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LIFE SOUNDLESS: New Generation of Eco-Friendly Asphalt with Recycled Materials

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Abstract: Noise pollution coming from traffic noise has become an important issue in urban areas. Road noise is one of the main sources of high-level traffic noise. Road noise depends not only on tires but on the pavement. Therefore, a study of mixture parameters should be performed to achieve good acoustic performance. Another important point which has to be taken into account is the acoustic performance durability. Gap-graded mixtures were selected for this project due to poor experiences with open-graded mixtures in terms of performance durability, where texture and clogging issues appeared a few years after paving. The LIFE SOUNDLESS project is seeking different ways to modify stone mastic asphalt mixes to improve the noise attenuation of pavements. A selection of mixes with different additives were created, where some waste materials were used. The selection of the best mixtures was done not only according to traditional mechanical parameters but also others, such as damping and dynamic stiffness. Once the best mixtures had been paved, the acoustic performances were measured several times to evaluate the performance durability. Several experimental methods like the close proximity (CPX) method and statistical pass by (SPB) method were used to check the sound generation and propagation of every pavement. The project was carried out on two roads overseen by the Junta de Andalucía in Seville (Spain). The difference between both roads was the traffic density and the average speed. The noise level has since been reduced by 3 dB and 7 dB on both sites.

Keywords: noise reducing pavements; road noise; CPX test; SPB test

1. Introduction

In 2002, the European administration established the need for noise maps and action plans for all owners of roads, railways, and airports to reduce noise pollution [1]. However, noise pollution continues to be a major issue in Europe. It is an important environmental issue, especially in urban areas where it affects a large number of people. Today, nobody questions the evidence on the relationship between environmental noise and its specific effects on health, such as cardiovascular disease, cognitive impairment, and sleep disorders [2]. Several epidemiological studies suggest that the increment in cardiovascular diseases is directly related to high exposure to noise levels (i.e., road and air traffic noise) [3].

Delving deeper into this idea, it is worth highlighting the results published in the Environmental Burden of Disease in Europe (EBoDE) project [4], which points to traffic noise as the second factor causing environmental stress. Moreover, it is remarkable that the trend is such that noise exposure has increased in Europe compared to other stressors (for example, exposures to smoke, dioxins, and benzene), which are decreasing.

In addition, learning impairment issues have been reported in several studies like Chetoni et al. [5] in the LIFE project GIOCONDA, which established some global noise score indicators for classroom evaluation of acoustic performances.

Road noise is one of the most significant noise sources in cities. It is highly dominated by road surfaces and tire condition. Several parameters from the road surface point of view, such as texture, mechanical impedance, and acoustic absorption are key to achieving a noise reducing pavement.

Sound pressure is a magnitude which is distributed in the field, wherein the level depends on the point where it is selected to be evaluated. To compare the acoustic performances of pavements, the microphone position and functional parameters have since been standardized. There are different methods that have been developed by the science community for this purpose.

The close proximity method (CPX) was designed to evaluate the sound generated by road surfaces using reference tires mounted on an approved test vehicle or trailer, with two microphone positions located near the tire-pavement contact zone [6]. This method allows measurement of the entire road in a continuous way, wherein, for every 20 m, a CPX index is assessed.

Several authors (including Licitra et al.) have studied the influence of tires on this test [7]. The ISO standard 11819-2 established that it is mandatory to carry out these tests with standardized tires as SRTT (standard reference test tires (ASTM)) for passenger vehicles and Avon tires for heavy vehicles. Moreover, several parameters have to be controlled during the test, such as air temperature, tire hardness, and speed. The CPX index is corrected depending on the deviation of these parameters.

The statistical pass by method (SPB) is applicable for the assessment of noise in traffic situations [8]. When road noise evaluation is being conducted, it is desirable that the average speeds of the vehicles start from 45 km/h and above. When this method is being used for the classification of surfaces, the contribution of the road surface should be dominant.

Several additives have been used as modified binders to improve the mechanical and thermal behavior, as well as the aging resistance. Some products include fibers and rubber polymers which are commercialized in the asphalt market. Some of them are currently raw materials derived from the fuel industry, while others are waste materials which have been recycled for a second use.

A wide variety of fibers have been used in asphalt mixtures, including cellulose, minerals (such as asbestos, metal fibers, etc.), synthetic polymer fibers (nylon fibers, polyester, polypropylene, aramid, etc.), fiberglass, etc., as well as recycled fibers from carpet fibers, tires, newsprint, and others. Small fibers confer an area increment per weight unit that is higher than filler materials. However, if they are only used as filler, the mixture may be expensive, and therefore, they are only present to modify the properties of the binder.

Serfass and Samanos [9] developed mixtures with modified bitumen, and, in conclusion, they found that fibers were able to avoid cracks and increased voids in the mixture. Adding fibers reduced the mixtures susceptibility to temperature variations.

Polypropylene (PP) fibers have also been used in mixtures with binder in a wet method as described by Abtahi, et al. in Reference [10]. The analysis of PP-modified bitumen can improve the consistency and properties of the asphalt concrete. A reduction in penetration and ductility was observed, but an increment in the softening point was also declared when the samples were compared to the unmodified asphalt. If the amount of fiber was increased, the Marshall stability and air void in the total mix (VTM) increased, while the flow and unit weight also decreased.

The use of fibers in asphalt using a dry method introduces a certain complexity due to their high specific surface and their consequences in terms of asphalt film thickness [11,12]. Length and diameter of the fibers should be taken into account to avoid problems with the road surface.

In the 1960s, powder natural rubber polymers were often used to improve pavement mixtures that were added into the mixer at the manufacturing center. Afterwards, new synthetic polymers were introduced, with clear examples which include polyethylene, ethylene vinyl acetate (EVA), and styrene-butadiene-styrene (SBS). Nowadays, four-fifths of the porous asphalt mixtures and discontinuous grading curves are made using polymer-modified bitumen.

Modifiers increase the asphalt deformation resistance under repeated stress and fatigue, thereby the reducing cracks and susceptibility of the asphalt to temperature variations layers as well. These modifiers are usually applied directly to the asphalt material before mixing with the stone material.

These additives (e.g., sulfur) act on the binder viscosity and improve their resistance to deformation. Sulfur can be used as pellets after the addition of SBS, for example, improving the polymer adhesion to create a more elastic mixture [13]. Polyethylene in stone mastic asphalt (SMA) pavements can help to reduce by 34% the pavement thickness, exhibiting a better lifespan and reducing temperature susceptibility.

