Title

Two-Layer Porous Asphalt: Main Properties to Decrease the Noise Emissions

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Abstract

Road transportation is one of the major sources of noise emissions that seriously affects human health. The porous surfaces are sound absorbing which helps to reduce noise pollution. For this purpose, different two-layer porous asphalt mixtures have been evaluated both mechanically and functionally, in order to develop an asphalt mixture that reduces noise generated between tires and road. This research focuses on the variables that determine the main properties to be considered: texture wavelength spectrum, acoustic absorption and flow resistivity. Void content, thickness and the maximum aggregate size are the variables that should be controlled to decrease the noise emissions.

Keywords

Two-layer porous asphalt, noise, texture, acoustic absorption

Word count: 5264

1. Introduction

Over 12,000 premature deaths in Europe are ascribed to noise long-term exposure every year due to health problems such as sleep disturbances, stress and cardiovascular diseases, according to the European Environmental Agency (EEA). Road traffic noise is the most dominant source of environmental noise, with an estimated 113 million people affected by long-term daily average noise levels of at least 55 dB(A) and 79 million people affected by night-time noise levels of at least 50 dB(A) [1]. The use of porous asphalt (PA) mixture as wearing course has emerged as a popular solution to help address this issue, due to there is evidence that PA mixture decreases noise levels produced between tire and road by 3-4 decibels (dB) respect to a dense mixture according to previous studies [2]–[4]. This type of mixture is produced with lower quantity of fine aggregates than dense mixtures to obtain high void content, which reduces the noise level and also allows the drainage of water through its structure improving the surface runoff. In addition, more benefits such as good skid resistance and reduced splash and spray in wet conditions have been reported in the literature [5]. Furthermore, the two-layer porous asphalt (2LPA) mixture allows to modify the texture respect to conventional PA mixtures, which further improves sound absorption maintaining the other advantages. Considering all these advantages, porous mixtures are often used on inter-urban roads where they are most useful for controlling run-off and improving safety in wet conditions at high speeds.

In the United States (US), a PA mixture should contain between 18 and 22 % voids to be considered a PA mixture, while in Europe a content of more than 20 % is necessary [6]. The void content of these mixtures directly influences the durability of the mixtures, whereby a high void content usually results in a shorter service life compared to dense mixtures. In addition, this high porosity exposes the bituminous binder to higher rates of oxidation and moisture damage, preventing the aggregates from holding together. The most common failure observed in PA mixtures is the loss of coarse aggregate from the pavement due to abrasive traffic loads, called raveling [7]. The onset of this phenomenon is usually due to poor bonding at the binder-aggregate interface or loss of cohesion within the asphalt mortar [8].

To improve structural capabilities and avoid the problems mentioned, multiple additives and modifiers have been incorporated into the PA mixtures. The most commonly used solution is polymer modified bitumen (PMB) as it provides higher ductility and elastic recovery, being one of the preferred materials by the US to achieve a more durable PA mixture [9], [10]. Fibers are also added to increase the mechanical performance of the mixture; previous studies have reported increases in tensile strength, fracture energy properties and toughness with the addition of fibers [11]–[13]. Furthermore, fibers stabilize the mixture by preventing binder drainage and can act as a barrier to prevent crack formation and propagation [13], [14]. Among the fillers, hydrated lime (HL) reduces the chemical ageing of bitumen and improves the strength and modulus of the mixtures, as reported in previous studies [15]. It is also an excellent additive for preventing moisture damage.

Porous surfaces exhibit acoustic absorption. It is generally acknowledged that introducing acoustic absorption in the pavement material results in lower traffic noise levels [3], [4], [16], [17]. This acoustic absorption is an effective suppresser of rolling noise produced by a tire rolling on a road surface. Part of the mechanism is some reduction of sound transmission over the absorbing surface, but the main effect is that such an absorbing surface suppresses the amplification of sound by the acoustic horn composed between the road surface and the curved tire tread band [18]. Since for cars rolling noise is already dominant at speeds above 30 km/h and for trucks at speeds above 70 km/h, reducing rolling noise is an efficient means in the control of total vehicle noise. In addition, the porous surface also suppresses the propagation of propulsion noise that is originating from the power train and reflected against the surface before propagating into the environment.

The absorption spectrum of a grain like structure such as a porous asphalt concrete surface shows strong peaks and valleys (see Figure 1). Effective noise reduction requires a tuning of the absorption spectrum to the emission spectrum of the tire, considering the oblique reflection at the surface [4], [18]–[20]. Tuning is accomplished mainly by varying the thickness of the porous layer. Increasing thickness leads to lowering of the frequencies of the absorption peaks. For cars an optimal absorption is expected at about 800-1000 Hz, for trucks it should be 700 to 900 Hz (optimums depend also slightly on the speed of the vehicles). Properties like flow resistance and tortuosity do also affect the absorption characteristics but in a more complicated way. Maintaining the porosity at levels between 16 % and 24 % will generally suffice in obtaining satisfactorily values for tortuosity and flow resistance.

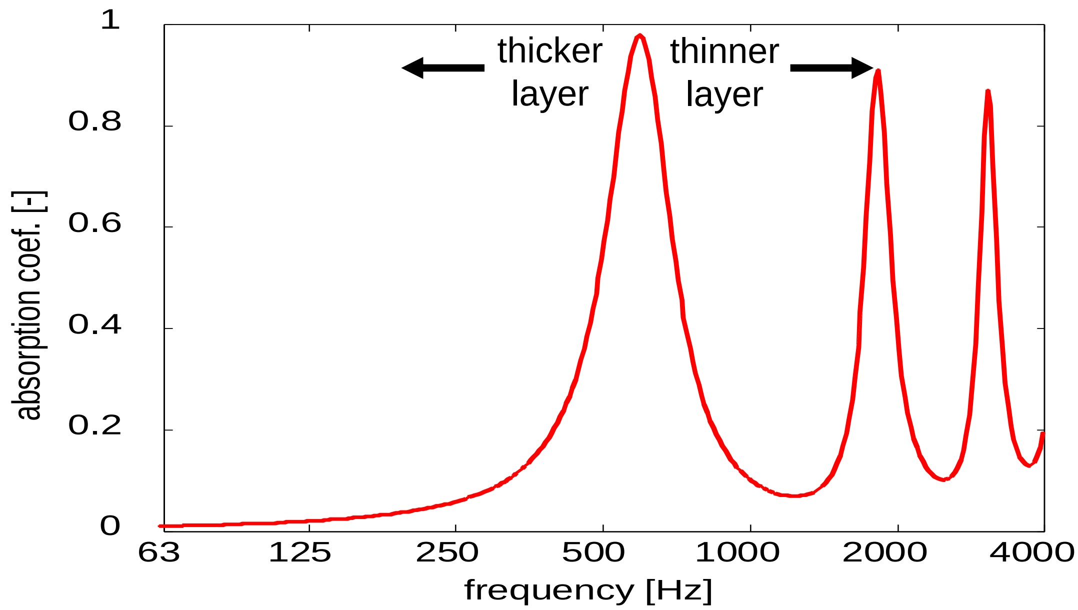

Figure 1. Graph of a typical absorption spectrum for a porous road surface. Varying the thickness of the porous layer results in variation of the frequencies of maximal absorption.

