Science of the Total Environment 736 (2020) 139597

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Dynamic stiffness of road pavements: Construction characteristics-based model and influence on tire/road noise

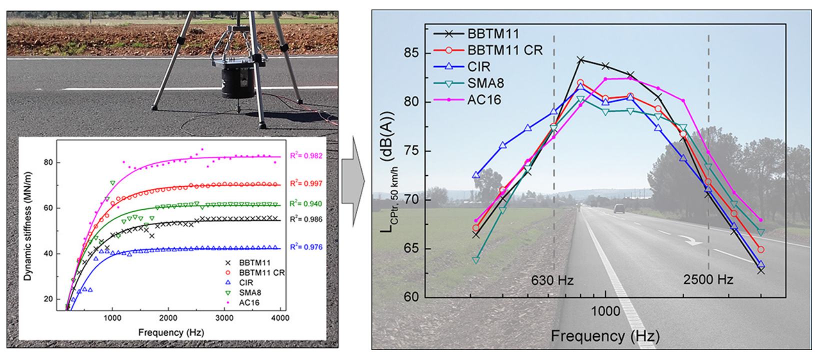
V.F. Vázquez *, F. Terán, S.E. Paje

University of Castilla-La Mancha, Laboratory of Acoustic Applied to Civil Engineering, Avda. Camilo José Cela s/n, 13071 Ciudad Real, Spain

HIGHLIGHTS

- Environmentally friendly mixes (cold or with crumb rubber) are acoustically assessed.
- The dynamic stiffness of CIR pavements reduces tire/pavement noise.
- Lower dynamic stiffness reduces tire/pavement noise at frequencies above 2 kHz.
- MPD of hot bituminous mixtures reduces tire/pavement noise at high frequencies.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 February 2020
Received in revised form 5 May 2020
Accepted 19 May 2020
Available online 23 May 2020

Editor: Pavlos Kassomenos

Keywords:
Dynamic stiffness
Tire/pavement noise
Close Proximity (CPX)
Cold-In place Recycling
Macrotexture

ABSTRACT

Tire/pavement noise is produced by the interaction between a tire and the road surface. Complex noise generation mechanisms are involved in this process. Dynamic stiffness (or mechanical impedance) is considered as a related reduction/amplification mechanism. Despite its potential importance, in conventional hot bituminous mixtures this mechanism has little influence on tire/pavement noise. This is because the dynamic stiffness of tire treads is significantly lower than that of the hot bituminous mixes (conventional road surfaces). This paper presents a field assessment of the dynamic stiffness of five experimental sections with different characteristics: from the environmentally friendly mixes such as the Cold-In place-Recycled (CIR) pavement to the gap graded hot bituminous mixtures with crumb rubber (CR) from end of life tires (ELTs). The obtained dynamic stiffness spectra are fitted using a Boltzmann Sigmoid function. The relationships between the fitting coefficients and a few pavement construction characteristics are assessed in order to model the pavement dynamic stiffness as a function of these characteristics. In addition to dynamic stiffness, several surface characteristics such as the Close ProXimity (CPX) sound levels from the tire/pavement interaction, macrotexture in terms of the Mean Profile Depth (MPD), unevenness in terms of the International Roughness Index (IRI), and acoustic absorption are studied. According to our results, lower dynamic stiffness values are related to lower noise levels at high frequencies. No relationship was observed between the low dynamic stiffness values and noise attenuation at medium frequencies in this research work.

1. Introduction

Environmental noise is one of the main problems in urban areas. This type of pollution is related to health issues such as cardiovascular

* Corresponding author at: LA[2]IC, University of Castilla-La Mancha, 13071 Ciudad Real, Spain.

E-mail address: victoriano.fernandez@uclm.es (V.F. Vázquez).

https://doi.org/10.1016/j.scitotenv.2020.139597
0048-9697/

disease or sleep disturbance (Han et al., 2018; Vienneau et al., 2015; Hanigan et al., 2019; Meyer et al., 2019). Therefore, there is a growing concern in society with regard to the risks associated with noise exposure. Traffic noise is largely, the main noise source in cities. Furthermore, within traffic noise, tire/pavement noise predominates at speeds higher than 40 km/h (Li et al., 2018).

According to the literature, the main tire/pavement noise generation mechanisms are related to the pavement texture (Sandberg, 1987), mainly macrotexture, which is mostly related to higher noise levels at low frequencies of the tire/pavement noise spectrum. However, other mechanisms are also related to tire/pavement noise reduction/amplification, such as the acoustic absorption by the pavement or the pavement stiffness (Sandberg and Ejsmont, 2002).

Several experimental tests are designed to measure the capability of a structure to resist motion when subjected to a specified force (stiffness). The main characteristic is named as dynamic modulus (E^*). It is calculated using standardized laboratory test methods such as bending, direct tension-compression, and cyclic indirect tension tests (EN 12697-26, 2004). These tests also enable the determination of the damping or phase angle of a specified pavement. This angle is related to the acoustic behavior of pavements. However, the literature reports other road parameters that influence tire/pavement noise, such as the mechanical impedance or the dynamic stiffness (Sandberg and Ejsmont, 2002). These parameters can be determined by field tests (non-standardized) that provide information on the real performance of a specified road. Several research works have addressed the measurement of these road surface characteristics in the past few years as indicated below.

Lin et al. (2016) obtained an in situ dynamic modulus (E^*) of pavements from nondestructive techniques for measuring pavement density and surface-wave phase velocity. Meanwhile, Wahengbam and Rajbongshi (2015) evaluated the dynamic stiffness modulus in asphalt concrete (AC) pavements using the theory of linear visco-elasticity. However, although related, these studies do not directly correlate their results with tire/pavement noise measurements.

Studies conducted by Biligiri et al. calculated the damping properties and phase angle of pavements using dynamic modulus (E^*) laboratory tests. These works established the effect of phase angle and damping on tire/road noise (Biligiri, 2013a; Biligiri and Kaloush, 2014). Biligiri (2013b) also studied the relationship between the complex dynamic modulus (E^*) (laboratory tests) and tire/pavement noise of poroelastic road surfaces (PERS). A PERS is a wearing course for roads, with a very high content of interconnecting voids and the use of rubber (of other elastic products) as a main aggregate. This work established that E^* of PERS was approximately 20–1500 times lower than that of a typical AC mix, providing a potential noise-dampening response. Meanwhile, Liao et al. (2014) also employed the E^* tests to correlate stiffness and sound levels. However, they observed a relevant correlation only in the Stone Mastic Asphalt (SMA) mixtures.

