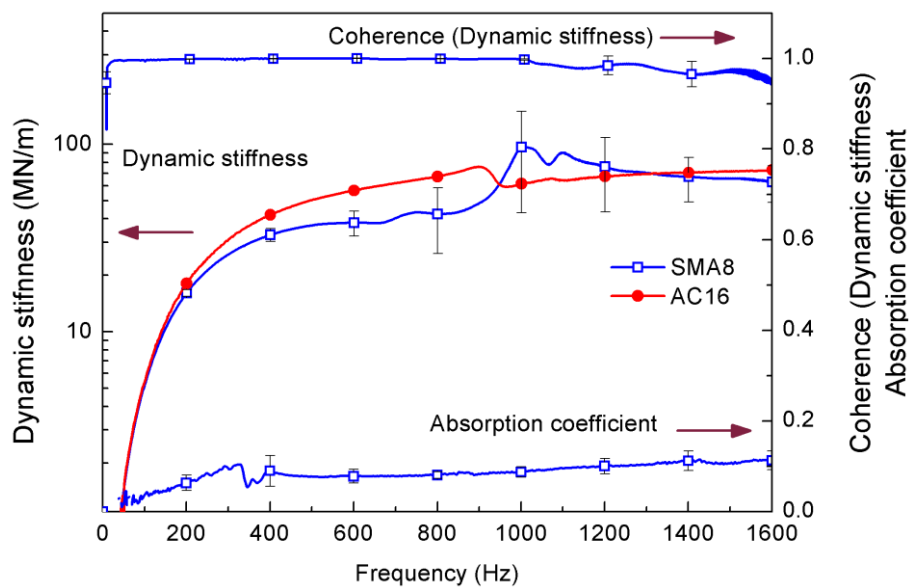
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299 4.2. Dynamic stiffness and acoustic absorption

300 Measurements of the dynamic stiffness of the pavement were also carried out on the test track
 301 section by means of a shaker and an impedance head. The measured dynamic stiffness of the

302 SMA8 mixture was slightly lower than that of a conventional bituminous mixture-type
 303 asphalt concrete (AC) (see Fig.7). This figure also shows the coherence function of the
 304 dynamic stiffness spectrum (close to unity), which is an indicator of the reliability of the
 305 measurement. According to the results, the addition of CR to the mixture SMA8 does not
 306 reduce the dynamic stiffness of the studied section, in order to make dynamic stiffness an
 307 effective tire/pavement noise attenuation mechanism.

308 On the other hand, the acoustic absorption of the mixture SMA8 was measured in laboratory
 309 (samples) by means of an impedance tube. Low values of the absorption coefficient, below
 310 0.2, were measured up to 1600 Hz of the sound spectrum (Fig.7). According to our results,
 311 neither dynamic stiffness nor the acoustic absorption may act as a key noise reduction
 312 mechanism within the studied section.



313

314 Fig. 7. Dynamic stiffness, and its coherence function, measured in the SMA8 bituminous
 315 mixture. The acoustic absorption coefficient is also shown.

316 *4.3. Macrotecture and unevenness according to the national standards*

317 The MPD and IRI assessment also allows to characterize the functional characteristics of the
318 test track section that are related to the comfort and the safety of the road users. For the
319 functional characterization, the threshold values (roads) included in the Spanish PG3 have
320 been considered. The minimum macrotexture values for a wearing course depend on the
321 construction characteristics of the assessed wearing course. These values should be measured
322 according to the sand patch test (Mean Texture Depth; MTD). The minimum MTD values
323 included in the PG3 are: 0.7 mm (AC), 1.1 mm (BBTM A) and 1.5 mm (BBTM B and PA).
324 The average MPD value from the continuous profile measurement of the test track section is
325 around 1 mm. From the average MPD value, the Estimated Texture Depth (ETD) can be
326 calculated according to the following expression [17]:

$$327 \quad \text{ETD} = 0.2 + 0.8 \cdot \text{MPD}$$

328 with ETD and MPD in mm.

329 The calculated ETD is equal to 1 mm and it can be compared to the values included in the
330 PG3 (MTD). This value is slightly lower than the minimum value of other gap-graded
331 bituminous mixture; ETD = 1.1 mm for BBTM A mixture. However, considering that the
332 uncertainty associated with the sand patch test may be higher than 0.2 mm due to the site-to-
333 site variations, the macrotexture of the test track section would be at the lower limit of the
334 accepted values for roads included in the PG3.