An additional constraint in the design of low noise surfaces is the higher texture that a porous surface generally exhibits. This leads to increased tire tread band vibration and resulting higher noise radiation that will partially neutralize the noise reducing effect [4], [17]. Higher textures also result in higher rolling resistance of the tire [16]. Thus, apart from the tuning of the acoustic absorption, control of the texture is required.

The main purpose of this research is to analyze the variables that influence the main properties to be considered when obtaining an asphalt mixture that reduces the noise emissions generated between the tire and the road; always maintaining a good mechanical performance of the mixtures. For this purpose, several PA mixtures will be mechanically analyzed and subsequently combined to form 2LPA mixtures and subjected to different tests to analyze their texture, acoustic absorption and flow resistivity. These results will help to find out which mixtures obtain a greater noise reduction.

2. Materials and methods

a. Materials

For the preparation of the specimens, a commercial polymer modified bitumen (PMB) has been used in all cases, as this is normal when using porous asphalt (PA) mixtures. Table 1 shows its main characteristics.

Table 1. Characteristics of the bituminous binder used: PMB 45/80-65.

Test	***Standard***	***PMB 45/80-65***
Penetration (25 ºC, dmm)	EN 1426	55
Specific Gravity	EN 15326	1.03
Softening point (ºC)	EN 1427	74.1

Fraass brittle point (ºC)	EN 12593	-13
Ductility force (5 ºC, J/cm^2)	EN 13589	3.11
Elastic recovery (25 ºC, %)	EN 13398	92

In relation to the aggregates, three types of material have been used: ophite was used for the coarse fraction while limestone was used for the fine fraction and filler; finally, hydrated lime was added to complete the filler fraction due to its better adhesion to bitumen. Their physical characteristics are presented in Table 2.

Table 2. Physical properties of the aggregates.

Property	***Specification***	***Value***	***Standard***
Ophite			
Los Angeles coefficient	13	≤ 20	EN 1097-2
Specific weight (g/cm3)	2.787	-	EN 1097-6
Polished stone value (PSV)	60	≥ 56	EN 1097-8
Flakiness Index (%)	8	≤ 20	EN 933-3
Limestone			
Los Angeles coefficient	25	< 25	EN 1097-2
Specific weight (g/cm3)	2.705	-	EN 1097-6
Sand equivalent	78	> 55	EN 933-8
Hydrated lime			
Specific weight (g/cm3)	1.959	-	EN 1097-6
CaO content (%)	> 90 %	-	-

In addition, one type of synthetic fiber was used as reinforcement and binder stabilizer in the mixtures. The selected fiber was aramid pulp (Pulp), which is a type of fibrillated chopped aramid fiber that has been used as a reinforcement in previous researches [21]–[23], based on which it was decided to use 0.05 % fiber content in the mixtures, as the optimal percentage. Pulp has high thermal resistance as well as high tensile strength. Its shape (Figure 2) is characterized by small stratified branches with fibrillar surfaces and length approximately 1 mm.

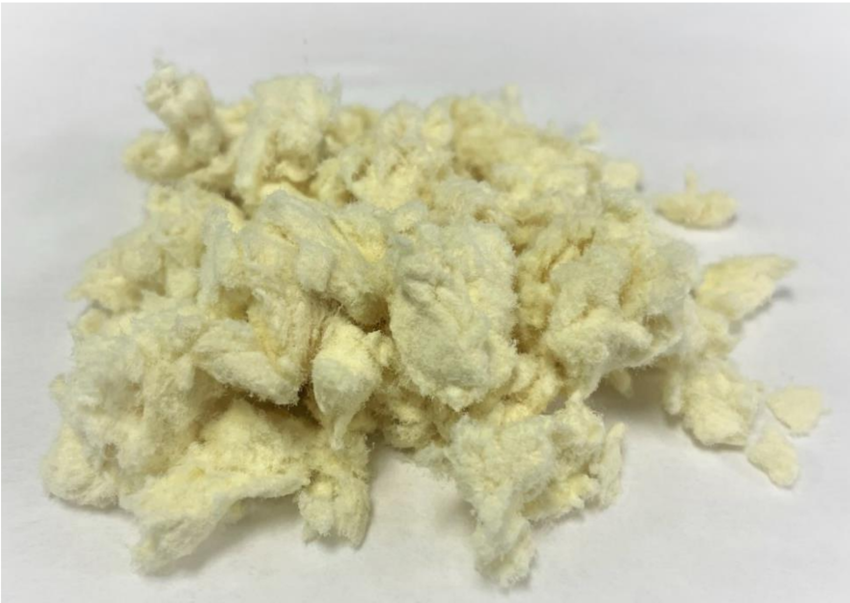

Figure 2. Illustration of the fibers used as reinforcement (Pulp)

b. Experimental designs

The experimental design of the mixtures has been carried out trying to improve their functional properties and to maintain a good mechanical behavior at the same time. For this study, different PA mixtures were designed and combined to make the two-layer porous asphalt (2LPA) mixtures. Table 3 and Table 4 summarize the PA mixtures and the 2LPA mixtures obtained from their combination, respectively.

Table 3. Characteristics of the PA mixtures.

Mixture ID	***Binder content (%)***	***Fiber content (%)***	***Air void content (%)***
PA6A	6.5	0.05	22.3
PA6B	6.0	0.05	24.3
PA6C	6.0	0.05	26.8
PA8A	6.0	0.05	25.4
PA8B	6.0	0.05	23.1
PA11A	5.3	0.05	26.0
PA11B	5.5	0.05	23.8
PA16	4.8	-	28.7
PA22	4.5	-	26.8

Table 4. 2LPA mixtures.

