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Functional Performance of Stone Mastic Asphalt Pavements in Spain: Acoustic Assessment

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Abstract: Environmental noise is one of the problems modern societies face today. Traffic noise, especially the noise produced from tire/pavement interaction, plays a main role in environmental noise. Pavement rehabilitation with new bituminous mixtures is a good option for combatting noise pollution in urban areas. This paper studies the functional performance of two bituminous mixtures of stone mastic asphalt (SMA), fabricated with the same polymer modified binder, but with different maximum aggregate size (MAS) (SMA11 and SMA16). The acoustic absorption, the dynamic stiffness, the surface texture and the tire/pavement noise were assessed. The bituminous mixture type SMA16 has higher texture levels at nearly every depicted wavelength of the texture spectra. This characteristic may lead to its higher average tire/pavement sound level compared to the mixture SMA11. The influence of each texture wavelength on the different frequency bands of the tire/pavement noise spectrum was studied, however, this relation is not a simple matter. This paper also presents low-noise pavement labeling methodology (LNP labeling$^{LA^2IC}$). The mixtures SMA11 and SMA16 are labeled at 50 and 80 km/h. An acoustic label is a valuable tool for construction companies and urban planners to use in order to define the best option against noise when pavement rehabilitation must be carried out.

Keywords: tire/pavement noise; close proximity; texture spectrum; functional performance; surface characteristics; stone mastic asphalt; noise label

1. Introduction

Environmental noise is one of the main problems in modern societies. In urban areas, noise pollution is mostly due to traffic, whose main noise source is the tire/pavement noise that occurs when speed is higher than 40 km/h [1]. The European Noise Directive (END) 2002/49/EC [2] of the European Parliament and Council, relating to the assessment and management of environmental noise (and the Spanish Noise Law 37/2003 [3]), indicates that local authorities have to expand the noise maps and the action plans in order to mitigate this type of pollution. Some of the actions taken against noise are traffic management, the construction of noise barriers, or the vehicle speed reduction [4,5]. However, the only solution that reduces noise without affecting service level and without visual impact is pavement rehabilitation by means of new pavement with improved acoustic characteristics. The use of these surfaces is one of the most often applied actions against traffic noise all over the world [6].

Based on research reports and engineering studies, it has been shown that the use of stone mastic asphalt (SMA) bituminous mixtures (UNE-EN 13108-5 [7]) can improve the rutting resistance and durability of pavements (structural performance) [8]. On the other hand, the use of gap-graded bituminous mixtures, such as SMA mixes, could reduce the noise generated by the tire/pavement interaction (functional performance) [9]. SMAs are hot bituminous mixes consisting of a coarse aggregate skeleton, and a high binder and filler content (5%–7% and 8%–12% by weight of mixture, respectively). These mixtures are designed to have a low air void content (3%–8%). The high binder content provides durability through an increased film thickness around the aggregate particles. In addition, these mixtures typically contain a cellulose or mineral fiber to prevent drainage of the binder.

Despite their good performance, SMA mixtures are not commonly used in Spain, where the pavement industry has preferred the use of other gap-graded bituminous mixtures, such as bétons bitumineux très minces (BBTM mixes); asphalt concrete for very thin layers [10]. Nevertheless, the interest for this type of mixtures has recently grown in Spain. Research Projects such as the SMA Project (2010–2013) [11] have been developed in recent years. The main goal of the SMA Project was to increase knowledge about SMA mixtures' behavior and to adapt them to the existing exigencies in Spain. Meanwhile, SMA mixtures are commonly used in other countries. Many international studies on SMA mixes and tire/pavement interaction (such as noise emission by the Close ProXimity method, or CPX) have been performed. Bennert and Maher [12] studied the tire/pavement noise emissions of two SMA pavements with different maximum aggregate sizes (MAS) in New Jersey, USA. This study established that the nominal aggregate size of hot mix asphalt influences the generated noise. Ahammed et al. [13] studied the relationship between texture and tire/pavement noise of SMA mixtures in Ontario, Canada. According to this work, certain textures limit the generation and/or propagation of tire/pavement noise. Miljković and Radenberg [14] studied the acoustic performance of an experimental "noise-reducing asphalt" (with a thin noise-reducing surface layer), developed from an SMA aggregate skeleton, in Germany. According to the conclusions of this paper, the research on noise-reducing surfaces and the experience from European countries should lead to the adoption of European specifications for noise-reducing asphalt pavements. In Belgium, Vuye et al. [15] studied tire/pavement noise evolution (up to 34 months after pavement construction) of an SMA mixture, regarding other experimental pavements such as the double-layer porous asphalt concrete. The evolution of the SMA mixture was better than those of the other experimental mixtures (with lower initial CPX levels). Sweczko-Zurek et al. [16] assessed the rolling resistance and the tire/road noise of the bituminous mixture type SMA11. Acoustic measurements were carried out by means of the TireSonic Mk.4, which was designed and developed by Technical University of Gdansk (TUG). According to this paper, the measured CPX levels of SMA11 pavements were between 89 and 91 dB(A) at 50 km/h, and between 96 and 99 dB(A) at 80 km/h. Gardziejczyk et al. [17,18] studied the noisiness and acoustic durability of low noise pavements in Poland. A SMA11 bituminous mixture was assessed in this study by means of the statistical pass by method (SPB). The SPB levels obtained were also related to a CPX noise classification, establishing that the SMA11 pavement was within the "normal noise class" (96.5–99.4 dB(A)). Vaitkus et al. [19] studied SMA bituminous mixtures from an acoustic absorption point of view. According to this research, their sound absorption coefficient was lower than 0.2. Finally, Sangiorgi et al. [20] have recently studied SMA11 bituminous mixtures (with and without crumb rubber (CR) added by a "dry-hybrid technology") by means of the CPX method. The SMA11 mix without CR showed a CPX value of around 88.4 dB(A) at 50 km/h after 15 months in service. As deduced from the number of recent publications, there is great interest in knowing the acoustic behavior of this type of mixtures (SMAs), in order to establish specifications for noise-reducing asphalt pavements in the near future. This work assesses some surface characteristics of two experimental bituminous SMA type mixtures built in Spain (after two months in service conditions). These two mixtures were built with the same polymer modified binder, but a different maximum aggregate size (MAS) (11 and 16 mm respectively).