335 On the other hand, the IRI assessment implies the determination of the percentage of
336 hectometers within different ranges of IRI values. The 20 m sub-sections shown in Fig.4 have
337 been employed for this assessment since the total length of the studied pavement is 350 m.
338 Table 3 shows the IRI values and the percentage of sections that have to meet them when a
339 pavement is rehabilitated according to PG3.

340 Table 3. IRI values and percentage of sub-sections that have to meet them in rehabilitated
 341 sections according to PG3.

	IRI (m/km)	1.5	2.0	2.5	3.0
% of sub-sections	Highways PG3	50	80	100	-
	Other roads PG3	-	50	80	100
	<i>Test track (SMA8)</i>	<i>41</i>	<i>76</i>	<i>94</i>	<i>100</i>

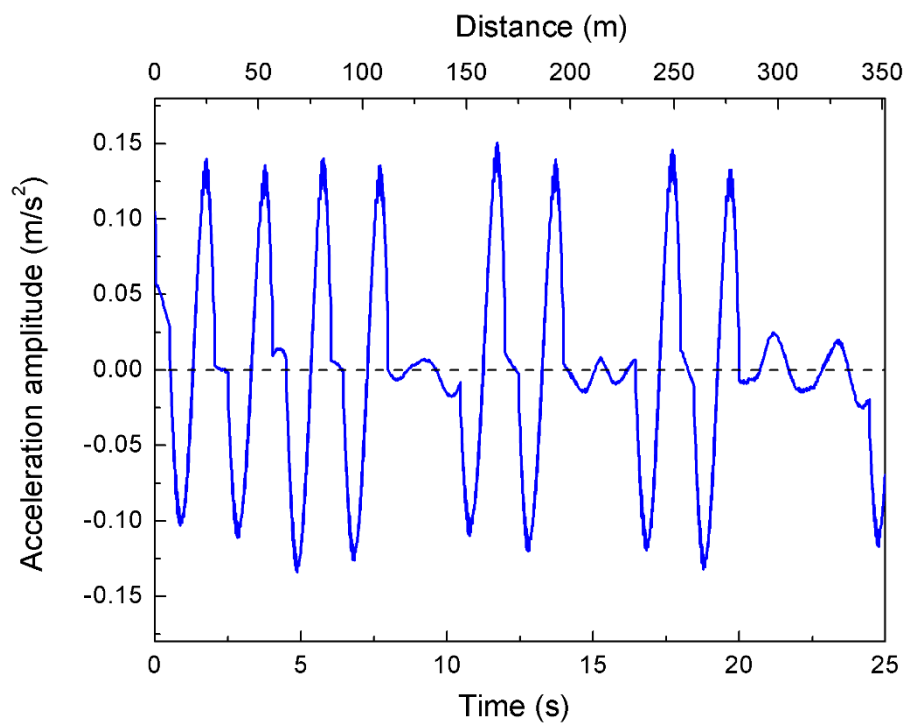
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343 Table 3 shows that the rehabilitated track (urban section) agrees with PG3 for the
 344 specifications of rehabilitated pavements to be used in roads, but it does not agree with the
 345 highway specifications. However, one should take into account that the unevenness of the
 346 studied pavement is affected by underground urban services such as cables and pipes. The
 347 presence of these services should not affect so much in the unevenness of highways.

