Low-noise road mixtures for electric vehicles

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Abstract

The road pavements of the future should be designed to take into account the variation of the traffic noise due to traffic increase and electric vehicles (EVs) diffusion. Indeed, EVs are very different from internal combustion engine vehicles. Importantly, they could be quieter than traditional vehicles at low frequencies, but could be noisier at high frequencies. This study aims at presenting the acoustic and mechanical performance of two asphalt concretes that were designed to reduce the problem mentioned above. In more detail, an experimental investigation was carried out to test samples of asphalt concretes with low nominal maximum aggregate sizes, with and without crumb rubber, added applying the dry method. A gyratory compactor was used to make the samples and acoustic and mechanic properties were tested. Results show that mechanistic-related strategies such as the addition of crumb rubber could improve the acoustic performance. Consequently, there is probably room for improving design criteria.

Keywords: traffic noise, electric vehicles, low-noise road mixtures, acoustic and mechanical performances, crumb rubber.

1 Introduction

The diffusion of the electric vehicles (EVs) will change the current characteristics of traffic noise. Consequently, the road pavements of the future should be designed to take into account the aforementioned variation.

As is well known, the noise produced by vehicles mainly refers to propulsion engine (especially for speeds lower than 40 km/h), and to tyre-road interaction (e.g., for speeds greater than 40 km/h) [1, 2, 3]. Hence, designers are trying to act on both the sources mentioned above. On the one hand, mechanical engineers and acoustic physicists are working on characterizing and minimizing the noise produced by vehicle engines and tyres (of EVs and Internal Combustion Engine Vehicles, ICEVs). On the other hand, road and environmental engineers are working on the development of road surfaces that minimize the noise produced by tyre-road interaction, and on other solutions (e.g., noise barriers) to isolate the Noise Sensitive Receptors (NSRs) from traffic noise. Regulations and directives to control and minimize traffic noise were enacted. These official prescriptions provide advices and guidelines that aim at protecting the environment and the NSRs from the pollution due to noise and address problems related to the quietness of the EVs. For instance, the Directive 70/157/EEC and the UNECE Regulation 51 [4] address the type-approval of motor vehicles in relation to permitted noise levels both under moving and stationary conditions. In particular, these two documents include procedures for noise measurement (e.g., noise emitted by EVs must only be measured in motion) and report admitted noise limits (e.g., for eight categories of vehicles, including both passenger vehicles and goods vehicles, the limits currently range from 74-80 dB(A)). In more detail, the test procedures defined in the UNECE Regulation 51 are those defined in the following ISO standards: 1) ISO 362:1998 (i.e., moving vehicle test 1 of the Regulation above). This standard has been withdrawn and currently two standards are given: ISO 362-1:2015 - Measurement of noise emitted by accelerating road vehicles — Engineering method — Part 1: M and N categories and SO 362-2:2009 - Measurement of noise emitted by accelerating road vehicles — Engineering method — Part 2: L category. 2) ISO 5130:2007 (i.e., stationary vehicle test of the regulation above). This standard has been revised by ISO 5130:2019 Acoustics — Measurements of sound pressure level emitted by stationary road vehicles. In addition, the assessment and the management of environmental noise in Europe is regulated by the EU Directives 2002/49/EC, and 2015/996/EC, and by the Common NOise aSSessment methOdS (CNOSSOS-EU). In more detail, the CNOSSOS-EU aims at improving the reliability, consistency and comparability of noise assessment results by means of noise mapping of road, railway, aircraft, and industrial noise [5]. Whereas, to face the problems related to the excessive quietness of the EVs, the Commission Delegated Regulation (EU) 2017/1576 mandates that, since 1 July 2021, all new types of electric and hybrid cars must be equipped with the acoustic vehicle alerting system (AVAS). This latter will automatically generate a sound for speeds lower than 20 km/h, and during reversing [6, 7].

Since EVs have a different type of propulsion engine with respect to ICEVs, the frequency components of the noise produced by EVs are different, i.e., EVs are quieter than ICEVs at low frequencies, but could be noisier at high frequencies. These results can be derived from the study related to the LIFE E-VIA project (LIFE18 ENV/IT/000201) (see e.g., [8, 9, 10]).

