Non-destructive technique for dynamic stiffness and acoustic assessment: study of gap graded mixtures with different content in bitumen

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Abstract

This work presents a non-destructive technique applied to wearing course mixtures that allows us to characterize their surface. Different samples of gap-graded bituminous mixtures with different content of bitumen were studied in order to determine the influence of their composition on dynamic stiffness. Comparisons between the stiffness obtained with the non-destructive technique and those obtained in accordance to international standards are also made. The dynamic stiffness could play an important role in tire/road noise emissions since similar texture surfaces could generate different levels of tire/road noise. Moreover, absorption measurements were also conducted to assess the acoustic behavior of the mixes. Gap-graded bituminous mixtures are similar to porous asphalt pavements, and they provide an excellent macrotexture that improve traffic safety, especially with wet pavement. They are thin pavements which are designed with high content of bitumen. In this study, two different types of bitumen were used: polymer modified bitumen and high viscosity modified bitumen with rubber. Mixtures will be classified according to their ability to generate rolling noise.

1 Introduction

Different strategies in order to reduce tire/road noise have been proposed in the last years. Every strategy is focused in one or more noise generation mechanisms [1] and influence tire/road noise in different ways. Pavements with different characteristics, as porous asphalts [2] or gap graded bituminous mixtures [3, 4], could mitigate the noise generation due to absorption mechanisms, whereas mixtures with small aggregate sizes could result in pavements with less texture. These pavements could be quieter, since impact and vibration noise generation mechanisms are less important. On the other hand, the use of different compounds as special bitumen or additives could modify the behavior of the mixtures and reduce the tire/road noise generated. The use of crumb rubber (CR) as bitumen modifier could improve the mechanical characteristics of the pavement [5], but not only, crumb rubber could also affect the noise generated and result in low tire/road noise levels [3]. When crumb rubber particles are used, it is necessary to indicate the way they are incorporated to the mix. There are two techniques for CR incorporation to the binder: the dry and wet processes. In a dry process, CR is in the mixture replacing some of the solid fraction, whereas in the wet process, CR is added to bitumen before mixing it with the aggregates. In the first case CR is used as a part of the aggregates, whereas in the second case CR is used as a binder modifier.

In this study, two different types of gap-graded mixtures were studied: mixtures with polymer modified bitumen and high viscosity mixtures added by wet process. The mixtures have been tested in order to determine their dynamic stiffness spectrum [6] by means of a dynamic exciter. Dynamic stiffness is not regarded as a pure generation mechanism, but a related amplification or reduction mechanism. Mechanical impedance measurements were also carried out to achieve an estimation of the Young Modulus of the mixtures studied [7]. These measurements were compared with those obtained in accordance to international standards [8].

Besides the dynamic stiffness and mechanical impedance tests, the sound absorption coefficient [9, 10,] and the intrinsic parameters [11] of the mixtures studied have been assessed in order to achieve an acoustic study of the mixtures.

2 Experimental Set-up

2.1 Dynamic stiffness and mechanical impedance measurements

Dynamic stiffness has been achieved by means of the non-resonant method [12] directly on the upper face of the samples studied. The experimental set-up was composed of an impedance head which record the movement and force signals, a dynamic exciter and amplifier. A multi-analyzer system was used to record the specimen response and to produce the Fast Fourier Transform (FFT) spectra of the dynamic stiffness. The equipment is governed by a laptop.

The dynamic stiffness (S) can be expressed in terms of complex numbers between the force (F) and the displacement (d) vectors of a tested surface.

$$S=\frac{F\ [N]}{d\ [m]} \tag{1}$$

The experimental set-up allows us to obtain the driving-point dynamic stiffness, since the displacement of the tested surface is measured at the point of application of the driving force. Therefore, the dynamic driving-point stiffness is measured. The samples have been tested by application of a random signal generated by the dynamic exciter, between 10 Hz and 6.4 kHz.

The mechanical impedance function was achieved from the dynamic stiffness function, since mechanical impedance (I) can be expressed as Force (F) versus velocity (v) evaluated on sample surface.

$$I=\frac{F\ [N]}{v\ [m/s]} \tag{2}$$

And the velocity of the tested surface can be achieved from the displacement (d).

$$v = j\omega d \tag{3}$$

Where $\omega = 2\pi f$, and f is the frequency of vibration.

