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Determination of the Sound Absorption Capacity of Hydraulic Concrete Mixtures Added with Waste Tire Rubber

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Abstract

There are different types of pollutants that are harmful to the environment, including smog, chemicals that are dumped into rivers, scrap tires, etc. The latter have the particularity that it is not possible to recycle them to manufacture new tires. In the present work, hydraulic concrete plates added with waste tire rubber were manufactured to modify their sound absorption capacity. It was found that the rubber additions produce changes in the density of the material and in the sound absorption capacity. When the material is exposed to high-frequency sounds that correspond to high-pitched sounds, its absorption capacity increases. On the contrary, when the test frequency is low, that is, bass sounds, the sound absorption capacity decreases. The results obtained in this work suggest that the proposed mixtures are suitable for the possible manufacture of acoustic insulating shields.

Keywords

Hydraulic Concrete, Waste Tire Rubber, Sound Absorption, Noise Reduction Coefficient

1. Introduction

Today the physical and mental health of human beings both in their homes and in their workplaces is of vital importance. Noise pollution has been found to promote diseases such as stress, sleep disorders, behavioral disturbances, poor performance, hypertension, heart disease, diabetes and obesity, cognitive impairment in childhood, to name the most outstanding [1] [2] [3]. Noise pollution today has become one of the biggest environmental and public health problems of our days due to the incessant development of cities and the increase in population. Maria Foraster, an ISGlobal researcher specializing in noise and health, mentions that "Of all the disease burden attributed to poor urban planning, traffic noise represents 36%, a percentage even higher than that attributed to air pollution" [4]. The website: Green Line CEUTA Smart City, reports that the sources of noise pollution, which by the way, are very diverse, are located mainly in cities and can be included in four basic categories that are:

1) Pollution from vehicle circulation that mainly includes engine noise, noise from tires rolling on the pavement and noise produced by the vehicle when displacing air. This type of contamination corresponds to approximately 80%.

2) Acoustic pollution from carrying out industrial works and constructions. It corresponds approximately 10%.

3) Pollution the movement of railways. It corresponds to approximately 6% of the total noise.

4) And finally, the presence of bars, music venues and other types of activities that correspond to 4%.

At the same time, materials technology is constantly advancing in the search for more durable and comfortable materials, but also friendly to the environment [5]. Many countries, especially those in the First World, are currently reviewing their laws in favor of a more sustainable and ecological future. The aim pursued is to achieve sustainable development, based on the prevention, reuse, recycling and revaluation of waste products. The dumping of construction waste (CW) without prior treatment is prohibited to promote recycling and revalue the waste that reaches treatment plants. Regarding the disposal of the tires, it was established that, as of July 16, 2003, no landfill with whole used tires will be admitted, not even the chopped ones.

The current trend is the development and use of alternative materials, the concrete one of them. Various studies have been made on concrete added with waste or recycled polymers. This is with the intention of giving waste polymers a beneficial use and removing them from dumps, but also for the economic advantage that it can represent. These studies have resulted in the improvement of some of its concrete properties, for example, the durability of concrete has been increased using fly ash [6] and slag, without detriment to its resistance. Likewise, several studies have been carried out trying to modify its mechanical properties, but also its acoustic properties, by adding rubber from waste tires [7] [8] [9] [10]. Such additions have been reported to decrease their mechanical strength but also affect their fracture mode in a way that could be beneficial [8]. Regarding acoustic properties, it has been found that rubber additions to concrete also modify its behavior [7] [9] [10].

Sound is actually waves that propagate through an elastic medium, causing a change in the pressure of the medium, which produces an auditory sensation that can be detected by a person with normal hearing capacity, or by a sound detection instrument for sensing sound waves within a range of frequencies and intensities perceived by the human ear. It originates in some medium a series of compressions and rarefactions, moving through it at a speed that depends on the nature of the medium itself. Acoustic absorption or sound absorption, is the common name to refer to the ability of all materials to absorb a portion of the energy of sound waves when they affect them, thus reducing the amount of sound energy that is reflected by the material [11]. In addition, the sound absorption capacity is a measure that indicates the amount of dB absorbed by a material for each cm^2 of surface area and is obtained by first calculating the sound absorption coefficient and the noise reduction coefficient.