Mixture ID	***Thickness (mm)***	***Top layer***		***Bottom layer***	
		Mixture	***Thickness (mm)***	***Mixture***	***Thickness (mm)***
PA8A + PA22	70	PA8A	20	PA22	50
PA8A + PA16	60	PA8A	20	PA16	40
PA8A + PA11A	50	PA8A	20	PA11A	30
PA8B + PA11B	40	PA8B	20	PA11B	20
PA6A + PA11B	40	PA6A	20	PA11B	20
PA6A + PA8B	40	PA6A	20	PA8B	20
PA6B + PA8B	40	PA6B	20	PA8B	20
PA6C + PA8B	40	PA6C	20	PA8B	20

All the mixtures had a void content of more than 20 %, with some of them reaching values even higher than 25 %. This high percentage of voids has been applied in order to achieve a reduction in the noise emissions of the interaction between the tire and the road. In some cases, such as PA8A and PA8B, several mixtures were designed with the same maximum aggregate size but different particle size distribution in order to improve the balance between mechanical performance and functional properties of the previous one. The mixtures were designed with a high bitumen content and low number of fines to achieve higher void content, so to prevent bitumen drainage and also as reinforcement, fibers were incorporated. The only mixtures that did not contain fibers were PA16 and PA22 because their bitumen content was lower than in the other mixtures.

c. Specimen manufacturing

A traditional procedure was used to manufacture the specimens in this study. The production temperature was the one recommended by the provider of the bitumen (170 °C). The main difference respect the conventional mixtures was the addition of the fibers. They were included by dry way in the aggregates fraction (previous to the incorporation of the binder), and mixed for

1 minute. This method was chosen because of its reproducibility on a real scale plant without the need to upgrade the asphalt plant equipment.

To produce the 2LPA, the top layer was directly laid on the bottom layer without applying a tack coat, while the bottom layer was still warm (around 110 °C). This method was used because it was considered the tack coat would have performed as a barrier between layers, decreasing the communication of the air voids.

d. Experimental set-up

Figure 3 presents the experimental tests carried out, which can be divided into two categories: (1) mechanical tests to determine the mechanical performance of the PA mixtures and (2) functional tests to determine the acoustic characteristics of the 2LPA mixtures.

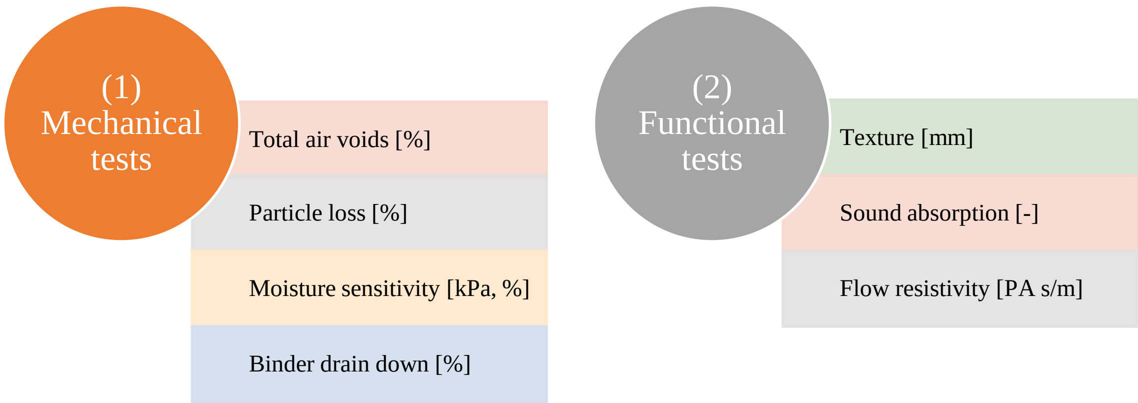

Figure 3. Experimental tests carried out.

The mechanical tests were performed for each mixture independently. Although the bottom layer does not suffer directly the traffic loads, the same tests were carried out because multiple combinations of 2LPA were performed, so some mixtures which are used as the bottom layer in one combination are applied as the top layer in another. Besides, it was important to fully understand their mechanical behavior.

Through the volumetric properties, the total air voids are determined. These results are important because the higher the void content, the higher the permeability and also increased noise reduction. In order to evaluate the raveling resistance of the mixtures, the Cantabro particle loss test was carried out. This test is conducted on cylindrical specimens that have been conditioned according to EN 12697-17 standard before being subjected to the Los Angeles Machine without abrasive load for 300 revolutions at 30 rpm. Other criteria of durability come from assessing the indirect tensile strength (ITS) and testing the moisture sensitivity of the mixtures, which is measured in terms of the indirect tensile strength ratio (ITSR). These tests are also carried out on cylindrical specimens that have been previously conditioned according to EN 12697-12 standard. In this case, the batch of specimens is divided into two groups to conduct the test in dry and wet conditions. Finally, the combination of a high percentage of bitumen and few fines, even containing fibers, can lead to binder run-off. So, to evaluate the stability of the binder at high temperatures, the binder drainage test is carried out in a mesh basket according to EN 12697-18 standard. This value should not exceed 0.3 % by weight of the total mixture according to previous studies [24].

Regarding the functional properties, texture is maximized as to control the texture induced rolling resistance if the tire and the texture induced noise production by the vibrating tire tread surface. Rolling resistance is found to be related to the overall texture level. Texture induced noise exhibits a more specific wavelength spectrum dependency, where longer wavelengths have a positive relation with noise (higher texture level causes higher noise, while at shorter wavelengths an inverse relation is observed (higher texture level produces less noise). The required texture was thus defined as a target wavelengths spectrum that shall not be exceeded in the longer wavelengths bands and has a minimum for the shorter wavelengths.

The texture is measured by evaluating the surface height profile of the road along a line. In the case of car tires, the wavelength range of the road texture that is relevant for texture-induced rolling noise is 200 mm to 5 mm. To achieve statistically reliable results, the measurement length should cover several wavelengths; ISO 13473-4 recommends at least 13 times the longest wavelength band. The sound absorption of a road pavement refers to the acoustic absorption of a plane wave under perpendicular incidence. The appropriate standard measurement method is the "impedance tube" ISO 10534-2. The absorption coefficient (α) is determined by calculating the incoming energy and the energy that is not reflected. To prevent the occurrence of higher cross modes in the impedance tube the maximum applied frequency is defined by the diameter of the tube. In the case of pavement acoustics, the frequency of interest is below 1800 Hz, which implies a diameter of maximum 100 mm. To obtain the greatest possible reduction for cars on an inter-urban road where the speed is around 100 km/h, the absorption peak should be between 800 and 1000 Hz. Finally, the procedure for the determination of the air flow resistance of road surfaces on-site is chosen to be as close as possible to the one described in the standard DIN EN 12053.