Several asphalt concrete mixtures were designed to reduce traffic noise acting on the tire-road interaction. Krag et al. (2013)[11] reported results of the application of the Close ProXimity (CPX) method on a multitude of road pavements (i.e., Asphalt Concrete, AC, Stone Mastic Asphalt, SMA, Ultra-Thin Layer Asphalt Concrete, UTLAC, etc. with different Nominal Maximum Aggregate Size, NMAS). Based on this latter study, AC6o (i.e., open AC mixture with NMAS equal to 6 mm) resulted the quietest mixture (L_{CPX} of about 89 dB(A) using the SRTT reference tyre and moving at 50 km/h; L_{CPX} of about 93 dB(A) using the SRTT reference tyre and moving at 80 km/h) among those mentioned above (L_{CPX} = 89-96 dB(A) and L_{CPX} =93-102 dB(A) considering the two reference speeds mentioned above). Kowalski et al. (2016)[12] presented the results of the CiDRO project, where asphalt concrete AC 11 (reference), stone mastic (matrix) asphalt SMA 5 and SMA 8, open graded friction course OGFC 8 and OGFC 11, porous asphalt PA8 and PA11 were considered as noise reducing solutions. PA8 (air voids of about 22–24%) and OGFC 8 (air voids of about 14%) resulted the most performing (for Polish climate conditions) for the high-speed roads located outside the cities, and the urban roads, respectively. Kleiziene et al. (2019)[13] measured the noise (CPX method at 80 km/h) from 18 low-noise pavements consisting in asphalt concrete mixtures belonging to the classes SMA, AC, PA, a low noise asphalt mixture called TMOA, soft asphalt (SA). The CPX level ranged from 95.1 to 98.8 dB(A). Ling et al. (2021)[14] concluded that the following mixtures have good noise reduction performance 1) Porous asphalt pavement (PA; Air void content, AV = 15-20%; noise reduction = 3-6 dB(A); sound absorption peak = about 0.7 at 1000 Hz). 2) Rubber asphalt pavement (RAP; vertical vibration reduction of tires = 9.67%; Attenuation of vibration = 20%-25% greater than that of ordinary asphalt pavement; noise reduction = 1-10 dB(A)). 3) Ultra-thin wearing course (UTWC; consisting of gap-graded asphalt mixtures and emulsified asphalt; with a thickness of 20-30 mm; with NMAS=4.75-9.5 mm; noise reduction = 2.9 dB(A)). 4) Porous elastic road surface (PERS; consisting of rubber particles, asphalt mixture and polyurethane resin; with porosity = 20-40%; rubber content of about 20% volume of the total asphalt mixture or 1%-3% weight of the total asphalt mixture; noise reduction = 6-13 dB). 5) Stone mastic asphalt pavement (SMA; consisting of gap-graded skeleton dense asphalt mixture with voids filled with asphalt binder, stabilizer and finer aggregate; AV=3-8%; sound absorption peak = about 0.3 at 800 Hz). 6) Porous Ultra-Thin Overlays (PUTO; consisting of the combination of PA and UTWC. They allow for significant sound absorption in the frequency range 250-1250 Hz; good tire-road noise reduction and skid resistance). 7) Three-layer pavement structure (TLPA; consisting of the first two top layers with a thickness of 30 mm, and the third lower layer with Helmholtz-like cavities). 8) Helmholtz type porous asphalt (HPA; reduce 3 dB(A) noise more than double-layer porous asphalt pavement). 9) Curling Prefabricated Noise Reduction Pavement (CPNRP; two-layer pavement consisting of the combination of the rolled prefabricated pavement called "Rollpave" and an emulsified asphalt, with significant sound absorption frequency is 300-

1300 Hz; reduces tires-road noise). Praticò et al. (2020) [15] studied the correlation between surface and volumetric properties (e.g., acoustic absorption, drainability, texture, and friction), and found that these properties are linked to intrinsic factors (e.g., gradation and bitumen content) and extrinsic factors (e.g., traffic load), and decay over time (reduction of friction and high-frequency acoustic absorption). Finally, they proposed an experimental method to design porous asphalts to account for the aforementioned correlations and factors. Vázquez et al. (2020)[16] reported that traffic noise levels at high frequencies can be attenuated by reducing the dynamic stiffness (or mechanical impedance) road pavements. Praticò et al. (2021) [17] found that the addition of crumb rubber can contribute to lowering the mechanical impedance, the dynamic stiffness, and the acoustic response of the dense asphalt concrete mixtures (AC6d).

The remaining part of this paper is organized as follows. Section 2 reports the main objectives of the study and the tasks that were carried out to achieve the objectives mentioned above. Section 3 focuses on methods. Section 4 refers to the description of the experimental investigation. Section 5 shows the results of the study and the related discussions. Section 6 summarizes the main conclusions.

