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

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ABSTRACT

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

***Keywords**:*

Tire/pavement noise;

Action Plans against noise;

Surface characteristics;

Mean Profile Depth;

Vertical accelerations;

Stone Mastic Asphalt;

Highlights:

- Some sections of the pavement with SMA8 stand out for their good acoustic performance
- The relationship between macrotexture and tire/pavement noise has been studied
- The macrotexture does not entirely explain the good acoustic performance
- The acceleration spectrum shape depends on the pavement aging and conservation

1. Introduction

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

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

Expensive and not always accepted acoustic barriers are the most widespread solution to mitigate the noise produced by the main sources [13], but also innovative solutions, such as monitoring using a wireless sensor network, are studied [14, 15]. However, one of the best solutions to reduce noise in the surroundings, thus preventing health effects, is to use pavements with improved acoustic features. Gap-graded bituminous mixtures with crumb rubber (CR) may be an effective way to reduce noise, as well as the End-Of-Life (EOL) tires disposal on landfills [16, 17], which is a significant environmental problem because tires are highly durable and non-biodegradable [18]. CR can be incorporated into asphalt mixes by means of the dry or the wet processes. In the dry process CR is used as a portion of the fine aggregate, while in the wet process the CR acts as an asphalt binder modifier [19].

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

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

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

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

2. Measurement methods

Preliminary investigations had been made by the LA^{2}IC (Laboratory of Acoustic Applied to Civil Engineering) to develop a methodology for geo-referenced Close ProXimity measurements in order to assess the acoustical performance of asphalt pavements [41]. A TiresonicMk4-LA^{2}IC trailer (Fig.1) assembled using the Pirelli P6000 reference tire was used in the Close ProXimity sound measurements as part of the test vehicle. Two microphones are mounted very close to the test wheel, in order to evaluate exclusively the acoustical performance of the asphalt mixtures. During the measurements the vehicle speed was kept close to the chosen reference speed. After measurements, sound levels were corrected by temperature to the reference temperature of 20 Celsius degrees (-0.05 dB(A) / ºC), considering previous research works [42]. Corrections by speed to the reference speed of 50 km/h were also accomplished.

On the other hand, the longitudinal profile measurements of the street were carried out using the so-called LaserDynamicPG-LA^{2}IC. It is composed by a commercial high-speed profiling laser device installed at the vehicle front (Fig.1). The laser was designed for quality control of the pavement surfaces, and it allowed to measure profiles of the wearing course, as well as vertical accelerations of the front part of the vehicle.

Fig. 1. Semi-anechoic chamber of the TiresonicMk4-LA^{2}IC (rolling on the SMA8 pavement) and a detail of the Laser profiler at the front part of the vehicle.

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

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

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

3 Test track section

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

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

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_3Ca	< 0.063	7.0
Bitumen 50/70	-	5.7
CR from EOL	<0.63	0.5

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)