3. Results and discussion

a. Mechanical performance

Firstly, despite the high binder content, none of the mixtures exceeds the maximum recommended binder drainage value of 0.3 % (Table 5). It is considered that, as expected, the addition of fibers contributed to stabilize the high binder content in the mixture, thus preventing its leakage.

Table 5. Binder drain drown results.

Design	PA6A	PA6B	PA6C	PA8A	PA8B	PA11A	PA11B	PA16	PA22
BD (%)	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.08	0.00

Secondly, raveling resistance is an important factor to measure the durability of the PA since this is the typical type of failure observed in these mixtures. The result of particle loss test is related to the void content of the mixtures, as can be seen in Figure 4.

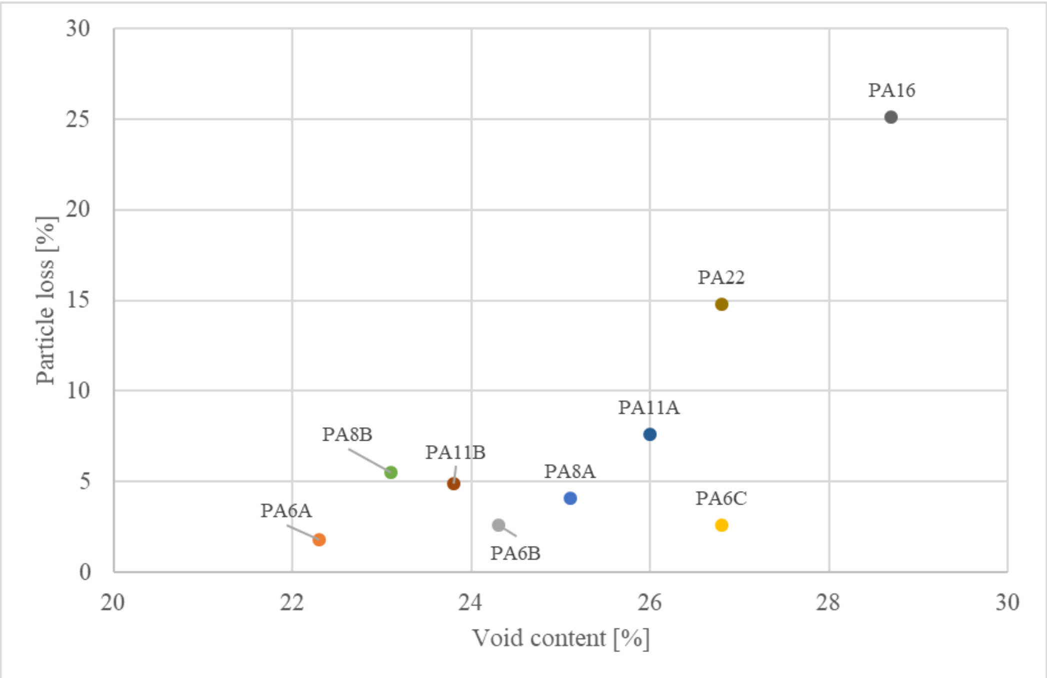

Figure 4. Results of the particle loss test vs void content of the PA mixtures.

All the mixtures presented a void content higher than 22 % and almost all have a particle loss of less than 10 %, which means that their resistance against raveling is really good. PA22 and especially PA16 obtained a significantly higher particle loss, this is probably due to they were the only ones without fibers. However, their performance is not bad if we consider the very high percentage of voids.

Finally, the indirect tensile strength (ITS) in both dry and wet conditions from all designs were evaluated in order to obtain the moisture sensitivity results depicted in Figure 5. It is observed from the results that the tensile strength of the mixtures decreases considerably as the porosity increases. The lowest values were obtained by PA16 with a void content around 29 % and which did not incorporate fibers, while the highest values were obtained by PA6A with a void content around 22 % and whose mixture, in this case, contained fibers. This behavior is especially highlighted in the case of wet samples. Concerning the resistance to water damage, almost all mixtures showed values above 85 %. The only mixtures with lower performance were, again, the mixtures without fibers (PA16 and PA22), and the two mixtures with the lowest percentage of voids whose resistance at dry conditions was remarkably high (PA6A and PA8B).

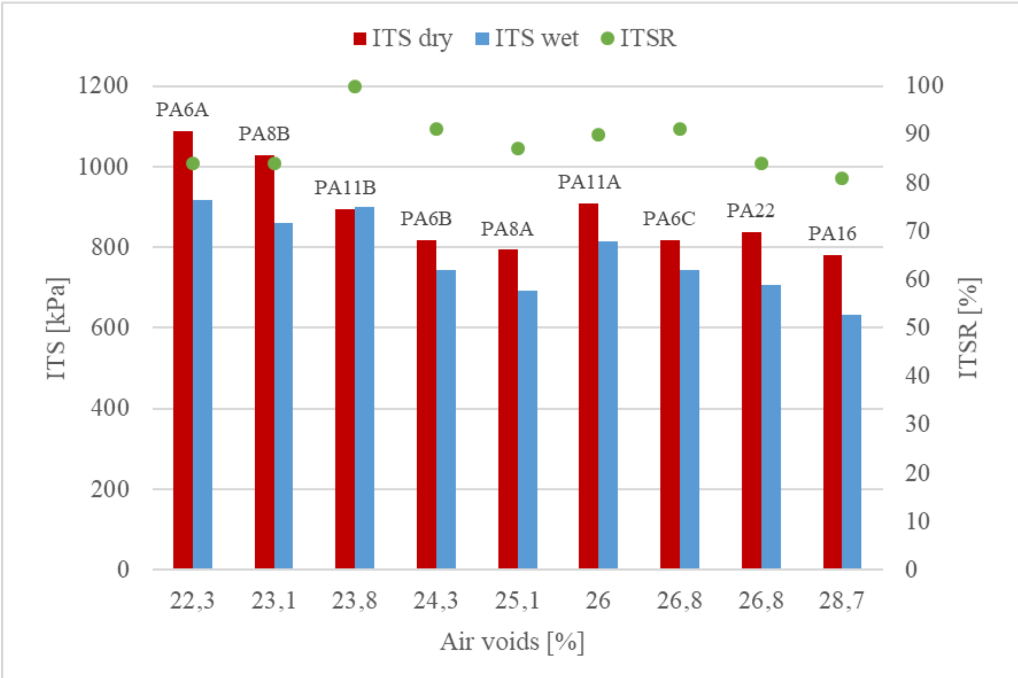

Figure 5. ITS and ITSR values of the PA mixtures.

b. Functional performance

Different properties have been analyzed in order to determine their impact to decrease the noise emissions. The results have been divided depending on these properties.