2 Objectives

This study aims at presenting the acoustic and mechanical performances of two mixtures that were designed to reduce the problems related to traffic noise due to traffic increase and EVs diffusion.

Based on the results of the literature review carried out in the section above, an open Asphalt Concrete (AC) with Nominal Maximum Size Aggregate (NMAS) of 6 mm (herein called AC6) was selected as reference mixture. Subsequently, two mixtures, i.e., an AC6* (without treated crumb rubber, TCR), and an AC6** (with TCR) were designed. In more detail, a treated crumb rubber termed RARX was used. Finally, the following tasks were carried out to achieve the aforementioned objectives: Task 1) Design of the experimental investigation. Task 2) Design of the mixtures and creation of the samples with and without TCR. Task 3) Testing of samples with and without TCR. Task 4) Analysis of the results.

3 Method

3.1 Task 1: Design of the experimental investigation

An experimental investigation was designed. Two types of mixtures (AC6* and AC6**) and three percentages of bitumen per mix type were considered. Table 1 provides an overview of the main scheduled tests.

Table 1 – Tests to carry out.

Test	Parameter	Unit of measure	Standard	Ref.
Dimensional Analysis	Thickness (t) Diameter (D)	mm mm	UNI EN 12697-36 N/A	[18] N/A
Macro-texture	Mean texture depth, (SH=MTD)	mm	UNI EN 13036-1 ASTM E965-15	[19, 20]
Micro-texture	Pendulum Test Value (PTV)	dimensionless	UNI EN 13036-4	[21]
Volumetrics	Weight (W) $G_{mbCorelok}$ AV_G	g dimensionless %	N/A ASTM D6752 / D6752M ASTM D6857 / D6857M ASTM D6925 – 15	N/A [22] [23, 24]
Mechanical response	Mechanical Impedance (MI) Dynamic Stiffness (K)	N×s/m N/m	UNI EN 29052-1	[17, 25, 26]
Acoustic response	Road Acoustic Response (RAR)	dB related to 20 µPa	N/A	[17]

Symbols. AVG = Air void content as an effect of gyratory compaction. MI = Mechanical Impedance measured using the impact hammer test. RAR = Road Acoustic Response measured using the impact hammer as source and a microphone as receiver.

3.2 Task 2: Design of mixtures and production of the samples with and without TCR

Two asphalt concrete mixtures were tested, i.e., an AC6* (without treated crumb rubber, TCR), and an AC6** (with TCR). Several samples were produced using the gyratory compactor. The following table (Table 2) summarizes the main features associated with the six samples selected for this study and with their compaction. Figure 1 shows the samples produced during this study.

Table 2 – Samples' compaction and features.

Type of mixture	**Sample ID**	**Bitumen by mix weight [%]**	**TCR by mix weight [%]**	**Gyratory compactor revolution number**	**Sample dimensions (thickness × diameter) [mm × mm]**	**Sample weight [g]**	**G_{mb_DIM} [-]**
AC6*	**AC6o_3%B_0%TCR_21**	3.2	0.0	210	117.4 × 97.5	2066.09	2.36
AC6*	**AC6o_5%B_0%TCR_22**	5.2	0.0	210	117.2 × 97.5	2109.57	2.41
AC6*	**AC6o_7%B_0%TCR_23**	7.2	0.0	210	119.6 × 97.5	2154.78	2.41
AC6**	**AC6o_3%B_2%TCR_24**	3.0	2.0	210	123.7 × 97.5	2105.22	2.28
AC6**	**AC6o_5%B_2%TCR_25**	5.0	2.0	210	107.0 × 97.5	2151.30	2.39
AC6**	**AC6o_7%B_2%TCR_26**	7.0	2.0	210	123.9 × 97.5	2198.26	2.36

Symbols. AC6 = Asphalt Concrete with Nominal Maximum Aggregate Size of 6 mm. 3%B = Percentage of bitumen of 3% (w/w by the total weight of the mixture). 0%TCR = Percentage of TCR of 0%. G_{mb_DIM} = Bulk Specific Gravity calculated considering the characteristics of the sample (dimensions and weight).

Importantly, because of the fact that the dry process was used to incorporate the TCR into the mixtures, the percentage of TCR was maintained constant at 2%, while the percentage of bitumen was varied between 3% and 7%, approximately. Note that 1) The gyratory compactor revolution number was maintained constant for all the samples (i.e., 210). 2) The presence of the TCR seems to negatively affect the in-lab compaction level of the samples (cf. G_{mb_DIM}).