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

4. Analysis of measurements and discussion

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

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

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

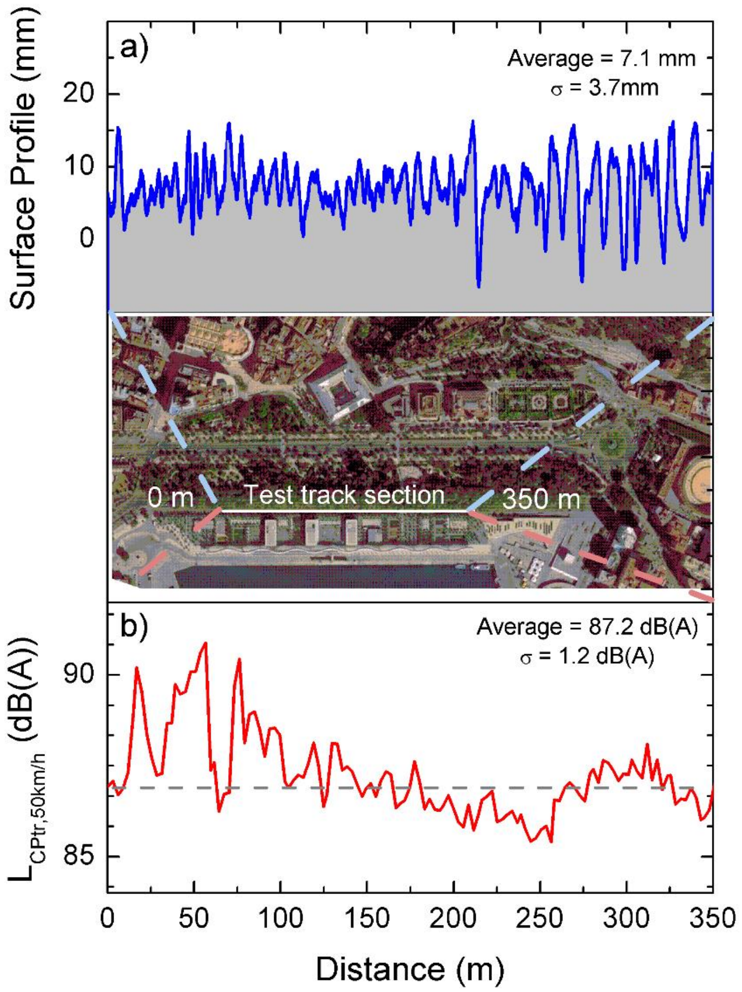

Fig. 3. (a) Surface profile of the SMA8 pavement and (b) continuous tire/pavement sound levels corrected by the speed and the temperature.

As it is shown in Fig.3, there is no clear relationship between the pavement profile and the tire/pavement sound levels. However, the homogeneity of the pavement profile along the studied section should be highlighted. Despite of this, the tire/pavement sound levels depend significantly on the specific section in which they are measured. More specifically, the $L_{CPtr, 50\ km/h}$ levels between 20 m and 100 m distance are the highest, as it is shown in Fig.3b, with values above 90 dB(A). On the other hand, there are other sections where sound levels are considerably lower: between 85 dB(A) and 86 dB(A). The arithmetic average of the measured sound levels in the middle of the 350 m road segment was 87.2 dB(A). This CPX value is lower than the 90.6 dB(A) reported by Miljkovic and Radenberg [23] in a SMA8 mixture without CR. However, differences might be due to the aging of the mixtures when tested, since they studied the SMA8 mixture within the first three years of service. The acoustic aging of rubberized and non-rubberized SMA bituminous mixtures has been reported by other research papers [26, 40]. On the other hand, the values measured agree with those reported by Sangiorgi et al. [28] at 50 km/h driving speed for a SMA8 mixture without CR (86.3 dB(A) and 88.4 dB(A) after nine and fifteen months in service conditions, respectively).

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

After the speed and temperature corrections the SMA8 section has an excellent noise reduction level according to the LA^2IC accreditation methodology [29]; According to this methodology, the achieved reduction is about 3 dB(A) (compared with a conventional bituminous mixture type Asphalt Concrete AC16, after eight years in service conditions). However, the reasons for the difference in terms of noise levels in the same pavement (Fig.3) throughout the section should be sought in the texture characteristics of the studied pavement.

In this work, the pavement texture was studied by means of the macrotexture depth (MPD) and the unevenness (IRI). Figure 4 compares the tire/pavement sound levels and the MPD/IRI values. Arithmetic average values are shown in this figure every 20 m intervals (sub-sections), in order to facilitate the analysis. The results show that in this studied section there is not a clear relationship between the tire/pavement sound levels and the unevenness. Higher IRI values do not lead to high sound levels. This observation agrees with the work of Liao et al. [44], although, a stronger relationship between the IRI and $L_{CPtr,\ 50km/h}$ levels was observed by Vazquez and Paje [45] in other BBTM type gap-graded pavements. On the other hand, the MPD might influence the tire/pavement sound levels: the highest $L_{CPtr,\ 50km/h}$ values are related to larger MPD values in the first 100 m of the test section. However, there are other sections between 200 m and 250 m where relatively high MPD values coincide with the lowest tire/pavement sound levels recorded.