The surface characteristics studied in this work are: the acoustic absorption, the dynamic stiffness, the surface texture, and the tire/pavement noise. The tire/pavement noise is assessed by means of the CPX method (near field conditions). According to the literature review, the acoustic behavior of SMA mixtures has indeed been studied in different countries. However, there are research gaps that still needs to be addressed. This work aims to study some of them. First, the acoustic behavior of SMA bituminous mixtures has not been studied according to the CPX methodology in Spain yet. The obtained results are compared and discussed with respect to those achieved in other countries. The assessed mixtures have different MAS. The MAS influence on dynamic stiffness, acoustic absorption, and tire/pavement noise is studied in this work. Finally, this paper presents a new labeling methodology to classify pavements in Spain according to their tire/pavement noise emissions. The assessed pavements are classified by the Laboratory of Acoustics Applied to Civil Engineering (LA^2IC), according to the low-noise pavement labeling (LNP labeling$^{LA^2IC}$) methodology. Pavement labeling provides information about the acoustic performance of a given surface. This information might be employed by local authorities in order to expand their implementation of action plans for the European Noise Directive (END). Bituminous mixtures with a good noise reduction capacity (previously labeled according to LNP labeling$^{LA^2IC}$) might be employed in urban areas with problems related to traffic noise (environmental noise) [21,22].

2. Project Design

Two pavement test sections, consisting of two types of SMA bituminous mixtures, were built and studied in this research work. The mixtures were built with different MAS. The construction characteristics of these mixtures are shown in Table 1. The volumetric and mechanical properties of the mixes were characterized according to different laboratory tests (Spanish Standard Association, AENOR). The parameters included in Table 1 [23] are: maximum density (UNE-EN 12697-5 [24]), apparent density (UNE-EN 12697-6 [25]), mixture binder content (UNE-EN 12697-39 [26]), air void content (UNE-EN 12697-8 [27]), and stiffness modulus (UNE-EN 12697-26 [28]).

Table 1. Construction characteristics of studied mixtures stone mastic asphalt (SMA).

Mix	Layer Thickness (cm)	Maximum Density (kg/m^3)	Apparent Density (kg/m^3)	Binder (Mix) (%)	Air Void Content (%)	Stiffness Modulus (MPa)
SMA11	4.0	2510	2345	5.58	6.55	2515
SMA16	4.5	2511	2391	5.66	4.75	3400

Both experimental sections were fabricated with polymer modified asphalt 45/80-65 and cellulose fibers (0.3% by weight of the aggregate). The experimental test sections were located between the city of Alzira and the highway CV-50 (Figure 1). The SMA11 section has a length of 500 m, whereas the SMA16 section has a length of 250 m. A bridge separated both experimental sections, as shown in Figure 1.

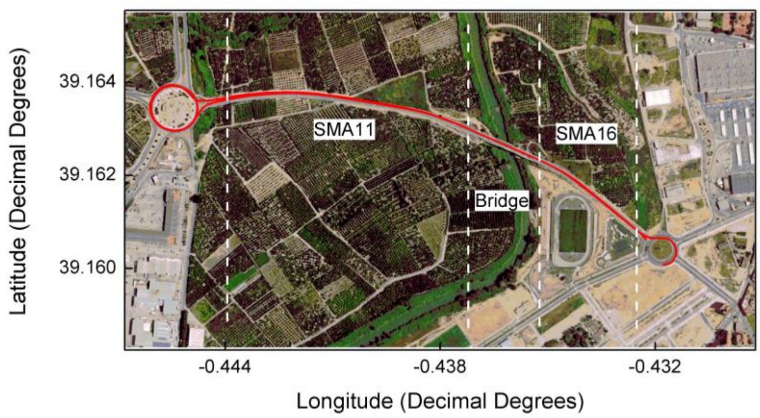


Figure 1. Experimental test tracks near Alzira (Valencia), showing the GPS coordinates of the studied test sections of stone mastic asphalt mixtures SMA11 and SMA16.

3. Measurement Methods and Equipment

3.1. Close Proximity

Geo-referenced monitoring (CPX) of the experimental sections was carried out in order to assess the acoustical performance of the studied SMA pavements. Trailer TireSonic Mk4-LA^{2}IC (TUG, Gdansk, Poland) (Figure 2) was employed for CPX measurements. The equipment is composed of a semi-anechoic chamber, within which two microphones are mounted very close to the wheel, at a distance of 20 cm above the pavement and 10 cm from the wheel (orientation angles of 45° and 135° with respect to the plane of the wheel), in order to measure exclusively the sound produced by the tire/pavement interaction. A reference tire Pirelli P6000 was employed for acoustic characterization. The inflation pressure of the tire was 240 kPa. During measurements, the vehicle speed was kept close to the reference speeds (50 or 80 km/h). The tire/pavement sound levels were corrected for speed variations around the selected reference speed [29]. For this purpose, the relationship between sound levels (L_{CPtr}), and the instant speed (v) was studied. The logarithmic regression between these magnitudes was established in each bituminous mixture (Equation (1)):

$$L_{\mathrm{CPtr}} = A + B\cdot\log(v) \tag{1}$$

From the logarithmic regression (Equation (1)), the coefficient B of each bituminous mixture was determined. Subsequently the measured sound levels (L_{measured}) were corrected ($L_{\mathrm{Corrected}}$) according to Equation (2), where $v(t)$ is the instant speed, measured by a digital tachometer, v_{ref} is the reference speed, and the constant B was determined from Equation (1).