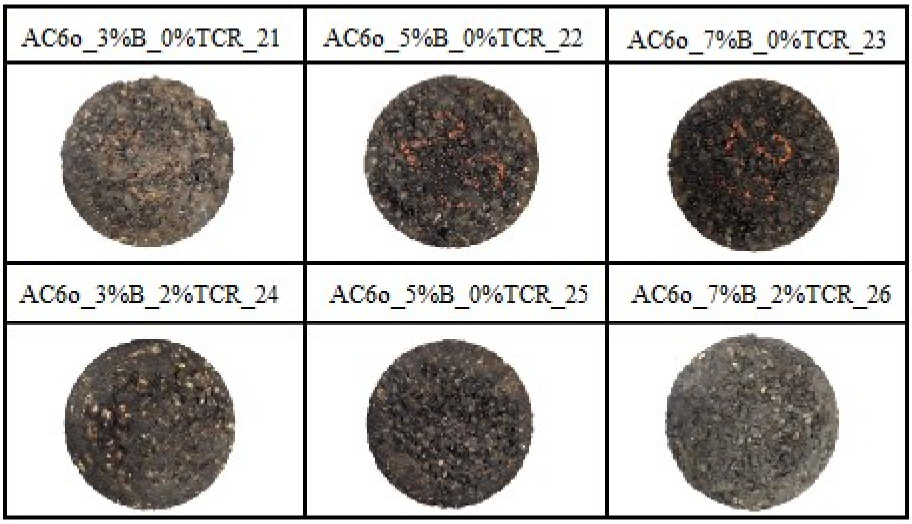


Figure 1 – Upper surfaces of samples.

4 Experimental investigation

4.1 Task 3: Testing on samples with and without TCR

Six samples (with or without TCR) were tested in order to estimate the parameters listed in Table 1 and 3. The following figure shows the main devices. Note that the method and the system used to measure both mechanical and acoustic responses of the samples tested in this study is the same described in [17].

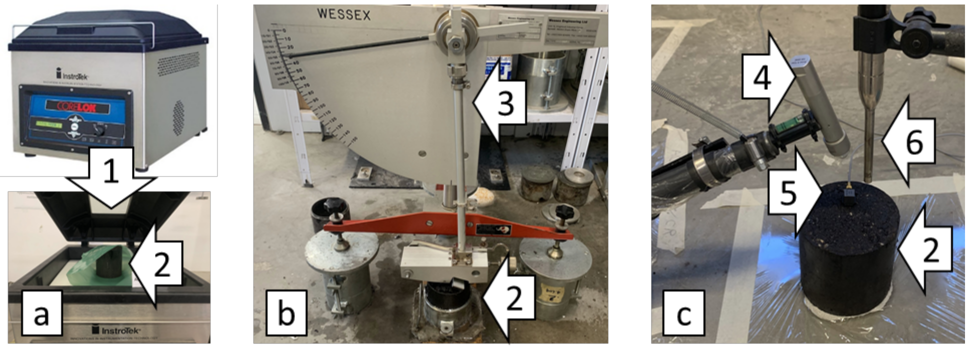


Figure 2 – Main devices.

Notes. 1: Corelok machine. 2: Samples. 3: Pendulum tester. 4: Impact hammer. 5: Accelerometer. 6: Microphone.

5 Results and discussions (Task 4)

The results of the study are shown below (Tables 3-6 and Figures 3-5). In particular, Table 3 reports the mechanical and acoustic characterization of the samples under investigation.

Table 3 – Samples' main properties.

Sample ID	**AV_G [%]**	**MTD [mm]**	**PTV [-]**	**$G_{mb\_Corelok}$ [%]**	**MI_max [N×s/m]**	**K_max [N/m]**	**RAR_max [dB]***
AC6o_3%B_0%TCR_21	9.78	0.41	68	2.37	9.6 E+03	8.6E+07	56.20
AC6o_5%B_0%TCR_22	4.88	0.34	67	2.42	8.2 E+04	1.2E+08	50.34
AC6o_7%B_0%TCR_23	1.11	0.37	68	2.42	2.1 E+05	1.5E+09	51.73
AC6o_3%B_2%TCR_24	9.66	0.20	69	2.29	1.4 E+05	2.3E+09	52.31
AC6o_5%B_2%TCR_25	1.76	0.28	66	2.39	1.4 E+04	1.1E+08	55.13
AC6o_7%B_2%TCR_26	0.26	0.53	66	2.39	1.6 E+05	5.7E+08	48.77

Symbols. Sample IDs: see above. AV_G = Air void content as an effect of gyratory compaction. MTD = Mean Texture Depth. PTV = Pendulum Test Value. $G_{mb\_Corelok}$ = Bulk Specific Gravity measured using the Corelok machine. MI = Mechanical Impedance measured using the impact hammer test. K = Dynamic Stiffness measured using the impact hammer test. RAR = Road Acoustic Response measured using the impact hammer as source and a microphone as receiver.
* = Based on the results shown in Figure 4.