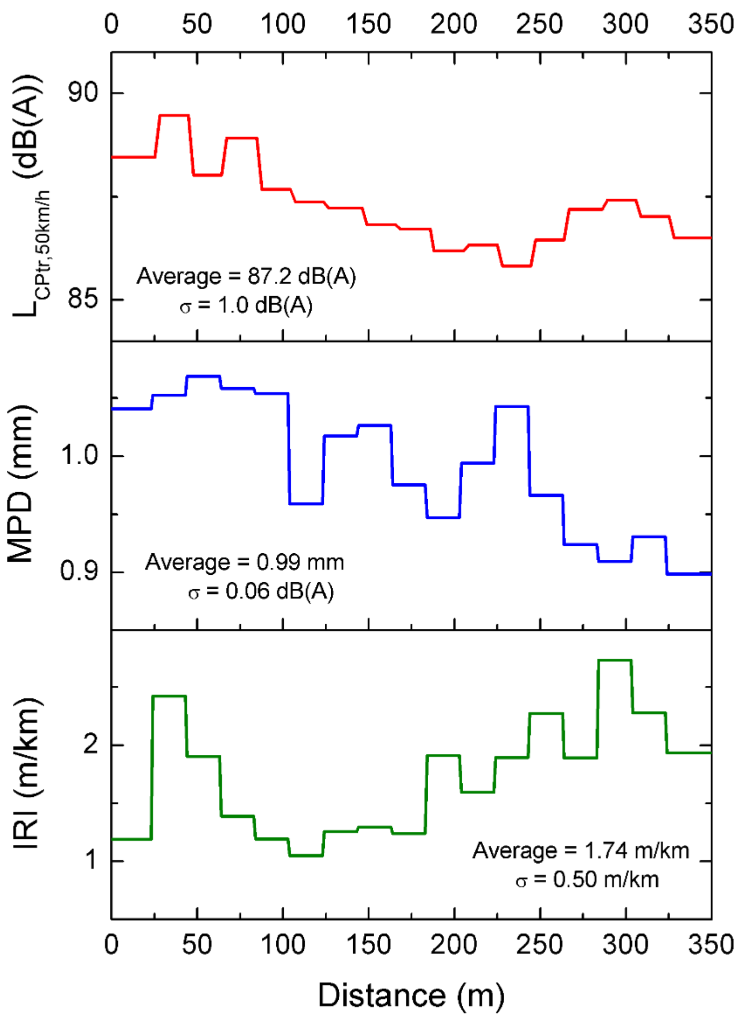

Fig. 4. Averaged $L_{CPtr,\ 50km/h}$ levels, MPD and IRI values each sub-section of 20 m length.

In order to further study the relationships between MPD, IRI and the $L_{CPtr,50\ km/h}$ noise levels, the adjustment between the one-third-octave band frequency of the tire/pavement noise and the MPD/IRI values of each sub-section was analyzed. The R-square coefficient at every frequency band of the tire/pavement sound spectrum is shown in Fig.5. The R-square is defined as a positive number; however, this figure also shows the positive/negative slope of the adjustment. When the magnitudes are directly proportional, they are depicted in the upper half of the chart, whereas if there is an inversely proportional relationship they are depicted in the lower half.

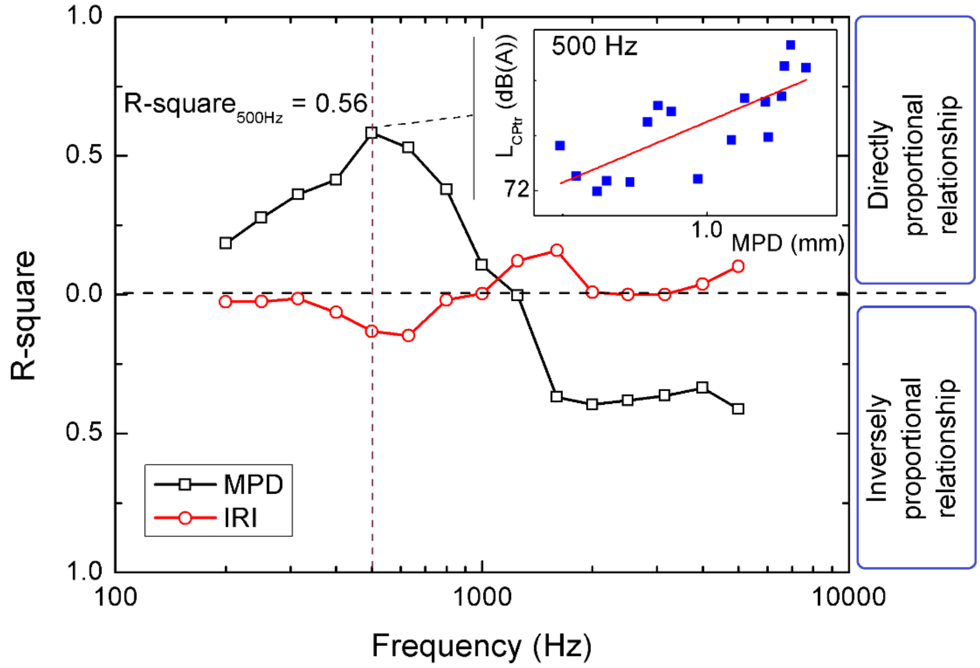

Fig. 5. R-square values between IRI/MPD and $L_{CPtr,\ 50km/h}$. A detail of a linear fitting between MPD and $L_{CPtr,\ 50km/h}$ at the frequency of 500 Hz is included.