348 *4.4. Vertical acceleration assessment*

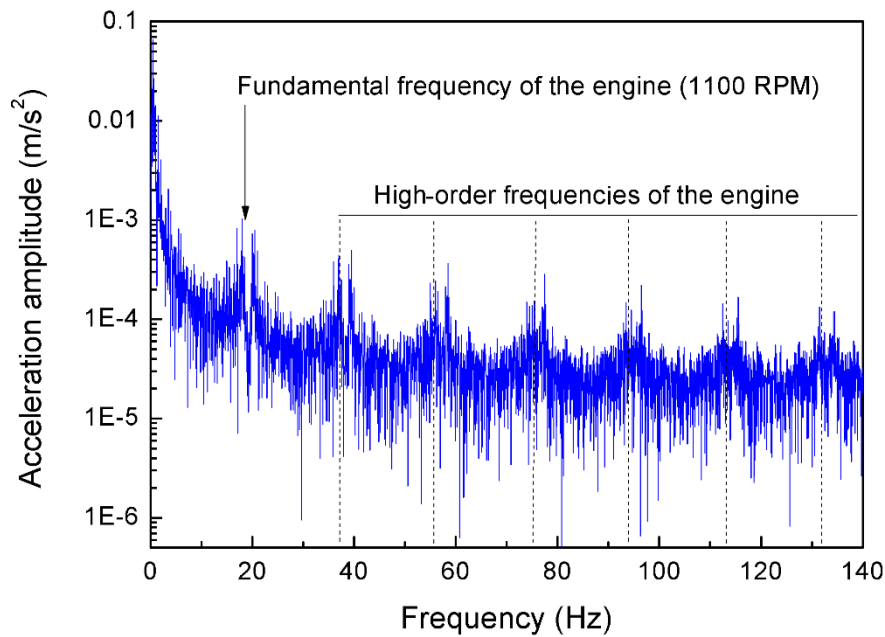
349 Vehicle accelerations induced by irregularities on road pavements may lead to discomfort of
 350 the vehicle users, cause mechanical problems in the vehicles or even accidents [35]. It is well
 351 known that vertical accelerations of vehicles increase with the amplitude of the pavement
 352 irregularities [49]. The acceleration recorded in the vehicle depends not only on the pavement
 353 but also on the mechanical characteristics of the vehicle itself (e.g. flexibility of the tires,
 354 suspension system, mass distribution, driving velocity, etc.). However, if the vehicle
 355 characteristics and speed are kept constant, the study of the vertical acceleration gives a
 356 valuable information about the pavement performance. In this paper, the vehicle acceleration
 357 assessment allows to characterize the SMA8 wearing course as well as to compare its
 358 behavior with that of more aged pavements. The registration of vertical accelerations of the
 359 pavement/vehicle system (at a driving speed of 50 km/h) was carried out during the
 360 longitudinal pavement profiling by means of the LaserDynamicPG-LA²IC. The vertical

361 accelerations induced by the studied SMA8 bituminous mixture profile are shown in Fig.8.
 362 This figure shows that there are predominant vertical acceleration frequencies. The vehicle
 363 vertical acceleration signal could be described by a combination of sinusoidal waves, whose
 364 resulting maximum acceleration amplitude value is around 0.14 m/s^2 .



365
 366 Fig. 8. Vertical vehicle accelerations in the test track section with bituminous mixture SMA8.

367 The main frequencies and amplitudes of the vertical acceleration signal were determined
 368 using the Fast Fourier Transform (FFT), which allows to obtain frequencies governing the
 369 response of the pavement/vehicle system (SMA8). The FFT of the acceleration amplitude up
 370 to 140 Hz is shown in Fig.9. There is a relatively dominant frequency at around 19 Hz,
 371 meanwhile the high-order frequencies are at 38 Hz, 57 Hz and so on. These frequencies may
 372 be related to the frequency of the engine: 1100 revolutions per minute according to the
 373 vehicle tachometer, which corresponds to 50 km/h driving speed. These frequencies will be
 374 ignored in this paper, which focuses on the pavement surface assessment.



375

376 Fig. 9. FFT of the vertical acceleration signal up to 140 Hz, highlighting the engine frequency

377

and its high-order frequencies.

378 Figure 10 shows a detail of the spectrum of the vertical acceleration amplitude and its phase

379 angle up to 2.5Hz, where the maximum acceleration amplitudes are included. According to

380 the spectral analysis, the fundamental frequency of the acceleration signal is 0.5 Hz. The

381 harmonics are also depicted in Fig.10 (1 Hz, 1.5 Hz, 2 Hz). There are other frequencies

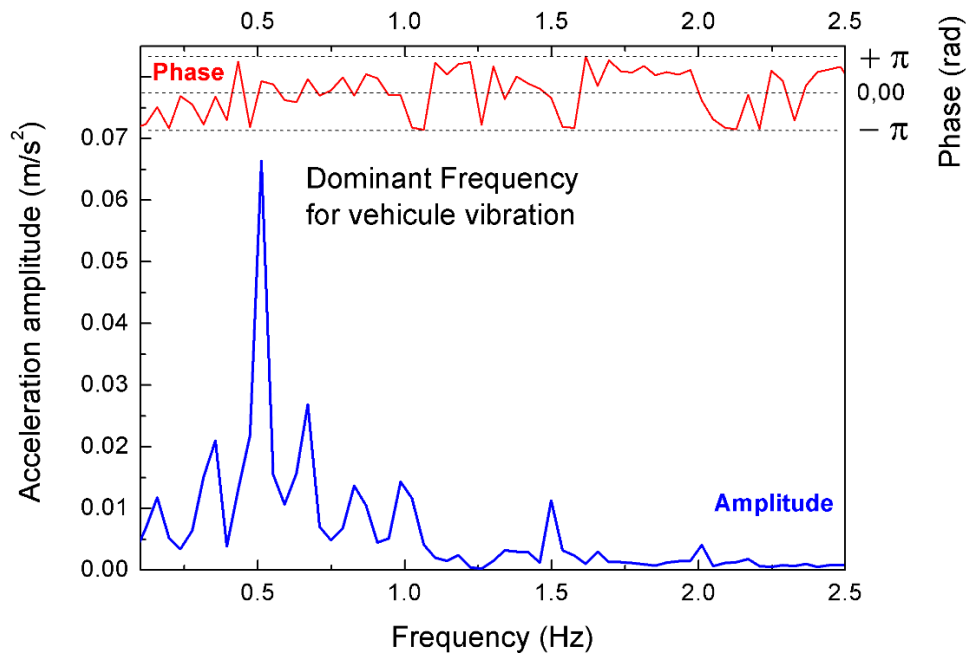
382 around the dominant one that stand out in this figure, i.e. 0.35 Hz or 0.67 Hz, however these