Rubber modified concrete is very effective in absorbing sound energy, impact energy, and also energy from mechanical vibrations compared to pure concrete. Some researchers found that sound absorption and noise reduction coefficient increased with increased replacement levels of more than 20% crumb rubber [12] [13] and suggested that the higher sound absorption of rubber-concrete is due to the increase of air voids in the concrete. On the other hand, the inclusion of rubber in the concrete results in greater durability and elasticity, which gives rise to its use in important areas such as impact absorber in the construction of road elements and sound, in sonic barriers and also in buildings earthquake resistant, etc [13]. In the present study, rubber from waste tires was introduced as a substitute for sand in the concrete using different proportions. It was found that certain proportions of rubber promote an improvement in the sound absorption capacity of concrete and some other compositions decrease it. Variations in density were also found with respect to other reported works. The objective of this research is to evaluate the use of the fine fraction of recycled aggregates from rubber waste from end-of-life tires in the manufacture of concrete sheets.

2. Experimental Setup

Concrete samples were prepared with scrap tire rubber as a replacement for fine aggregate, to modify its noise reduction coefficient according the compositions indicated in **Table 1**.

The mixtures were cast in molds with a wooden base and galvanized steel spacers, see **Figure 1**. The product obtained was concrete slabs 12.5 cm long by 10.5 cm wide by 2 cm thick. The samples were demolded after 24 h (see **Figure 2**) and left to rest for 7 days in a vertical position to avoid possible deformation.

Subsequently, the samples were tested in a sound power measurement system, where the acoustic energy, in dB, transmitted through the test specimen was determined. The measurement system consists of two closed tunnels. The first tunnel houses a speaker that acts as the source of sound waves and the second, houses an Hti brand decibel meter, model HT-80A, to measure the intensity of

Table 1. Proportions of aggregates used in the concrete mixtures of the present study and sample of the rubber used for the preparation of the samples.

Sample	Vol % sand	Vol % rubber
0	100	0
5	95	5
10	90	10
15	85	15
20	80	20
25	75	25

Figure 1. (a) Wooden base mold and steel spacers. (b) Samples cast in the mold.

Figure 2. Example of the platelets obtained after 24 h of setting.

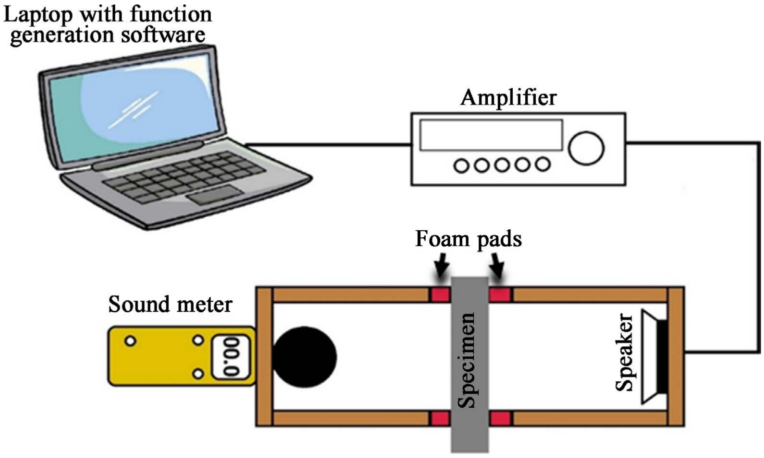

Figure 3. Representative scheme of the system used in the present investigation.

the output signal. A laptop preloaded with function generation software was attached to the speaker. The computer signal was transmitted to an amplifier through a coaxial cable and once the signal was amplified, it was retransmitted to the device's speaker. The reading of the intensity of the sound signal transmitted through the test specimen is read on the display of the decibel meter. The system configuration is shown in Figure 3. The function generation software allows the variation of the intensity of the input signal, as well as the generation of different types of waves that can be sinusoidal, square or sawtooth. For the present work a sinusoidal waveform was used. The function generator also allows selection of the frequency of the generated wave. In the present study, six octave bands were used, which were 125 Hz; 250 Hz; 500 Hz; 1000 Hz; 2000 Hz and 4000 Hz.