According to Fig.5 there is no clear relationship between the IRI and the tire/pavement sound levels measured in the mixture SMA8 because the corresponding R-square values are lower than 0.2 at any frequency. This result contrasts with the relationship found elsewhere in other gap-graded bituminous mixtures [45]. Nevertheless, the unevenness may not be related to the mixture type, but to the construction process and/or the pavement deterioration, since the unevenness is composed by higher pavement wavelengths. Figure 5 also shows the significant influence of the macrotexture depth (MPD) on the tire/pavement noise at different frequencies. larger MPD values of the studied mixture SMA8 are related to lower tire/pavement noise at frequencies higher than 1 kHz. This could be explained because the MPD reduces noise at these high-order frequencies due to a lower dispersion of the sound [17]. On the other hand, larger MPD values are related to higher tire/pavement sound levels at frequencies up to 800 Hz. These results agree with the existing literature [46, 47]. The maximum R-square value between MPD and $L_{CPtr,\ 50km/h}$ is 0.56 and it is found at 500 Hz (see detail in Fig.5). However, a stronger relationship between MPD and low frequencies of $L_{CPtr,\ 50km/h}$ was expected in this test track section, because the tire/pavement noise at low frequencies is generally related to impact and vibration generation mechanisms, and consequently, to the macrotexture. The results included in Fig.5 suggest that the tire/pavement sound levels at low frequencies might be affected by other mechanisms in this mixture, because the MPD cannot totally explain these values by itself. This behavior at low frequencies is also not due to the character of the surface texture, that is expressed by the parameter *c* [41]. This parameter *c* was calculated as the ratio between the average MPD and the Root Mean Square (RMS) of MPD data measured throughout the test track section. Values of *c* up to 0.95 are characteristics of negative textures, whereas *c* values from 1.05 define the positive textures. According to previous works, positive texture would increase the mechanical generation of tire/pavement noise, whilst negative texture would reduce its generation/propagation [48]. In the SMA8 the parameter *c* was stablished around 1.00, so the pavement texture is considered as neutral.

There are some sections of the studied pavement with high MPD values according to Fig.4, particularly in the first 100 m of the tested road segment. The differences in MPD values may influence the tire/pavement sound spectrum. The influence of large MPD values on the pavement acoustics is reflected in Fig.6, where the frequency spectrum map ($L_{CPtr,\ 50km/h}$) of the test section is shown. At sections with larger MPD values (in the first 100 m) the frequency spectrum mapping, (obtained for a driving speed of 50 km/h) shows higher noise values between 600 Hz and 1600 Hz, and lower noise values between 1600 Hz and 2500 Hz. The lower noise values could be explained by the dispersion of the sound, as it was said before, but the higher sound emissions between 600 Hz and 1600 Hz are not only related to the macrotexture depth (MPD). Possibly, the reason of these higher noise values is within the pavement texture; other parameters, such as the dominant texture wavelengths, could explain these values in the pavement type SMA8. On the other hand, the sections around 150 m and 225 m from the starting point of the test, also present large MPD values (see Fig.4), but the sound spectrum in Fig.6 indicates that the MPD of these sections does not dominate the acoustic behavior of the pavement.