On the other hand, new products coming from waste materials are being used to better improve the properties of the bitumen. The increase in manufactured goods and consumer habits have led to an increase in waste materials, which should be recycled. Different types of waste materials can be obtained from the following sources, such as polyethylene terephthalate (PET), Bakelite, polypropylene (PP), epoxy, polyvinyl acetate (PVA), melamine, polyvinyl chloride (PVC), polyester, polystyrene (PS), polyurethane, low-density polyethylene (LDPE), urea–formaldehyde, high-density polyethylene (HDPE), and alkyd. All of them can be softened for a temperature range between 155 °C to 165 °C for inclusion in the pavement construction process [14].

The addition of recycled tire rubber to the bitumen is perhaps one of the most studied mixtures. The results showed that the addition of these recycled materials increases the toughness of the SMA mixtures without significantly affecting their permanent deformation. SMA pavements using recycled tire rubber and recycled glass were analyzed by Ghasemi and Marandi in 2013 [15]. The addition of glass instead of recycled rubber did not produce a negative impact on the bituminous binder—it even slightly improved it, except for the fracture toughness. An optimal mixture was created, based on 5% recycled rubber and 5% recycled glass, which improved all the properties.

Polyethylene improves fatigue, permanent deformation, and creates a lower susceptibility temperature, along with great moisture resistance [16,17]. The use of high-density polyethylene (HDPE) from bags to modify the binder was studied together with other materials, such as the exterior bumpers of vehicles (thermoplastic polyolefin (TPO)) [18]. In conclusion, the use of recycled materials increased, depending on the modifier, the viscosity range between 6 °C and 12 °C, and it reduced by more than 50% the permanent deformation and fatigue resistance. The authors focused on the material source heterogeneity in order to be controlled.

Regarding the process, the mixing of additives into the mixture is an important feature that drives different mixture characteristics:

- Dry process: This involves the direct incorporation of plastic waste that is mixed with aggregate at about 170 °C before adding in the bitumen at around 160 °C. It has been found that rubber, for example, in this procedure, helps to reduce the noise generated [19]. The biggest advantage of this technique is the possibility of covering the aggregate with a plastic layer, thereby improving the aggregate's surface and giving it better properties for adhesion with the bitumen. In addition to this technique, it is possible to use more than 15% of the mixture as plastic waste products to reduce the costs of bitumen, and this is not usually limited by the type of plastic products used.
- Wet process involves the simultaneous mixture of bitumen and plastic waste before joining them to the aggregate. Generally, it is used with proportions of 6% to 8% in plastic waste, which increases the melting point of the bitumen and thus becomes a more flexible pavement in winter. Any size, shape, and material of plastic, rubber, etc. can be used, but its inconvenience is that the process needs more mechanical force to mix, and it also consumes more energy [14].

The noise attenuation achieved with these products is also described in this introduction. Several experiences involving waste materials and SMA pavements are described below.

In the EU project SILENCE, SMA mixtures were optimized to reduce road noise. The Danish Road Institute (DRI) found an initial noise reduction from passenger cars of 4 dB in relation to a dense asphaltic concrete (DAC 11) reference pavement [20]. Concurrently, Practicò, F. et al. show in Reference [21] that SMA produces an initial reduction of 4–5 dB from a DAC 11 mixture and 3 dB at the end of its lifespan.

In the same study, Practicò, F. et al. introduce a new generation of SMA developed with a maximum aggregate size of 5 or 6 mm, and 100% crushed materials that are very cubical with good polish resistance values, with the presence of fibers in the mix and polymers or powdered crumb rubber. This new generation of SMAs has air void contents between 5% and 10%, which is much higher than conventional SMAs [21].

Another study conducted at Paseo de Cures, Malaga, involved a SMA8 50/70 mixture that comprised NFU at a weight of 0.5%, which revealed the importance of dynamic stiffness in the generation of noise. The mixture reached good noise reduction at speeds between 50 and 80 km/h. It was further demonstrated that the mixture had good acoustic properties, achieving noise attenuations of 6 dB from an AC 16 surf [22].

According to the Eiffage Infraestructuras experience in the Spanish project "Proyecto SMA" [23], the use of nylon fiber, tire rubber, and/or recycled plastic can improve the properties of SMA pavements. For this recycling experience, the plastomer's quantity should be about 0.5% of the mixture and the percentage of nylon in the mixture should be about 0.2% of the total weight of the mixture. The goal of the project was to increase the constitution percentage to reach 1%, but when considering other additives this proportion may vary. The mixing technique to investigate this was the "dry process". Noise attenuation of 6 dBA was achieved for an SMA8 mixture with 12% voids, while adding rubber from the automotive industry and nylon fiber tires, with respect to the old DAC mixture.

Several experiences at an asphalt rubber friction course (ARFC) [24] in Arizona, USA, showed how the presence of crumb rubber may reduce road noise by up to 6 dB. There was also a similar experience on highway I-19 which had 3/8 open-grade aggregates and 9% of binder.

In Italy, rubberized technologies have also been introduced, and noise attenuation of about 4–5 dB has been achieved, with respect to the reference surface, at speeds of around 50 km/h, according to Licitra et al. in Reference [25]. Several rubberized gap-graded 0/8 mixtures were compared to a long-aged DAC 0/12. The bitumen was modified by the addition of rubber crumb recycled from scrap tires using a wet process.

Another company, Collosa, carried out one test track in 2009 using DLPA12 with 1% crumb rubber (end-of-life tires–ELT) which was added in a wet way, where the CPX measurements performed at a 50 km/h speed were 86 dBA and then 92 dBA at 80 km/h [26]. Compared to a reference road (AC 16 surf) built in the same place (P 230 between Saldaña and Herrera, Spain), the acoustic attenuation obtained was 3 dB.

In a research project carried out in California and Arizona, Biligiri [27] studied 36 different surfaces where a damping parameter was estimated. He showed that asphalt rubber mixes with crumb rubber provided a higher noise-damping response than the conventional dense-graded asphalt (DGA) mixes due to extra binder, higher porosity, and rubber inclusions. An estimation of the damp coefficient was done, along with ultrasonic pulse velocity tests.

However, the literature review did not reveal noise results for pavements where the binder had been modified with plastic waste.

Finally, an aspect no less interesting in the issue of rolling noise in pavements is the durability of acoustic performance. Among the different studies, it is worth mentioning the study by Licitra et al., in which the variability of acoustic performances of pavements was shown over time [28]. Several linear and logarithmic regression models were used to determine the annual rate of loss of the acoustic performance of pavements. According to these authors, the rate conforming to the logarithmic model was a better fit to the experimental data measured.