The measurements were made as follows: First, the function generation software was configured to output a sinusoidal type wave with a frequency of 125

Hz. Then, in the measurement system, in the sample cavity, a wooden frame was placed and the sound source was turned on. This step was carried out to measure the sound power of the source without a sample but keeping the distance between the sound source and the decibel meter, that is, without any obstacle. The sound power value of the source was recorded and the wooden frame was removed. A concrete sample was then placed and the power of the sound transmitted through the sample was measured recording the corresponding value. This operation was carried out for all of the concrete compositions and also for all frequencies.

Calculation of the Noise Reduction Coefficient

The acoustic properties of a material can be determined by calculating the sound absorption capacity and noise reduction coefficient of the material. The sound absorption capacity is a measure that indicates the property that a material has to retain sound within itself per unit area, without letting it out completely. It is calculated using Equation (1) [14] [15] [16] [17].

$$A = \sum_{i=1}^{n} s_i \alpha_i \tag{1}$$

where s is the incidence surface of the sound beam and α, which is given by Equation (2), is the sound absorption coefficient.

In Equation (2), E_t is the acoustic energy transmitted through the sample and E_i is the sound energy emitted by the sound source. In the same way, the noise reduction coefficient (NRC) indicated by Equation (3) [14] [15] [16] [17], is the arithmetic average of the sound absorption coefficient of a material, but evaluated at different frequencies or bands.

$$\alpha = 1 - \frac{E_t}{E_i} \tag{2}$$

$$\text{NRC} = \sum_{i=125}^{4000} \alpha_i / n \tag{3}$$

where i takes the values of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and n is the number of frequencies tested, in this case 6.

3. Results

Once the samples were obtained, tests were carried out to determine their density and the noise reduction coefficient. By definition, the density of a material is the amount of its mass divided by the volume that mass occupies. The determination of the approximate density was made by measuring the mass of the samples on a digital scale of 3000 g capacity. The samples were then immersed in a known volume of water and the volume of water displaced by the sample was measured. The results obtained are shown in **Table 2** and **Figure 4**.

From **Figure 4**, it can be seen that the additions of rubber to concrete decrease its density, however, such decrease is not as high as might be expected. The maximum density was 1307.47 kg/m^3 and corresponds to concrete without rubber.

Table 2. Approximate density of concrete samples with rubber.

Vol % Rubber	Density (kg/m^3)	% Weight decrease
0	1307.47	0.0
5	1300.03	0.6
10	1292.31	1.2
15	1283.67	1.8
20	1271.39	2.8
25	1262.63	3.4

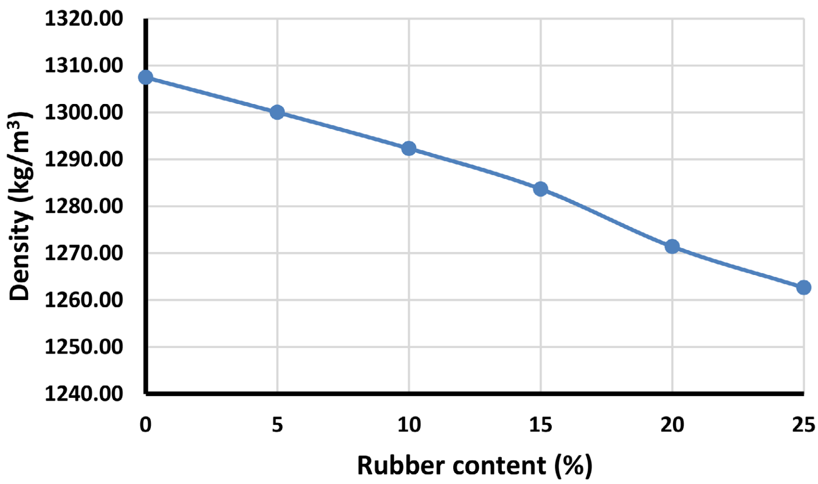

Figure 4. Density of rubber-added concrete samples as a function of their rubber content.