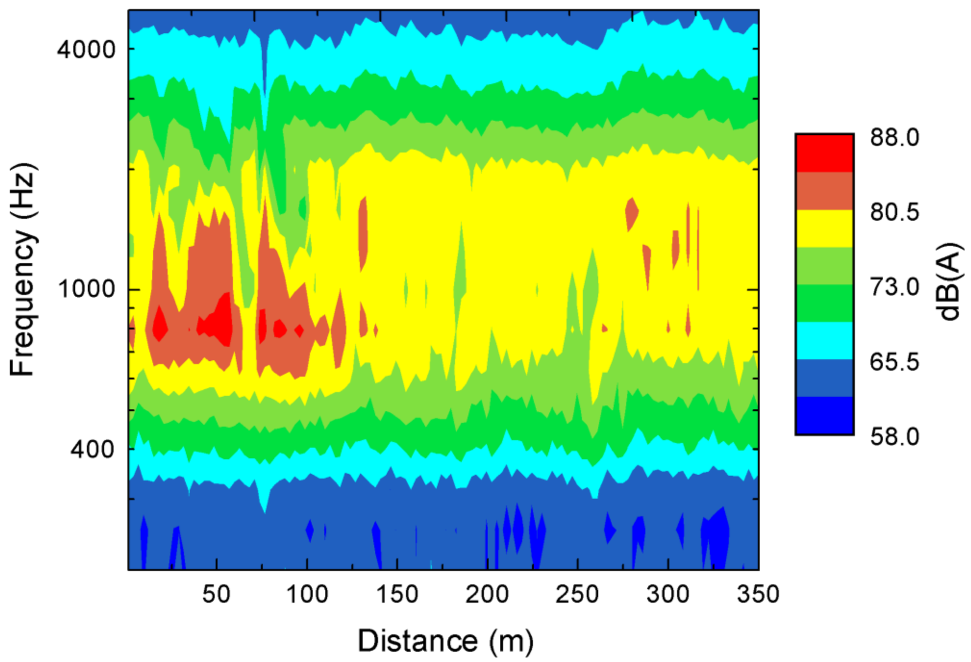

Fig. 6. Sound frequency spectrum map ($L_{CPtr, 50km/h}$) of the test section.

4.2. Dynamic stiffness and acoustic absorption

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

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

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

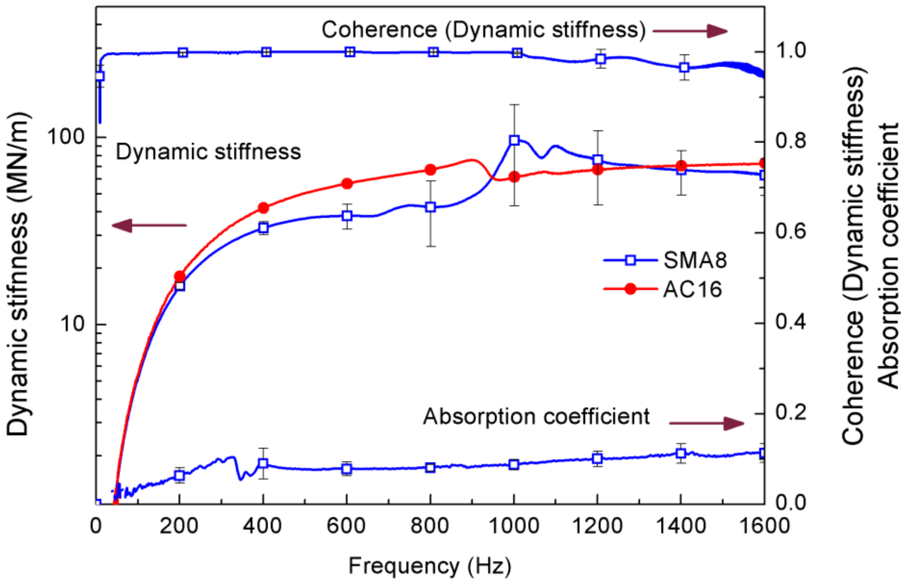

Fig. 7. Dynamic stiffness, and its coherence function, measured in the SMA8 bituminous mixture. The acoustic absorption coefficient is also shown.

4.3. Macrotexture and unevenness according to the national standards

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

$$ETD = 0.2 + 0.8 \cdot MPD$$

with ETD and MPD in mm.

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

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

Table 3. IRI values and percentage of sub-sections that have to meet them in rehabilitated 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
	Test track (SMA8)	*41*	*76*	*94*	*100*

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

4.4. Vertical acceleration assessment

Vehicle accelerations induced by irregularities on road pavements may lead to discomfort of the vehicle users, cause mechanical problems in the vehicles or even accidents [35]. It is well known that vertical accelerations of vehicles increase with the amplitude of the pavement irregularities [49]. The acceleration recorded in the vehicle depends not only on the pavement but also on the mechanical characteristics of the vehicle itself (e.g. flexibility of the tires, suspension system, mass distribution, driving velocity, etc.). However, if the vehicle characteristics and speed are kept constant, the study of the vertical acceleration gives a valuable information about the pavement performance. In this paper, the vehicle acceleration assessment allows to characterize the SMA8 wearing course as well as to compare its behavior with that of more aged pavements. The registration of vertical accelerations of the pavement/vehicle system (at a driving speed of 50 km/h) was carried out during the longitudinal pavement profiling by means of the LaserDynamicPG-LA^{2}IC. The vertical accelerations induced by the studied SMA8 bituminous mixture profile are shown in Fig.8. This figure shows that there are predominant vertical acceleration frequencies. The vehicle vertical acceleration signal could be described by a combination of sinusoidal waves, whose resulting maximum acceleration amplitude value is around 0.14 m/s^2.

