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Mechanical and Acoustic Performance of Concrete Containing Vermiculite and Rubber

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The excessive production of new tires and the inappropriate disposal of waste tires have caused serious environmental and public health problems. To properly dispose of this environmental liability, these rubber residues have been used in cement composites to improve some of their properties in the hardened state. This study evaluates the incorporation of rubber and vermiculite residues in concrete in terms of mechanical and acoustic properties. Different concrete compositions were defined where rubber waste and vermiculite were used to replace the natural sand mass. To characterize the concretes, mechanical and acoustic tests, and analysis of the microstructure of the material were carried out to better understand its properties. An improvement in the acoustic properties can be seen in the composites with rubber and vermiculite. Thus, the great contribution of this research is the development of concrete compositions for acoustic barriers, technically viable, adding environmental benefits.

Keywords: *Alternative materials, rubber waste, lightweight aggregates.*

1. Introduction

In Brazil, according to the Resolution of the National Council for the Environment (CONAMA) 272[1], excessive noise causes damage to physical and mental health, particularly affecting hearing. Motor road vehicles are one of the main sources of noise in the urban environment, and there is a need to use appropriate technologies to mitigate noise pollution. The maximum noise emission limit for motor vehicles is 80 dB.

According to Law nº 4,092[2], noise pollution above 80 dB can cause ulcers, irritation, manic-depressive excitement, psychological imbalances, degenerative stress and can increase the risk of heart attacks, strokes, infections, osteoporosis, high blood pressure and hearing loss, among other illnesses.

ABNT NBR 10151[3] establishes a procedure for measuring and evaluating sound pressure levels indoors and outdoors in buildings, in areas intended for human occupation, depending on the purpose of land use and occupation. The limits of sound pressure level depending on the type of inhabited areas and the day and night period respectively, are from 70 dB to 60 dB for predominantly industrial area up to 40 dB to 35 dB for rural residential area, being in this range, area urban residential, hospitals, schools, with a predominance of commercial, cultural, leisure and tourism activities.

A variety of materials can be used for road traffic noise suppression panels and barriers. In addition to the barrier material, surface treatment texture can depend on several factors, including aesthetic requirements, execution techniques, maintenance and the type of barrier material. Anti-noise barriers can be built with soil, concrete, masonry, wood, metal and other materials[4-6]. Concrete block and panel acoustic barriers provide stability and help minimize traffic noise[4].

Concrete is a good insulator, however, a poor sound absorber[7]. As a way to improve the acoustic performance of concrete, it is a viable alternative to incorporate lightweight and porous aggregates in its composition[8]. The lightweight aggregates widely used in concrete production are: vermiculite, expanded clay, expanded polystyrene, perlite and others[6,9].

Vermiculite is a lightweight aggregate consisting of magnesium, aluminum and iron silicates. When heated, vermiculite expands and results in a material of low specific mass and high porosity, with thermoacoustic properties[9-11].

The cement composites with vermiculite present properties in the fresh state as increased workability, water absorption, porosity and decreased density of the composite. In the hardened state it presents reduced mechanical strength[12] and good thermoacoustic properties[10,13].

In the civil construction sector, concrete is one of the construction materials that has incorporated rubber waste from tires to replace the aggregates, in order to reduce the extraction of non-renewable resources and add properties that improve its performance in service. Research reports that the incorporation of tire rubber as aggregate in concrete causes reduction of workability, density, compressive and tensile strength, modulus of elasticity, and improvement of damping, thermoacoustic properties[14-19].

The National Solid Waste Policy, instituted in Brazil through Law No. 12,305[20], has promoted the use of waste as an alternative to minimize the extraction of natural materials and the inadequate disposal of waste in nature.

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In addition, the National Environment Council (CONAMA) Resolution No. 416[21] has encouraged the use of unserviceable tires in various sectors of the economy as a way to properly dispose of this environmental liability.

According to the National Association of the Tire Industry (ANIP)[22], 56,643,379 were sold in 2022. According to data from the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA)[23] from 2009 to 2020, 7,728,410.55 tons of waste tires were disposed of in an environmentally appropriate manner, coming from more than 2,594 collection points throughout Brazil.