Figure 3 shows the spectra of the Mechanical Impedance (MI) and Dynamic Stiffness (K) of the six samples under test in the range 0-3200 Hz. Figure 4 shows the spectra of RAR for the six mixtures. In this figure 1) The frequency range is divided into four frequency sets, i.e., very-low (0-40 Hz), low (40-400 Hz), medium

(400-1600 Hz) and high (1600-3200 Hz) frequencies. 2) RAR values are expressed in Pascal and in dB. Figure 5 shows RAR spectra in the range 0-3200 Hz. In this figure 1) The frequency range is represented in 1/3 octave bands (a representation that is more detailed than the one in Figure 4). 2) RAR values are expressed in Pascal and in dB. Finally, Table 4 reports the Pearson coefficients of the parameters reported in Table 3, Table 5 reports the Pearson coefficients between RAR and MI and Table 6 reports the Pearson coefficients between RAR and K.

Table 4 – Pearson coefficients between the parameters reported in Table 3.

	$\mathrm{AV_G}$	**MTD**	**PTV**	**$\mathrm{G_{mb\_Corelok}}$**	**MI_max**	**K_max**	**RAR_max**
$\mathrm{AV_G}$	1.0	-0.5	**0.7**	**-0.7**	-0.3	0.2	0.5
MTD	-	1.0	-0.5	0.5	-0.2	-0.5	-0.4
PTV	-	-	1.0	-0.6	0.5	**0.7**	0.2
$\mathrm{Gmb_{Corelok}}$	-	-	-	1.0	0.0	-0.6	-0.2
MI_max	-	-	-	-	1.0	**0.8**	**-0.7**
K_max	-	-	-	-	-	1.0	-0.2
RAR_max	-	-	-	-	-	-	1.0

Table 5 – Pearson coefficients between RAR and MI.

RAR	**MI (0-40 Hz)**	**MI (40-400 Hz)**	**MI (400-1600 Hz)**	**MI (1600-3200 Hz)**
(0-40 Hz)	-0.42	-0.42	-0.35	0.15
(40-400 Hz)	***-0.80***	-0.47	-0.33	-0.10
(400-1600 Hz)	***-0.84***	***-0.82***	***-0.77***	-0.39
(1600-3200 Hz)	-0.39	-0.11	-0.06	-0.59

Table 6 – Pearson coefficients between RAR and K.

RAR	**K (0-40 Hz)**	**K (40-400 Hz)**	**K (400-1600 Hz)**	**K (1600-3200 Hz)**
(0-40 Hz)	-0.41	-0.46	-0.31	0.15
(40-400 Hz)	***-0.80***	-0.40	-0.31	-0.11
(400-1600 Hz)	***-0.83***	***-0.78***	***-0.76***	-0.39
(1600-3200 Hz)	-0.41	-0.01	-0.08	-0.60

Based on results, it is possible to state that:

- By referring to the effect of bitumen percentage for samples without TCR, the increase of the percentage of bitumen (from 3% to 7%) causes the reduction of the air void content (from about 10% to about 1%). When %B=5%, the average depth of pavement surface macrotexture, MTD has a minimum. A negligible effect on the skid resistance (PTV = 67-68) is observed. A slight increase of the bulk specific gravity (the $\mathrm{G_{mb\_Corelok}}$ varies from 2.37 to 2.42) is observed. A considerable reduction of the mechanical response (expressed in terms of MI and K) is observed. RAR reaches a minimum for %B=5%.
- By referring to the effect of bitumen percentage for samples with TCR, the increase of the percentage of bitumen seems to lead to the reduction the air void content (from about 10% to about 0.3%), while MTD increases, PTV decreases (from 69 to 66), and a slight increase of the bulk specific gravity is observed (the $\mathrm{G_{mb\_Corelok}}$ varies from 2.29 to 2.39). MI and K reach a minimum for intermediate values of asphalt binder percentage, while the corresponding RAR appears to have a maximum.