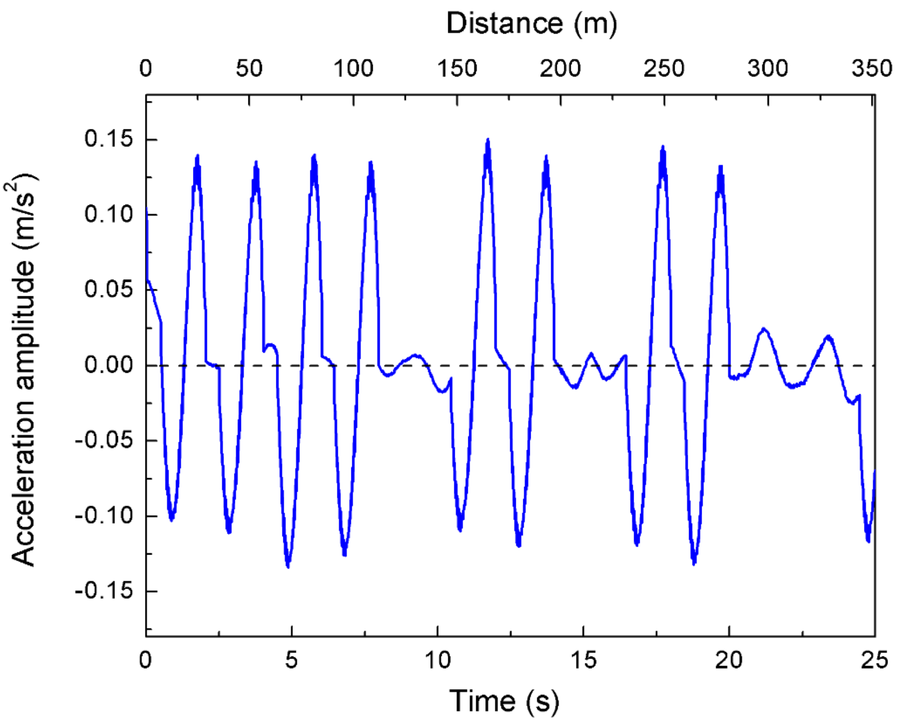

Fig. 8. Vertical vehicle accelerations in the test track section with bituminous mixture SMA8.

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

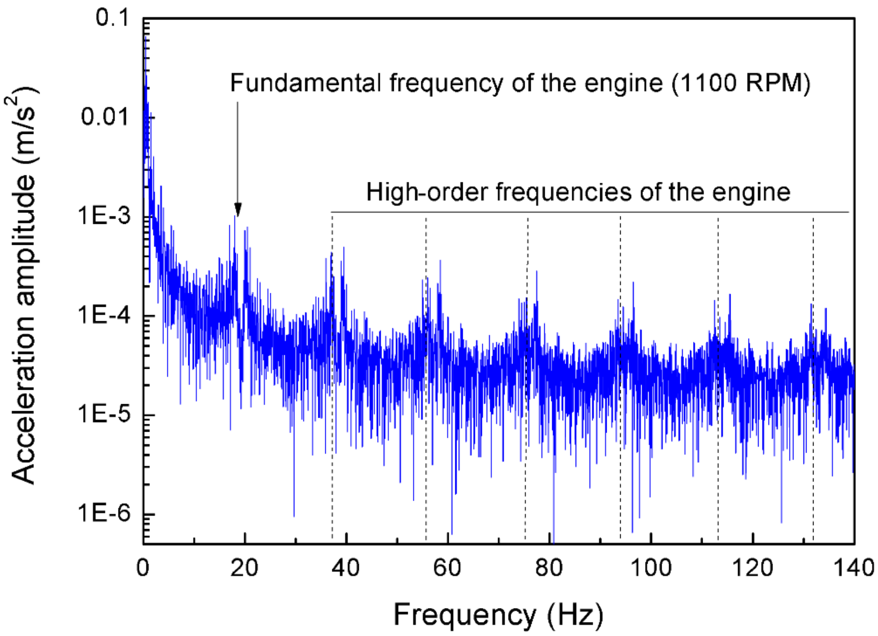

Fig. 9. FFT of the vertical acceleration signal up to 140 Hz, highlighting the engine frequency and its high-order frequencies.