The minimum density value was 1262.63 kg/m^3, which corresponds to the sample with 25% rubber. This decrease represents 3.4% compared to the densest sample, which is the concrete without rubber. During the acoustic tests it was found that there is a proportional relationship between the input sound power, I_{in}, and the output sound power, I_{out}, that is, the intensity of the output signal increased when the intensity of the input signal also increased. However, it was found that there is an interval in the input intensity level in which the output intensity level presents very little variation, as can be seen in Figure 5, which shows the variation of the output intensity as a function the strength of the input signal.

The range of input intensities with little variation of the output intensities was taken as the adequate to make the I_{out} measurements for the calculation of the sound absorption coefficients for each concrete composition. Since the variation in the output intensity is minimal, the values of the sound absorption coefficient can be considered reliable. The values of the sound absorption coefficient and the noise reduction coefficient calculated with Equations (2) and (3) respectively for each frequency, are indicated in Table 3.

Table 3 shows the Sound Absorption and Noise Reduction Coefficients calculated with Equations (2) and (3) respectively, as a function of the rubber content

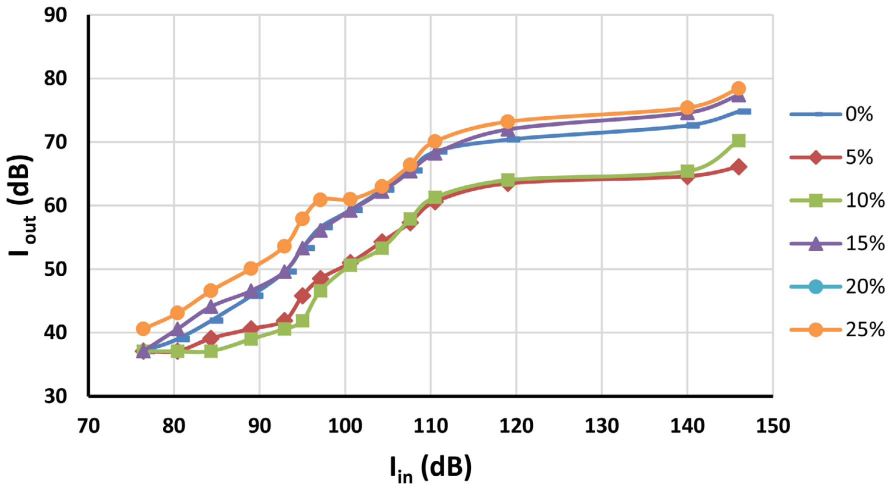

Figure 5. Variation of the intensity of the output signal as a function of the intensity of the input signal.

Table 3. Sound absorption coefficient (SAC) and noise reduction coefficient (NRC) as a function of the rubber content and frequency.

Frequency (Hz)	Rubber content (Vol. %)					
	0	5	10	15	20	25
125	0.4096	0.4096	0.3719	0.4058	0.2881	0.3875
250	0.1854	0.2323	0.2847	0.2663	0.1109	0.1171
500	0.4339	0.4422	0.4582	0.4372	0.3742	0.4663
1000	0.4896	0.5010	0.4747	0.5342	0.4641	0.5072
2000	0.5480	0.5516	0.6177	0.5972	0.5530	0.5578
4000	0.5208	0.5082	0.5444	0.4962	0.5081	0.4890
NRC	0.4312	0.4408	0.4586	0.4561	0.3830	0.4158

and the frequency in Hz of the input signal I_{in}. The graph of Figure 6 shows the data for the Sound Absorption Coefficient as a function of the rubber content in the test samples.

It can be observed that the rubber content affects the noise reduction coefficient, this effect being more notorious in the octave bands corresponding to the frequencies of 125 Hz and 250 Hz, which, by the way, are the lowest and correspond to bass sounds. When the frequency is 125 Hz, the increase in the rubber content in the concrete sample produces slight variations in the behavior of the noise absorption coefficient in the composition space from 0% to 15% rubber. These variations are actually very small and are in the range from 0.4096 for the samples with 0% and 5% rubber, up to 0.3719 that corresponds to the sample with 10% rubber. As can be seen, the difference is only 0.0377. Subsequently, the SAC value drops to 0.2881 in the sample with 20% rubber, which represents a decrease in the reduction capacity of the material of approximately 42% with respect to the highest SAC values that were exhibited by the samples with 5%.