2.2 Acoustic absorption

In the case of a dense pavement, the incident sound wave is reflected and little energy is absorbed. On the contrary, for porous surfaces, part of the energy is absorbed by heat conversion. The acoustic absorption coefficient (α) is defined by the relation (Eq. 4) between the incident acoustic energy ($E_{incident}$) and the absorbed acoustic energy ($E_{absorbed}$) by the surface (without return).

$$\alpha = \frac{E_{absorbed}}{E_{incident}} \tag{4}$$

The acoustic absorption coefficient value depends on the one hand on the facility of the wave to enter the material pores and on the other hand on the friction with the internal surface structure, which participates in the sound energy dissipation [13]. It is believed that in porous mixes with interconnected air void net, the noise reduction is essentially caused by suction, reflection and dispersion inside the pores [14].

To evaluate the acoustic absorption of compacted core samples, an impedance tube was employed. The impedance tube allowed measurement between 50 Hz and 1600 Hz. Sound plane waves are generated inside the tube and two microphones at fixed locations measure the sound wave pressure of the travelling waves inside the tube. A multi-analyzer system was used to obtain the normal incidence acoustic properties of the sample. Sound absorption was determined over the extended frequency range with a resolution of 2 Hz and with 100 spectrum averages at the microphone position.

2.3 Mixture intrinsic properties

Various researchers carried out different studies on sound absorption to evaluate the acoustic behaviour from different pavements [15-18]. One of the most important aspects of the pavement acoustic behaviour is the pavement energy absorption generated by the tire/road interaction. This absorption is directly related to internal characteristics such as porosity (Ω), tortuosity (q^2) or static airflow resistivity (R).

Porosity (Ω) for a determined volume is defined by the ratio between the volume of air contained in the cavity and the total volume. It is a key parameter with an important role in acoustic propagation in porous medium that can be related to air void content (*AVC*), as follows in Equation 5 [19].

$$\Omega = \frac{AVC}{1+AVC}, 0 < \Omega < 1 \tag{5}$$

Tortuosity is defined by the ratio of actual length of pore channel to overall length of sample; this is the sinuosity of the actual flow path in a porous medium. It is directly related to shape of the pores and the cross section variation along the pore length, as to the existence of collateral ramification [20].

Tortuosity can take low values ($q^2 = 1$) for porous materials with pores aligned, and high values ($q^2 = 4$) for porous media with high resistivity [21].

Finally, porous material static airflow resistivity (R) indicates, indirectly, some of its structural properties. It can be used to establish correlation between material structure and some of its acoustical properties.

If the resistivity is too high, sound wave cannot easily enter the medium. If it is too low, there is not enough friction to dissipate sound energy significantly. For acoustical materials, the range of values for the static airflow resistivity is approximately 10^3 to 10^6 ($N.s.m^{-4}$).

2.4 Hamet/Bérengier model

The propagation above porous ground used in this model is described in [22]. This phenomenological model considers that the material structure could be assimilated to a rigid skeleton formed by the material aggregates, cracks in the rigid skeleton are filled with air, where the acoustic wave propagates, with an energetic degradation process due to viscous and thermal loss. The structural properties of acoustic material determine air fluid behaviour inside the material. Adjusting the model to absorption measurements using the least square method allows the obtaining the intrinsic parameters.

3 Mixtures studied

This work is focused in the study of different mixtures type BBTM 11 A according to EN-13108-2 with a maximum aggregate size of 16 mm. The air void content in the mixtures was around 20 % (E 12697-6), whereas the apparent density was around 2.0 g/cm^3. Moreover, the stiffness of the mixtures was achieved by the Standard 12697-26 [8].

The mixtures studied are divided in two groups. The first one was constructed with polymer modified bitumen (BM3c), whereas the second one has high viscosity modified bitumen manufactured with crumb rubber (BMAVC according to Spanish specifications [23]). The bitumen percentage used to manufacture the mixture was between 4.5 % and 6 % of the total mix weight. The samples were manufactured with 100 mm in diameter and 38 mm in height. Table 1 shows the main characteristics of the samples studied. The bitumen and air void content considers the weight of the aggregates and the weight of the total mix respectively.