- Based on Table 4, strong correlations (Pearson coefficients of about ±0.7 and about ±0.8) are observed between the couples MI_max-K_max, MI_max-RAR_max, PTV-K_max, AV_G-PTV, and AV_G-$G_{mb\_Corelok}$. Moderate linear correlations (Pearson coefficients of about to ±0.5 and ±0.6) are observed between the couples PTV-$G_{mb\_Corelok}$, $Gmb_{Corelok}$-K_max, AV_G-SH, AV_G-RAR_max, MTD-PTV, MTD-$G_{mb\_Corelok}$, MTD-K_max, PTV-MI_max. At the same time, weak correlations (Pearson's coefficients of about ±0 and ±0.2) are observed among the remaining couples, except that for the couple MTD-RAR_max, where the Pearson coefficient is about -0.4.
- Based on Tables 5 and 6, strong negative correlations (Pearson coefficients in the range between -0.76 and -0.84) are observed between the road acoustic response (RAR@40-400 Hz) and the mechanistic response (MI and K).
- The effect of TCR on RAR appears quite questionable (cf. Figure 4 and 5). This could depend on the use of low percentages.

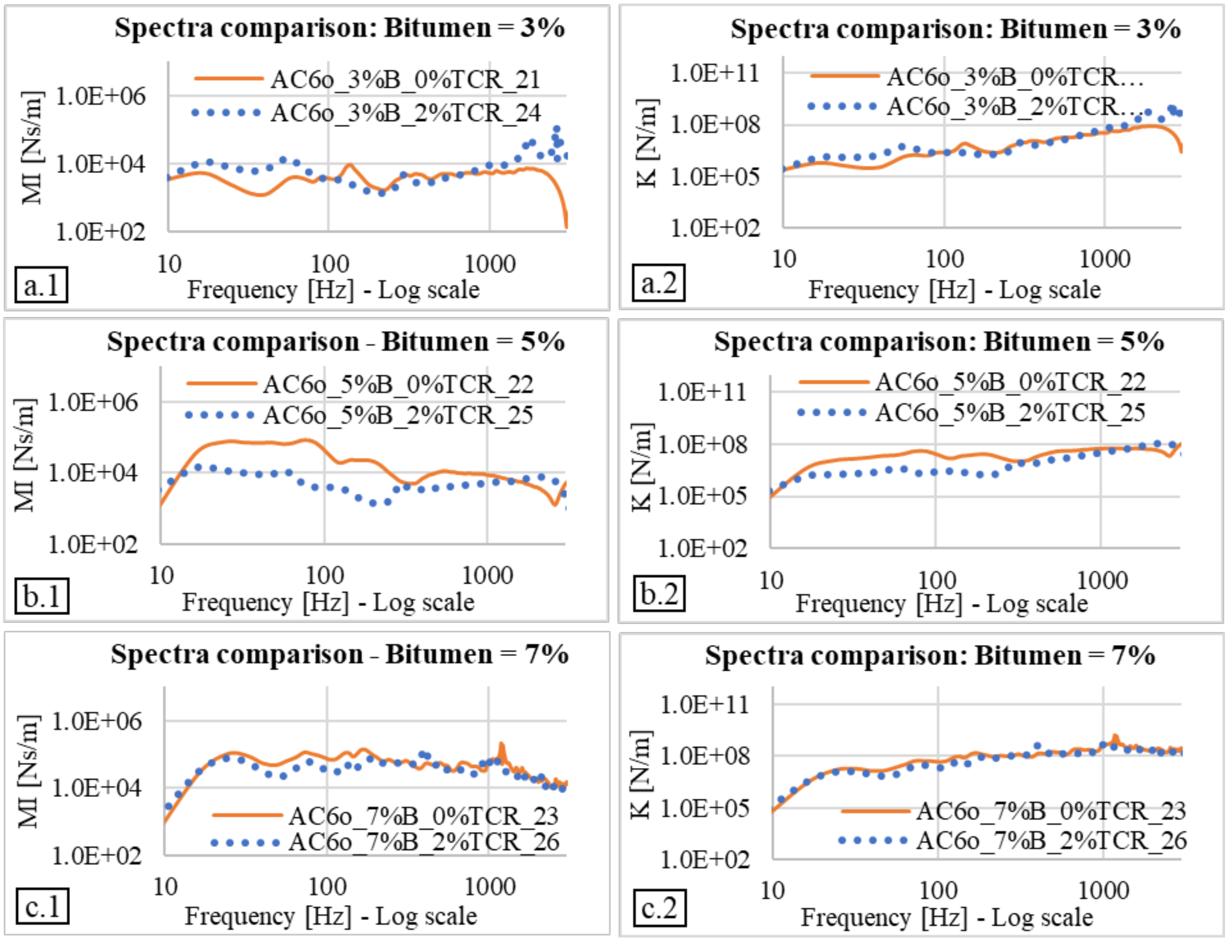


Figure 3 – Mechanical Impedance (MI) and Dynamic Stiffness (K) spectra.