However, as mentioned before, the dynamic modulus (E^*) tests are not the only way to stablish the stiffness of a pavement surface. Li et al. (2016) studied the relationship between the mechanical impedance and the complex modulus E^*. In this work, the authors measured the mechanical *transfer* impedance (the velocity and force at different positions are tested) with an impedance hammer and three accelerometers. The study demonstrated a logarithmic relationship between both the magnitudes. Morcillo et al. (2019) also performed mechanical impedance tests using an impact hammer and an accelerometer. They obtained the mechanical impedance and damping of the pavements. However, this work did not achieve a clear correlation with the tire/road noise levels they measured. Freitas et al. (2015) calculated the damping of road materials, using an instrumented hammer and an accelerometer, in order to establish tire/road noise models for noise prediction. Finally, Vázquez et al. (2018a) studied the acoustic performance (noise, texture, stiffness, and absorption) of a Cold-In place Recycled pavement (CIR). This work assessed the dynamic stiffness using a shaker and an impedance head and related it with the acoustic behavior of the mixture.

It can be concluded from the number of research papers on the relationship between stiffness and tire/pavement noise that there is an interest in comprehending this relationship. However, the main sound frequencies affected by stiffness remain unclear. This research work would help to fill this knowledge gap.

This study aims to assess the dynamic stiffness spectra of five road pavements (field measurements) and to relate them to certain construction characteristics of bituminous mixtures, such as the maximum aggregate size, binder content, air void content, and bulk density. Based on this, the study proposes a fitting model for predicting the dynamic stiffness. The other surface characteristics studied in this work are the macrotexture (Mean Profile Depth (MPD)), unevenness (International Roughness Index (IRI)), acoustic absorption (absorption coefficient), and tire/pavement noise levels (Close Proximity method (L_{CPtr})). Finally, this study also investigates the relationship between the dynamic stiffness and one-third octave bands of the tire/pavement noise spectrum. This paper will aid in understanding the importance of dynamic stiffness in tire/pavement noise levels. Moreover, the fitting model would enable the estimation of the dynamic stiffness spectrum of a specified bituminous mixture from its construction characteristics, without the need for performing special test works. The pavements assessed include environmentally friendly mixes such as those fabricated at ambient temperature (CIR) or with crumb rubber from end-of-life tires (ELTs) (Wang et al., 2018; Gómez-Meijide et al., 2016; Gu et al., 2019). A few of these pavement characteristics influence their dynamic stiffness, and therefore, their acoustic performance.

2. Measurement methods

2.1. Dynamic stiffness

Dynamic stiffness is a pavement characteristic that is related to surface vibration, and thereby to tire/pavement noise generation. Dynamic stiffness (S) is the relationship between the force acting on a structure (F) and its surface displacement (x), in terms of complex numbers (Vázquez and Paje, 2016a; Fahy and Walker, 2004):

$$S = F/x \tag{1}$$

According to the literature, dynamic stiffness influences noise at medium frequencies (800 Hz to 1250 Hz) (Sandberg and Ejsmont, 2002). This influence occurs when the hardness of the road surface and tire are of similar order of magnitude, for instance, when poroelastic surfaces (PERS) are employed (Sandberg and Ejsmont, 2002; Bendtsen et al., 2013). Other similar pavement magnitudes studied in literature, for pavement design or tire/pavement noise studies, are the relationship between force and displacement velocity (mechanical impedance) (Li et al., 2016; Kuijpers and Schwanen, 2005), energy dissipation within a structure (damping) (Biligiri, 2013a; Freitas et al., 2015), and complex modulus (E^*) (Wahengbam and Rajbongshi, 2015; Biligiri, 2013b).

Dynamic stiffness has been assessed in this work by the Non-Resonant Method, using a vibration exciter and an impedance head (Vázquez and Paje, 2016a; Vázquez et al., 2016). The impedance head enables the assessment of the *driving-point stiffness* of a pavement surface. This implies that motion and force signals are tested at the same point of the pavement surface. Sweep signals with frequencies between 10 Hz and 7 kHz are used for pavement excitation. The measurements were conducted in the interval between 14 °C and 30 °C (ambient temperature).

2.2. Macrotexture and unevenness

The surface profiles of the sections have been obtained using a commercial high-speed profiling laser device for road quality

Table 1
Construction features of the assessed wearing courses.

Wearing course	Construction characteristics
BBTM11	Gap-graded hot bituminous mixture. Conventional 50/70 penetration grade bitumen.
BBTM11 CR	Gap-graded hot bituminous mixture. High viscosity modified bitumen (35/50). Crumb rubber by the wet process (20% by weight of bitumen)
CIR	Cold-In place Recycled bituminous mixture Bituminous emulsion type C60B5 Reclaimed Asphalt Pavement (100%)
SMA8	Gap graded hot bituminous mixture. Conventional 50/70 penetration grade bitumen Crumb rubber by the dry process (0.5% of the total mix)
AC16	Hot bituminous mixture type asphalt concrete Conventional penetration grade bitumen (35/50)

control. The surface profile data are collected in conjunction with their GPS coordinates by a control box. The Mean Profile Depth (MPD) (ISO 13473-1, 2019) and International Roughness Index (IRI) (ASTM E1926-08, 2015) are calculated from these data. The MPD is a parameter that characterizes the macrotexture depth (texture wavelength between 0.5 mm and 50 mm) (PIARC, 1987). According to the literature, the macrotexture is related to higher tire/pavement noise levels at lower frequencies (Sandberg and Ejsmont, 2002; Liao et al., 2014). Meanwhile, the IRI is a ride quality parameter of a pavement. IRI is related to texture wavelength varying from 500 mm to 100 m. According to the literature, noise levels correlate poorly with pavement unevenness. However, there may be a certain relationship between tire/pavement noise and unevenness which should be investigated further (Liao et al., 2014).

2.3. Acoustic absorption

The acoustic absorption has been assessed in laboratory, using an impedance tube and cylindrical samples with a diameter of 10 cm, and compacted with bituminous mixture extracted directly before being laid over the road. The impedance tube enables measurements between 50 Hz and 1.6 kHz. Further details of the measurement technique are given elsewhere (Paje et al., 2013; Luong et al., 2014).