2. Objectives of the Project LIFE SOUNDLESS

The project LIFE SOUNDLESS, "New generation of eco-friendly asphalts with recycled materials and high durability and acoustic performance", aims to demonstrate the effectiveness and durability of noise-reducing mixtures of the SMA (stone mastic asphalt) type to mitigate noise pollution at the source. It also focuses on the effectiveness of these mixtures in Mediterranean climates (Southern Europe), where the weather conditions are very different from conditions in the northern countries. The open-grade mixes tested in countries with warm weather sometimes give problems of aggregates segregation, thereby becoming noisier surfaces over a short time.

The main drivers of the project include the search for additives which improve the noise attenuation of the mixes and increase the stability of the mixtures during their lifespan, taking into account the circular economy. Therefore, the incorporation of additives manufactured using waste materials from other industries has been proposed. This project aims to encourage public organizations to apply these types of solutions to noise pollution.

Two test tracks were selected to show how these mixtures could reduce acoustic contamination. Both test tracks were located in Seville on two roads which connect Seville with two-bedroom cities, such as Utrera and Coria. One of these test tracks tried to simulate an interurban road with a high density of vehicles and a medium speed of 80 km/h. The other one tried to simulate an urban road with a lower capacity and a maximum speed of 50 km/h.

This paper attempts to show the most important goals achieved in this project. A first description of the initial situation is done, where the acoustic tests carried out during the project are explained. Second, a description of the additive selection is done, where the testing methods employed are also described. In the last part of the paper, new mixtures developed in the project are described, and also the results of the acoustic performance and its durability are assessed.

This project was led by the General Directorate of Infrastructures of the Junta de Andalucía (DGI) and the construction company Eiffage Infraestructuras, which is a specialist in the design and implementation of asphalt mixtures. The Cidaut Foundation also participated as a partner, wherein it is specialized among other fields in the analysis and proposal of solutions related to noise and vibration. This project received financing from the LIFE program of the European Union.

3. Initial Evaluation of the Test Tracks

In the LIFE SOUNDLESS project, two test tracks near Seville city were chosen. One of them was in A-376 road pk 2 to pk 3 in Montequinto. This test track has an average daily traffic (ADT) of 100,000 vehicles. The average speed of this track is 70 km/h. This test track had old dense asphalt with poor texture and a great number of failings, such as cracking and raveling.

The second track was on the road A-8058 between pk 3 and pk 4 in Gelves. This second test track has an ADT of 26,000 vehicles at an average speed of 50 km/h. In this section, a double layer porous asphalt of nine years was set before starting the project.

The first acoustic test done in the project was an evaluation of the sound pressure level during one day at different points, as can be seen in Figure 1.

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

Figure 1. (**a**) Image of the test track on the A-376 road. 1 and 2 are the points where the microphones have been placed. (**b**) Image of the test track on the A-8058 road.

The sound pressure equivalent levels for different day periods were calculated, and they are presented in the Table 1.

Table 1. Equivalent sound pressure level values.

Equivalent Noise Levels A-Weighting	A-8058	A-376-1	A-376-2
L_{night} (dBA)	63	70	73
L_{day} (dBA)	70	76	79
$L_{evening}$ (dBA)	69	76	78
L_{den} (dBA)	72	79	81

Not only have the noise levels been evaluated, but the frequency analysis as well. The aim of this analysis was to evaluate the dominant source of these test tracks. Dominant frequencies around 1000 Hz were found in Figure 2 in both test tracks, which were compatible with road noise sources [29].

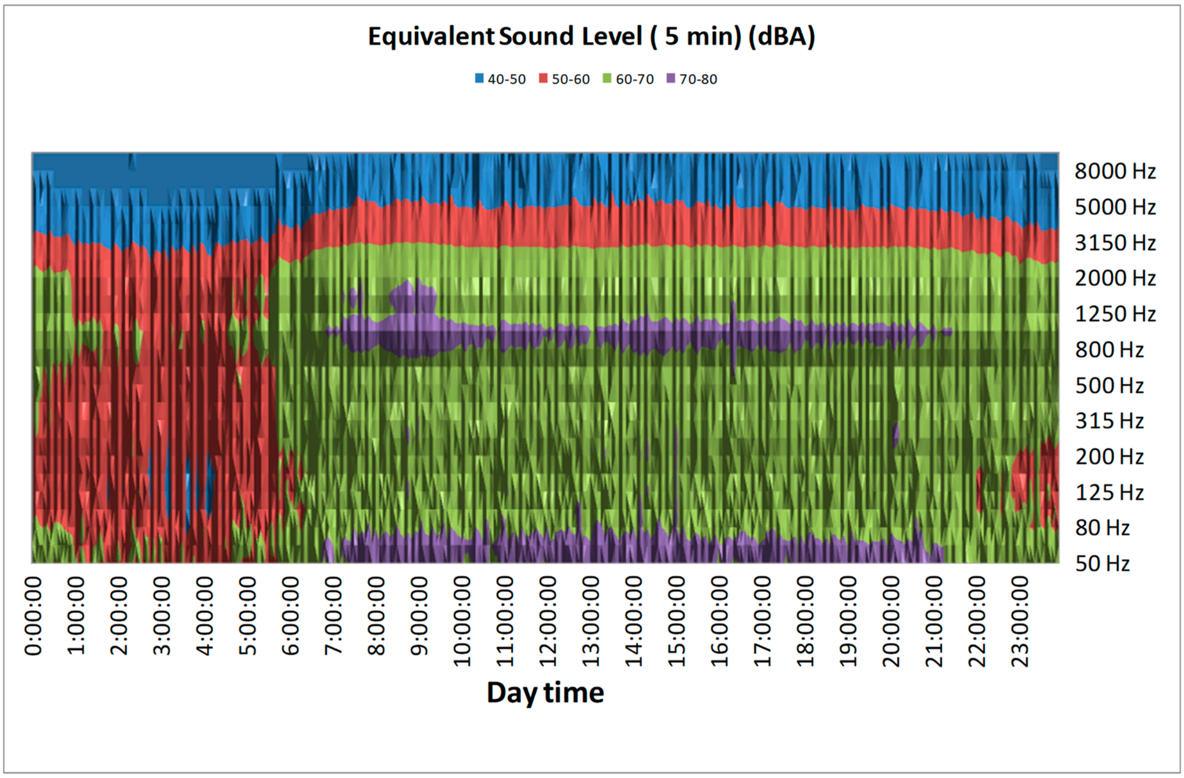
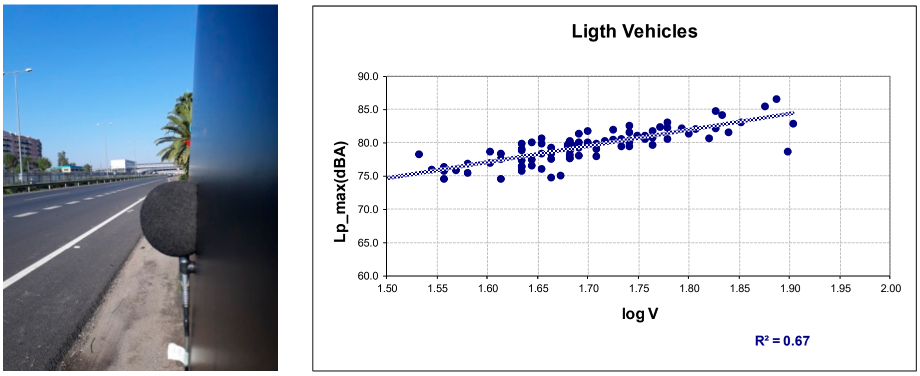


Figure 2. Frequency analysis of sound pressure levels at point 1 at the A-376 site.