383 frequencies of the spectral analysis may be linked to the windowing of the sinusoid signal,

384 and the corresponding spectral leakage. A longer acceleration signal should reduce the

385 leakage; however, the signal cannot be longer since it is related to the length of the measured

386 test track section (350 m) and the employed reference speed (50 km/h).



387

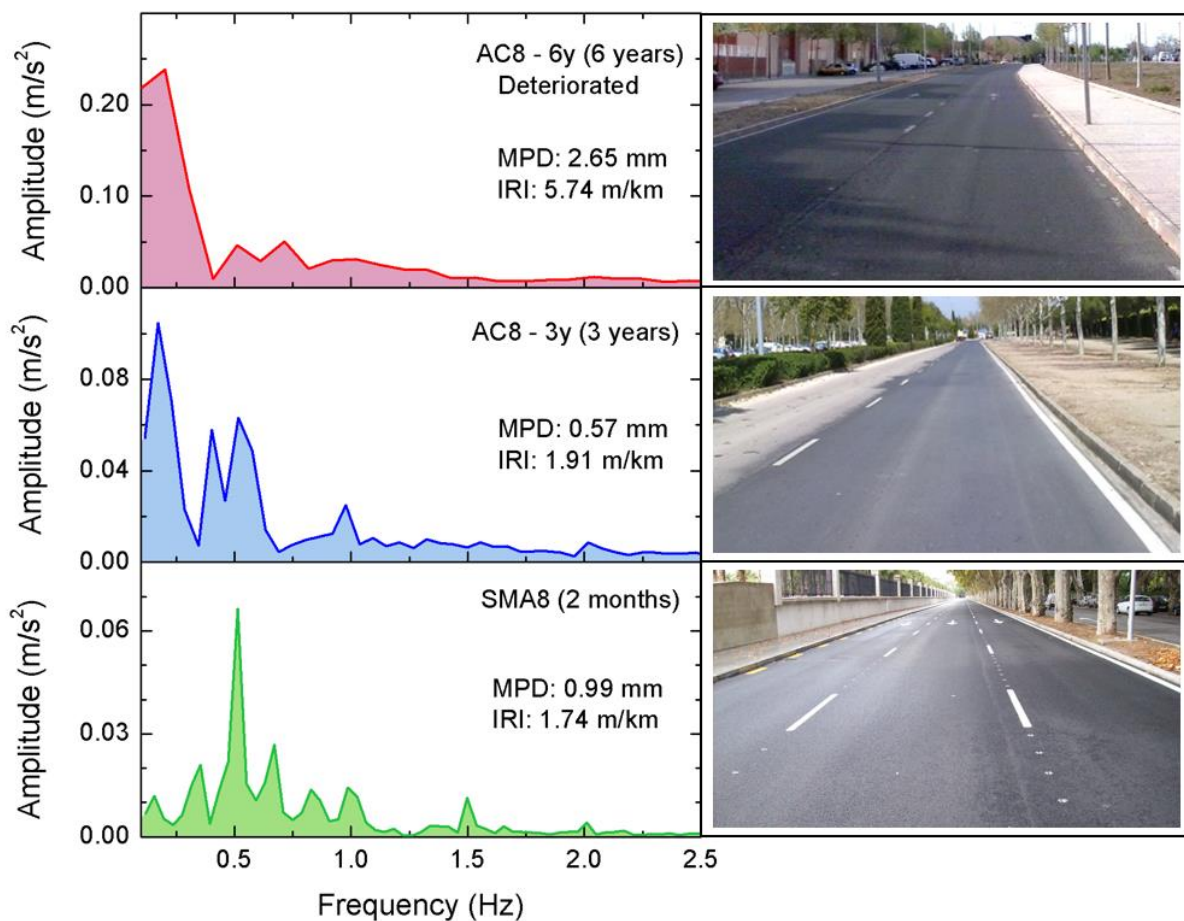
388

Fig. 10. Detail of the vertical acceleration FFT up to 2.5 Hz.