Figure 10 shows a detail of the spectrum of the vertical acceleration amplitude and its phase angle up to 2.5Hz, where the maximum acceleration amplitudes are included. According to the spectral analysis, the fundamental frequency of the acceleration signal is 0.5 Hz. The harmonics are also depicted in Fig.10 (1 Hz, 1.5 Hz, 2 Hz). There are other frequencies around the dominant one that stand out in this figure, i.e. 0.35 Hz or 0.67 Hz, however these frequencies of the spectral analysis may be linked to the windowing of the sinusoid signal, and the corresponding spectral leakage. A longer acceleration signal should reduce the leakage; however, the signal cannot be longer since it is related to the length of the measured test track section (350 m) and the employed reference speed (50 km/h).

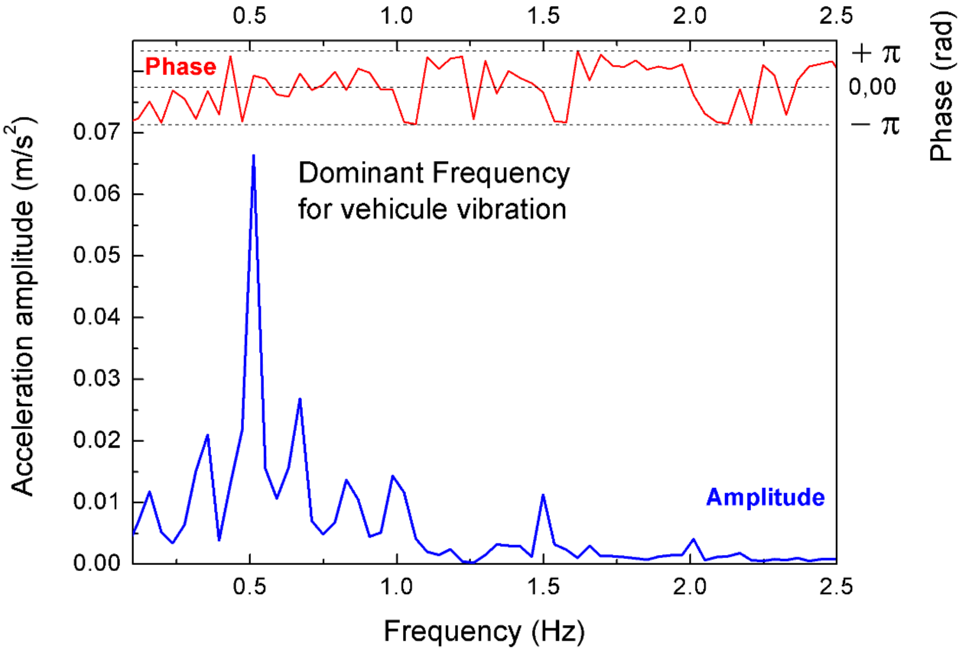

Fig. 10. Detail of the vertical acceleration FFT up to 2.5 Hz.

In this study, the vertical acceleration spectrum of the mixture SMA8 are compared with those of two conventional AC dense bituminous mixtures with a maximum aggregate size of 8 mm. These mixtures are also located in urban lanes and the only difference between them is their age: 3 and 6 years in service conditions (referred to as AC8-3y and AC8-6y respectively). These three mixtures have the same maximum aggregate size which suggests that it does not affect the differences on the recorded vehicle accelerations. The same vehicle and testing equipment are used in the three measurements to facilitate the comparison. The acceleration spectra of the studied mixtures are shown in Fig.11. The macrotexture depth, given by the Mean Profile Depth (MPD), and the unevenness obtained from the international roughness index (IRI) of the studied sections are also indicated in Fig.11. In addition to the age of the pavements, the pavement aging has been assessed by means of the visual inspection and the unevenness (IRI). The IRI is considered by researchers and road agencies as a pavement performance indicator [50, 51], and therefore, may be looked as a surrogate indicator for aging. According to the Spanish PG3, the maximum IRI value of a rehabilitated road section must be lower than 3.0 m/km.