It is observed that, even when dealing with materials of different natures, rubber and vermiculite, both provide similar properties to concrete, such as: decrease in density, reduction in mechanical properties, and improvement in acoustic performance. There are several studies that deal with the properties of concrete with the replacement of sand by rubber or vermiculite. However, there are few studies that deal with the joint use of both materials, tire rubber and expanded vermiculite in concrete, and that address the properties studied in this research.

Thus, the main technological contribution of this research is the proposition of concrete compositions for the construction of acoustic barriers, which have technical and environmental advantages within the road sector.

2. Materials and Methods

2.1. Production of concretes

The concretes proposed in this research used the following materials: high initial strength Portland cement, quartz sand, expanded vermiculite and rubber from scrap tires (Figure 1), basaltic gravel, drinking water and a superplasticizer based on polycarboxylate ether. The physical and chemical characterization of the component materials of the concretes is presented in Table 1. The rubber particles were sieved and the material used was the one passing through the 1.18 mm sieve.

The concretes were produced by replacing the sand with rubber and vermiculite residues, as shown in Table 2. A mixer with an inclined axis and capacity of 120 liters, at a temperature of 20º C ± 5º, was used. The concretes were cast in metallic molds, and after 24 hours, the samples were demolded and subjected to a wet curing process for 28 days.

2.2. Tests in fresh and hardened state

The consistency of concrete in the fresh state was determined by the slump test, in accordance with ABNT NBR 16889[24].

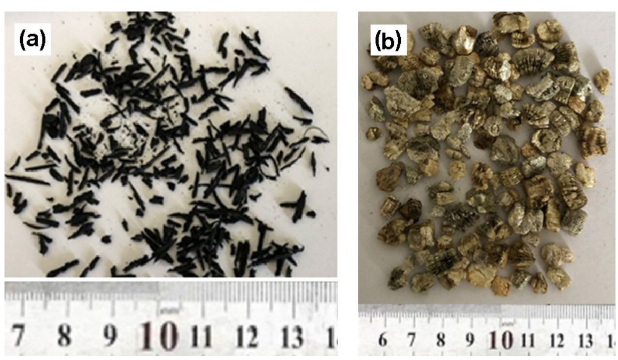

Figure 1. Materials used: (a) rubber; (b) vermiculite.

Table 1. Physical characterization of materials.

Physical properties	Material					
	Cement	Fine aggregate	Coarse aggregate	Rubber	Vermiculite	Silica fume
Specific mass (g/cm^3)	3.07	2.65	3.00	1.16	0.45	2.21
Unit mass (g/cm^3)	-	1.50	1.56	0.35	0.12	-
Maximum size (mm)	-	0.60	19.00	-	4.80	-

Table 2. Consumption of mass materials used in the production of concretes.

Mixtures	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Silica fume (kg/m^3)	Rubber (kg/m^3)	Vermiculite (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
CONTROL	365	905.20	912.5	36.50	-	-	219	-
R10V40	365	452.60	912.5	36.50	39.62	61.48	219	4.19
R20V30	365	452.60	912.5	36.50	79.24	46.11	219	3.28
R30V20	365	452.60	912.5	36.50	118.86	30.74	219	2.55
R40V10	365	452.60	912.5	36.50	158.48	15.37	219	1.97

For the determination of compressive strength, specific mass, water absorption, tensile strength and static modulus of elasticity, cylindrical rectified specimens (100 mm x 200 mm) were tested after 28 days. These mechanical tests were carried out in a universal machine with a load capacity of 600kN.

To determine the compressive strength, cylindrical specimens were tested in accordance with ABNT NBR 5739[25]. The determination of the specific mass, water absorption were tested with cylindrical specimens, after 28 days, according to the specifications of ABNT NBR 9778[26]

The tensile strength was determined according to ABNT NBR 7222[27], applying load at a constant velocity of 0.05 ± 0.02 MPa/s.