$$L_{\mathrm{Corrected}}(t) = L_{\mathrm{measured}}(t) + B\cdot\log(v(t)/v_{\mathrm{ref}}), \tag{2}$$

Measurements were corrected by temperature, from the pavement temperature of 25 °C. The relation between pavement temperature and sound levels was considered to be −0.05 dB(A)/°C, taking into account previous works and literature [5,15,30]. Although the temperature variations between measurements were insignificant, levels were corrected for comparative purposes (LNP labeling$^{\mathrm{LA^2IC}}$).

Figure 2. Reference tire inside the semi-anechoic chamber, and rear microphone.

3.2. Surface Profile

In situ texture measurements were carried out on the experimental sections by means of the so-called LaserStaticPG-LA^{2}IC (Greenwood Engineering, Brøndby, Denmark). This equipment is composed of a 63 cm-long laser frame with a scanner. The scanner is moved along the laser frame rail, and a magnetic band in the rail assures the number of registered data on a given distance (data points every 0.1 mm). Due to the characteristics of the measurement device, data were not speed dependent, although the laser displacement was done manually.

From the measured profile, the mean profile depth (MPD) was calculated for each studied pavement. The MPD was calculated according to the international standard UNE-EN ISO 13473-1 [31], and characterized the macrotexture amplitude of the wearing course of a pavement.

From measured data, the texture spectra were also calculated. These spectra show the texture level in decibels, as a function of the wavelength (or spatial frequency). The profile texture level $L_{t,m}$ of the fractional octave band m is described by the following equation:

$$L_{t,m} = 10 \cdot \log(Z_{\mathrm{pm}}/Z^2{}_{\mathrm{ref}}), \tag{3}$$

where Z_{pm} is the power spectral density within the fractional band m, obtained from the result of the Fourier transform of the filtered profile amplitude, and Z_{ref} is the reference value of the surface amplitude (10^{-6} m).

The characterization of the texture spectrum of a given pavement contains valuable information regarding tire/road noise generation, since each texture wavelength influences this type of noise differently. As shown in Figure 3, texture wavelengths between 1 and 10 mm may lead to noise reduction, due to a higher dispersion of the sound (lower "horn effect" and lower stick-slip and stick-snap noise generation mechanisms) [9,32]. On the other hand, texture wavelengths around 100 mm lead to higher tire/pavement noise levels, due to impact and vibration generation mechanisms, since these wavelengths are of the same order of magnitude of the tire tread.

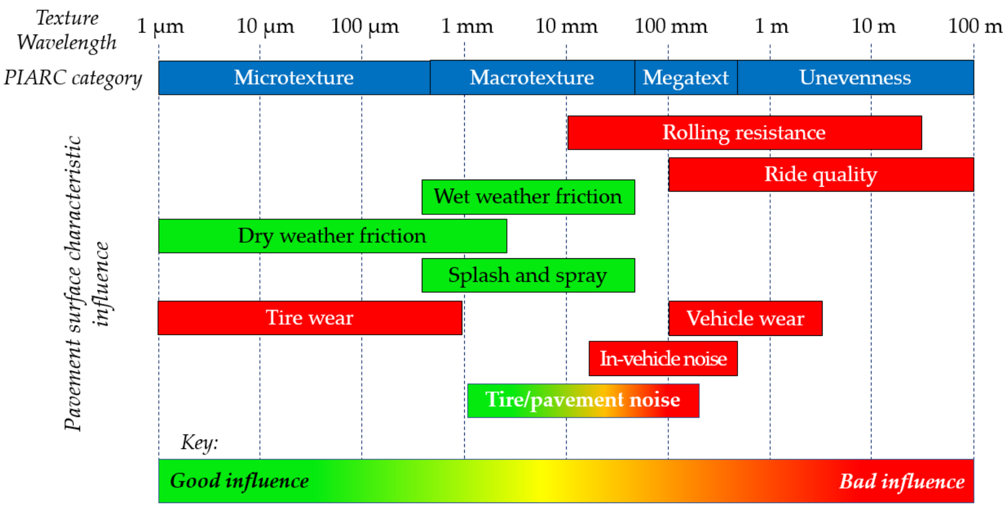


Figure 3. Texture wavelength range for each of the categories and their influence (safety, comfort, noise, wear, etc.) [32,33].

3.3. Sound Absorption

Acoustic absorption relates the energy of the incident acoustic wave and the energy absorbed by the pavement surface (without return). According to the literature, acoustic absorption may play an important role in tire/pavement noise attenuation when pavements with high air void content (higher than 15%–20%) are employed [34]. Absorption measurements have been conducted using an impedance tube of 100 mm inner diameter, with a loudspeaker mounted at one end that produces plane, stationary, and random sound waves. The impedance tube allowed us to study the acoustic absorption between 50 Hz and 1.6 kHz. Bituminous mixture was taken from the road during paving operations and compacted in sample cores using a Marshall compactor (UNE-EN 12697-30 [35]). Subsequently, the samples were covered laterally with Teflon in order to avoid the air gap between the specimens and the tube. More details of the measurement technique are given elsewhere [36].