This noise measure was an easy way to obtain a first evaluation, but it did not allow a comparison between different situations (different places, different times). To compare the acoustic performance of the solutions developed, other standardized traffic noise measurements were assessed at the two selected sections.

The statistical pass by noise test (SPB) [8] enables the assessment of traffic noise in one section in correlation with vehicle speed. This test is used to characterize the noise of the entire traffic. SPB tests were carried out on the two selected sections. The backing board variant was used because there were important obstacles (e.g., fences, safety barriers, parked cars) in the area which made the environment far from being a free field. The next images (Figure 3) show the setup of the test performed to achieve data from this test, and also an analysis of those data. Owing to the lack of heavy vehicles on these roads (ISO standard recommends at least 40 vehicles), the results for this vehicle type were not considered in this paper.



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

Figure 3. (**a**) Image of the statistical pass by noise test (SPB) test at A-376 site. (**b**) Results of Lp_max at A-8058 site for the regression analysis.

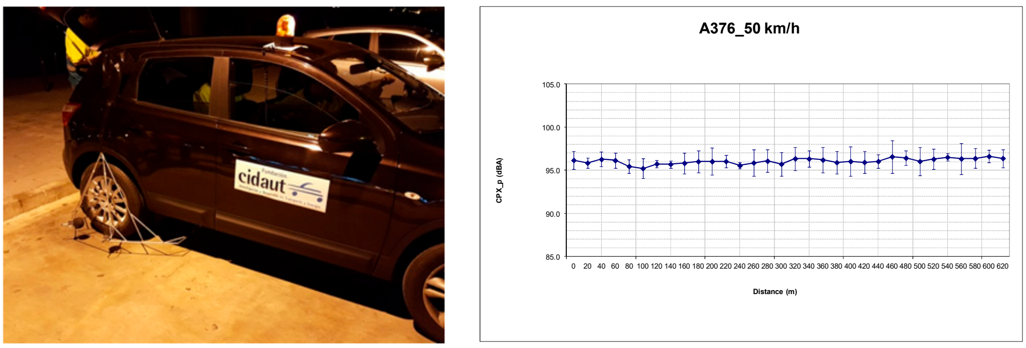
The measurements were analyzed according the procedure established in the ISO 11819-1 standard. The SPB values obtained for every site are presented in Table 2.

Table 2. SPB values measured at both test tracks at the beginning of the project.

Statistical Pass by Index for Light Vehicles	SPB (dBA) at 50 km/h
A-8058	74
A-376	77

Additionally, the close proximity (CPX) method was also performed on the two selected sections [6]. This method provided a continuous measurement (every 20 m) for all the test tracks. This test was used to characterize the rolling noise in proximity. The CPX (self-propelled vehicle) tests were carried out by Fundación Cidaut and are shown in Figure 4a. The CPX_*p* parameter was determined using SRTT in the rear axle of the vehicle according to the ISO 11819-2 standard specifics. For all the CPX measurements carried out in this project, the temperature correction was performing according to normative procedures, as well as the speed correction (B = 30).

Site A-8058 was characterized at 50 km/h and Site A-376 at 50 and 80 km/h. Tests were performed in both directions. An illustration of the results obtained for one test track can be seen in Figure 4b.



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

Figure 4. **(a)** Image of the self-propelled vehicle used for the close proximity (CPX) measurements. (**b**) Results of CPX_*p* at the A-376 site at 50 km/h.

The overall values for all the test tracks are shown in Table 3. In addition, the standard deviation of each test track is also presented.

Table 3. Close proximity (CPX) method values measured in both test tracks at the beginning of the project.

CPX_*p* Values	CPX (dBA) at 50 km/h		CPX (dBA) at 80 km/h	
	Mean Value	**Dev std**	**Mean Value**	**Dev std**
A-8058	93	1	-	-
A-376	96	1	104	1

All values are rounded to the nearest integer. Uncertainty is not estimated for these CPX measurements.

The main conclusion from these tests was that the initial noise levels were high and that rolling noise dominates other sources.

4. Additive Selection for Better Acoustic Properties

As noted earlier, the aim of the project is to identify new additives that can improve contact between the tire and the pavement to reduce the noise radiation of the tire. Part of the tasks in this project involved choosing these additives.

Additives and new mixtures were collected by Eiffage Infraestructuras. Eiffage also designed the mixes to ensure that they complied with PG3 (the Spanish standard for asphalt mixtures) requirements.

Figure 5 shows the different waste materials used as additives for improving the acoustic properties of pavements. Several materials, such as rubber crumb and nylon fibers coming from end-of-life tires (ELT), as well as plastics coming from green houses, wires, and master batches were employed as additives.

The addition of these additives was done using the dry way (fibers included). No variations in thickness or properties were detected in the construction of the specimens or in the subsequent construction of the test sections.

Figure 5. Materials used for generating the additives for asphalt mixes.

To further study the additives, different compositions of the materials led to 23 different mixtures which were designed and tested. Four of them were used as a reference (1 AC16 and 3 SMA8), two of them had greenhouse plastics (0.5–1%), two of them included plastic coming from recycled wires (0.5–1%), two of them comprised nylon from ELT (end life tires) (0.2–0.5%), six of them included crumb rubber (CR) from ELT (0.5%–2% of CR with different percentages of bitumen), one of them had CR from ELT and plastic cables (0.5% + 0.5%), two of them had CR from ELT and greenhouse plastics (0.5% CR + 0.5% plastic and 1% Plastic + 0.5% CR), and two of them had plastic from masterbatches (0.5–1.0%). All SMA mixtures were manufactured with the same binder and aggregates.

All the mixtures met the requirements of Spain's PG3 standard for bituminous mixtures, in terms of voids, water sensibility, and resistance to permanent deformations. Thus, the final criterion for the selection of the mixtures was acoustic performance.