389 In this study, the vertical acceleration spectrum of the mixture SMA8 are compared with
 390 those of two conventional AC dense bituminous mixtures with a maximum aggregate size of
 391 8 mm. These mixtures are also located in urban lanes and the only difference between them is
 392 their age: 3 and 6 years in service conditions (referred to as AC8-3y and AC8-6y
 393 respectively). These three mixtures have the same maximum aggregate size which suggests
 394 that it does not affect the differences on the recorded vehicle accelerations. The same vehicle
 395 and testing equipment are used in the three measurements to facilitate the comparison. The
 396 acceleration spectra of the studied mixtures are shown in Fig.11. The macrotexture depth,
 397 given by the Mean Profile Depth (MPD), and the unevenness obtained from the international
 398 roughness index (IRI) of the studied sections are also indicated in Fig.11. In addition to the
 399 age of the pavements, the pavement aging has been assessed by means of the visual
 400 inspection and the unevenness (IRI). The IRI is considered by researchers and road agencies
 401 as a pavement performance indicator [50, 51], and therefore, may be looked as a surrogate

402 indicator for aging. According to the Spanish PG3, the maximum IRI value of a rehabilitated
 403 road section must be lower than 3.0 m/km.

404 From the visual inspection, important distresses were found in the deteriorated pavement
 405 AC8 with 6 years in service conditions. This surface presented alligator cracking, wheelpath
 406 longitudinal cracking and longitudinal/transverse cracking. Mixture AC8-3y was visually in
 407 good conditions despite its age, whereas the mixture SMA8 did not present any distress after
 408 two months in service conditions.



409
 410 Fig. 11. FFT of the vertical acceleration when crossing pavements AC8-6y, AC8-3y and
 411 SMA8. A detail of each studied pavement, from visual auscultation, is also included.

412 The aging process seems to be responsible of the vertical acceleration spectrum shape. Aging
 413 and deteriorated bituminous mixtures may produce higher maximum acceleration amplitudes,

414 at lower frequencies. As shown in Fig.11, the section AC8-6y (deteriorated) has the higher
415 unevenness. The unevenness is related to higher wavelengths and it seems to explain the
416 higher vertical acceleration frequencies at lower frequencies, measured in the aged
417 pavements. This is related to the equation: $f = n \cdot v$; where f is the time frequency (Hz); n the
418 spatial frequency and the reciprocal of the wavelength (m^{-1}), and v is the vehicle speed (m/s^2).

419 According to the results, the vertical acceleration of the pavement/vehicle system is a surface
420 characteristic that can provide valuable information in the field auscultation of pavements in
421 service conditions. The acceleration pattern of vehicles crossing a given road is affected by
422 pavement-related factors such as its aging, its possible damages and/or its construction
423 process, among others.

424 **5. Conclusions**

425 On field acoustic assessment of a bituminous mixture type SMA was carried out by means of
426 the Close ProXimity method. The bituminous mixture was fabricated with a maximum
427 aggregate size of 8 mm and with CR added by the dry process. Measurements were
428 conducted after two months in service conditions. In addition to the acoustic assessment,
429 some surface characteristics were studied and related to the tire/pavement noise levels. These
430 characteristics include the macrotexture depth by the MPD, the unevenness by the IRI, the
431 dynamic stiffness and the acoustic absorption. Finally, the vertical accelerations of the
432 pavement/vehicle system were also studied and related to the pavement performance (age,
433 IRI and distresses from the visual inspection). The tested properties are related to the acoustic
434 behavior of the bituminous mixture, as well as to the comfort and safety of road users. The
435 main results of the study are as follows:

- 436 - Some sub-sections of the studied pavement stand out for their low tire/pavement
437 sound levels measured according to the Close ProXimity method. These sections are

438 about 3 dB(A) lower than a conventional AC pavement with eight years in service
439 conditions. According to these results, the SMA8 mixture could be used as noise
440 mitigation measure within the Action Plans of cities with problems related to noise,
441 especially when other noise attenuation measures are not possible or insufficient.