3.4. Dynamic Stiffness

Dynamic stiffness is a pavement property related to surface vibration and therefore, to traffic noise (tire/pavement interaction). It is defined as the complex relationship between the vertical force applied to a given surface and its vertical displacement. Dynamic stiffness measurements were carried out in the laboratory. Three Marshall samples for each mixture (from bituminous mixture taken during road construction) were assessed by means of a non-destructive procedure [37]. The measurement technique is composed of a shaker (Brüel and Kjaer 4809, Nærum, Denmark) and an impedance head (Brüel and Kjaer 8001) that measures force and motion of the surface to be tested. Sweep signals between 10 Hz and 7 kHz were used for sample excitation. From force and motion signals, the frequency response functions (coherence and dynamic stiffness) were determined with a 1 Hz resolution. In order to avoid undesired vibrations, the samples were conditioned before testing, their bases were regularized by a thin plaster layer.

3.5. Low-Noise Pavement Labeling Methodology in Spain

Low-noise pavement labeling (LNP labeling$^{\text{LA}^2\text{IC}}$) is an acoustic assessment methodology developed by the Laboratory of Acoustics Applied to Civil Engineering in order to classify the bituminous mixtures employed in road paving and give them an added value related to their low-noise generation capacity. The LNP labeling$^{\text{LA}^2\text{IC}}$ methodology is based on the LA^{2}IC experience in acoustic assessment, mainly by means of the close proximity (CPX) method. Subsequently, the assessed test track sections are classified into three categories of *mezcla bituminosa sono-reductora* (MBSR), or low-noise bituminous mixture, by comparing their noise reduction capacity with that of an asphalt concrete pavement (bituminous mixture type AC 16 surf S) after eight years in service conditions. The LNP labeling$^{\text{LA}^2\text{IC}}$ methodology establishes three MBSR classes [38]:

- MBSR Class A: Excellent tire/pavement noise reduction.
- MBSR Class B: Good tire/pavement noise reduction.
- MBSR Class C: Acceptable tire/pavement noise reduction.

The acoustic assessment of the bituminous mixtures to be labeled was carried out according to the CPX methodology. The test track sections must have at least 100 m length, and the measurements are accomplished at 50, 80, and/or 110 km/h, depending on the section characteristics and the scope of the study. Four consecutive measurements, with three reference tires (tourism tires), should be done in order to achieve the homogeneity and the mean value of the measured sound levels. The sections to be assessed should be located within urban or peri-urban areas, where tire/pavement noise is mainly generated by cars, not by heavy goods vehicles. The experimental sections must be assessed after a minimum service of two months, and measurements must be corrected by temperature (reference temperature 20 °C) and speed (50, 80, and/or 110 km/h), in order to homogenize the tire/pavement noise levels of different measurements. Figure 4 shows the reference values for the pavement labeling according to the LNP labeling$^{\text{LA}^2\text{IC}}$ methodology.

MBSR class	A	B	C
Noise reduction dB(A) (Reference: AC 16 surf S)	>3	1.5< <3	1.5>
50 km/h	87 dB(A)≤	87 – 88.5 dB(A)	88.5 – 90 dB(A)
80 km/h	95 dB(A)≤	95 – 96.5 dB(A)	96.5 – 98 dB(A)
	Excellent noise reduction	Good noise reduction	Acceptable noise reduction

Figure 4. Noise reduction reference values (LNP labeling$^{\text{LA}^2\text{IC}}$) for Spanish pavements classified as MBSR Class A, Class B, and Class C (50 and 80 km/h).

4. Results and Discussion

Reference sections were studied by different measurement techniques in order to characterize their functional performance. The tests evaluated some of their surface characteristics such as the acoustic absorption, the dynamic stiffness, the surface profile, and the tire/pavement noise.

4.1. Acoustic Absorption and Dynamic Stiffness Measurements

The acoustic absorption of the studied bituminous mixtures was assessed in the laboratory, using sample cores fabricated with the bituminous mixture, and employed during the paving operations. The results obtained are shown in Figure 5a. Three sample cores were tested in each case. Moreover, the base line of the empty impedance tube is also depicted in Figure 5a.

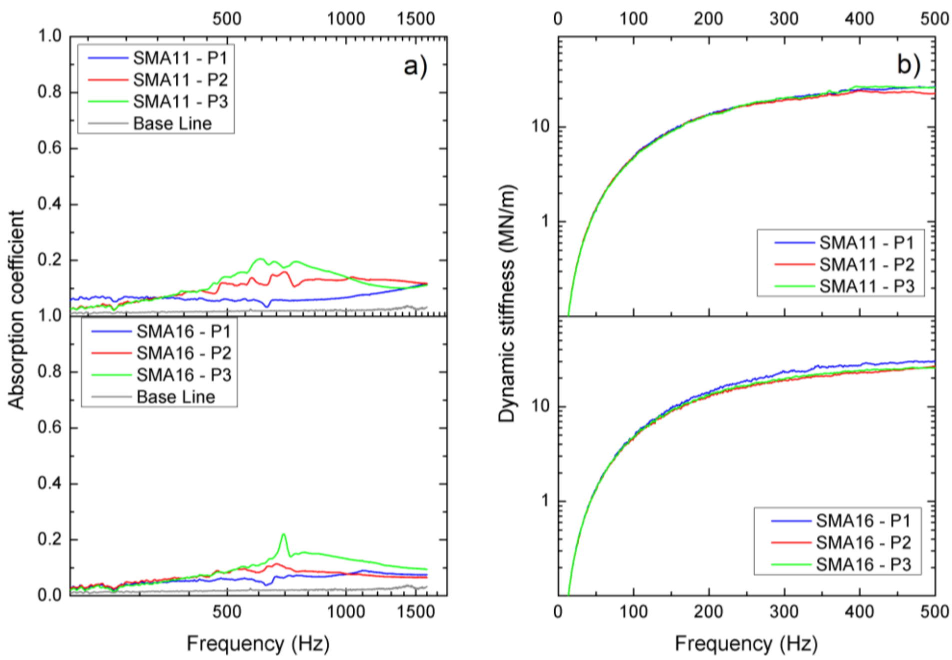


Figure 5. Acoustic absorption spectra (**a**) and dynamic stiffness spectra (**b**) of studied bituminous mixtures. Three sample cores were tested in each case.