2.4. Tire/pavement noise levels

The rolling noise assessment has been conducted using a semi-anechoic chamber that isolates tire/pavement sound from external traffic noise. A reference tire and two microphones are located inside the semi-anechoic chamber at specific distances. The measurements are subsequently corrected by speed (50 km/h) and temperature (20 °C) for comparison purposes. Considering previous research works (Bueno et al., 2011), a correction factor of −0.05 dB(A)/°C is used to adjust the measured sound levels to the reference temperature of 20 °C. The tire/pavement sound levels are corrected for speed variations around the reference speed (v_{ref}), according to the following Eq. (2) (Paje et al., 2013):

$$L_{corrected}(t) = L_{measured}(t) - B \cdot \log\left(\frac{v(t)}{v_{ref}}\right) \quad (2)$$

where the speed constant B is the slope of the logarithmic regression of the sound pressure level and speed:

$$L_{CPtr} = A + B \cdot \log(V) \quad (3)$$

The reference tire is preserved under controlled conditions, of humidity and temperature, between measurements (Vázquez et al., 2016; Vázquez et al., 2018b).

3. Studied materials

Different wearing courses have been studied and compared. The experimental test track sections were monitored after being laid. Their assessment would enable the determination of the influence of surface characteristics such as the dynamic stiffness, macrotexture, or acoustic absorption, on tire/pavement noise. The pavements studied are detailed in Table 1.

BBTM, CIR, and SMA mixtures are studied owing to their special characteristics: BBTM and SMA are gap graded bituminous mixtures that reduce noise, according to the literature (Mioduszewski and Gardziejczyk, 2016). Furthermore, BBTM11 CR and SMA8 are fabricated with crumb rubber added by the wet and dry processes, respectively. Meanwhile, CIR bituminous mixes are fabricated at ambient temperature using Reclaimed Asphalt Pavement. The characteristics of CIR pavements influence their dynamic stiffness and thereby, the tire/pavement noise (Vázquez et al., 2018a). Finally, the bituminous mixture AC16 is studied because AC mixes are widely used for road construction in Spain. Each section has been assessed after two months under service conditions. The exception is section AC16 which is assessed after 10 years under service conditions. The age and properties of the section AC16 is representative of an average road section in Spain. The pavement properties are included in Table 2.

4. Analysis of measurement and discussion

4.1. Dynamic stiffness spectra

Field measurements of dynamic stiffness have been conducted on the surface layers previously described, in order to determine the relationship between this surface characteristic and tire/pavement noise. Fig. 1 shows the pavement surfaces during the field assessment. The results achieved for the dynamic stiffness spectra of the studied pavements are presented up to 4 kHz. According to the literature, dynamic stiffness (or mechanical impedance) ranging from 500 Hz to 2000 Hz influences tire/pavement noise (Li et al., 2016) and reduces it at medium frequencies (800 Hz to 1250 Hz) (Sandberg and Ejsmont, 2002). However, the measurements are affected by a resonance between 500 Hz

Table 2
Characteristics of the studied wearing courses.

Wearing course	Maximum aggregate size (mm)	Binder content (%)	Air void content (%)	Bulk density (kg/m^3)	Age
BBTM11	11	5.2	6.7	2430	2 months[a]
BBTM11 CR	11	8.3	5.7	2326	2 months[a]
CIR	22	5.3	12.0	1851	2 months
SMA8	8	5.7	4.9	2382	2 months
AC16	16	5.0	4.2	2355	10 years

[a] The acoustic and texture assessment was conducted two months after paving operations. However, owing to research limitations, the dynamic stiffness measurements were accomplished after three years under service conditions.

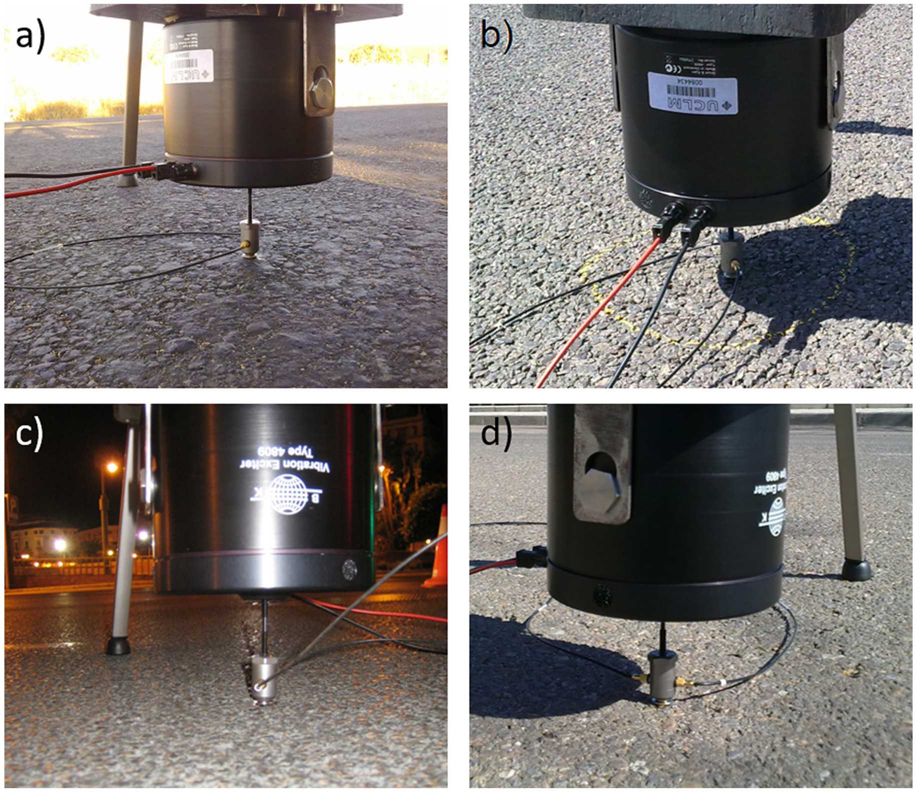


Fig. 1. Dynamic stiffness equipment (exciter and impedance head) during field assessment on sections: a) CIR, b) BBTM11 CR, c) SMA8, and d) AC16.

and 1500 Hz, which obstructs the analysis. Other studies have also reported the occurrence of this resonance in mechanical impedance measurements. An example is the impedance hammer test conducted by Li et al. (2016). In this research work (Li et al.), the resonance was located between 1000 Hz and 2000 Hz. This resonance reflects the behavior of the system composed of the measurement device and the pavement, rather than the real dynamic stiffness of the pavement (Vázquez et al., 2016). Therefore, a dynamic stiffness fitting model is proposed in order to characterize the pavement behavior without resonances, as well as to correlate the fitting curves to the construction characteristics of a specified bituminous mixture.