442 - The correlation between the macrotexture depth (MPD) and the unevenness (IRI) with
443 the different frequency bands of the tire/pavement sound spectrum was studied for the
444 test track section SMA8. The unevenness does not directly influence tire/pavement
445 noise at any frequency band. The MPD influences noise at relatively low frequencies
446 (mainly 500 Hz - 600 Hz), but also at higher frequencies (from 1.6 kHz) of the sound
447 spectrum. However, the acoustic behavior of the SMA8 section cannot be only
448 explained by the variations of the MPD.

449 - The vertical accelerations of the testing vehicle driving at 50km/h speed show that the
450 main vibration frequency induced by the pavement is 0.5 Hz. The frequency content
451 of the acceleration is closely connected to the state of conservation of a pavement.
452 Degraded surfaces (high IRI values and surface distresses) produce higher
453 acceleration amplitudes at lower frequencies.

454 The methodology of analysis presented in this work could permit to model the acoustic
455 performance of pavements in the future, based on other surface characteristics such as the
456 macrotexture, the unevenness or the dynamic stiffness. However, other noise related features
457 of the pavements that should be addressed in the future are their microtexture, the dominant
458 texture wavelengths, the slip resistance and the tire hardness variations. On the other hand,
459 the vertical acceleration assessment employed in this work could give a reference of the state
460 of conservation of a given pavement. These findings will increase the knowledge in order to
461 design pavements with durable and effective noise mitigation features.

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466 **References**

- 467 [1] European Commission, 2014. *The EU explained: Transport publication online*.
468 http://europa.eu/pol/index_en.htm. <http://europa.eu/!bY34KD>.
- 469 [2] European Commission 2017. Report from The Commission To The European Parliament
470 And The Council On The Implementation Of The Environmental Noise Directive, in
471 accordance with Article 11 of Directive 2002/49/EC. COM/2017/0151 final
- 472 [3] Licitra G, Cerchiai M, Teti L, Ascari E, Fredianelli L. *Durability and variability of the*
473 *acoustical performance of rubberized road surfaces*. *Applied Acoustics* 2015;94:20–28.
- 474 [4] Soares F, Freitas E, Cunha C, Silva C, Lamas J, Mouta S, Santos JA. *Traffic noise:*
475 *Annoyance assessment of real and virtual sounds based on close proximity*
476 *measurements*. *Transportation Research Part D: Transport and Environment*
477 2017;52:399–407.
- 478 [5] Basner M, Babisch W, Davis A, Brink M, Clarck C, Janssen S, Stansfeld S. *Auditory and*
479 *non-auditory effects of noise on health*. *Lancet*. 2014;383:1325–1332.
- 480 [6] Miedema HME, Oudshoorn CGM. *Annoyance from transportation noise: Relationship*
481 *with exposure metrics DNL and DENL and their confidence intervals*. *Environmental*
482 *Health Perspectives*. 2001;109:409-416.

- 483 [7] Sygna K, Aasvang GM, AAmodt G, Oftedal B, Krog NH. *Road traffic noise, sleep and*
484 *mental health*. Environmental Research. 2014;131:17-24.
- 485 [8] Lercher P, Evans GW, Meis M. *Ambient noise and cognitive processes among primary*
486 *schoolchildren*. Environment and Behavior. 2003;35:725-735.
- 487 [9] Minichilli F, Gorini F, Ascari E, Bianchi F, Coi A, Fredianelli L, Licitra G, Manzoli F,
488 Mezzasalma L, Cori L. *Annoyance Judgment and Measurements of Environmental*
489 *Noise: A Focus on Italian Secondary Schools*. 2018;15:208
- 490 [10] Vienneau D, Schindler C, Perez L, Probst-Hensch N, Roosli M. *The relationship*
491 *between transportation noise exposure and ischemic heart disease: a meta-analysis*.
492 Environmental Research. 2015;138:372-380
- 493 [11] Licitra G, Ascari E, Fredianelli L. *Prioritizing Process in Action Plans: A Review of*
494 *Approaches*. Current Pollution Reports. 2017;3:151-161.
- 495 [12] Vogiatzis K, Remy N. *From environmental noise abatement to soundscape creation*
496 *through strategic noise mapping in medium urban agglomerations in South Europe*.
497 Science of the Total Environment 2014;482-483:420–431.
- 498 [13] Fredianelli L, Del Pizzo A, Licitra G. *Recent development in sonic crystal as barriers for*
499 *road traffic noise mitigation*. Environments. 2019;6:14.
- 500 [14] Zambon G, Roman HE, Smiraglia M, Benocci R. *Monitoring and Prediction of Traffic*
501 *Noise in Large Urban Areas*. Applied Sciences. 2018;5:251.