Notes. TCR: treated crumb rubber. %B: percentage of bitumen.

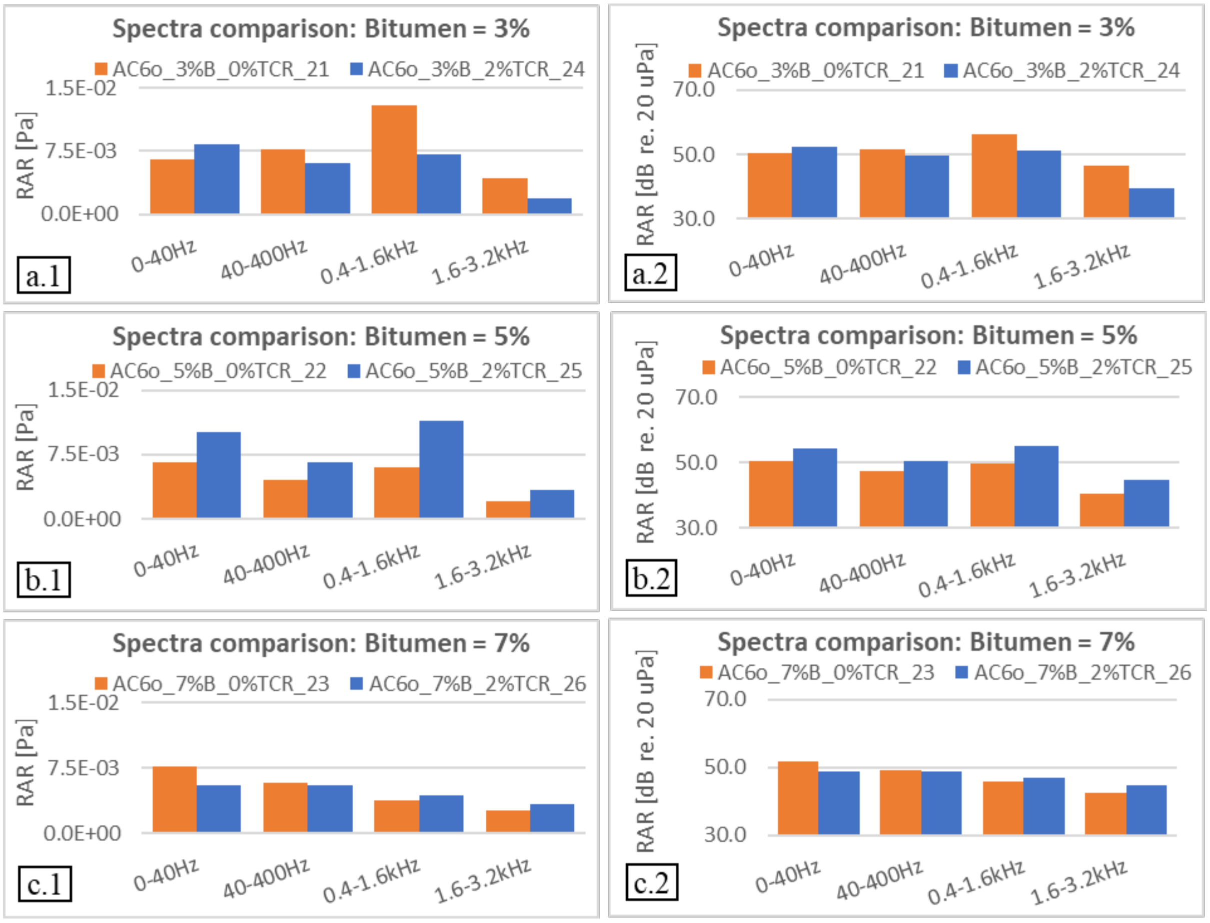
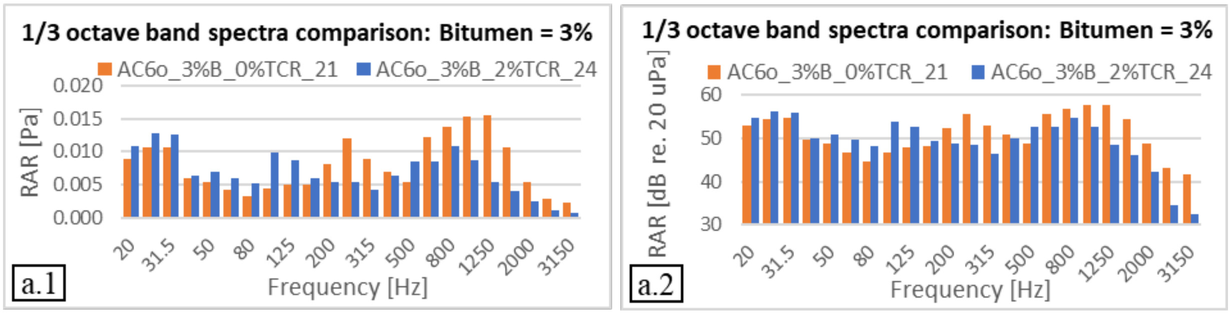