The acoustic laboratory of Fundación CIDAUT performed the acoustic validation of the mixtures. Three different measurements were carried out for every mixture (i.e., three specimens for each mixture) and these included mechanical impedance, texture, and acoustic absorption. The thickness of all the tested specimens was 25 mm.

- Mechanical impedance. This is defined as the ratio of the driving force to the induced velocity. It is an overall indicator of the stiffness and energy dissipation properties of the pavement. Moreover, the tire excitation capacity of the pavement can be explained using this parameter. From this curve, the Young's modulus and damping could be estimated. The frequency response function was measured using a 1 degree of freedom system based on the mixture specimen. An impact hammer and accelerometer were used to measure the frequency response function (Figure 6). The measurement was repeated five times at three different points for every specimen. For every mixture, three different specimens were tested.
- Texture. Macrotexture was measured using the mean texture depth (MTD) volumetric method. The procedure followed regulation EN 13036-1:2000. For noise reduction, a negative and medium texture is preferred.
- Acoustic absorption. The method used for these tests followed ISO 10534-2. The test allows measurement of the absorption coefficient of a surface versus the normal incidence of sound, enabling evaluation of the sound absorption properties of a pavement. All the test specimens were cylindrical with a 100 mm diameter.

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

Figure 6. (**a**) Mechanical impedance setup. (**b**) Impedancimeter.

After analyzing all the parameters for all the specimens considered, it was concluded that mechanical impedance was the most relevant parameter in selecting a quieter mixture. The mechanical impedance impact was in a frequency range between 600 and 1200 Hz, being where the road noise spectrum was higher. Moreover, the values of the sound absorption coefficients for all the mixtures manufactured for this project were below 0.2.

The mechanical impedance could be measured by applying an impact to the road surface and recording the response of the material in terms of its vibration. In existing studies [30,31], tests using an impedance hammer are commonly used. The mechanical impedance of the contact surface was estimated from the frequency response function measured by the impedancimeter. An accelerometer was used to measure the movement produced in the impedancimeter by the impact force, which was measured using a force cell. Figure 7 shows a scheme of the measurements, and the equation used in the estimation of the impedance in the road,

$$Z_{road}(w) = Z(w) - i\, w\, m_i$$

$$Z(w) = \frac{F(w)}{V(w)}$$

where Z_{road} is the impedance of the surface, Z is the impedance measured in the impedancimeter (force/velocity), and m_i is the impedancimeter mass. $F(w)$ is the excitation force measured in the force cell located in the impedancimeter and $V(w)$ is the velocity integrated from the accelerometer signal [28], while w is the angular frequency.

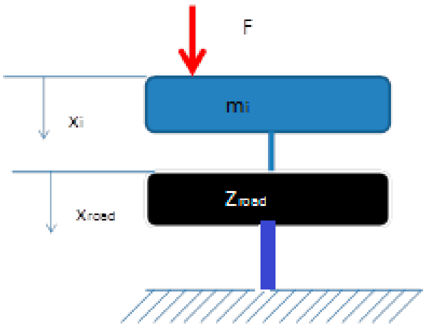


Figure 7. Mechanical impedance scheme.

The damping parameter is obtained by the mobility function (Velocity/Force) measured in the impedancimeter, using the peak picking technique described in Reference [32],

$$\delta = \frac{\Delta f}{2 f_n}$$

where f_n is the resonance frequency of the system and Δf is the frequency difference, wherein the amplitude in the mobility function falls to 3 dB with respect to the resonance value.

Figure 8 shows the measured impedance and the Z_{road} estimated using this method.

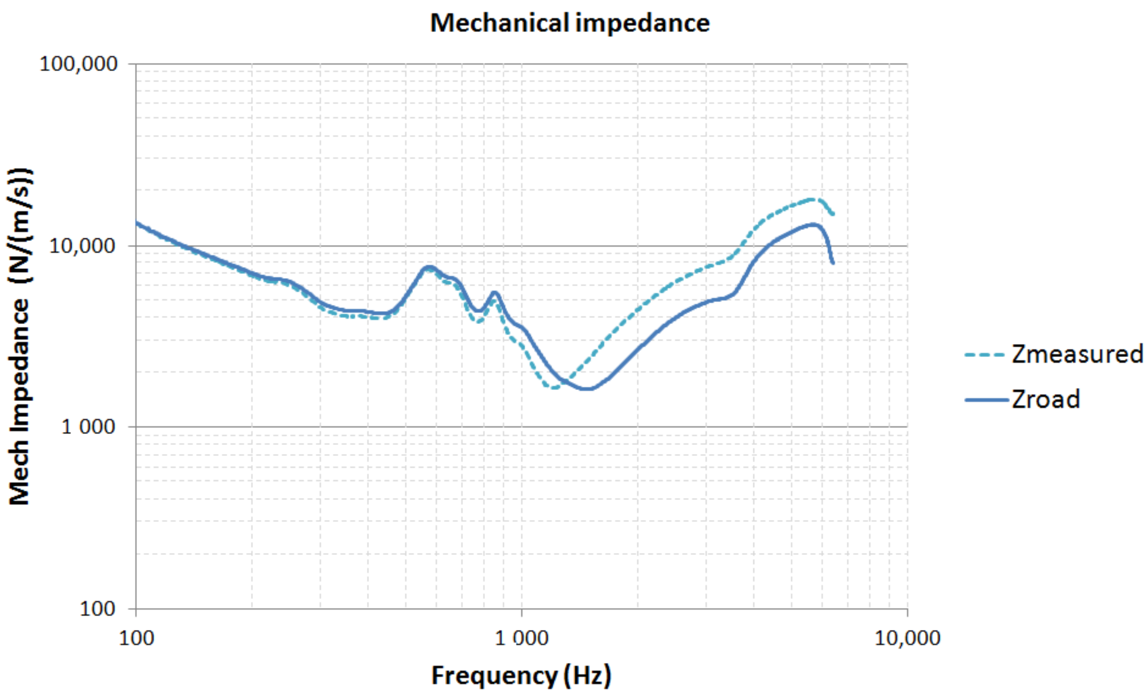


Figure 8. Impedance measurement and the mechanical impedance estimated for the road.

The frequency for the minimum value of Z_{road} was selected to evaluate the dynamic Young's modulus of the pavement,

$$E = \frac{k * h}{\pi r^2}$$

where *k* is the stiffness constant determined using the resonance frequency, *h* is the thickness of the pavement, and *r* is the radius of the impedancimeter.

The averaged values for the dynamic Young's modulus and damping for all the specimens are presented in Figure 9. From these data, the selection of the best pavements was conducted. All the analyzed samples were SMA08, except for the reference surfaces, which were selected as a dense mixture type AC 16 surf. The differences between them were the additives and the composition. Several waste materials were also used, as previously explained.