Fig. 2 shows the measured dynamic stiffness spectra. A jump due to the resonance can be observed in the curves between 500 Hz and 1500 Hz. A Boltzmann Sigmoid fitting curve has been employed for the adjustment (See Eq. 4). The Boltzmann Sigmoid curve is characterized by the maximum (A_2) and minimum (A_1) values and a characteristic value (f_0) describing the point where the frequency (f) is equidistant from the minimum and maximum values. The slope (df) indicates the range in which the transition between minimum and maximum occurs.

$$S(f) = A_2 + \frac{A_1 - A_2}{1 + e^{\left(\frac{f - f_0}{df}\right)}} \tag{4}$$

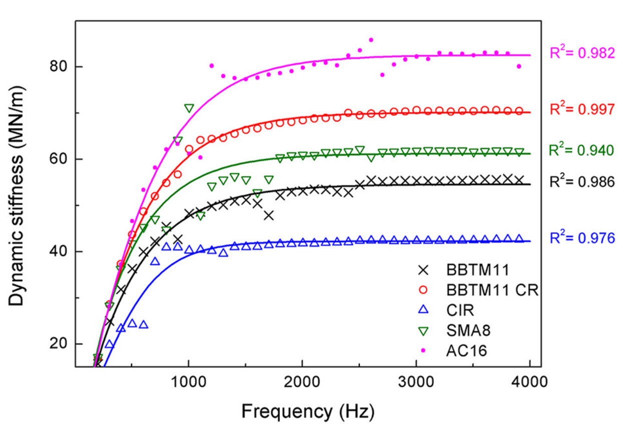


Fig. 2. Dynamic stiffness spectra of studied sections (symbols) and the Boltzmann Sigmoid fitting functions (lines). The coefficient of correlation (R^2) of each Sigmoid fitting function is also shown in the figure.

According to the results achieved, the dynamic stiffness spectrum depends on the bituminous mixture tested. Hence, the lower dynamic stiffness values of the CIR mixture influence the tire/pavement noise levels produced in this pavement. The relationship between the dynamic stiffness and tire/road noise spectra is subsequently investigated in this study in order to define the most affected frequencies.

As observed earlier, the CIR is the softest bituminous mixture, whereas AC16 after 10 years under service conditions is the stiffest. According to Fig. 2, the shapes of the dynamic stiffness curves depend on the construction characteristics of the mixtures, from among other factors. The age of the mixes could also influence the shape of the curves. However, owing to research limitations, this study focuses only on the dependence of the dynamic stiffness spectrum on the construction characteristics.

The construction characteristics of the studied bituminous mixtures have been correlated with the Sigmoid coefficients to identify their relationship. These construction characteristics are the maximum aggregate size, binder content, air void content, and bulk density. These may be related to the shape of the dynamic stiffness spectrum, particularly to the initial slope of the curve (df) and maximum value (A_2) attained at higher frequencies.

The linear fitting between the studied construction characteristics and Sigmoid coefficients are shown in Fig. 3. For each coefficient, the fitting chart with the higher coefficient of determination R^2 is highlighted. The slope of the curves (df) is highly related to the bulk density of the bituminous mixtures. A higher bulk density results in a

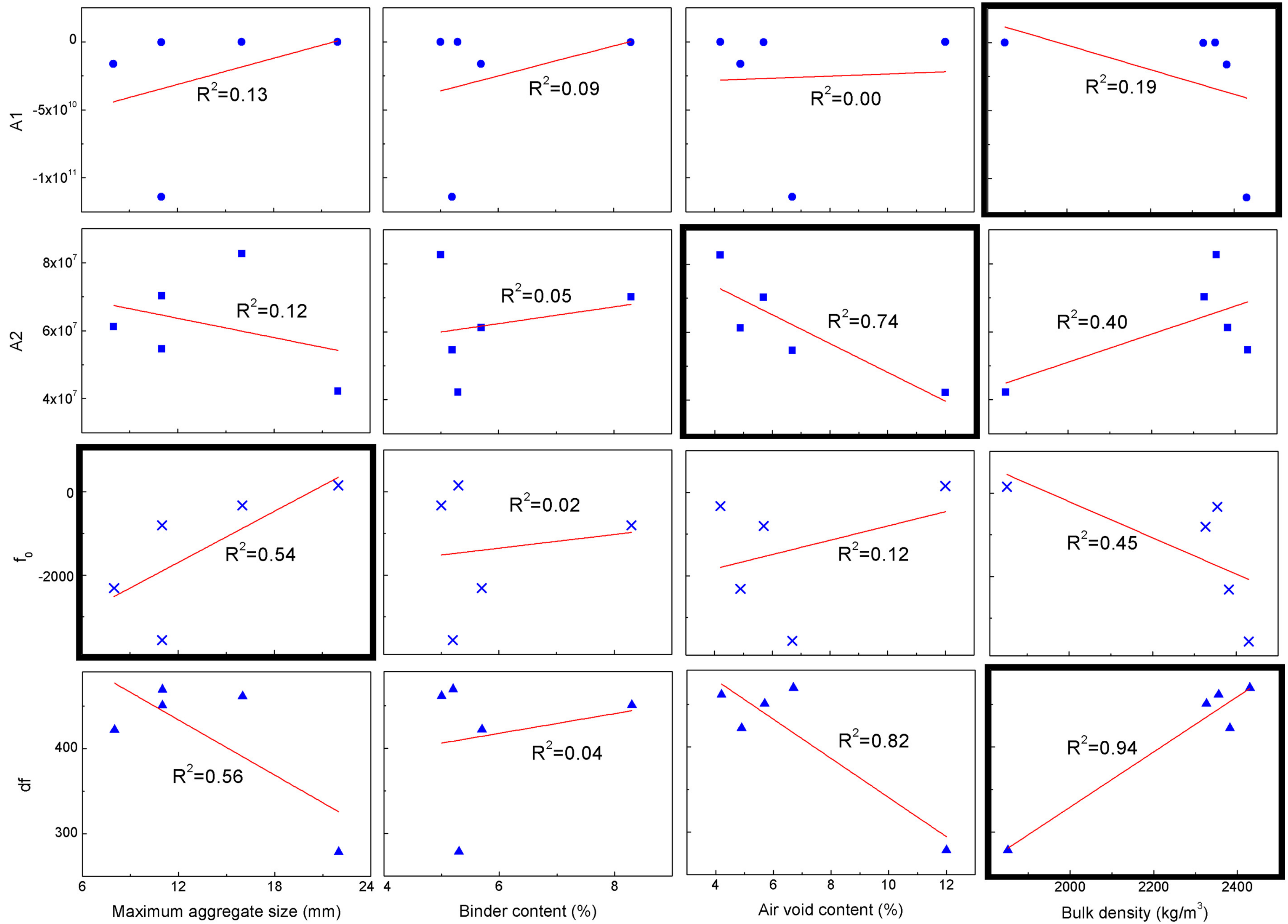


Fig. 3. Relationship between construction characteristics and Boltzmann coefficients.

higher slope, whereas a higher air void content reduces it. Meanwhile, the maximum value (A_2) of the dynamic stiffness spectra is related to the air void content of the bituminous mixtures. The maximum aggregate size and binder content of the mixtures do not appear to be significantly correlated with the achieved Sigmoid coefficients.