Sample	**7.3**	**8.3**	**10.3**	**11.3**	**13.3**	**14.4**
Bitumen		BM3c			BMAVC	
Bitumen content (%)	4.5	5.5	6.0	4.5	5.5	6.0
Air void content (%)	21.2	20.1	20.7	21.8	21.1	21.5
Apparent density (kg/m^3)	1965	2021	1970	1963	1938	1975
Stiffness (MPa)	1780	1716	1501	3718	4054	4456

Table 1: Characteristics of the mixtures studied.

4 Experimental results and discussion

4.1 Dynamic Stiffness

The experimental set-up employed to determine the dynamic stiffness is shown in Figure 1. After testing the samples, dynamic stiffness can be plotted as a function of the frequency. The dynamic stiffness spectra of the six samples texted are shown in Figure 2.

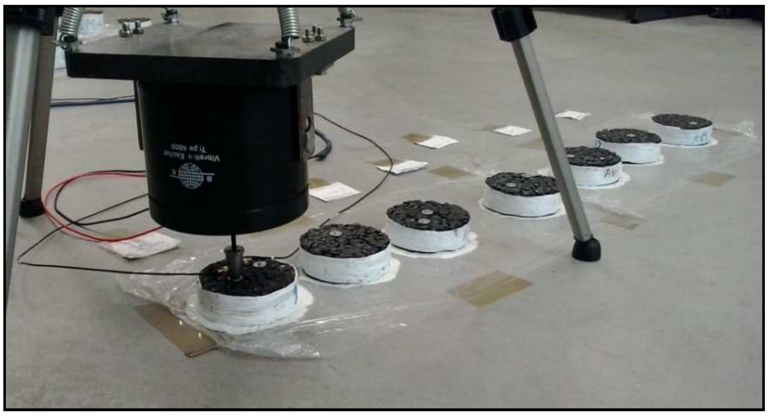

Figure 1: Experimental set-up for dynamic stiffness assessment and samples studied.

As shown in Figure 2, dynamic stiffness is greater with increasing frequencies until it reaches an asymptotic value at frequencies near to 1 kHz. From this figure, it can be concluded that dynamic stiffness of the different samples is very similar. They have approximately the same gradient at low frequencies; likewise the function value at higher frequencies (1 kHz) is rather similar.

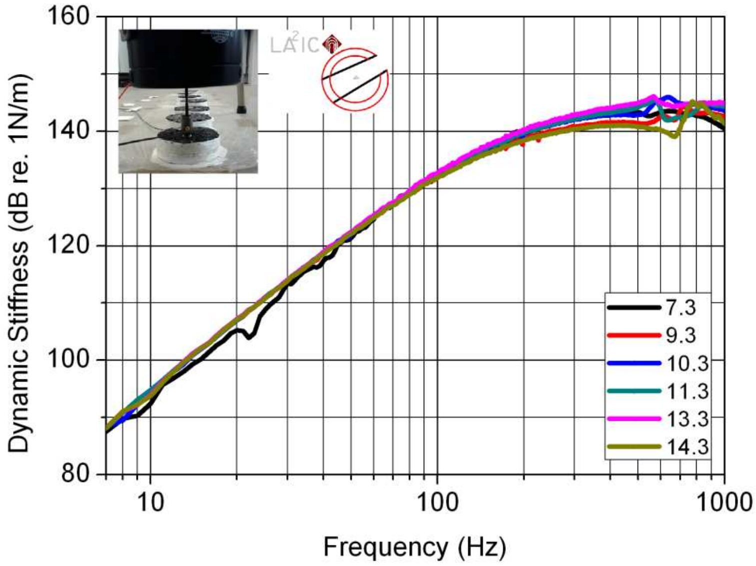

Figure 2: Dynamic stiffness spectra of the BBTM 11 A samples studied.

Between 2 kHz and 3 kHz takes place a leap in the dynamic stiffness function, this leap is thought to be due to the support conditions of the specimens, since the samples studied were fixed to the concrete floor of the laboratory by means of a thin plaster layer. This layer allows compensating superficial irregularities of the samples, avoiding undesired vibrations. Figure 3 shows the coherence function and the angle phase of one of the six samples tested (sample 10.3). As it can be seen, at 2.5 kHz a resonance phenomenon occurs. This fact affects the dynamic stiffness spectra, thus, frequencies between 2 and 3 kHz has not been taken into account in this study. This behavior was observed in every sample studied.