As shown in this figure, the acoustic absorption coefficients measured in both experimental sections did not reduce the noise produced in the tire/pavement interaction as depicted values are lower than 0.2 for any frequency band. Similar results were achieved for both mixtures SMA11 and SMA16. Acoustic absorption may lead to noise reductions at high frequencies of the tire/pavement noise spectra. This reduction is related to the air void content (interconnected voids) of the mixes. Thus, high acoustic absorption values are expected in mixtures with high air void contents [9]. The studied bituminous mixes have air void contents lower than 10% (Table 1), therefore, an outstanding acoustic absorption capacity was not expected in these mixtures.

Dynamic stiffness was assessed in the laboratory by means of a non-destructive test [37]. The dynamic stiffness measurements were carried out on the same sample cores used during the acoustic absorption assessment. The results are shown in Figure 5b. According to the achieved results, dynamic stiffness is not affected by the maximum aggregate size of the studied bituminous mixtures. The dynamic stiffness values at 400 Hz are 25.0 MN/m (σ = 1.3 MN/m) and 24.7 MN/m (σ = 2.2 MN/m) for bituminous mixture types SMA11 and SMA16, respectively. The dynamic stiffness of bituminous mixtures does not depend on the MAS of the mixes. However, other construction characteristics such as the binder type or the additives of the mixture might lead to higher dynamic stiffness variations (and therefore different acoustic behavior). The deformation of a bituminous mixture is more related to the binder characteristics, since the binder holds the aggregates together and the stiffness of the binder is much lower than that of the aggregates.

4.2. Surface Profile Measurements

The surface profile measurements were conducted on the experimental sections after two months in service conditions. These measurements were carried out on each experimental section. From the texture profiles, the MPD was calculated according to the UNE-EN ISO 13473-1 [31]. The average MPD values achieved were 1.9 mm (σ = 0.6 mm) and 2.2 mm (σ = 0.7 mm) for bituminous mixture types SMA11 and SMA16, respectively. The MPD of the bituminous mixture SMA16 is a little bit higher than that of the SMA11. This may be due to their higher MAS. However, taking into account the homogeneities (standard deviation σ) of the measurements, the differences between their macrotexture amplitudes (MPD) are not big enough to justify a different acoustic behavior.

Besides the characterization of the macrotexture amplitude of the experimental bituminous mixtures, this paper studies their texture spectra. The spectra were calculated following the UNE-EN ISO 13473-1. The calculated texture spectra are shown in Figure 6. An inset in this figure shows a detail of the surface of the studied bituminous mixtures. The bituminous mixture with a high texture level at higher wavelengths is SMA16. This result may be linked to its higher MAS. On the other hand, the texture levels at low wavelengths are rather similar, although SMA16 is the mixture with higher texture, again. According to these results, the bituminous mixture SMA16 may produce higher noise levels (higher texture level at 100 mm wavelength) at low frequencies (400–500 Hz), due to impacts and vibrations. However, this bituminous mixture also may reduce noise (higher texture level between 1 and 10 mm wavelength) at high frequencies (2500–8000 Hz) due to a higher dispersion of the sound [34]. These considerations will be evaluated later (together with the tire/pavement noise spectra of the studied bituminous mixtures), since the influence of the texture spectrum on the tire/pavement noise also depends on the dominant noise generation mechanisms of a given bituminous mixture.

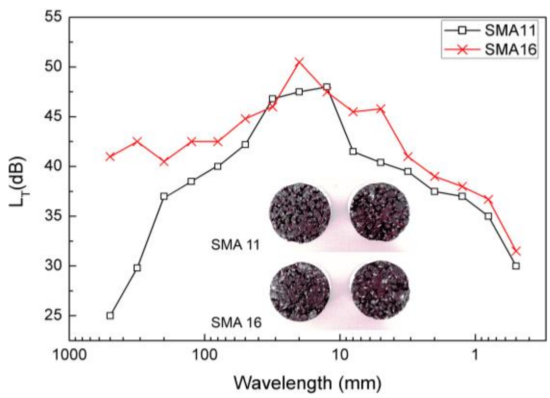


Figure 6. Texture spectra L_T calculated from surface profile measurements and a detail of the studied bituminous mixture types SMA11 and SMA16.

4.3. Close Proximity Measurements

The acoustic assessment of the experimental test sections has been accomplished by means of the close proximity method (TireSonic Mk4-LA^{2}IC). These sections were studied at 50 and 80 km/h, since they were located within a peri-urban road. During auscultation, the pavement temperature kept constant at 25 °C, and the tire pressure (before measurements) was 240 kPa. Four consecutive CPX measurements along the experimental test track sections (SMA11 and SMA16) were carried out for repeatability purpose at each reference speed (see Figure 7).

As shown in Figure 7, the studied sections show a good repeatability. The longitudinal tire/pavement noise levels agree among the different measurements. The data collected at the bituminous mixture laid on the bridge (see Figure 1) were not analyzed in depth, since this is out of the aim of this research work. However, it is an interesting topic, since the tire pavement noise levels measured on the bridge seemed to be lower than those of the adjacent road sections. The characteristics of this infrastructure may somehow affect tire/pavement noise.