The test to determine the static modulus of elasticity was performed in accordance with ABNT NBR 8522-1[28]. The dynamic modulus of elasticity was performed according to ASTM C215[29] and ASTM E1876[30], using the Sonelastic® equipment, which uses the impulse excitation technique, a non-destructive dynamic method, allowing the calculation of elastic modulus from the sound emitted by the specimen when suffering a small mechanical blow[31], shown in Figure 2. In this test, cylindrical rectified specimens of 100 mm x 200 mm were used at 28 days of age.

2.3. Sound attenuation

For the acoustic characterization, a non-destructive ultrasonic test was performed to calculate the sound velocity and the sound attenuation coefficient. Measurements were performed using an ultrasonic wave pulsator (Olympus - Panametrics NDT Epoch) according to ISO 9712[32], in six cylindrical samples of 100 mm x 200 mm for each mixture, at 28 days. The test was performed at a frequency of 1000 kHz for compression waves (P waves), using two longitudinal wave transducers (a transmitter and a receiver).

Concrete is generally assumed to have isotropic behavior, although its heterogeneity and possible loss of isotropy at the molding process are recognized. It must be remembered that an isotropic material is one where the elastic properties are the same in different directions, while it's opposite (anisotropic) has different properties in different directions, and it occurs in materials with well-defined internal structures such as wood. A more detailed discussion about this subject can be founded at Bertoldo et al.[33]. They demonstrate the isotropic behavior of concrete using ultrasound wave propagation, and validate the hypotheses as an isotropic material.

The sound velocity (pulse velocity), which is generally defined as the specimen height divided by the transit time, was calculated using the time recorded by the ultrasound device, and the distance covered by the wave (specimen height). The sound attenuation coefficient is determined by measuring the reduction in amplitude of an ultrasonic wave, which has traveled a known distance through the material and is given by Philippidis and Aggelis[34]:

$$\alpha = -\frac{20}{X}\log\left(\frac{A_X}{A_0}\right) \tag{1}$$

Where:
A_0 = initial amplitude of the ultrasonic wave (V) and A_X = amplitude (V) after the wave travels a distance X (cm).

2.4. Microstructure analysis

The samples were extracted from specimens of concrete and analyzed using the TESCAN model VEGA3 microscope with the Scanning Electron Microscopy (SEM) technique.

3. Results and Discussions

In the fresh state, the consistency results of the concretes indicated slump in the range of 85 ± 15 mm. Table 3 shows the results regarding compressive strength, specific mass and water absorption. The water absorption values were between 6 and 9%.

The rubber had a predominant influence on density compared to the vermiculite. The concretes had their densities reduced with the increase of rubber in the mixtures.

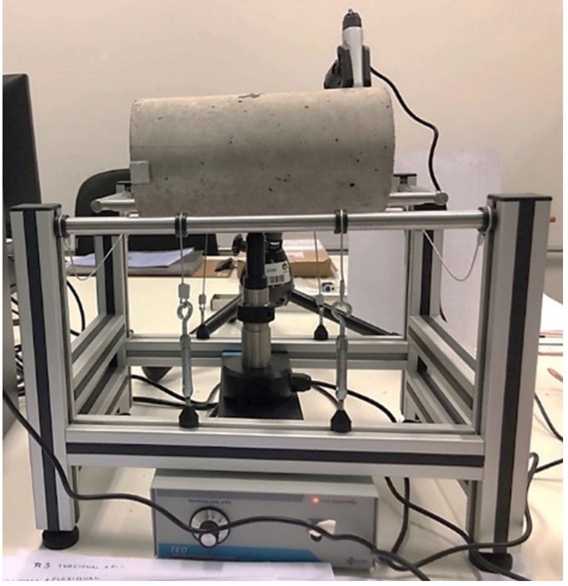

Figure 2. Dynamic test by impulse stimulus.

Table 3. Compressive strength and specific mass, water absorption of concretes at 28 days.