- 502 [15] Zambon G, Benocci R, Bisceglie A, Roman HE, Bellucci P. *The LIFE DYNAMAP*
503 *project: Towards a procedure for dynamic noise mapping in urban areas*. Applied
504 Acoustics. 2017;124:52-60.
- 505 [16] Cheng X, Liu Y, Ren W, Huang K. *Performance evaluation of asphalt rubber mixture*
506 *with additives*. Materials 2019;12:1200.
- 507 [17] Paje SE, Luong J, Vazquez VF, Bueno M, Miro R. *Road pavement rehabilitation using a*
508 *binder with a high content of crumb rubber: Influence on noise reduction*. Construction
509 and Building Materials 2013;47:789-798.
- 510 [18] Pacheco-Torres R, Cerro-Prada E, Escolano F, Varela F. *Fatigue performance of waste*
511 *rubber concrete for rigid road pavements*. Construction and Building Materials
512 2018;176:539-548.
- 513 [19] Hernandez-Olivares F, Witoszek-Schultz B, Alonso-Hernández M, Benito Moro C.
514 *Rubber-modified hot-mix asphalt pavement by dry process*. International Journal of
515 Pavement Engineering 2009;10(4):277-288.
- 516 [20] Bennert, T.; Maher, A. *Influence of pavement surface type on tire/pavement generated*
517 *noise*. Journal of Testing and Evaluation 2005;33:94–100.
- 518 [21] Ahammed, M.A.; Tighr, S.L.; Klement, T. *Quiet and durable pavements: Findings from*
519 *an Ontario study*. Canadian Journal of Civil Engineering 2010;37:1035–1044.
- 520 [22] Vaitkus, A.; Andriejauskas, T.; Vorobjovas, V.; Jagniatinskis, A.; Fiks, B.; Zofka, E.
521 *Asphalt wearing course optimization for road traffic noise reduction*. Construction and
522 Building Materials 2017;152:345–356.

- 523 [23] Miljkovic, M.; Radenberg, M. *Thin noise-reducing asphalt pavements for urban areas in*
524 *Germany*. International Journal of Pavement Engineering 2012;13:569–578.
- 525 [24] Vuye, C.; Bergiers, A.; Vanhooreweder, B. *The acoustical durability of thin noise*
526 *reducing asphalt layers*. Coatings 2016;6:21.
- 527 [25] Gardziejczyk, W.; Gierasimiuk, P.; Motylewicz, M. *Noisiness of the surfaces on low-*
528 *speed roads*. Coatings 2016;6:15.
- 529 [26] Gardziejczyk, W. *The effect of the time on acoustic durability of low noise pavements—*
530 *The case studies in Poland*. Transportation Research Part D: Transport and Environment
531 2016;44:93–104.
- 532 [27] Sweczko-Zurek, S.; Jaskula, P.; Ejsmont, J.A.; Kedzierska, A.; Czajkowski, P. *Rolling*
533 *resistance and tyre/road noise on rubberized asphalt pavement in Poland*. Road
534 Materials and Pavement Design 2017;18:151–167.
- 535 [28] Sangiorgi, C.; Tataranni, P.; Simone, A.; Vignali, V.; Lantieri, C.; Dondi, G. *Stone*
536 *mastic asphalt (SMA) with crumb rubber according to a new dry-hybrid technology: A*
537 *laboratory and trial field evaluation*. Construction and Building Materials
538 2018;182:200–209.
- 539 [29] Vazquez VF, Teran F, Luong J, Paje SE. *Functional performance of Stone Mastic*
540 *Asphalt pavements in Spain: Acoustic Assessment*. Coatings 2019;9:123.
- 541 [30] Cantisani G, Loprencipe G. *Road roughness and whole body vibration: Evaluation tools*
542 *and comfort limits*. Journal of Transportation Engineering 2010;136:818-826.