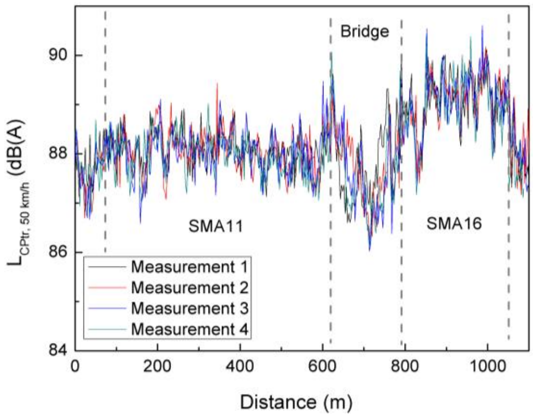
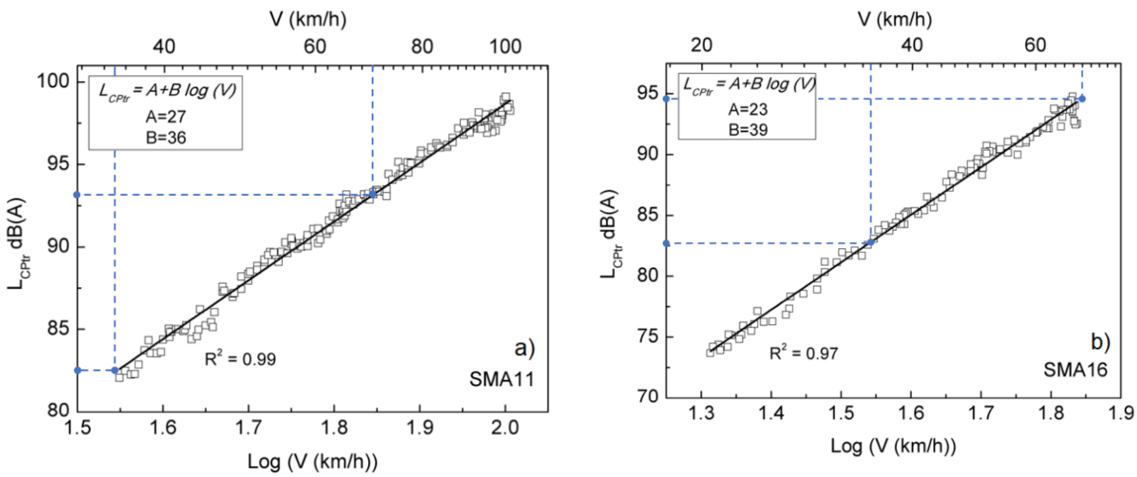


Figure 7. Repeatability of the tire pavement sound levels ($L_{\mathrm{CPtr,\,50km/h}}$) measured in the bituminous mixtures SMA11 and SMA16.

Although vehicle speed was kept around the reference speed during measurements, tire/pavement sound levels should be corrected for small variations. Figure 8 shows the L_{CPtr} sound levels as a function of the vehicle speed. The tire/pavement sound levels increase linearly in proportion to log(v). The value of the coefficients B was obtained from the linear fitting (see Figure 8), where the coefficient B is the so-called "speed constant" [30]. This coefficient characterizes the acoustic behavior of the studied bituminous mixtures and allows us to correct the L_{CPtr} levels for speed variations around the reference speed. The coefficient B of the SMA11 (B = 36 dB(A)) makes it more suitable for high speed roads than the mix with higher MAS (B = 39 dB(A)), whereas both mixtures could be used in paving operations of urban lanes. Figure 8 also shows a measure of the tire/pavement sound levels at 35 km/h (usual speed in urban areas) and at 70 km/h (interurban areas). Due to their different B coefficients, the sound levels pointed out by the linear regression (Figure 8) are similar at 35 km/h but differ by approximately 2 dB(A) at 70 km/h. This speed-dependent behavior should be also appreciated in the acoustic assessment at 50 and 80 km/h that is presented below.



(**a**) (**b**)

Figure 8. Linear regression of tire/pavement sound levels as a function of vehicle speed for the reference tire rolling on the bituminous mixtures SMA11 (**a**) and SMA16 (**b**).

The tire/pavement sound levels L_{CPtr} at reference speeds (not corrected by temperature), are presented in Table 2. Measured values have a high overall homogeneity (low standard deviation from the four whole measurements), since the auscultation methodology (CPX) is a very reliable measurement technique. Average values shown in this table must be corrected by temperature. Temperature is not a key factor when the measurements of different bituminous mixtures are carried out at the same temperature (SMA11 and SMA16 in this work). However, temperature corrections are needed in order to compare the tire/pavement noise levels measured under different conditions. In this work, the results have been corrected by temperature (from 25 to 20 °C) to label the surfaces according to the LNP labeling$^{LA^2IC}$ methodology. After temperature corrections (−0.05 dB(A)/°C), the average tire/pavement sound levels at 50 km/h were 88.3 and 89.2 dB(A), respectively, for bituminous mixtures SMA11 and SMA16, whereas the average values at 80 km/h were 95.3 and 96.6 (SMA11 and SMA 16, respectively). According to these results, the $\Delta L_{CPtr,\,50km/h}$ and $\Delta L_{CPtr,\,80km/h}$ values were 0.9 and 1.3 dB(A), respectively. This agrees with the conclusions extracted from the linear regression between L_{CPtr} and speed (Figure 8). The SMA11 mixture is more suitable for high speed roads than the SMA16.

Table 2. Mean tire/pavement sound levels of each continuous measurement, average, and homogeneity from the four measurements. Values are not corrected by temperature.