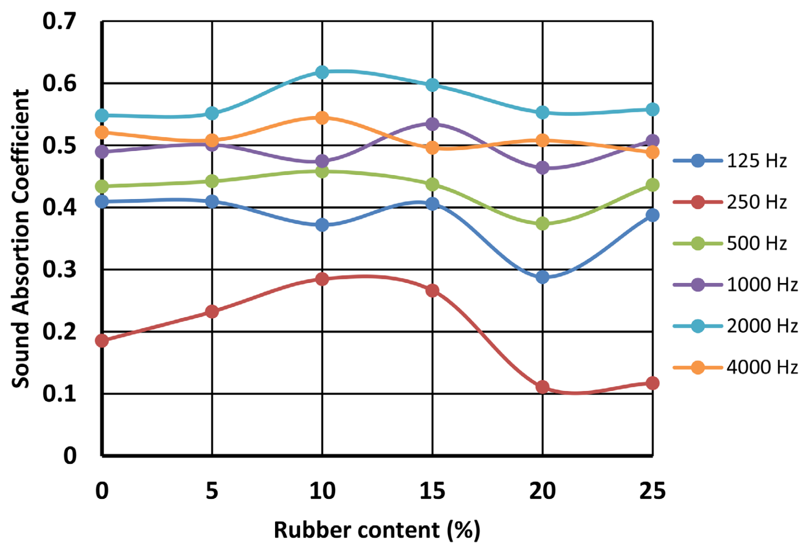

Figure 6. Variation of the sound absorption coefficient with respect to the rubber content in the samples and the test frequency.

and 0% rubber. On the other hand, the sample with 25% rubber showed a rise in SAC reaching the value of 0.3875, although this value is slightly lower than that of the samples with 0%, 5% and 15% rubber. At the 250 Hz frequency, the rubber additions produced notable changes in the SAC, but it is important to mention that the SAC values at this frequency in all of the rubber compositions were the lowest of all the frequencies tested. It can be seen that there was an increase in the SAC in the space between 0% and 10% of rubber with the values of 0.1854 and 0.2847 respectively. Subsequently, the SAC value decreased drastically to the value of 0.1109, which corresponds to the sample with 20% rubber. Regarding the frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, it can be observed that all the rubber compositions show SAC values greater than 0.4, but despite this, it was observed that the composition of 20% rubber shows a small decrease in SAC at the frequency of 500 Hz.

Figure 7 shows the variation of the sound absorption coefficient with respect to frequency for all the rubber compositions studied. It can be observed that, initially, that is, at the frequency of 125 Hz, all of the concrete compositions show values of the SAC that oscillate between 0.2881 dB in the sample with 20% rubber and 0.4096 for the samples of 0% and 5% rubber. When the samples were tested at a frequency of 250 Hz, a decrease in SAC was observed in all of them, with values ranging between 0.1109 corresponding to the sample with 20% rubber and 0.2847 in the sample with 10% rubber.

In this sense, it is worth mentioning that, of all the compositions studied, the 10% rubber sample was the one that showed the lowest SAC decay, but also the one that showed the highest SAC value when the test frequency was 2000 Hz. Otherwise, the 20% rubber sample showed the greatest SAC decay at the 250 Hz frequency. When the samples were tested at frequencies of 500 Hz and up to 2000 Hz, the SAC values increased, reaching maximum values when the samples were tested at 2000 Hz. At this frequency, the 10% rubber sample exhibited the maximum SAC value and the 0% sample showed the minimum. Subsequently, the SAC values decreased when the samples were tested at 4000 Hz, which correspond to very high-pitched sounds.