<u>*Thickness*</u>

One of the most important parameters is the thickness of the mixtures, which is inversely proportional to the frequency of maximum absorption. Figure 6 shows the peak of sound absorption results for different thicknesses of 2LPA mixtures.

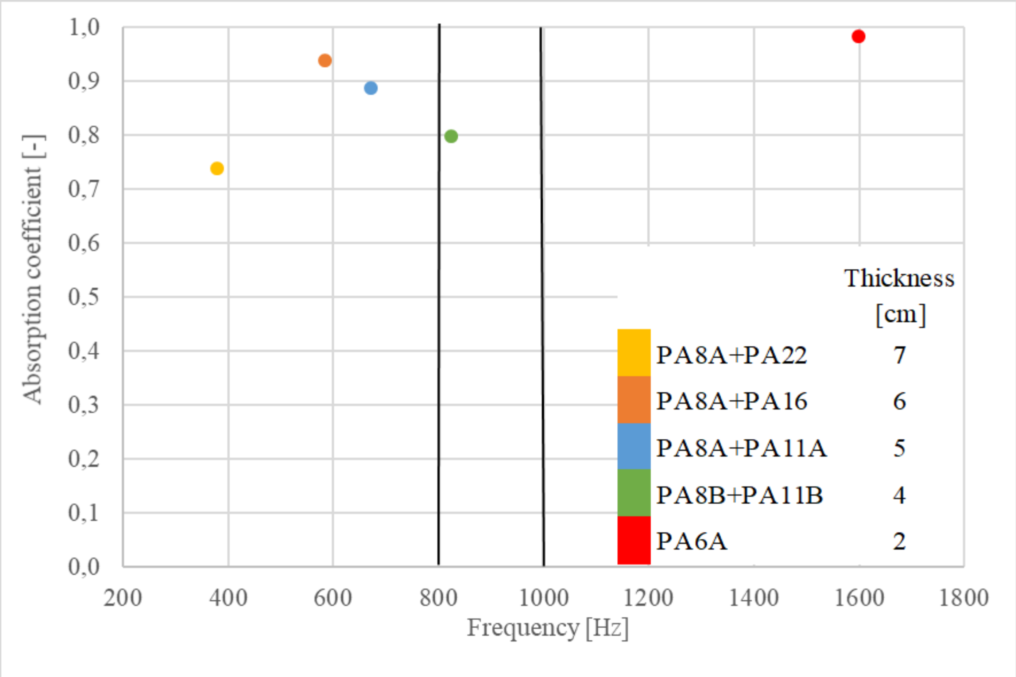

Figure 6. Absorption coefficient vs frequency.

The results show the relationship described above, since the peak in the thinnest mixture is in frequencies above 1400 Hz, while in the thickest mixture the peak is in frequencies below 400 Hz. For the objective range of an inter-urban road, 800 to 1000 Hz, the optimum thickness would be 40 mm. Although this thickness would be more adequate for a conventional PA mixture, as it will be explained later, the resulting mixture would not be optimum for noise reduction since the latter is affected by mix properties other than thickness.

On the other hand, thickness also seems to affect the flow resistivity, since the lower the thickness, the higher the flow resistivity, although the results are excellent in any case (Figure 7).

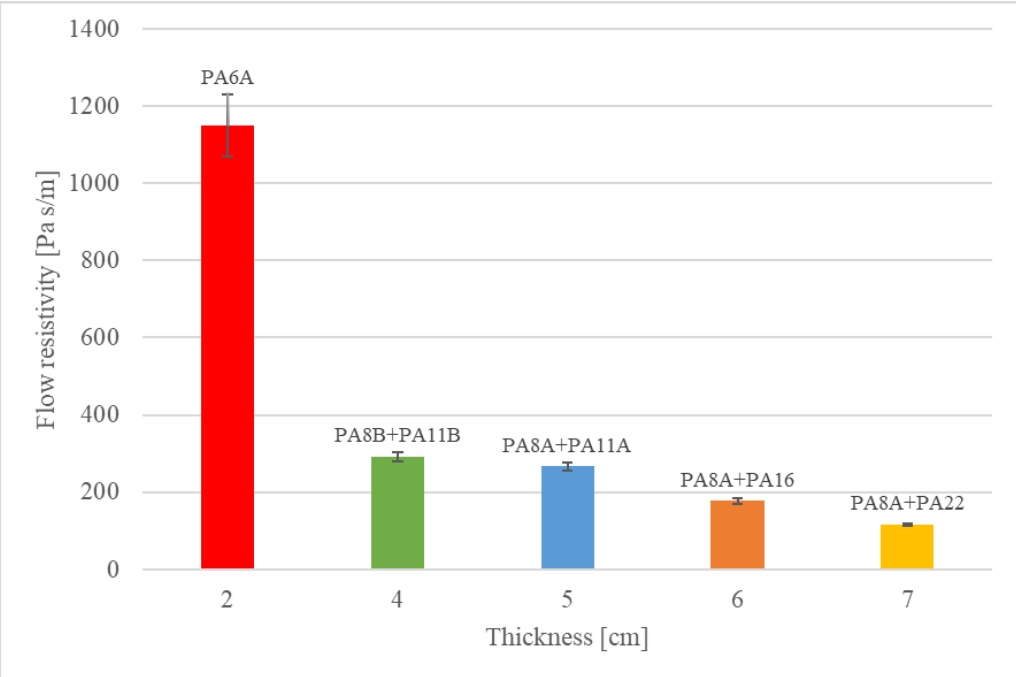

Figure 7. Flow resistivity of 2LPA specimens between 2 and 7 cm thick.