Mixtures	Compressive strength (MPa)	Specific mass (kg/m³)	Water absorption (%)
CONTROL	40.3 ± 3.35	2,269 ± 4	6.45 ± 0.15
R10V40	27.8 ± 1.91	2,135 ± 19	6.72 ± 0.17
R20V30	22.5 ± 0.84	1,997 ± 14	7.68 ± 0.30
R30V20	17.5 ± 0.86	1,944 ± 26	6.97 ± 0.15
R40V10	13.4 ± 0.43	1,833 ± 8	8.17 ± 0.12

This is due to the high friction between particles, the rough surface of the rubber and lower density[35,36]. Due to the hydrophobic nature of rubber, water adheres to its surface and increases air content in fresh concrete[37]. According to Koksal et al.[10], the addition of vermiculite also contributes to the density reduction, although it had less influence in this study.

The increasing incorporation of rubber in the mixtures has great influence on the compressive strength, causing a reduction of 31% for the R10V40, 44% for the R20V30, 56% for the R30V20 and 66% for the R40V10, in relation to the control mix.

This fact happens due to the low adhesion of the rubber to the cement paste, as can be observed in the analysis of the microstructure of the concretes, through the images of secondary electrons (SE), obtained through the scanning electron microscope (SEM), as shown in Figures 3 and 4. Figure 3 shows (a) the dense and compact structure of the control concrete. By increasing the rubber content in the mixtures, an increase in the porosity and number of voids in the cement paste, the presence of microcracks and an increase in the thickness of the transition zone between the aggregates and the paste can be observed, as shown in Figure 3(b), (c) and (d), respectively. In Figure 4 a defined transition zone and high porosity are shown.

According to ABNT NBR 8953[38], the mixtures shown in Table 3 can be classified as structural concrete (≥ 20 MPa), except for mixtures R30V20 and R40V10. Although these cannot be structural, it may be indicated for sealing elements with better acoustic performance. Concretes with 20%, 30% and 40% rubber are classified according to density as light, with density less than 2000 kg/m^3. There was a density reduction of 6% for the R10V40, 12% for the R20V30, 14% for the R30V20 and 19% for the R40V10, in relation to the control mix.

Comparing the results with research in which cement consumption and a/c ratio are close to this study, it was observed that Li et al.[17] produced concrete with cement consumption of 344 kg/m^3 with the replacement of 20% of the sand by rubber resulted in a compressive strength of 32.7 MPa, with a 24% reduction in concrete control.