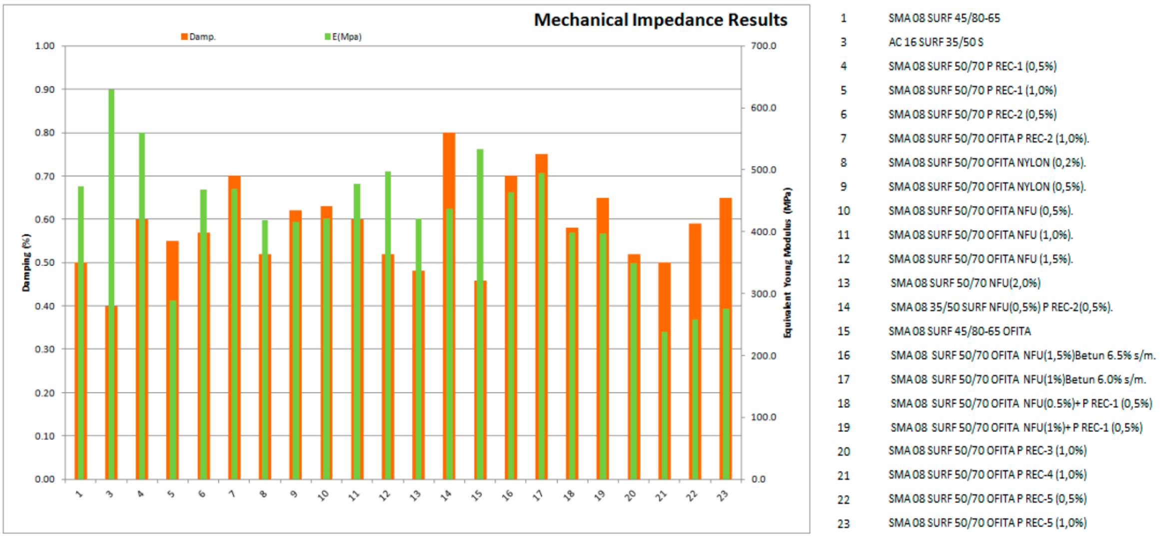


Figure 9. Mechanical impedance results for the 23 different mixtures.

It was found that the reference mixtures had a higher Young's modulus and lower damping (e.g., mixture 3). The higher the Young's modulus of the pavement, the lower the contact time between the tire and pavement. This means that a higher frequency range for the excitation modes was found and that the radiation of the tire is higher. Consequently, the higher the damping, the lower the excitation produced by the tire. On the other hand, there were some mixtures, i.e., mixtures 16 to 23, where the damping was higher and the dynamic Young's modulus was lower, which made them more suitable from an acoustic point of view.

From the results analysis, we obtained the following mixtures that were identified for use at the demonstration sites:

- Test track 1: A-8058. SMA8 with 1% ELT and 6 % bitumen 50/70, SMA8 with 1.5% ELT and 6.5% bitumen 50/70.
- Test track 2: A-376. SMA8 with 0.5% nylon, SMA8 with 0.5% P REC-4, SMA8 with 0.5% P REC-4 and 0.5% ELT. In addition, on this road a reference mixture (AC16 surf 35/50 S with 200 m) was also paved.

5. Implementation of the Solution and Acoustic Performance Assessment

The selected mixtures were paved at the test track sites. All the project partners decided on the correct locations where the kilometric points for paving these mixtures were:

- A-8058: From 3 + 350 km to 3 + 867 km (in both directions).
- A-376. Direction Sevilla–Utrera: From 2 + 200 km to 3 + 100 km. Direction Utrera–Sevilla: From 2 + 200 km to 2 + 745 km.

Figure 10 shows both test tracks after finishing the asphalt mixture paving.

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

Figure 10. (**a**) Image of the road A-8058 after paving the mixtures. (**b**) The same at A-376.

One month after finishing the works, the SPB and CPX tests were performed again to determine the acoustic reduction from each type of asphalt. The results are presented in Tables 4 and 5.

Table 4. SPB values before and after paving the mixtures.

Comparison of the SPB Index before and after	Initial Situation before the Works	After Paving the SOUNDLESS Mixtures
	SPB (dBA) at 50 km/h	SPB (dBA) at 50 km/h
A-8058	74	68
A-376_1% plastic	-	64
A-376_0.5% ELT + 0.5% plastic	77	68

For the A-376 (1% plastic) point, the traffic conditions did not allow measurement under the same conditions as the other two points. The SPB measurement had to be done at night to obtain isolated vehicles. During that period of time, the background noise, due to other activities in the zone, was lower.

From these data, it could be concluded that 6 dB had been reduced on the test track A8058 (low traffic and low speed) and 9 dB on the test track A-376 (high traffic and medium speed).

Moreover, the CPX method was used on the roads considered. As explained, in point 3, the CPX evaluation was carried out only using SRTT, such that the parameter showing the acoustic performance was CPX_*p*.

Table 5. CPX_*p* values before and after paving the mixtures.

Comparison of the SPB Index before and after	Initial Situation before the Works		After Paving the SOUNDLESS Mixtures	
	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h
A-8058_SMA8 1% ELT_6% bit 50/70	92		90	
A-8058_SMA8_1.5% ELT_6.5% bit 50/70	93		89	
A-376 _SMA8_1% plastic	96	104	91	97
A-376_SMA8_0.5% ELT + 0.5% plas	96	104	91	97
A-376_SMA8_0.5% Nylon fibers	96		91	
A376_AC16 surf	96	104	93	101

All values are rounded to the nearest integer. Uncertainty is not estimated for these CPX measurements. The standard for expanded uncertainty at a 95% coverage probability could be considered as 1 dB. For all the test tracks considered in the measurements carried out after finishing the SOUNDLESS mixtures works, the standard deviation was lower than 1 dB.

From these values, it could be concluded that these mixes may reduce noise by up to 7 dB at medium speeds (i.e., 80 km/h) from an old mix (10 years) and 4 dB from the standard new mixes (AC

16 surf). At low speeds (i.e., 50 km/h), the reduction from the old standard mixture was 5 dB and only 2 dB if the reference mixture was taken as the standard new asphalt mix.

Mixes with a high percentage of rubber crumb led to quieter roads. One explanation for this effect is the high percentage of bitumen that allows an increase in the damping of the contact, such that the tire does not emit a louder noise.

If the average sound spectra for every mixture was analyzed, the relevant differences could better explain the last comment. As seen in Figure 11, mixes with a high quantity of crumb rubber and bitumen presented lower values of sound pressure levels at frequencies where the tires emit noise (i.e., 315–800 Hz). Higher frequencies (i.e., 1000–5000 Hz) explained other mechanisms based on aerodynamic noise, where aspects like texture had more importance than contact forces.