It should be noted that the difference in values between the specimens with 40 mm up to 70 mm was small, while there was a big difference with the 20 mm specimen. One reason for these results could be the lack of enough air travel distance within the pore network in thinner specimens, which becomes sufficient after a certain limit. From that limit, the flow resistivity seems not to be so dependent on the thickness as on other variables, such as the void content and maximum aggregate size.

On the contrary, thickness did not seem to directly correlate with the surface texture of the specimens, a key property in the noise reduction ability of road surfaces. According to Figure 8, although the 40 mm thick mix had a higher texture than those of 50 mm and 60 mm, the one with the highest texture was the 70 mm thick mix.

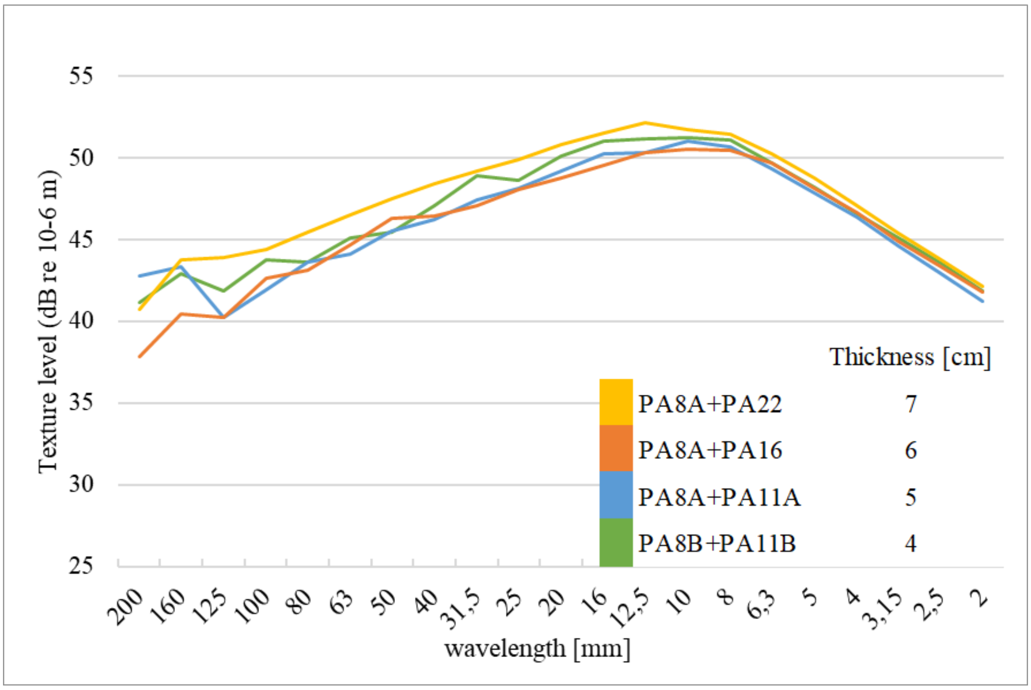

Figure 8. Texture wavelength spectrum of 2LPA mixtures with different thickness.

<u>*Surface layer texture*</u>

On the other hand, the texture of the top layer is expected to be more important than that of the bottom layer because the former is directly in contact with the tire. However, it has been observed that the bottom layer may condition the top layer texture when it is compacted on the bottom layer. This affirmation can be checked in Figure 9, where three texture spectra corresponding to two 2LPA mixtures and a PA mixture are shown. The top layer remained constant, PA6A, while different bottom layers are used in each specimen. It can be seen that between the 2LPA samples there is no appreciable difference; however, when only the top layer is tested (one layer PA), the resulting texture is lower. This may be due to the compaction process of the mixtures, since in the case of PA the compaction was carried out on a metal plate (smooth texture), while in the case of the 2LPA, the top layer was compacted on the bottom layer, which already had a void content of more than 20 % (high texture depth). Likewise, in Figure 9 it can also be observed that the texture wavelength spectrum of three samples with the same top layer and different bottom layers presented minimal differences. Therefore, it could be concluded that the variation of void content in the bottom layer does not significantly affect the texture of the top layer, although the use of a bottom layer does have an influence.

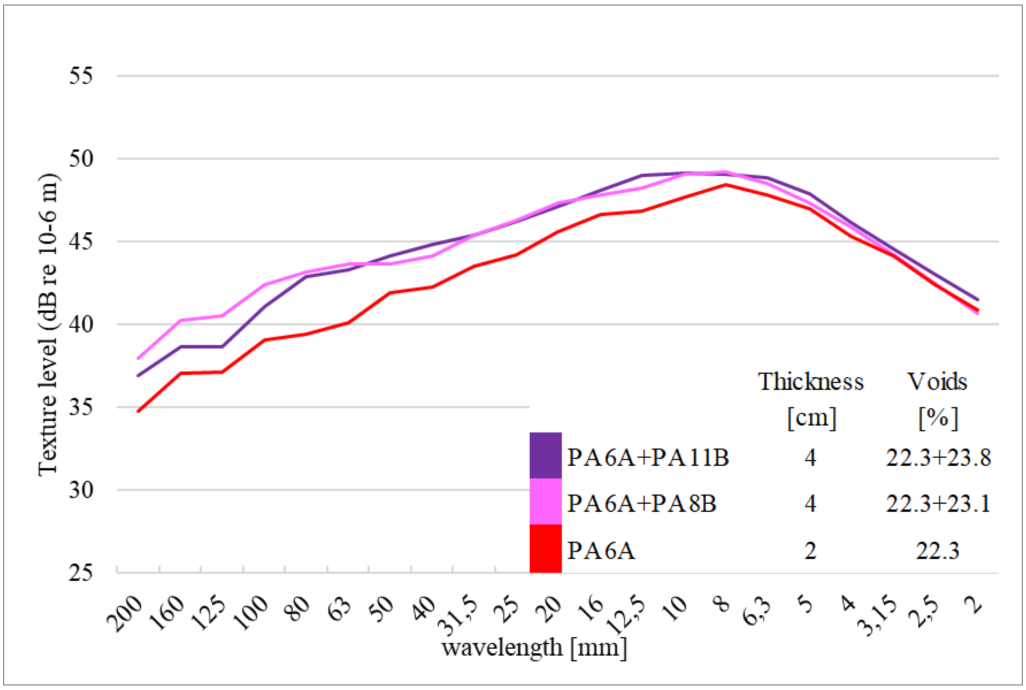

Figure 9. Texture wavelength spectrum of 2LPA mixtures with different bottom layer.