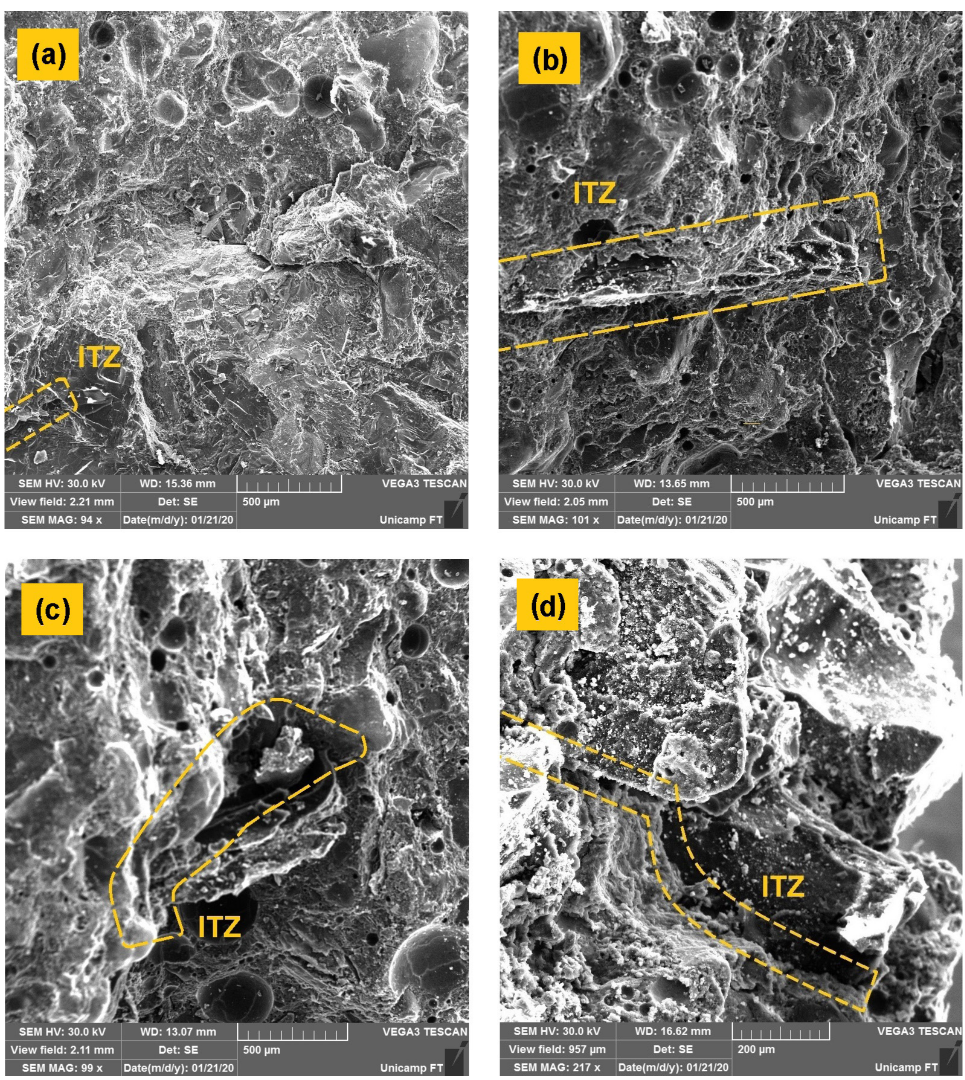

Figure 3. Scanning electron microscopy (SEM) images of concretes: (a) control; (b) R10V40; (c) R20V30; (d) R30V20.

In this research, the combined use of rubber and vermiculite decreased the loss of compressive strength. Another research that stands out is that of Mo et al.[9] who reported that when replacing expanded vermiculite by volume of sand by 30% and 60% in mortars, there was a 50% and 63% reduction in compressive strength, respectively.

The tensile strength results are shown in Table 4 for the 28 days of concrete age. As for the tensile strength, there is a tendency to decrease with the addition of rubber in the mixtures, however, this decrease is less significant than for the compressive strength. The reductions in tensile strength are: 17% for the R10V40, 31% for the R20V30, 59% for the R30V20 and 60% for the R40V10. Rubberized concrete has a greater effect on reducing compressive strength than tensile strength[39-41]. These results reveal an important relationship between strength and acoustic performances for the concretes.

The results of modulus of elasticity are shown in Table 4 and Figure 5 for 28 days of age. As with the other resistances, there is a reduction in the modulus of elasticity for increasing levels of rubber. The low modulus of elasticity of the rubber and its hydrophobic nature generates weak points inside the cement paste and causes a decrease in mechanical strength[8,14,15,42,43]. This can be proven by the images of the microstructure of the concretes presented in Figure 3 and 4.

It is also verified that the dynamic modulus of elasticity is slightly higher than the static for all mixtures: 3% for the control, 15% for R10V40, 12% for R20V30, 15% for R30V20 and 14% for R40V10.

The correlation between the modulus of elasticity and the compressive strength is shown in Figure 6. Other authors have also observed the decrease in the modulus of elasticity and improvement in the ability to absorb deformations in cement composites containing rubber[17,44].

The results from the empirical expressions that relate the static (Ec) and dynamic (Ed) modules, given by Popovics apud Neville[45] and Lyndon and Balendran[46], are shown in Figure 6. It is observed that for experimental values of the dynamic module (Ed) there is a correlation $Ed = 1.74\ fck^{0.8}$, $R^2 = 0.99$, and for experimental values of the static module (Ec) the correlation is given by $Ec = 1.19\ fck^{0.9}$, $R^2 = 0.99$.

The variability of the results shown in Figure 6 is justified by the multiphase nature of the concrete that influences the deformation module. In general, the reduction in mechanical properties of concrete with increasing levels of rubber has also been verified in previous studies[37,44,47-49]. Another factor that prevented mechanical properties from sharp reduction was the incorporation of silica in the mixture, contributing to densify the cement paste[8].