Reference Speed	Mix	Tire/Pavement Sound Levels L_{CPtr} (dB(A))					
		M.1	M.2	M.3	M.4	Average	Homogeneity (σ)
50 km/h	SMA11	88.17 ± 0.4	88.06 ± 0.5	88.11 ± 0.5	88.05 ± 0.4	88.10	0.05
	SMA16	88.9 9± 0.7	88.82 ± 0.6	88.93 ± 0.6	88.88 ± 0.6	88.90	0.07
80 km/h	SMA11	95.12 ± 0.5	95.17 ± 0.5	95.12 ± 0.5	94.97 ± 0.5	95.10	0.08
	SMA16	96.42 ± 0.4	96.34 ± 0.5	96.28 ± 0.4	96.20 ± 0.4	96.31	0.08

From the continuous measurements of tire/pavement sound levels, the L_{CPtr} spectrum of the two bituminous mixtures was calculated between 200 Hz and 5 kHz. Figure 9 shows the comparison between both spectra ($\Delta L_{CPtr} = L_{CPtr\text{-}SMA16} - L_{CPtr\text{-}SMA11}$) at every one-third octave band of the sound spectra calculated at 50 and 80 km/h. From Figure 9 some conclusions can be drawn:

- The shape of the ΔL_{CPtr} curves (Figure 9) is not speed-dependent.
- The relation between both spectra is speed-dependent. Differences between SMA11 and SMA16 are higher at higher speeds, and therefore, this result agrees with Figure 8.
- In spite of the different L_{CPtr} average values and homogeneities (50 km/h) of each test track section (Table 2), there are some points of the test track sections with similar tire/pavement noise levels, as indicated by the error range of each single measurement in Table 2. This does not occur at 80 km/h, where the differences between the average noise levels are higher.
- At low frequencies (up to 700 Hz), SMA11 is noisier than SMA16 in spite of its lower texture level at high texture wavelengths (Figure 6), which are related to impacts and vibrations.
- At high frequencies (from 2000 Hz), SMA16 is noisier than SMA11, in spite of its higher texture level at low texture wavelengths (Figure 6) (sound dispersion) and their similar acoustic absorption spectra.
- Medium frequencies (800–1000 Hz) are the dominant frequencies within the tire/pavement sound levels. The sound generation at these frequencies is governed by a combination of tire/pavement noise generation mechanisms [32]. Medium frequencies are responsible for the highest global sound levels measured in the mixture SMA16.

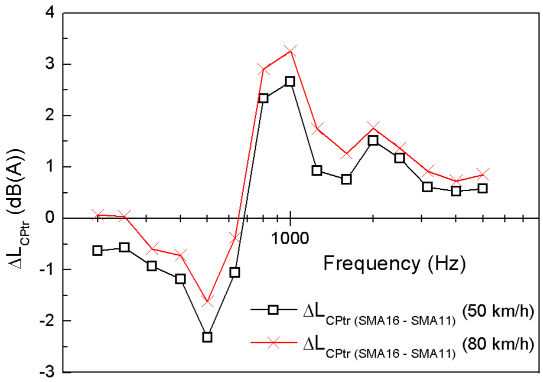


Figure 9. ΔL_{CPtr} values at every one-third octave band frequency of the sound spectra (50 and 80 km/h).

According to these results, the relationship between the different frequencies of the tire/pavement sound spectrum and the different wavelengths of the texture spectra should be further investigated. The mixture SMA16 had higher texture levels at almost every plotted wavelength (Figure 6). The SMA16 texture is responsible for its higher average tire/pavement sound levels. However, the texture wavelengths that dominate the sound level at each frequency band may depend on the pavement surface that is the object of study. Higher texture levels of mixture SMA16 (Figure 6) led to higher sound levels at medium/high frequencies (from 800 Hz) in its tire/pavement sound spectrum. In this sense, the differences between mixes at low texture wavelengths (Figure 6) were not big enough to result in lower L_{CPtr} values of mixture SMA16 at these frequencies (Figure 9). On the other hand, the acoustic behavior of both mixtures at low frequencies seems to have been influenced by their texture levels at wavelengths between 30 and 50 mm.

According to the overall noise results, the SMA16 bituminous mixture is noisier than the SMA11. The maximum aggregate size is directly related to higher overall tire/pavement noise levels, although this behavior is not reflected at every frequency of the tire/pavement noise spectra (Figure 9). This result agrees with other research works where the CPX-noise/MAS dependence was also established [12]. On the other hand, the measured L_{CPtr} values at 80 km/h were lower than those reported by other research works on the bituminous mixture type SMA10 (98 dB(A)) [15]. The measured L_{CPtr} values at 50 km/h were also lower than other values reported in aSMA5 mixture type (90.6 dB(A)) [14], although all the data were normalized at 20 °C. However, the higher noise values of SMA5 and SMA10 bituminous mixtures (80 and 50 km/h respectively) should be related to different construction characteristics or differences between the measurement techniques (for instance, the trailer employed for the CPX measurements). Besides, the average tire/pavement sound level measured at 50 km/h of mixture SMA11 (88.10 dB(A)) agrees with that presented in literature [16,20]. The average values measured at 80 km/h (95.10) also agree with the literature [16]. Some of these measurements were carried out with equipment (TireSonic Mk.4 by TUG, Gadnsk, Poland) similar to that employed in this research paper.

4.4. Labeling

The experimental test sections included in this research work are labeled after four consecutive measurements with the same reference tire (Pirelli P6000) at 50 and 80 km/h. Acoustic measurements were carried out according to the CPX methodology and subsequently corrected by temperature (20 °C) and speed. Measurements have been conducted with a single reference tire due to technical limitations. However, according to previous research works, the results obtained with the employed reference tire are representative of the acoustical performance of the studied sections [39].