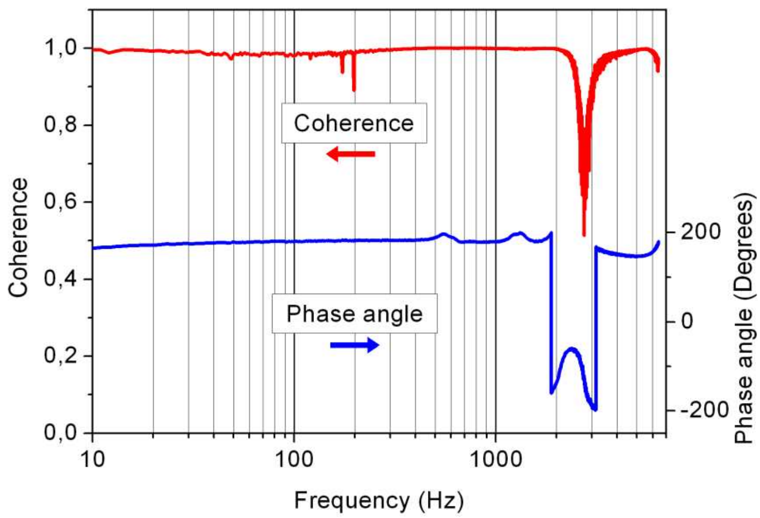

Figure 3: Coherence and angle phase spectra of one of the samples studied.

According to Figure 3, a good correlation between the force and the movement signals exists up to 1 kHz, where the dynamic stiffness function has been plotted. A good correlation between both signals, force and motion, is also achieved above 4 kHz. This behavior at high frequencies could be used by a theoretical model to get the Complex modulus (stiffness) of the tested materials. The study of the dynamic behavior of the samples at high frequencies could distinguish their complex modulus, and it is an assessment of the reliability of the dynamic stiffness measurements at low frequencies (up to 1 kHz).

4.2 Complex modulus estimation

The Complex modulus of the samples studied, with different content and type of bitumen is determined in this section. First, the mechanical impedance spectrum is obtained from the dynamic stiffness measurements carried out. Second, the mechanical point impedance spectrum may be determined from a Rayleigh-Wave model, according to Huebelt et al. [7]. An iterative method is used to fit both spectra curves. The fitting procedure is based on the minimization of an objective function.

The mechanical impedance fitting and measured have been plotted only for 10.3 and 13.3 mixtures, (BM3c and BMAVC respectively), although the estimation procedure is the same for every sample studied (Figure 4).