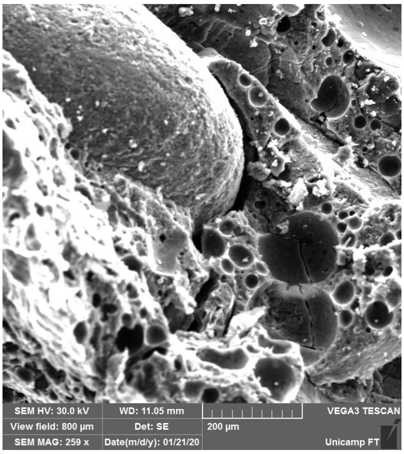

Figure 4. Scanning electron microscopy (SEM) image of concrete R40V10.

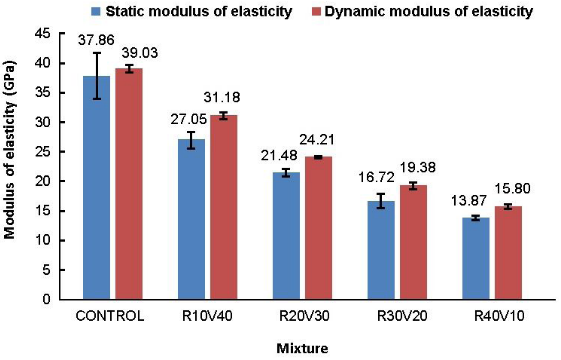

Figure 5. Modulus of elasticity (GPa) at 28 days.

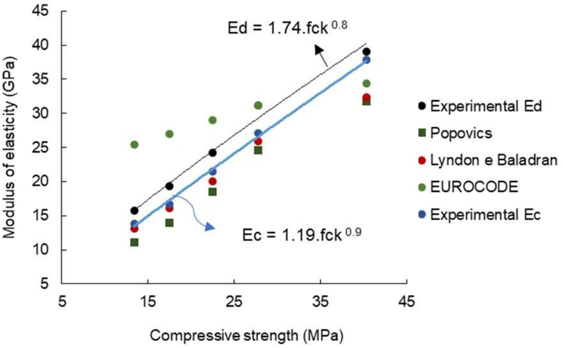

Figure 6. Correlation between modulus of elasticity and compressive strength.

Table 4. Results of static modulus of elasticity and dynamic modulus of elasticity tests of concrete at 28 days.

Mixtures	Tensile strength at 28 days (MPa)	Static modulus of elasticity (GPa)	Dynamic modulus of elasticity (GPa)
CONTROL	4.1 ± 0.75	37.86 ± 3.83	39.03 ± 0.60
R10V40	3.4 ± 0.06	27.05 ± 1.41	31.18 ± 0.60
R20V30	2.8 ± 0.13	21.48 ± 0.71	24.21 ± 0.18
R30V20	1.7 ± 0.06	16.72 ± 1.17	19.38 ± 0.53
R40V10	1.6 ± 0.02	13.87 ± 0.31	15.80 ± 0.37

Table 5. Results of sound velocity for compression waves.

Mixtures	Sound velocity (m/s)	Attenuation coefficient (dB/cm)
CONTROL	3,973 ± 124	4.24 ± 0.12
R10V40	3,610 ± 113	4.46 ± 0.10
R20V30	3,335 ± 27	4.70 ± 0.06
R30V20	3,040 ± 74	5.13 ± 0.13
R40V10	1,871 ± 54	5.35 ± 0.12

3.1. Sound attenuation

The velocity of sound and sound attenuation coeficiente are shown in Table 5 and in Figure 7 and Figure 8 for concrete at 28 days of age.

There is a decrease in sound velocity and an increase in sound attenuation coefficient with the increasing levels of rubber. This reflects an improvement in the acoustic performance of the material[8].

Porous materials are usually good acoustic insulators. Rubber significantly influenced this property compared to vermiculite, although the porous structure of vermiculite also favors the decrease in wave propagation velocity[10,13]. In previous studies Dehdezi et al.[50] also reported a 31% decrease in ultrasonic pulse velocity, for concrete with cement consumption of 370 kg/m^3, with 50% rubber replacing sand, compared to control concrete.