The noise reduction coefficient, NRC, represents the average value of the material's ability to absorb sound at different frequencies. Figure 8 shows the behavior of the NRC calculated with equation 3 for all mixtures of concrete with rubber. It can be observed that the additions of rubber do affect the acoustic properties of the concrete in a beneficial way in the composition interval from 5% to 15% rubber, being the sample of 10% rubber the one that showed the best

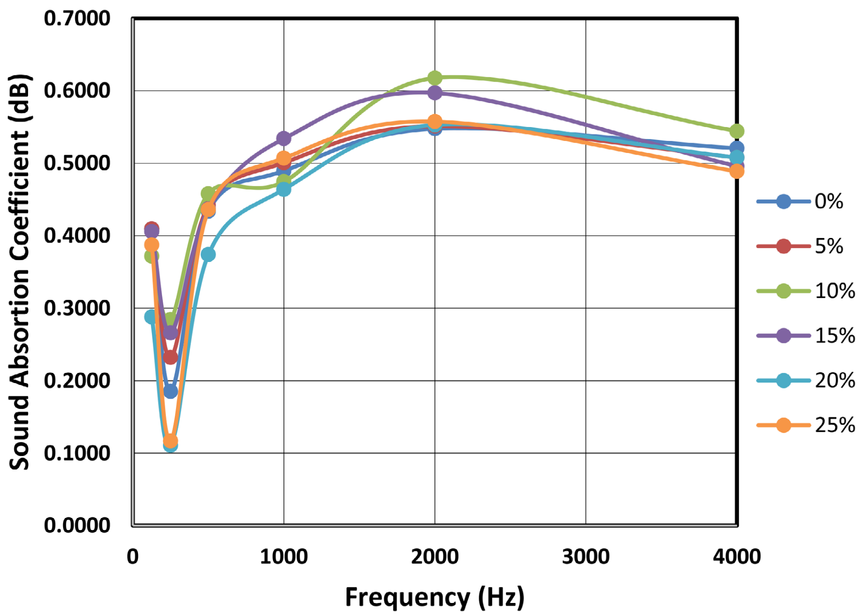

Figure 7. Variation of the sound absorption coefficient as a function of the test frequency.

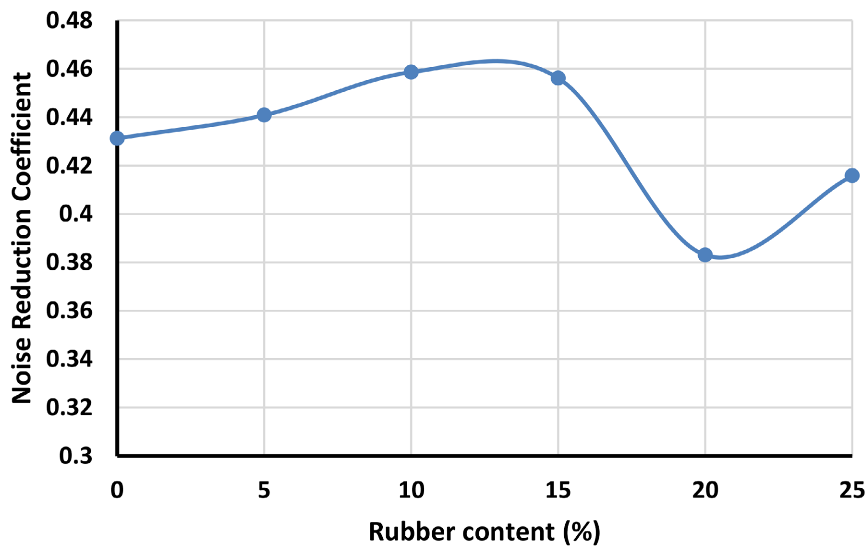

Figure 8. Variation of the noise reduction coefficient with the increase of the rubber content in the samples.

performance with respect to the sample with 0% rubber.

The improvement percentages with respect to the 0% rubber sample were 2.23% for the 5% rubber sample, 6.35% for 10% rubber and 5.77% for the 15% rubber sample. Subsequently, the NRC value drops drastically in the 20% and 25% rubber compositions, the 20% sample being the one that exhibited the lowest value. Such decreases represent 11.2% and 3.57% for the 20% and 25% rubber samples respectively.