- 543 [31] Harris NK, Gonzalez A, Obrien EJ, McGetrick P. *Characterisation of pavement profile*
544 *heights using accelerometer readings and a combinatorial optimization technique.*
545 *Journal of Sound and Vibration* 2010;5:497-508.
- 546 [32] Yuchuan D, Chenglong L, Difei W, Siyu L. *Application of vehicle mounted*
547 *accelerometers to measure pavement roughness.* *International Journal of Distributed*
548 *Sensor Networks* 2016:12.
- 549 [33] Loprencipe G, Zoccalo P. *Ride Quality Due to Road Surface Irregularities: Comparison*
550 *of Different Methods Applied on a Set of Real Road Profiles.* *Coatings* 2017;7:59.
- 551 [34] Wei L, Fwa TF, Zhe Z. *Wavelet analysis and interpretation of road roughness.* *Journal*
552 *of Transportation engineering-ASCE* 2005;131:120-130.
- 553 [35] Silva N, Shah V, Soares J, Rodrigues H. *Road anomalies detection system evaluation.*
554 *Sensors* 2018;18:1984.
- 555 [36] Staniek M. *Repeatability of road pavement condition assessment based on three-*
556 *dimensional analysis of linear accelerations of vehicles.* *Resilient and Safe Road*
557 *Infrastructure.* *IOP Conference Series-Materials Science and Engineering* 2018;356
- 558 [37] Souza VMA. *Asphalt pavement classification using smartphone accelerometer and*
559 *Complexity Invariant Distance.* *Engineering Applications of Artificial Intelligence*
560 *2018;74:198-211.*
- 561 [38] Project SMA. *Proyecto Mezclas Sostenibles Medioambientalmente Amigables (CDTI-*
562 *FEDER).* Available online: <http://www.proyectosma.eu/> (accessed on 30 April 2019).

- 563 [39] Freitas E, Silva L, Vuye C. *The influence of pavement degradation on population*
564 *exposure to road traffic noise*. *Coatings* 2019;9:298.
- 565 [40] Licitra G, Moro A, Teti L, Del Pizzo A, Bianco F. *Modelling of acoustic ageing of*
566 *rubberized pavements*. *Applied Acoustics* 2019;146:237-245.
- 567 [41] Vazquez VF, Luong J, Bueno M, Teran F, Paje SE. *Assessment of an action against*
568 *environmental noise: Acoustic durability of a pavement Surface with crumb rubber*.
569 *Science of the Total Environment* 2016;542:223-230.
- 570 [42] Bueno M, Luong J, Viñuela U, Teran F, Paje SE. *Pavement temperature influence on*
571 *close proximity tire/road noise*. *Applied Acoustics* 2011;72:829-835.
- 572 [43] Vazquez VF, Teran F, Huertas P, Paje SE. *Field assessment of a cold-in place-recycled*
573 *pavement: Influence on Rolling noise*. *Journal of Cleaner Production* 2018;197:154-162.
- 574 [44] Liao G, Sakhaeifar MS, Heitzman M, West R, Waller B, Wang S, Ding Y. *The effects of*
575 *pavement surface characteristics on tire/pavement noise*. *Applied Acoustics* 2014;76:14-
576 23.
- 577 [45] Vazquez VF, Paje SE. *Study of the road surface properties that control the acoustic*
578 *performance of a rubberized asphalt mixture*. *Applied Acoustics* 2016;102:33-39.
- 579 [46] Sandberg U, Ejsmont JA. *Tyre/Road Noise Reference Book*; INFORMEX: Kisa,
580 Sweden, 2002; ISBN 91-631-2610-9.
- 581 [47] Del Pizzo A, Teti L, Moro A, Bianco F, Fredianelli L, Licitra G. *Influence of texture on*
582 *tyre road noise spectra in rubberized pavements*. *Applied Acoustics* 2020;159:107080.

- 583 [47] Knabben RM, Trichês G, Vergara EF, Gerges SNY, Keulen W. *Characterization of*
584 *tire/road noise from Brazilian roads using the CPX trailer method*. *Applied Acoustics*
585 2019;151:206-214.
- 586 [48] Camara A, Vazquez VF, Ruiz-Teran AM, Paje SE. *Influence of the pavement surface on*
587 *the vibrations induced by heavy traffic in road bridges*. *Canadian Journal of Civil*
588 *Engineering* 2017;44(12):1099-1111.
- 589 [49] Gong H, Sun Y, Hu W, Polaczyk PA, Huang B. *Investigating impacts of asphalt mixture*
590 *properties on pavement performance using LTPP data through random forests*.
591 *Construction and Building materials* 2019;204:203-212.
- 592 [50] Robbins M, Tram N, Copeland A. *Determining the Age and Smoothness of Asphalt and*
593 *Concrete Pavements at the Time of First Rehabilitation using Long-Term Pavement*
594 *Performance PRogram Data*. *Transportation Research Record* 2018;2672:176-185.