Table 5 shows that the combined use of rubber and vermiculite was more effective, since using 40% rubber and 10% vermiculite to replace sand resulted in a 53% decrease in ultrasonic pulse velocity. The combined use of rubber and vermiculite helps to improve the material's acoustic properties. This fact can be justified by the acoustic properties of the materials, that is, the expanded vermiculite has voids inside that collaborate for the dissipation of energy.

The Figure 7 shows that the sound attenuation coefficient increases 5%, 11%, 21% and 26%, for R10V40, R20V30, R30V20 and R40V10, respectively, as compared to the CONTROL sample. However, Figure 8 shows that the sound velocity decreases 9%, 16%, 23% and 53% for R10V40, R20V30, R30V20 and R40V10, respectively, in relation to the CONTROL sample. These results confirm similar conclusions of other authors[8,51], that sound velocity decreases as the percent of rubber increases in the mixture.

Figure 8 also shows a comparison between density and sound velocity, where sound velocity decreases together with the density. This behavior occurs because rubber occupies a larger volume than the vermiculite and due the presence of water and/or air in the mixture. These results agree with Fraile-Garcia et al.[52], which reported that tire rubber waste reduces the sound velocity due to the decrease in density and to the presence of air. Sukontasukkul[53] found, for a frequency higher than 1000 Hz, that the concrete with lower density had a better absorption coefficient.

Finally, sound attenuation enhancement when rubber substitutes vermiculite can be associated with its non-polar nature, which can increase the number of air voids. However, this enhancement does not necessarily mean that the total porosity of the specimen increased. It may be also related to the replacement of vermiculite (dense aggregate) by rubber (less dense aggregate), the size, shape, or volume fraction of aggregates[51].

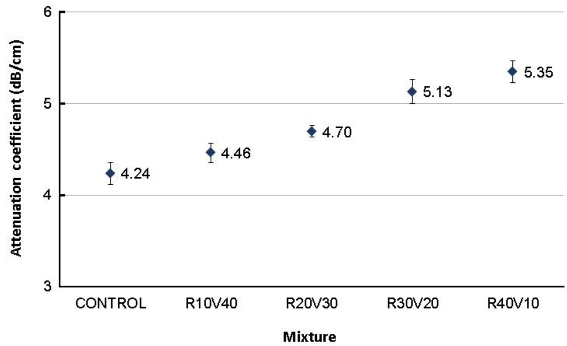

Figure 7. Sound attenuation coefficient.

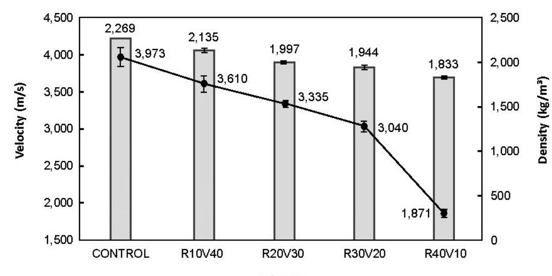

Figure 8. Specific mass and the longitudinal wave propagation velocity.

4. Conclusions

In the study of concrete mixtures containing rubber and vermiculite, it can be concluded:

- As for the compressive strength, the increase in the incorporation of rubber in the mixtures causes a reduction of 31% to 66% in relation to the control mixture. Concretes containing 0%, 10% and 20% rubber are classified as structural;
- The density reduction is in the range of 6% to 20% in relation to the control concrete. Concretes with 20%, 30% and 40% rubber are classified as light, with density lower than 2000 kg/m^3;
- As for the tensile strength, its decrease is less significant than for the compressive strength, being in the range of 17% to 60% in relation to the control concrete;
- The static modulus of elasticity is in the range of 37 GPa (control) and decreases with increasing rubber content up to 13 GPa (R40V10). The dynamic modulus of elasticity is on average 10% greater than the static modulus;

- Regarding the acoustic properties of concrete samples with rubber and vermiculite , the combined use of rubber and vermiculite is more effective in improving the acoustic properties of the material resulting in a decrease in the velocity of sound propagation and an increase in the acoustic attenuation coefficient. All compositions studied offer better acoustic performance to buildings than traditional concrete, with concrete with 40% rubber having the best acoustic performance.

5. Acknowledgments

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