Another important parameter also influencing the surface texture is the maximum size of aggregates in the top layer. It is linked to the thickness of the layer, since to reduce the texture of the mixture smaller aggregate sizes are needed and this limits the maximum thickness of the sample to avoid plastic deformations. This is where the design of a 2LPA mixture fits in, since a small particle size is used in the top layer to improve the texture while the addition of the bottom layer allows the proper thickness to be maintained for a good acoustic absorption. In this study, two maximum aggregates sizes were evaluated: 6 and 8 mm. These sizes were chosen because above 8 mm the texture is triggered and below 6 mm the mixture may have skid resistance problems. The results (Figure 10) showed that the lower texture is obtained when the maximum aggregate size decreases. This effect was more pronounced at longer instead of shorter wavelengths. Applying smaller aggregate sizes does not only reduce texture levels but also causes a slight shift to shorter wavelengths, as can be expected when the dimensions of the structure are reduced.

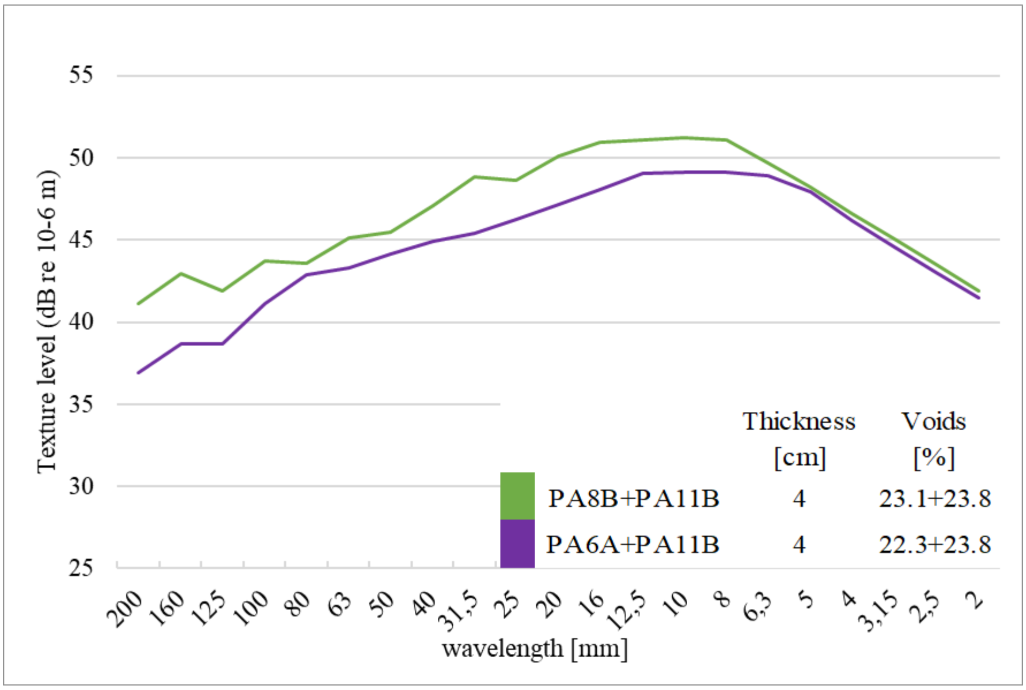

Figure 10. Texture wavelength spectrum of 2LPA mixtures with different top layer.

<u>*Void content*</u>

Finally, the influence of void content on the surface texture, the acoustic absorption and the flow resistivity are evaluated. It can be seen in Figure 11 that small changes in void content (between 22 and 26 %) do not influence the texture; however, these differences do affect the acoustic absorption (Figure 12). The higher the void content the higher the absorption coefficient, so as long as neither texture nor mechanical performance are affected, the more voids the mixture contains, the better the sound reduction achieved. On the other hand, in Figure 12, despite all the specimens had the same thickness, the mixture with the lowest void content presented the absorption peak at lower frequencies. This can partly be explained by the slightly larger tortuosity but more important is the effect of the higher flow resistance of the top layer. It is observed that with a higher flow resistance the spectral distance between first and second absorption peak increases leading to a sub-optimal absorption behavior [25]. A proper balance between thickness and void content should be kept.

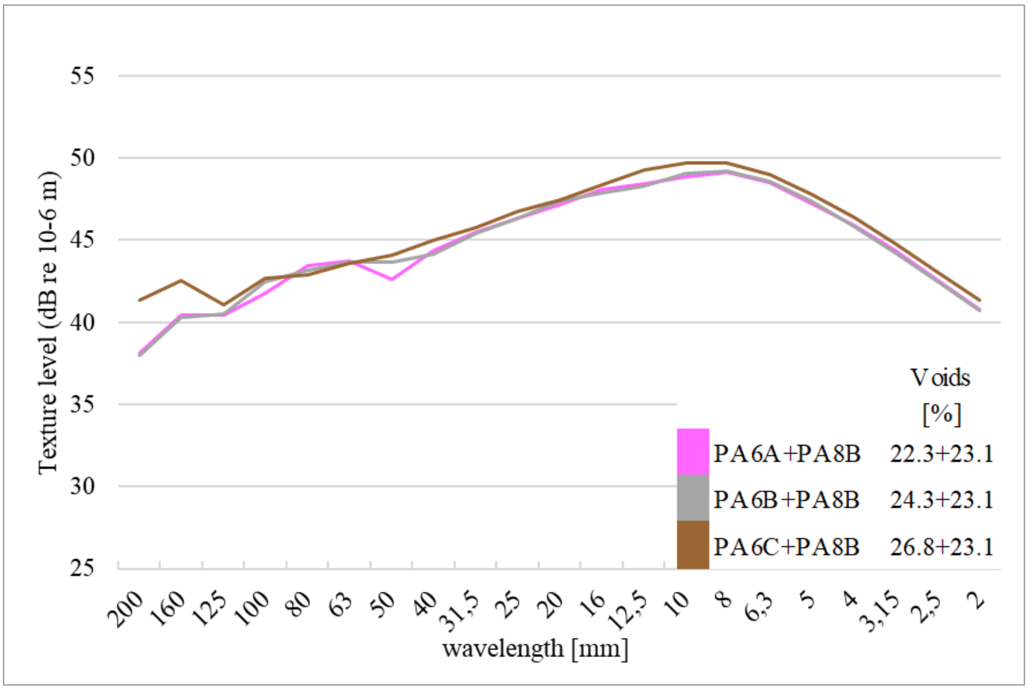

Figure 11. Texture wavelength spectrum of 2LPA mixtures with different void content in the top layer.