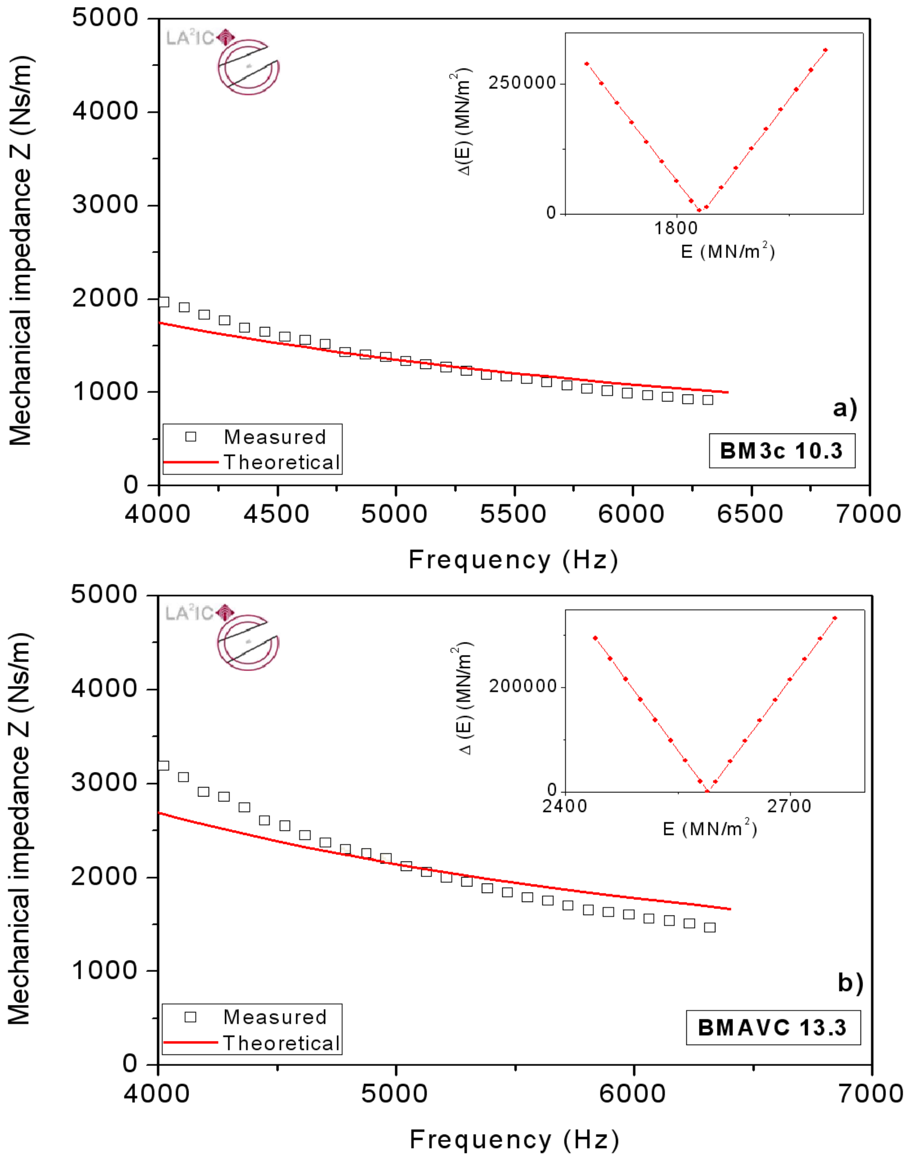

Figure 4: Mechanical impedance (magnitude); a) BM3c 10.3 y b) BMAVC 13.3, and fitting curve.

The behavior of the samples at high frequencies was presented, since at these frequencies, there are not resonance effects. The Young's moduli (E) of the mixtures studied that minimize the difference between the mechanical impedance measured and the theoretical curve are shown in Table 2. The temperature of the samples was 25 ºC. The apparent dynamic stiffness (EN 12697-26) is also shown in this table.

Sample binder	*E* (MN/m^2) Rayleigh-wave	*E* (MN/m^2) 12697-26
BM3c 7.3	2016	1780
BM3c 9.3	1596	1716
BM3c 10.3	1833	1501
BMAVC 11.3 (NFU)	2357	3718
BMAVC 13.3 (NFU)	2590	4054
BMAVC 14.3 (NFU)	3534	4456

Table 2: Young's moduli for the tested samples.

As it can be seen in Table 2, the stiffness of the samples with polymer modified binders is better represented by the model presented in this work than the samples with crumb rubber powder. Nevertheless, the dynamic stiffness modulus of these samples is higher than those achieved from the mixtures with polymer modified binder. On the other hand, the binder content of the mixtures influences the stiffness results, although this behavior has not observed so clearly in the mixtures with BM3c binder. Figure 5 shows the comparison between the complex modulus achieved by the Rayleigh-wave model and the 12697-26 international standard.

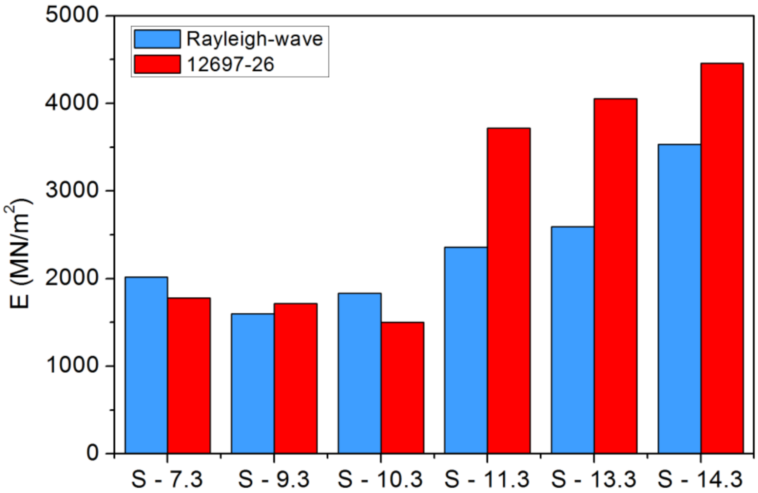

Figure 5: Complex modulus E by the Rayleigh-wave model and the International Standard 12697-26