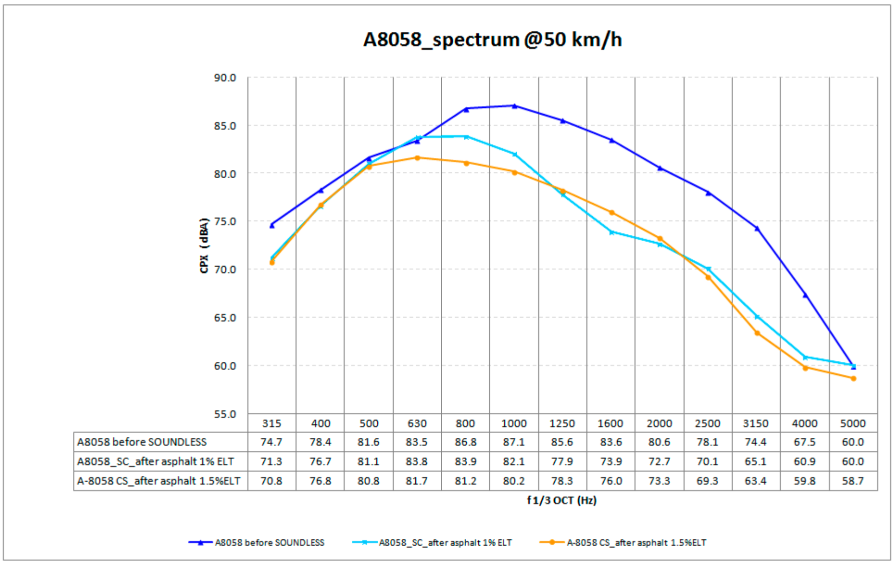


Figure 11. Average spectrum obtained on the A-8058 test track before and after paving the LIFE SOUNDLESS mixtures.

To evaluate the acoustic performance durability, both the SPB and CPX measurements were repeated every six months.

Table 6 presents the data obtained during three measurement campaigns after paving the SOUNDLESS mixes.

Table 6. SPB values before and after paving the mixtures.

Evolution of the SPB Index during the Project	Initial Situation before the Works	Campaign One (0 m)	Campaign Two (6 m)	Campaign Three (12 m)
	SPB (dBA)	SPB (dBA)	SPB (dBA)	SPB (dBA)
A-8058	74	68	68	68
A-376_1% plastic	-	64	67	64
A-376_0.5% ELT + 0.5% plastic	77	68	68	68

Overall, traffic noise did not increase during the first year. Table 7 shows data relating to road noise measured with the CPX method.

Table 7. CPX_*p* values after and before paving mixtures.

Evolution of CPX_*p* Index during Project	Initial Situation before Works		Campaign One (0 m)		Campaign Two (6 m)		Campaign Three (12 m)	
	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h	CPX (dBA) at 50 km/h	CPX (dBA) at 80 km/h
A-8058_SMA8 1% ELT_6% bit 50/70	92		90		90		90	
A-8058_SMA8_1.5% ELT_6.5% bit 50/70	93		89		90		89	
A-376_SMA8_1% plastic	96	104	91	97	91	96	91	97
A-376_SMA8_0.5% ELT + 0.5% plas	96	104	91	97	90	96	91	97
A-376_SMA8_0.5 Nylon fibers	96		91		91		91	
A376_AC16 surf	96	104	93	101	93	101	95	102

All values are rounded to the nearest integer. Uncertainty is not estimated for these CPX measurements.

One year later, no changes had occurred in the SOUNDLESS pavements regarding acoustic performances.

We checked the environmental noise one year after the equivalent sound pressure levels had been evaluated at the same points. Table 8 shows the values recorded one year after the SOUNDLESS pavements had been paved.

Table 8. Equivalent sound pressure level values one year after the asphalt paving.

Evolution of Equivalent Sound Pressure Level during the Project	Before the SOUNDLESS Project			1 Year after the SOUNDLESS Project		
	A-8058	A-376-1	A-376-2	A-8058	A-376-1	A-376-2
L night (dBA)	63	70	73	60	64	72
L day (dBA)	70	76	79	67	69	78
L evening (dBA)	69	76	78	66	69	77
L den (dBA)	72	79	81	69	72	81

Point 2 on the A-376 was out of the SOUNDLESS mixtures' influence, as seen in Figure 1a.

It could be seen that the overall sound pressure level had decreased by 3 dB on the A-8058 road, and 6 dB on the A-376 road during night time and 7 dB during the day. Point 2 on the A-376 road, which was not influenced by the SOUNDLESS pavements, showed that traffic conditions in both situations (i.e., before and after) were equivalent.

6. Conclusions

The LIFE SOUNDLESS project enabled a reduction in noise contamination in the test track areas. In urban areas, like the A8058 road, that have low speeds (50 km/h), the L_{day} was reduced by 3 dB. In an interurban area, like the A-376, with medium speeds (70 km/h), the L_{day} was reduced by 7 dB.

SOUNDLESS mixtures allow a reduction in road noise by 3 dB with respect to the new dense asphalt (AC 16 surf) at low speeds (50 km/h) and 4 dB at medium speeds (80 km/h). These values are similar to other studies in places with a similar climate.

These mixes were checked during the first year, and no significant reduction was detected. The average daily traffic was 100,000 vehicles for the interurban road and around 25,000 vehicles for the low speed road. No cracks or any other surface defaults were detected during the first year of life.

The best SOUNDLESS mixture was made with 1.5% ELT rubber crumb. This mixture led to a reduction in the radiation noise of the tire. This CPX_*p* value (89dBA) was far from the double layer porous asphalt (DLPA) mixture, where the CPX_*p* was around 86 dBA. Evaluation of the acoustic performance durability was done during the project and enabled a better comparison.

Waste materials, such as rubber crumb coming from end-of-life tires and plastics, could be used as new additives that can improve the acoustic properties of close-gap mixtures, such as SMA.