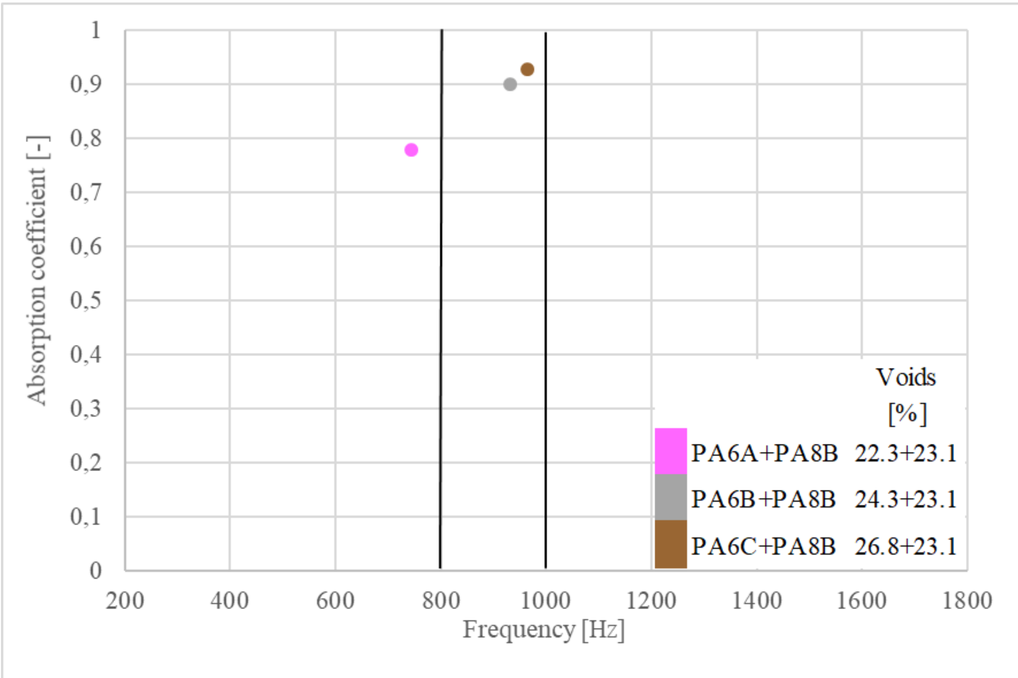

Figure 12. Absorption coefficient vs frequency.

The void content also affects the air flow resistivity (Figure 13). The higher the void content, the lower the flow resistance; such results make sense as air finds more room along the pore network to expand and to escape out of the mixture.

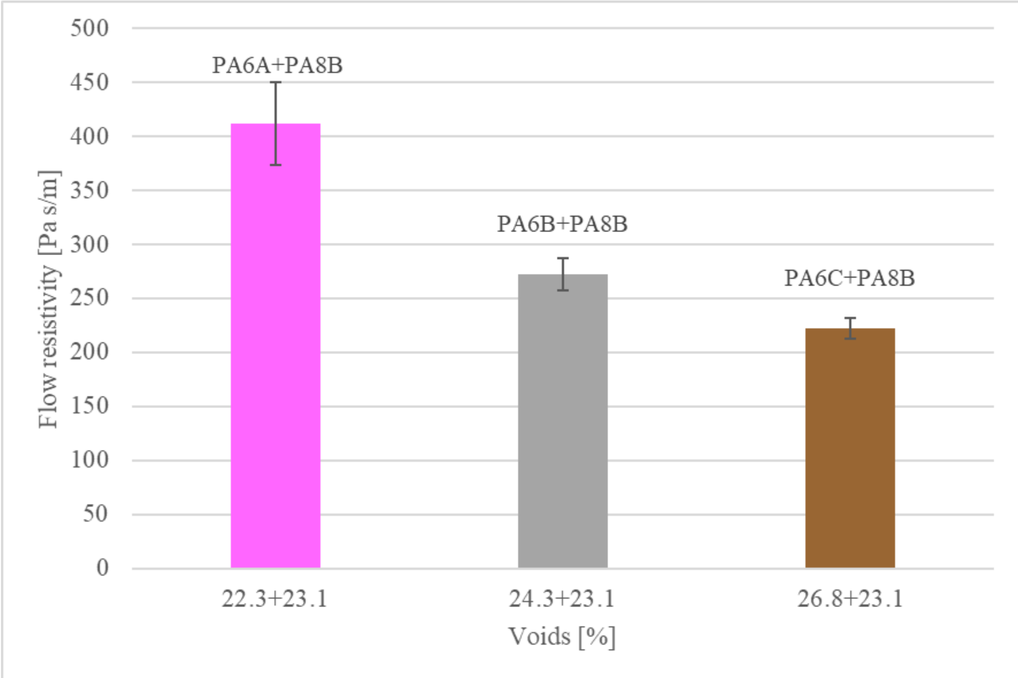

Figure 13. Flow resistivity of 2LPA specimens with different void content of the top layer.

4. Conclusions

Different porous mixtures with different gradation curves and modified with aramid pulp fibers (Pulp) have been designed to evaluate how their properties influence noise emission. The aim of this analysis is to optimize the design of porous mixtures from a mechanical and functional point of view, i.e. to achieve the lowest possible noise emission with the best possible mechanical behavior. The main findings are summarized as follows:

- The proposed PA mixtures have a good mechanical performance despite their high void content of more than 20 %, even exceeding 25 % in some cases. To ensure a good mechanical performance, the use of PMB, fibers and HL is highly recommended.
- The main parameters that affect acoustic absorption results are thickness and void content. The first, thickness, is related to the frequency at which the maximum absorption peak is obtained, while the second parameter, void content, is linked to the value of the absorption coefficient and, to a lesser extent, to the aforementioned frequency.
- The texture is mainly influenced by the maximum aggregate size of the top layer (the smaller the size, the lower the texture), although the bottom layer also has some influence because it adds texture to the base on which the top layer is compacted. Other parameters, such as thickness and void content, did not seem to have a significant influence on the surface texture of the mixture.
- The flow resistivity is mainly influenced by thickness and void content. It should be noted that this test does not seem to be decisive in case of porous asphalt as all the mixtures are well below the maximum limit.

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