4.3 Acoustic absorption measurements

The acoustic absorption coefficient of the mixes studied has been measured by means of the impedance tube. The results are shown in Figure 6. Every sample has a similar behavior. The absorption coefficient is low for low frequencies, whereas, around 600 – 700 Hz, a maximum value exists in the absorption coefficient. It is maybe due to the high void content of the mixtures. The maximum value is lower than 0.4.

The absorption mechanisms of the different samples studied (with crumb rubber, polymers, and different bitumen content) produce different tire/road noise levels, according to the results achieved in this work. It seems that mixtures with crumb rubber (BMAVC) have absorption peaks at higher frequencies than mixtures with polymer modified binder (BM3c).

The absorption coefficient measurements have been used in this work for the determination of the intrinsic parameters of the samples studied. The intrinsic parameters are shown in the next section.

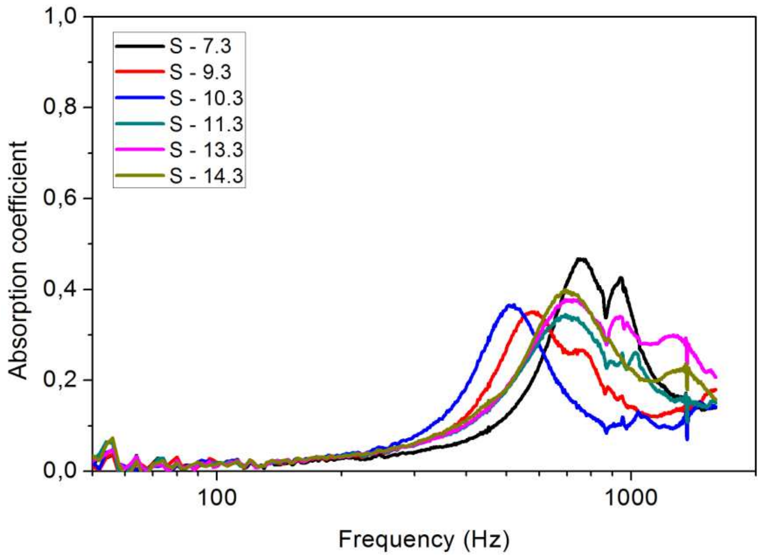

Figure 6: Normal incidence acoustic absorption spectra of the samples studied.

4.4 Intrinsic parameters

The optimisation model has been applied to both, samples with polymer modified bitumen and samples with high viscosity modified bitumen with rubber. The results are better with the sample with high viscosity bitumen presenting a higher dynamic stiffness. Figure 7 shows part of the results comparing the optimization for both types of samples.

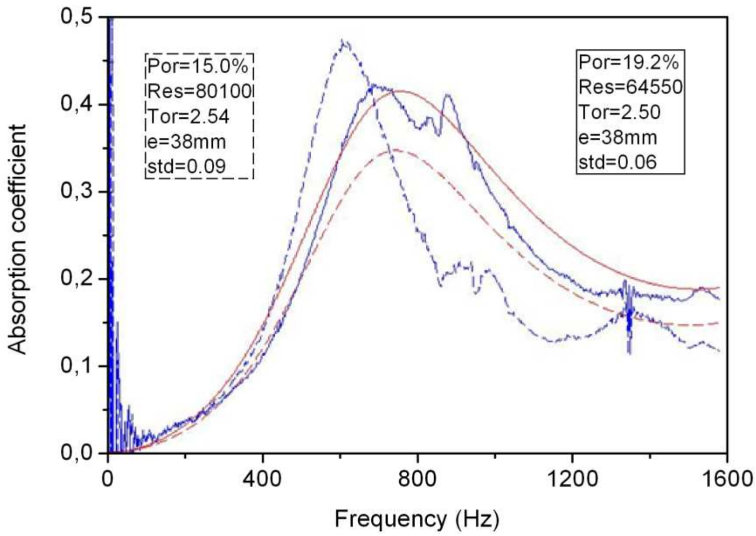

Figure 7: Adjustment curves with (full line) and without (dash) high viscosity binder with crumb rubber.