The design of bituminous mixtures with lower bulk density and higher air void content would result in more sustainable road surfaces with improved acoustic characteristics. This would reduce the tire/pavement noise owing to the *mechanical impedance effect* (Sandberg and Ejsmont, 2002). The analysis presented in this paper would help characterize the dynamic stiffness of pavements, thereby enabling the design of novel pavements with improved acoustic performance.

4.2. Acoustic absorption

Acoustic absorption is related to the air void content (connected voids) of the studied mixtures. When mixtures with high air void content (>20%) are assessed, absorption could reduce noise significantly (Sandberg and Ejsmont, 2002). Acoustic absorption measurements have been accomplished in laboratory using Marshall samples compacted in laboratory following the standard EN 12696-30. Fig. 4 shows the normal incidence acoustic absorption spectra of the studied bituminous mixtures. Acoustic absorption does not appear to be of significance in the noise performance of the studied sections. This is because the acoustic absorption is below 0.3 at any frequency in the studied interval (Fig. 4). These results agree with those measured in mixtures with low air void content (SMA). Here, the absorption was approximately 0.1 at frequencies between 400 Hz and 1600 Hz (Vuye et al., 2015; Vaitkus et al., 2017).

4.3. Macrotexture and unevenness

Main Profile Depth (MPD) and unevenness (IRI) could affect the acoustic performance of the studied sections. These characteristics have been determined from the profile, measured during field auscultation together with the tire/pavement noise levels (geo-referenced measurements following the same path). Fig. 5 shows the averages and standard deviations of the MPD and IRI of the studied bituminous mixtures.

The highest MPD values are measured in the gap-graded bituminous mixtures. The results are related to the construction characteristics of each section. The AC16 bituminous mixture is a conventional mixture with a closed surface (neither gap-graded or porous). Therefore, its surface profile is smoother (also owing to its age). Moreover, the higher MPD values of the BBTM mixtures (with respect to SMA, for example)

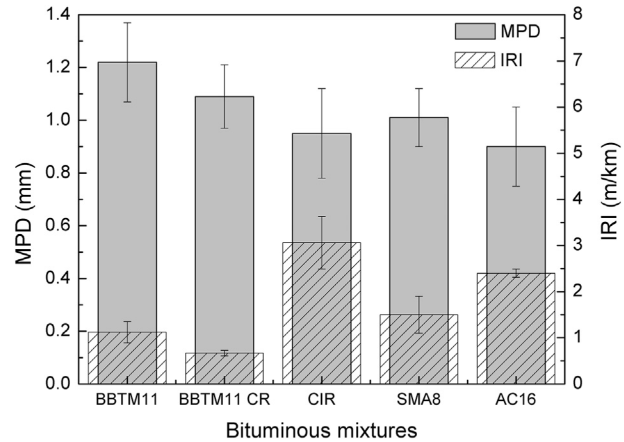


Fig. 5. Average MPD and IRI values of assessed sections.

may be related to their higher maximum aggregate size. Meanwhile, the MPD results of the CIR pavement should be highlighted. This mixture displays the highest maximum aggregate size (22 mm, from the reclaimed asphalt pavement). Nevertheless, its MPD value is the second lowest. This result is possibly owing to a more regular gradation of the CIR pavement aggregate sizes. However, the construction process of the CIR pavement affects its unevenness value, which is higher than that of the AC16 mixture that has been under service conditions for ten years. The high IRI values of the CIR pavement may be related to the paving operations. Considering this, special attention should be paid to the CIR construction processes. With regard to the acoustic performance, the higher IRI values could contribute to the production of higher tire/pavement noise levels at low-medium frequencies of the sound spectrum, because of impacts and vibrations. However, this affirmation must be investigated further.

4.4. Close proximity sound spectra

The acoustic absorption, dynamic stiffness, macrotexture (MPD), and unevenness (IRI) results are discussed considering the sound spectra (between 315 Hz and 4000 Hz) of the studied mixtures (Fig. 6). The sound spectra are effective for determining the tire/pavement noise generation mechanism involved in the measured noise levels. According to the literature, the medium frequencies of the tire/pavement noise spectrum are the result of a combination of noise generation

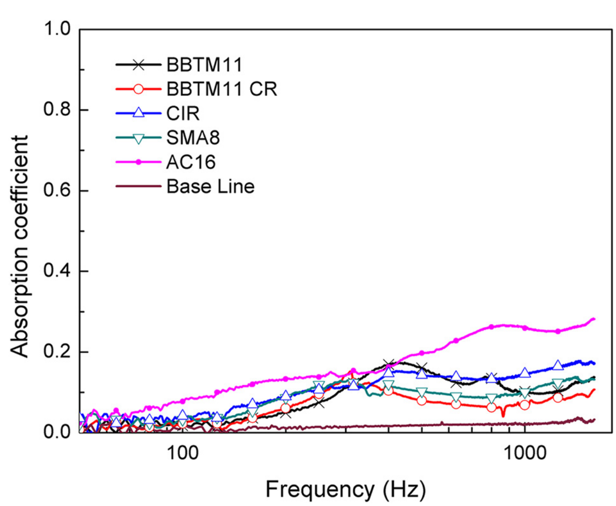


Fig. 4. Normal incidence acoustic absorption spectra of studied bituminous mixtures and the spectrum of the background source of radiation (base line).

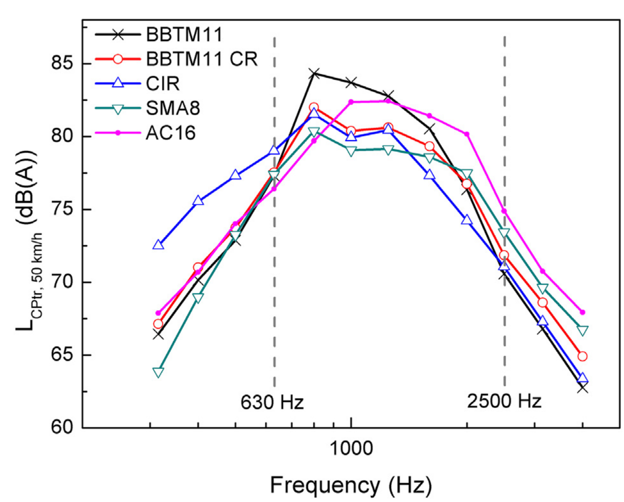


Fig. 6. Tire/pavement sound spectra (corrected by speed and temperature) of studied sections.

mechanisms, and related amplification/reduction mechanisms such as dynamic stiffness (Sandberg and Ejsmont, 2002).