According to the average values presented in Table 2, the experimental tracks were labeled according to the LNP labeling$^{\mathrm{LA^2IC}}$ methodology. Figure 10 shows the labels of bituminous mixtures SMA11 and SMA16 at 50 and 80 km/h. Each label includes the denomination and location of the mixture assessed, the company responsible for the paving operations, the MBSR class of the experimental track, and the reference speed of the acoustic assessment.

Both bituminous mixtures are labeled as Class B (good tire/pavement noise reduction) at 80 km/h. The LNP labeling$^{LA^2IC}$ methodology highlights the sound-reduction capacity of a given pavement. Additionally, the classification system presented by Gardziejczyk [18] is referred to the noise produced by the tire/pavement interaction (low, reduced, normal, increased, high). According to this classification system, the SMA11 mixture assessed in this research work would be classified as "reduced noise class" at 80 km/h.

The labels presented in Figure 10 point out the most appropriate bituminous mixtures for paving operations, depending on the usual speed of each test section (reference speed). Besides the acoustic label, the LA^{2}IC provides a report when the characteristics of the acoustic assessment and the tire/pavement noise values of each assessed section are included.

The acoustics label of bituminous mixtures according to the LNP labeling$^{LA^2IC}$ methodology is a valuable design tool for construction companies and urban planners to use in order to decide the best paving option when rehabilitation operations must be carried out in urban areas with problems related to traffic noise (acoustic pollution).

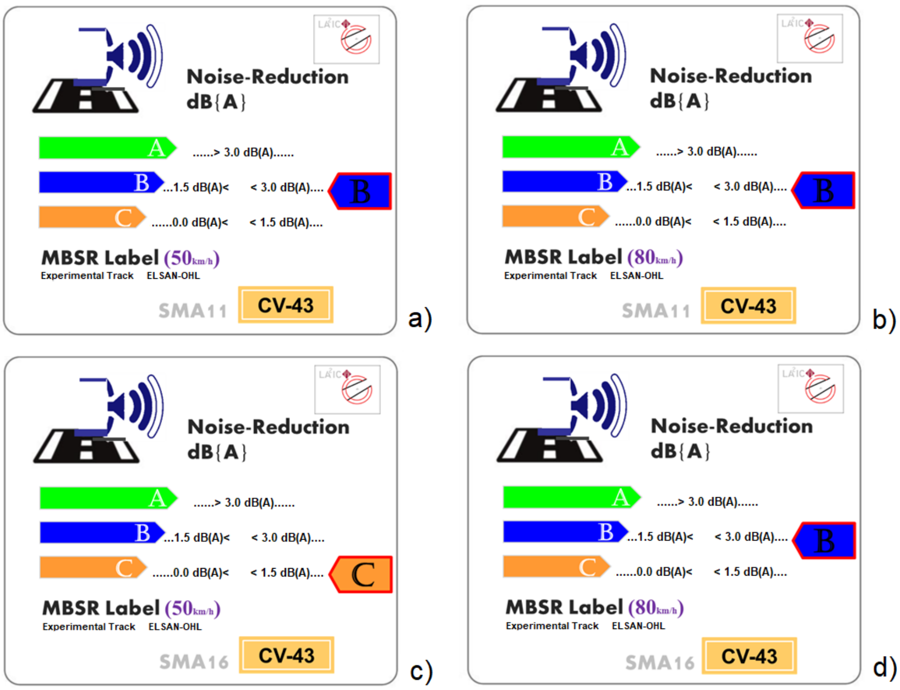


Figure 10. Acoustic labels according to the LNP labeling$^{LA^2IC}$ methodology: (**a**) SMA11 at 50 km/h; (**b**) SMA11 at 80 km/h; (**c**) SMA16 at 50 km/h; and (**d**) SMA16 at 80 km/h.

5. Conclusions

This research paper presents the functional performance (surface assessment) of two experimental sections built with SMA11 and SMA16 types of bituminous mixtures. Both mixtures have similar construction characteristics with regards to their binder type and additives, but they differ in their MAS. Moreover, this paper presents their acoustic labeling according to the LNP labeling$^{LA^2IC}$ methodology. The main conclusions at this stage are as follows:

- Acoustic absorption does not play an important role in the noise reduction capacity of the assessed bituminous mixtures with an air void content lower than 10%. The dynamic stiffness value measured is similar in both mixtures. Although the SMA16 mixture has higher average dynamic stiffness at 400 Hz, the differences between mixtures do not justify the higher tire/pavement sound levels of this mixture at medium frequencies.

- The different maximum aggregate sizes of the mixtures do not affect neither their acoustic absorption nor their dynamic stiffness.
- The bituminous mixture SMA11 is better for noise reduction than the SMA16 at 80 km/h. At 50 km/h, the differences between both mixtures are lower. This result may be connected to their MAS. According to the sound spectra, the SMA 16 is noisier at frequencies from 700 Hz, regardless of the reference speed.
- The acoustic behavior of SMA11 and SMA16 depends on the speed. This dependence makes the mixture SMA11 more suitable for paving operations in roads (higher usual speed).
- The SMA16 bituminous mixture has higher MPD values. Its higher macrotexture amplitude might produce the higher L_{CPtr} levels, however, the differences between the MPD values are not big enough to confirm this observation. Texture spectra measurements were conducted in order to identify the texture wavelengths related to the different frequencies of the tire/pavement sound levels.
- The SMA16 has higher texture levels than the SMA11 at nearly every wavelength, except for 12.5 and 31.5 mm, where this mixture has slightly lower values. In spite of their texture spectrum, the SMA 16 produces lower tire/pavement sound levels at low frequencies and higher levels at medium/high frequencies. The texture spectra may influence noise, but the main texture wavelengths affecting overall noise should be determined, as well as the wavelengths that rule the tire/pavement noise at each one-third octave band of a given bituminous mixture.

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