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References

1. Environmental Noise Directive. EU Directive. Directive 2002/49/EC of the European parliament and the Council of 25 June 2002 relating to the assessment and management of environmental noise. *Off. J. Eur. Commun.* **2002**, *12*, L189.
2. Kim, R. *Burden of Disease from Environmental Noise*; World Health Organization: Geneva, Switzerland; European Commission: Luxembourg, 2007.
3. Babisch, W. Traffic Noise and Risk of Myocardial Infarction. *Epidemiology* **2005**, *16*, 33–40. [CrossRef] [PubMed]
4. EBoDE Project. Environmental Burdon of Disease—European Countries. Available online: http://en.opasnet.org/w/EBoDE (accessed on 15 May 2018).
5. Chetoni, M.; Ascari, E.; Bianco, F.; Fredianelli, L.; Licitra, G.; Cori, L. Global noise score indicator for classroom evaluation of acoustic performances in LIFE GIOCONDA project. *Noise Mapp.* **2016**, *3*, 157–171. [CrossRef]
6. ISO/CD 11819-2 "Acoustics—Method for Measuring the Influence of Road Surfaces on Traffic Noise. Part 2: The Close-Proximity Method". 2017. Available online: https://www.iso.org/standard/39675.html (accessed on 20 June 2018).
7. Licitra, G.; Teti, L.; Cerchiai, M.; Bianco, F. The influence of tires on the use of the CPX method for evaluating the effectiveness of a noise mitigation action based on low-noise road surfaces. *Transp. Res. Part D* **2017**, *55*, 217–226. [CrossRef]
8. ISO 11819-1. "Preview Acoustics. Measurement of the Influence of Road Surfaces on Traffic Noise. Part 1: Statistical Pass-By Method". 1997. Available online: https://www.iso.org/standard/20232.html (accessed on 20 June 2018).
9. Serfass, J.P.; Samanos, J. Fiber-modified asphalt concrete characteristics, applications and behavior. *Asph. Paving Technol.* **1996**, *65*, 193–230.
10. Abtahi, S.M.; Esfandiarpour, S.; Kunt, M.; Hejazi, S.M.; Ebrahimi, M.G. Hybrid Reinforcement of Asphalt-Concrete Mixtures Using Glass and Polypropylene Fibers. *J. Eng. Fibers Fabrics* **2013**, *8*, 25–35. [CrossRef]
11. Celauro, C.; Praticò, F. Asphalt Mixtures Modified with Basalt Fibers for Surface Courses. *Constr. Build. Mater.* **2018**, *170*, 245–253. [CrossRef]
12. Zheng, Y.X.; Cai, Y.C.; Zhang, Y.M. Laboratory Study of Pavement Performance of Basalt Fiber-Modified Asphalt Mixture. In *Advanced Materials Research*; Trans Tech Publications: Zurich, Switzerland, 2011; pp. 175–179.
13. Asphalt Institute. *The Asphalt Binder Handbook*; Asphalt Institute: Lexington, KY, USA, 2011.
14. Gawande, A.; Zamre, G.S.; Renge, V.C.; Bharsakalea, G.R.; Tayde, S. Utilization of waste plastic in asphalting of roads. *Sci. Rev. Chem. Commun.* **2012**, *2*, 147–157.
15. Ghasemi, M.; Marandi, S.M. Engineering Properties of SMA Mixtures/Polymer/RGP Blends. *J. Zhejiang Univ.* **2013**, *2*, 97–106.
16. Gallego-Medina, J. *Mezclas Bituminosas con Betunes de alto Contenido en Caucho de Neumáticos: Una Elección por las Altas Prestaciones*; Universidad Politécnica De Madrid: Madrid, Spain, 2003.
17. Oda, S.; Fernandes, J.L. *Viabilidad Técnica de Usar Caucho de Neumático como Material de Pavimentación Asfáltica*; Universidad Estadual de Maringá: Maringá, Brazil, 2002.
18. Aguiar-Moya, J.P.; Villegas-Villegas, R.; Loria-Salazar, L.G.; Salazar-Delgado, J. *Use of Waste Products as Bitumen Modifiers in Costa Rica*; Laboratorio Nacional de Materiales y Modelos Estructurales Lanamme UCR, Universidad de Costa Rica: San Pedro, Costa Rica, 2013.

19. Expósito Paje, S. *Mezclas Asfálticas Con Polvo de caucho NFU: Evaluación Acústica En Servicio*; 4° número extraordinario CILA November 2013; Revista Técnica de la Asociación Española de Carretera: Madrid, Spain, 2013.
20. Hans, B. Urban Thin Quieter Pavements. In Proceedings of the Transportation Research Board Conference, Washington, DC, USA, 11–15 January 2009.
21. Praticò, F.; Anfosso-Lédée, F. Sustainability of Road Infrastructures Trends and Issues In Mitigating Traffic Noise Through Quiet Pavements. In Proceedings of the 5th International Congress, Dresden, Germany, 1–3 October 2012; pp. 203–212.
22. ASEFMA. *In Situ Measurement of the Dynamic Stiffness of a Mixture SMA8 (NFU) in Urban road. Influence on cataloguing as MBSR*; ASEFMA: Madrid, Spain, 2015.
23. Proyecto SMA. Propuesta de Normativa SMA para España. 2012. Available online: www.proyectosma.eu (accessed on 30 July 2018).
24. Quiet Pavement Technologies. Technical Committee D.2. Road Pavements. World Road Association Mondiales de la Route. Available online: www.piarc.org2013R10EN (accessed on 27 December 2018).
25. Licitra, G.; Cerchiai, M.; Teti, L.; Ascari, E.; Fredianelli, L. Durability and variability of the acoustical performance of rubberized road surfaces. *Appl. Acoust.* **2015**, *94*, 20–28. [CrossRef]
26. Morcillo, M.A.; Hernandez, M.J.; Gonzalez, J.A.; Hidalgo, A.; Garcia, C. *Several Approaches with Asphalt Rubber Pavements in Spain—Noise and Sustainability*; Institute of Noise Control Engineering: Lisbon, Portugal, 2010.
27. Biligiri, K.P. Effect of pavement materials' damping properties on tire/road noise characteristics. *Constr. Build. Mater.* **2013**, *49*, 223–232. [CrossRef]
28. Licitra, G.; Moro, A.; Teti, L.; Del Pizzo, A.; Bianco, F. Modelling of acoustic ageing of rubberized pavements. *Appl. Acoust.* **2019**, *146*, 237–245. [CrossRef]
29. Sandberg, U. *Ejsmont, J. Tyre/Road Noise Reference Bock*; Chapter 5; Informex: Evere, Belgium, 2002.
30. Schwanen, W.; Kuijpers, A.H.W.M. *Development of a Measurement System for Mechanical Impedance*; SILVIA Project Report SILVIA-M+P-013-01-WP2-230605; SILVIA: Woodstock, NY, USA, 2005.
31. Skov, R.; Andersen, B.; Bendtsen, H.; Cesbron, J. *Laboratory Measurements on Slabs from Full Scale PERS Test Sections*; European Acoustics Association: Naples, Italy, 2015.
32. Heylen, W.; Lammens, S.; Sas, P. *Modal Analysis Theory and Testing*; P.M. A. K U: Leuven, Belgium, 1984; ISBN 90-73802-61.