Fig. 6 highlights a few noteworthy results. First, the noisiest mixtures are those with the higher sound levels at medium frequencies (800–1600 Hz): BBTM11 and AC16. In addition, the acoustic behavior of the SMA8 mixture stands out at medium frequencies: its sound level at 1000 Hz is over 1 dB(A) lower than those of the other studied sections. The CIR mixture displayed the lowest dynamic stiffness. However, this mixture is not the least noisy at medium frequencies. Its tire/road noise levels at medium frequencies are marginally lower than those of the BBTM11 CR mixture, which displayed higher dynamic stiffness. According to these results, the dynamic stiffness of the CIR section could reduce its sound levels at medium frequencies (the CIR section displays the second lowest sound levels at medium frequencies, according to Fig. 6). However, there may be other noise generation mechanisms affecting these frequencies. For example, according to the literature, the IRI can influence the tire/pavement noise levels at 800 Hz of the sound spectra (Vázquez and Paje, 2016b). Further studies on CIR pavements should be conducted to determine the main noise generation mechanisms at the medium frequencies of the noise spectrum. Meanwhile, the CR in the SMA8 mixture (from ELTs, added by the dry process as an aggregate) could affect the surface stiffness, reducing the noise at medium frequencies. However, a reduction in the dynamic stiffness of SMA8 has not been observed (Fig. 2). The acoustic behavior of SMA8 at the medium frequencies of the sound spectra appear to be owing to a combination of the studied generation mechanisms, rather than one of these.

At high frequencies (from 2000 Hz), where the bands have less influence on the global tire/pavement noise levels, the experimental sections display a different acoustic behavior. Fig. 7a shows the relationship between the MPD and tire/pavement sound levels at 2500 Hz to clarify the behavior at high frequencies. At these frequencies, the acoustic levels appear to be related to the macrotexture, particularly in the hot bituminous mixtures: lower MPD values produce higher tire/pavement noise at high frequencies ($R^2 = 0.98$). This could be owing to a higher horn effect (Sandberg and Ejsmont, 2002). The CIR pavement is the exception to the behavior shown in Fig. 7a. Other texture parameters of CIR pavements may also affect noise generation at high frequencies, such as dominant texture wavelengths. The CIR pavement's noise behavior at high frequencies could also be owing to its low dynamic stiffness and sound dispersion and reflections.

The acoustic behavior at low frequencies (up to 630 Hz) (see Fig. 6) of the BBTM, SMA, and AC sections (hot mixtures) are rather similar notwithstanding their different MPD values. However, an important direct relationship between the MPD and noise ($R^2 = 0.83$) has been observed at the one-third octave frequency band of 800 Hz (Fig. 7b). It is likely that, the differences in macrotexture (MPD) among the hot mixtures are not sufficiently large to cause a different acoustic performance at low frequencies. Alternatively there may be other pavement texture characteristics (e.g., the texture spectra) that influence these frequencies of the tire/pavement sound spectrum.

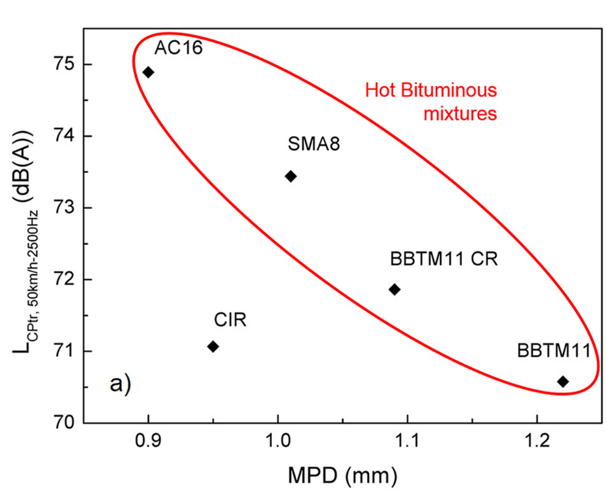
According to the results obtained, the more noisy behavior of CIR at low frequencies (below 800 Hz) (Fig. 6) is possible owing to its high IRI (see Fig. 5). However, although hot bituminous mixtures have different IRIs, these do not produce noise differences at low frequencies (e.g., 500 Hz in Fig. 6). Unevenness can produce higher tire/pavement noise levels at certain frequencies (Vázquez and Paje, 2016b). However, it is possible that IRI values should exceed a certain threshold to increase the tire/pavement noise levels considerably at low frequencies. This threshold would not be exceeded in the studied hot bituminous mixtures without affecting the tire/pavement noise levels at these frequencies.

4.5. Global Close ProXimity sound levels

The continuous tire/pavement noise levels ($L_{CPtr,\ 50km/h}$, corrected for speed and temperature) of representative 150 m long sections are presented in Fig. 8. The average $L_{CPtr,\ 50km/h}$ values and their homogeneity are presented in Table 3. The homogeneity has been calculated as the standard deviation of the corrected $L_{CPtr,\ 50km/h}$ values. It is a measure of the variability of the measurements (Paje et al., 2013).

Fig. 8 shows that the continuous tire/pavement noise levels (50 km/h) are between 88 and 91 dB(A) for the BBTM, CIR, and AC mixtures. The low noise levels of the SMA8 mixture are noteworthy. These levels are lower than 86 dB(A) in certain points of the section. However, although this mixture has the lowest average $L_{CPtr,\ 50km/h}$ level, it has the lowest homogeneity value (1.3 dB(A)).

The remaining studied bituminous mixtures display homogeneity values between 0.4 dB(A) and 0.9 dB(A). Among these mixtures, the CIR pavement is noteworthy. It displays a good homogeneity (0.5 dB (A)) and low average $L_{CPtr,\ 50km/h}$ level (88.4 dB(A)). The noisiest mixtures are the BBTM11 and AC16 mixtures. The BBTM and AC mixes are among the most used materials in pavement construction in Spain. The tire/pavement noise levels measured in the BBTM mixtures are similar to those measured by Swieczko-Zurek et al. (2017) in gap-graded bituminous mixtures with a similar maximum aggregate size (SMA11). In addition, the tire/pavement noise values of the SMA mixture agree with those reported by Sangiorgi et al. (2018) in a SMA8 mixture that was under service conditions for nine months.