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

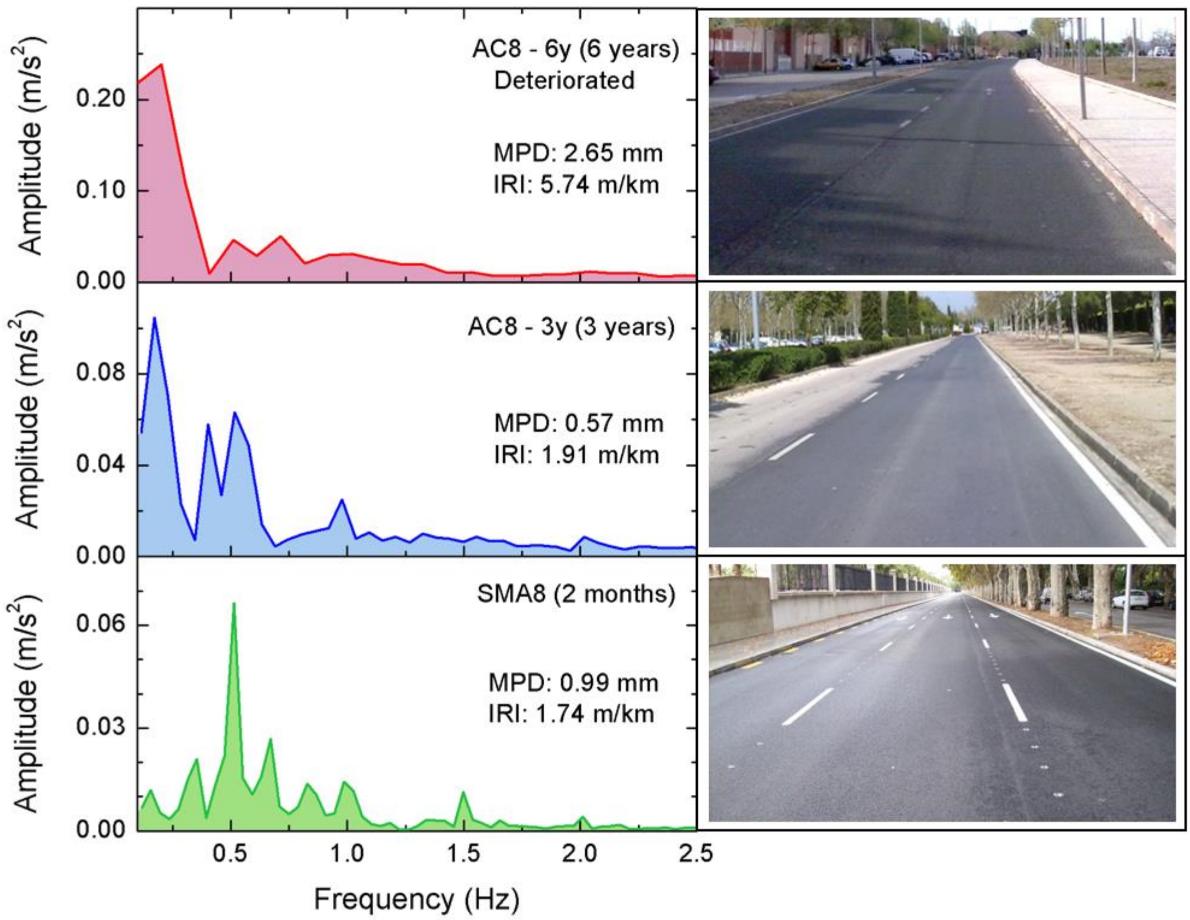

Fig. 11. FFT of the vertical acceleration when crossing pavements AC8-6y, AC8-3y and SMA8. A detail of each studied pavement, from visual auscultation, is also included.

The aging process seems to be responsible of the vertical acceleration spectrum shape. Aging and deteriorated bituminous mixtures may produce higher maximum acceleration amplitudes, at lower frequencies. As shown in Fig.11, the section AC8-6y (deteriorated) has the higher unevenness. The unevenness is related to higher wavelengths and it seems to explain the higher vertical acceleration frequencies at lower frequencies, measured in the aged pavements. This is related to the equation: $f = n \cdot v$; where f is the time frequency (Hz); n the spatial frequency and the reciprocal of the wavelength (m^{-1}), and v is the vehicle speed (m/s^2).

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

5. Conclusions

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

- Some sub-sections of the studied pavement stand out for their low tire/pavement sound levels measured according to the Close ProXimity method. These sections are about 3 dB(A) lower than a conventional AC pavement with eight years in service conditions. According to these results, the SMA8 mixture could be used as noise mitigation measure within the Action Plans of cities with problems related to noise, especially when other noise attenuation measures are not possible or insufficient.

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

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

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

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