Figure 4 – Road Acoustic Response (RAR) spectra.

Notes. TCR: treated crumb rubber. %B: percentage of bitumen.



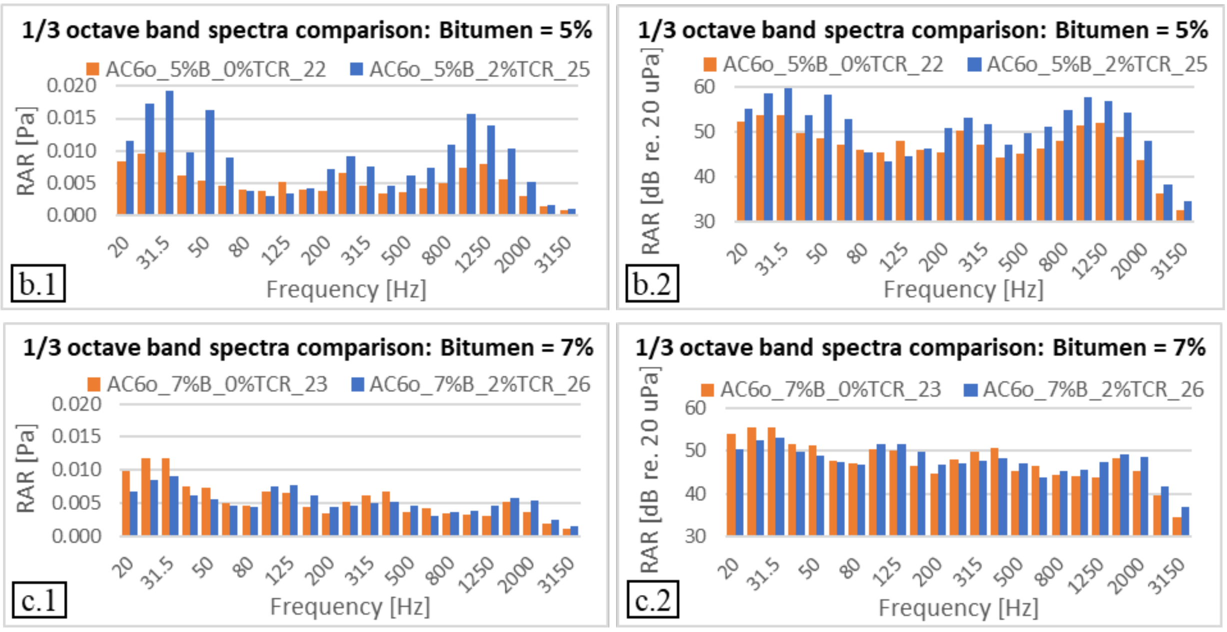


Figure 5 – Road Acoustic Response (RAR) 1/3 octave band spectra.

Notes. TCR: treated crumb rubber. %B: percentage of bitumen.

6 Conclusions

Future road pavements should face traffic increase and diversification towards EVs. This study aims at presenting the acoustic and mechanical performances of two asphalt concretes that were designed under the LIFE E-VIA project. Even if further investigations are needed, results show that there is a strong negative correlation between road acoustic response and mechanistic response. In more detail, the linear correlation between RAR (400-1600 Hz) and MI (for frequencies lower than 1600 Hz) appears to be strong and negative. Future works will focus on setting up a more robust factorial plan of experiments to investigate about RAR representativeness and about its negative correlation with the mechanistic response. This could unveil interesting perspectives when using higher contents of crumb rubber or/and using substitute or synergistic strategies.

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