Table 3 resumes the results concerning the intrinsic parameters. Measurements have been realized on both faces of the sample (upper and lower) to observe any influence of the direction of compaction.

Type	Binder Content (%)	α_{max} (d.u.)	f (Hz)	Air flow Resistivity R ($N.s.m^{-4}$)	Tortuosity q^2 (d.u.)	Porosity Ω (%)	AVC (%)	Sample
PolymerMod. Binder (BM3c)	4.5	0.47	745	60100	2.37	13.7	21.2	7.3 l
	4.5	0.47	615	80100	2.54	15.0	21.2	7.3 u
	5.5	0.35	603	157100	2.35	11.0	20.1	9.3 l
	5.5	0.34	555	152200	2.33	13.0	20.1	9.3 u
	6.0	0.35	503	264900	2.12	14.0	20.7	10.3 l
	6.0	0.36	519	280000	2.11	13.7	20.7	10.3 u
High visc. Binder (BMAVC)	4.5	0.34	597	145500	2.31	13.0	21.8	11.3 l
	4.5	0.34	701	91050	2.52	14.3	21.8	11.3 u
	5.5	0.38	713	88850	2.31	19.3	21.1	13.3 l
	5.5	0.42	709	64550	2.50	19.2	21.1	13.3 u
	6.0	0.40	703	85300	2.48	17.3	21.5	14.3 l
	6.0	0.42	759	69900	2.49	15.9	21.5	14.3 u

Table 3: Intrinsic parameters (u = upper face; l = lower face).

It appears that a more rigid sample those with high viscosity binder or few polymer-modified binder (sample 7.3) gives better adjustment (in black in the table) between the modelled and measured curves. Those samples present an airflow resistivity in the range of [60000-92000] $N.s.m^{-4}$. The type of binder and the direction of compaction seem to have no influence on the tortuosity and the porosity. Regarding the peak of appearance of the maximum absorption, the specimens with high viscosity binder absorb at slightly higher frequencies that the specimen with conventional binder.

5 Conclusions

Pavement stiffness could be an important factor in rolling noise. On the other hand, crumb rubber seems to be a good option in order to achieve pavements with improved characteristics, and to reduce environmental pollution due to the end-of-life tires. Thus, this work studies the influence of the samples with crumb rubber added by wet process, respect to pavements with polymer modified binder. Different bitumen content has been also studied. Moreover, the intrinsic parameters of the samples studied have also been achieved. The main conclusions that can be derived at this stage are as follows.

At low frequencies, dynamic stiffness differences between the mixtures studied have not found. These mixtures have different characteristics, but these differences do not produce different dynamic stiffness spectra at low frequencies. The sound generation mechanisms related with dynamic stiffness do not seem to influence the overall tire/road noise levels.

From the mechanical impedance measurements, at high frequencies, the Complex Modules of the samples studied have been achieved by an iteration model. The values achieved agree with those achieved by the international standards: mixtures with crumb rubber are stiffer than those without crumb rubber. Although, the differences found by the iteration model are lower than those of the international standard. Maybe that is due to the small differences between the mixtures analyzed.

The acoustic absorption coefficients of the samples studied were measured with an impedance tube. The highest absorption coefficients took place around 600 -700 Hz (0.4) Thus, this mechanism could have an important role in the attenuation of the tire/road noise levels generated.

According to the intrinsic parameters, differences between the mixtures with polymer modified binder and the high viscosity binder with crumb rubber were found. Mixtures with crumb rubber seem to have less air flow resistivity and more tortuosity and porosity. The intrinsic parameters of these mixtures displace the absorption peak to higher frequencies. BMAVC mixtures could have higher complex modulus, but the absorption behavior of these mixtures, at high frequencies, could affect the dispersion of the noise generated by the tire/road contact, thus, the overall tire/road noise of the BMAVC mixtures studied could be reduced.

Acknowledgements

This work was partially supported by the Spanish Ministerio de Economía y Competitividad (MINECO) and FEDER, in the framework of the project BIA 2012-32177. The authors also wish to thanks CDTI and ELSAN for their valuable assistance throughout the project CENIT2007-1014 (FENIX).

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