Finally, the sound absorption capacity of each concrete composition was determined with Equation (1). Since each composition was tested separately, the values of i and n are reduced to 1, so Equation (1) remains as follows:

$$A = s_1 \alpha_1 \tag{4}$$

For the present investigation, the value of s_1 is 49 cm^2 since the test tunnel window has these dimensions. The values of A for all the samples are shown in Table 3 and in the graph of Figure 9. As it can be seen, such graph resumes all of the before mentioned data and confirms that, effectively the rubber additions to the concrete enhance the acoustical properties of the concrete. However, there are two compositions which exhibit the best absorbative properties which are the 10% and 15% rubber content. In the same way, there are two rubber compositions with the lowest absorbative properties which are 20% and 25%. This means that not necessarily high rubber additions to the concrete enhance its acoustical properties but just can decrease such properties.

4. Discussion

The noise reduction coefficient is an average assessment of how much sound an acoustic material can absorb, that is, how much sound will pass through the material. In this sense, the more absorbent the material, the more silence there will

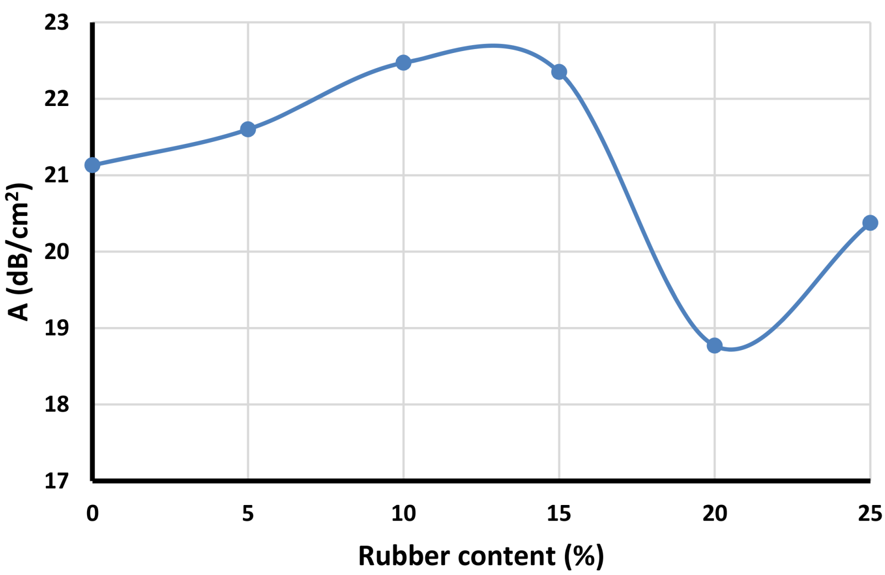

Figure 9. Effect of the rubber content in the samples on their sound absorption capacity per cm^2.

be in a given space. There are materials that completely reflect any sound wave that hits them. These types of materials do not absorb sound, so their sound absorption coefficient is zero. On the contrary, there are materials that are capable of absorbing sound, and the sound absorption coefficient can indicate how much sound these materials can absorb. To determine if a material is absorbent or not, the noise reduction coefficient is used since it encompasses all the octave bands tested. Those materials that have noise reduction coefficients greater than 0.5 are considered absorbent materials. On the other hand, NRC ratings range from 0 to 1 and a NRC of 0 means the product does not absorb sound. Otherwise, NRC of 1 means that the product absorbs all sound. The higher the NRC, the better the product will absorb sound.