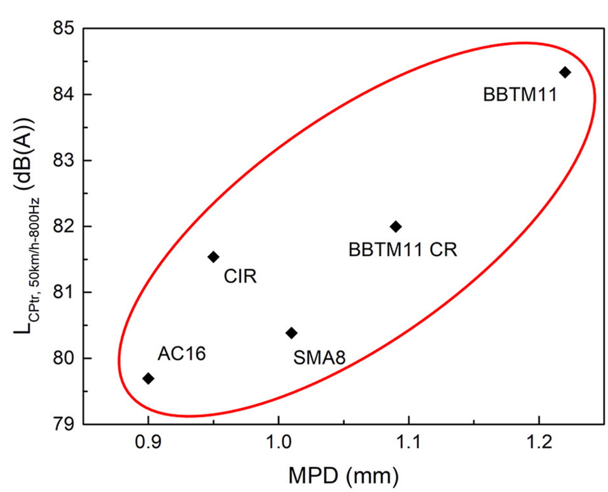


Fig. 7. Relationship between MPD and tire/pavement sound levels at a) high frequencies (2500 Hz) and b) medium frequencies (800 Hz).

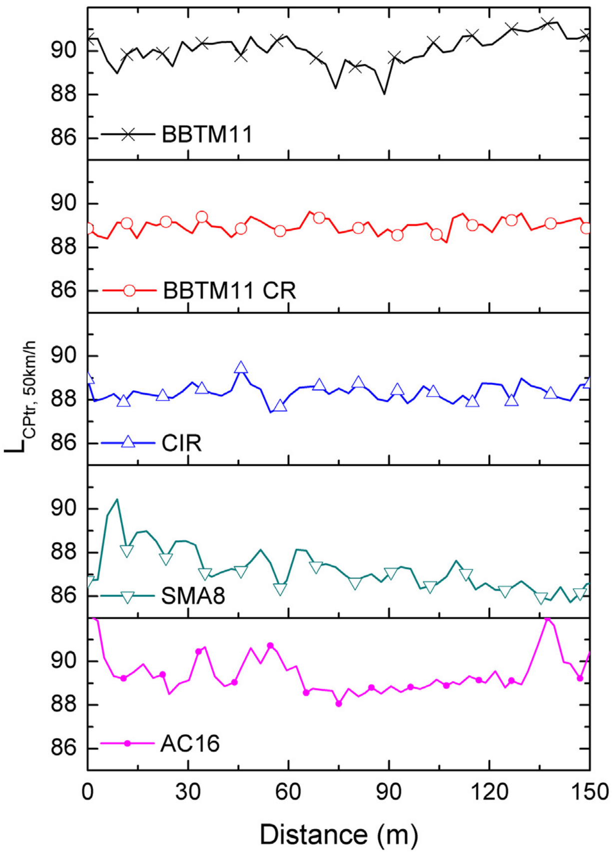


Fig. 8. $L_{CPtr,\ 50km/h}$ global sound levels of a representative length of studied sections.

4.6. Dynamic stiffness and tire/pavement noise relationship at different frequencies

The dynamic stiffness is a pavement feature that is related to the tire/pavement noise generation. This section presents an analysis of the in-situ dynamic stiffness of the studied mixtures and its relationship with the noise produced. Table 4 presents the measured dynamic stiffness values at 400 Hz as well as the standard deviation of the measurements. According to this table, the studied hot bituminous mixtures display dynamic stiffness values higher than 31 MN/m at 400 Hz. Meanwhile, the low dynamic stiffness values measured in the CIR mixture could justify low tire/pavement noise levels at 50 km/h (Fig. 6).

The relationship between the tire/pavement noise levels and dynamic stiffness are studied. According to the results, there is an inverse proportional relationship at frequencies up to 800 Hz, whereas a direct proportional one occurs at frequencies higher than 1000 Hz. Fig. 9 shows the relationship at certain discrete frequencies of the tire/pavement noise and the dynamic stiffness spectra. The dynamic stiffness values are extracted from the proposed Boltzmann Sigmoid fitting curves. The frequencies 400 Hz, 1000 Hz, 2000 Hz, and 4000 Hz are plotted, so that the behavior in the low/medium/high frequencies can be observed. According to our results, low dynamic stiffness values produce higher noise levels at low frequencies, whereas the noise levels at higher frequencies are reduced. Therefore, higher dynamic stiffness values would not be significantly related to the impact and vibration noise generation mechanism (low frequencies), which is generally related to the pavement macrotexture. The higher values of dynamic stiffness would increase the noise at higher frequencies, which is likely to affect the air pumping or the horn effect (air displacement in/out of cavities between tire tread and road). The tire/road noise of medium frequencies (around 1 kHz), is the least affected by dynamic stiffness, with R^2 values of approximately 0.1. This observation disagrees with other research works (Sandberg and Ejsmont, 2002) where the maximum noise attenuation owing to the use of surfaces with low stiffness is located at the peak frequencies of 800–1250 Hz. The tire/road noise levels at medium frequencies do not depend on the dynamic stiffness values. However, neither the macrotexture nor the absorption measurements determines the medium frequency noise values (the MPD of the CIR mixture is one of the lowest, whereas there are no differences among the absorption results). Therefore, this behavior should be owing to another non-assessed pavement characteristic such as the dominant texture wavelengths (texture spectrum) or a combination of different noise generation mechanisms. The effect of surface dynamic stiffness on noise levels should be investigated further to increase the knowledge on the noise frequencies affected by pavement dynamic stiffness variations.

Table 3
Average tire/pavement noise levels and homogeneity of each experimental section.

Surface type	$L_{CPtr,\ 50km/h}$ (dB(A))	Homogeneity (σ) (dB(A))
BBTM11	90.1	0.7
BBTM11 CR	88.9	0.4
CIR	88.4	0.5
SMA8	87.6	1.3
AC16	89.3	0.9

Table 4
Measured dynamic stiffness at 400 Hz and standard deviation.

Surface type	Dynamic stiffness (MN/m)	Standard deviation (σ) (MN/m)
BBTM11	31.6	5.6
BBTM11 CR	37.1	3.4
CIR	23.2	5.9
SMA8	36.0	1.2
AC16	36.8	1.0

5. Conclusions

The field assessment of different road sections has been conducted to model the pavement dynamic stiffness based on a few of its construction characteristics, and to identify its role in tire/pavement noise generation. The main conclusions at this stage are as follows:

- A fitting model for the dynamic stiffness spectrum has been proposed, using a Boltzmann Sigmoid function. The coefficients of the function are correlated to a few construction characteristics of the bituminous mixtures.
- Bituminous mixtures designed with lower bulk density and higher air void contents improve the acoustic performance of pavements by reducing the dynamic stiffness. The maximum aggregate size and binder content do not influence the shape of the dynamic stiffness spectrum.
- Dynamic stiffness appears to be the main factor causing the low tire/pavement noise levels of the CIR pavement. However, a combination of noise generation mechanisms (MPD, IRI, Acoustic absorption) may influence the noise at medium frequencies. As a result, the BBTM11 CR section (higher dynamic stiffness, measured after three years in service) displays tire/pavement noise values similar to those of the CIR mixture at medium frequencies (800–1600 Hz). Nevertheless, the dynamic stiffness of this mixture would be increased during these three years owing to the aging process. The relationship between the pavement aging and dynamic stiffness should be investigated further.
- The high frequencies (2500 Hz) of the sound levels of tire/pavements decrease as the MPD increases, particularly among the hot

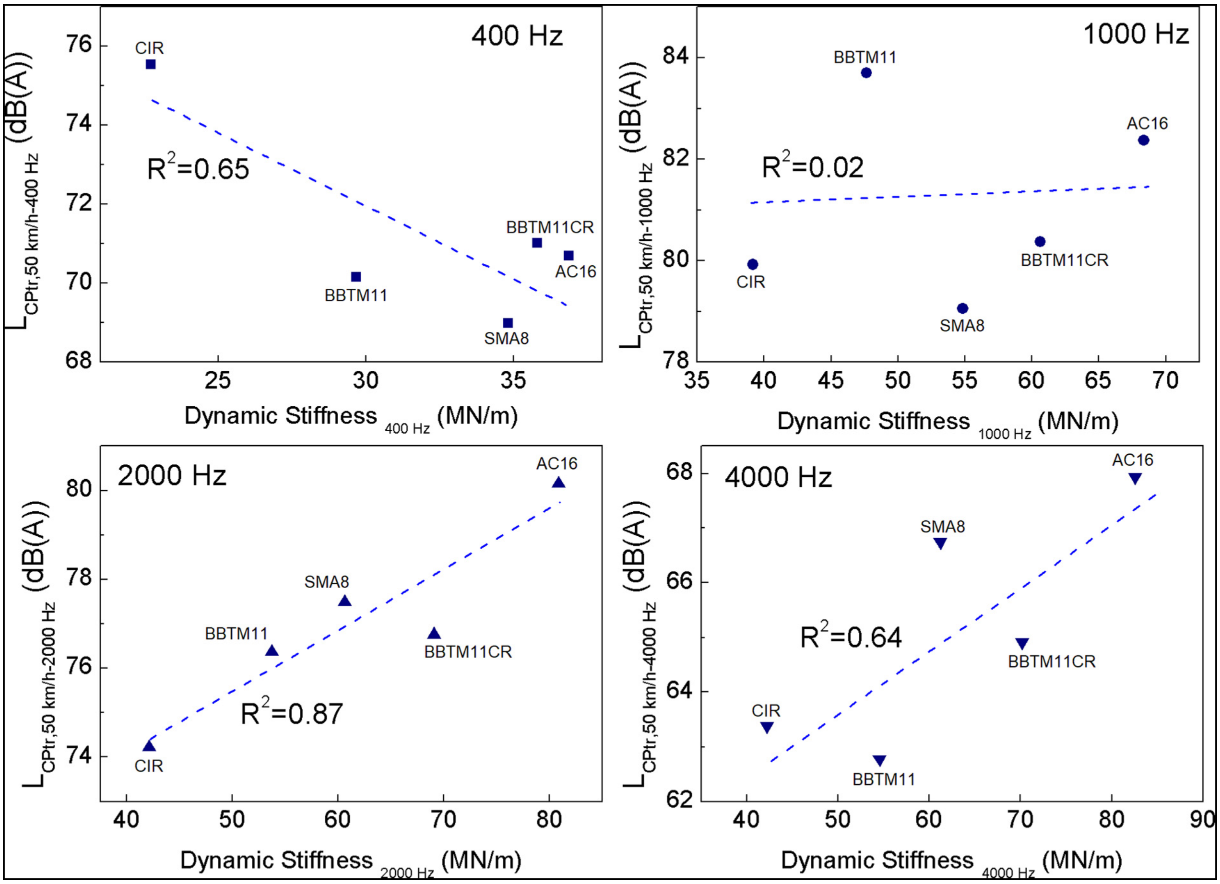


Fig. 9. Relationship between dynamic stiffness and $L_{CPtr,\ 50km/h}$ sound levels at different frequencies of the spectra (400, 1000, 2000 and 4000 Hz).

bituminous mixtures. The MPD and tire/pavement sound levels are directly correlated at 800 Hz.

- Considering the hot bituminous mixtures (BBTM, SMA, AC), the tire/pavement sound levels at low frequencies are similar notwithstanding their different MPD values. The MPD influences noise at low frequencies (impacts and vibrations). However, there should be other texture parameters that balance their noise levels at these frequencies. A study of the texture spectra in the wavelength domain would help understand the relationship between noise and pavement texture.
- From the obtained results, the dynamic stiffness and tire/pavement noise levels are directly proportional at high frequencies and inversely proportional at low frequencies (up to 1 kHz). Medium frequencies are the least affected according to our results. However, these frequencies may be affected by a complex combination of noise generation mechanisms, and none of these would stand out from others.

The bituminous mixture SMA8 is the least noisy paving solution among the studied surfaces. Its behavior is mainly owing to its low tire/pavement noise levels at medium frequencies. CIR pavements appear to be a good option to abate noise. However, CIR paving operations should be improved in the future to reduce the high IRI values measured in this research work.

CRediT authorship contribution statement

V.F. Vázquez: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **F. Terán:** Conceptualization, Investigation, Writing - review & editing. **S.E. Paje:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was partially supported by the Spanish Ministry of Economy and Competitiveness, with European Regional Development Funds (FEDER), within the framework of the National Plan for Scientific Research (Project Reference number: TRA2016-77418-R (AEI/FEDER, UE)). The authors wish to acknowledge P. Castro and Mª Rosa López of *Servicio de Carreteras CR*, (*Consejería de Fomento JCCM*) for their valuable assistance.

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