It has been reports that the thickness and density of a product, are two factors in the calculation of a noise reduction coefficient. An acoustical product with an NRC rating of 0.95 means that 95% of the sound in the space is absorbed, while the other 5% is reflected. Several studies have been carried out on the sound absorption of concrete added with rubber in different proportions, finding similar results, but also with some discrepancies [10] [11] [18] [19]. It has been reported that the inclusion of ground rubber in some materials promotes improved noise absorption properties [11] [20] [21] [22] [23]. Niall *et al.* [11] studied the effect of replacing fine aggregate with rubber particles on the acoustic properties of concrete using compositions of 7.5% and 15% by volume of rubber, at frequencies of 63, 125, 250, 500, 1000, 2000, 4000 and 5000 Hz, in plates of 245 × 245 × 100 mm and a volume of 0.078 m3. They found that there is a decrease in the density of concrete by adding rubber to it. Additionally, they determined that the density of the samples with 7.5% vol and 15% vol rubber were approximately 2300 kg/m^3 and approximately 2235 kg/m^3 respectively. In the present study, the densities found were 1300 kg/m^3 and 1284 kg/m^3 for the samples with rubber contents of 5% vol. and 15% vol. respectively. It can be seen, there is a big difference. In this sense, this discrepancy could be due to the difference in the design of the mixtures. In the present study, the proportions of the aggregates were made in accordance with the provisions of a Mexican Cement Builders Manual for the preparation of a concrete with a resistance of 250 kg/cm^2. Along the same lines, Phattharachai *et al.* [24] designed and fabricated lightweight concrete samples for structural applications adding rubber as a substitute for fine aggregate in proportions from 10% vol to 50% vol in intervals of 10. He and his team found that the samples with rubber contents of 10% vol and 20% vol exhibited densities of 1752 kg/m^3 and 1728 kg/m^3 respectively. Which, although they are lower than those reported by Niall *et al.*, are higher than those of the present study. Again, such a discrepancy may be due to the design and proportions of the aggregates in the mixes.

Regarding the noise absorption capacity of mixtures with different rubber contents, Niall *et al.* report low SAC values, between 0.06 and 0.018 when the samples are tested at frequencies of 250 Hz, 500 Hz and 2000 Hz. In the present work the lowest values of the SAC were recorded at the frequencies of 125 Hz and 250 Hz, however, even when they are the lowest in the present work, that is, between 0.1 and 0.4, such values are higher than those reported by Niall *et al.*. Likewise, in the present study, the highest values of the SAC correspond to the frequency of 2000 Hz and oscillate in the range of 0.54 and 0.61. In this same sense, the SAC values reported by Phattharachai *et al.*, although they are not the same as those found in this work and neither are the proportions of aggregates, they are closer. For example, they report an increase in the SAC value when the test frequency increases, which was also observed in this work.

It has been reported that those rubber-containing materials that exhibit sound absorption coefficients in the range from 0.3 to 0.7 are considered to be good sound-absorbing materials. The results obtained in the present study suggest that the proportions used are adequate for the preparation of a noise-absorbing material.

5. Conclusions

A study was conducted to determine the sound absorption capacity of 5 hydraulic concrete mixes using waste tire rubber as a substitute for sand.

It was found that the additions of rubber produced a decrease in the density of the concrete. The densities obtained in the present study were compared with those reported in the literature by Niall *et al.* and Phattharachai *et al.* in rubber compositions similar to those of the present work, finding that theirs are higher. Such difference is presumed to be due to the proportion of the aggregates used for the preparation of the mixtures. In the present study, the proportions of aggregates were selected based on a Mexican Cement Builders Manual for a concrete with a load factor of 250 kg/cm^2.

It was also found that rubber additions to hydraulic concrete produce changes in its sound absorption coefficient, SAC, as a function of test frequency. The rubber additions produce a decrease in the SAC when exposed to low frequencies, that is, bass sounds of 250 HZ, being the compositions with 20% vol and 25% vol of rubber the ones that showed the lowest values of all. Subsequently, an increase in the SAC value was observed at the frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, observing the highest values of the SAC at the frequency of 2000 Hz. In this sense, the samples that exhibited the best values of the SAC were those of 10% vol and 15% vol of rubber whose SAC values were 0.61 and 0.59 respectively.

It has been reported that rubber-containing materials that exhibit sound absorption coefficients in the range from 0.3 to 0.7 are considered to be good sound-absorbing materials [25-27]. In the present investigation, the studied mixtures exhibit SAC values greater than 0.3 when exposed to frequencies of 500 Hz and higher, so it is presumed that the proposed samples have the potential to be used as acoustic insulating materials for high-frequency sounds and/or treble.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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