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Thermal and Acoustic Properties of Rubberized Mortars for Coatings

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Recycled crumb rubber can be sustainable used in mortar both to mitigate nature aggregate consumption, reducing environmental pollution, as well, to improve the acoustic and thermal performance of buildings, without damaging its mechanical properties. This paper explores workability, microstructure, mechanical, thermal and acoustic properties considering increasing contents of crumb rubber (0%, 5%, 10%, 15% and 20% replacement, by volume, of fine aggregate). Mortar characterization tests were carried out in the fresh and hardened state. It has been found that replacing the aggregate with scrap tyre rubber reduced the compressive strength on average 12% and 67% and for tensile strength 35% and 53%, for the contents of 10% and 20% respectively, compared to the reference. Furthermore, it was found that the reductions in thermal conductivity reached 16% and 29% and an increase in acoustic attenuation on average 12% and 13%. Moreover, scanning electron microscopy images were analyzed, justifying the mechanical results obtained. Although the experimental results indicated that the workability and mechanical strengths decreased with the increase of rubber replacement rate, the studied mixtures met the standard specifications, and thus suitable for walls and ceilings coating applications, improve the acoustic and thermal performance of buildings and as a sustainable material.

Keywords: *cement-based mortars, recycled crumb rubber, sustainability, mechanical properties, thermal and acoustic performance.*

1. Introduction

Mortars produced with waste is a sustainable and low-cost option, and in many times can mitigate nature aggregate consumption, maintain or improve certain mechanical, acoustic and thermal properties[1,2]. Given the concerns with tire waste, in the environmental area because they are considered as breeding grounds for different types of vectors[3,4], in addition to the tire components being difficult to decompose materials that, if incinerated, pollute the environment due to the highly toxic due[5-7]. Waste tires are accumulated in huge piles around the world, since they are not naturally biodegradable, so the stock of waste tires has recently become a global environmental concern[8]. According to Karakurt[9], more than 1.5 billion tires are obtained worldwide every year. In Brazil, 20.520800 units of tires were manufactured between January and June 2020, according to the National Tire Industry Association[10]. Today, while the world is shifting to a circular economy, research on waste tire rubber continues, with the goal of developing high value-added applications and simultaneously assisting in a critical environmental issue[11]. Depending on the waste management program, scrap tires can represent an environmental disaster or a full-featured end product[2]. To ensure that waste tires are disposed of correctly, Resolution No. 416, instituted by the CONAMA[12], specifies the proper disposal of waste tires, in addition to establishing collection points for these tires in municipalities with more than 100 thousand population. Waste tires are made with rubber and oil, are not biodegradable and must be treated in an environmentally friendly way, being reused or recycled. This process adds benefits related to the preservation of the environment, as well as, for the economy generating jobs and income. One of the ways of recycling tires is lamination, in which the material is cut into strips and used for the manufacture of sofas, tubes, soles, rugs, floors. Another way is the addition of bituminous materials used in the construction of pavements. Obtained from the tire's calorific value, a rubber is also used as an alternative fuel. The use of waste tire rubber in construction appears to be a promising solution. Due to the high demand for concrete, even the replacement of a small portion of the aggregates with rubber waste from recycled tires can help to save natural resources, in addition to contributing to waste management[13].

2. Literature Review

The rubber residue from waste tires has important physical and mechanical characteristics, which make it strongly recommended to be used in civil construction in concrete[14-18] and mortar[19-22]. Seeking to mitigate the harmful effects of its disposal on the environment[23]. These applications can be analyzed in two conditions: fresh and hardened. As for properties in the fresh state, it is known that there is a decrease in workability with the addition of rubber, as well as the incorporation of air in the mixture[7,23,24].

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In the hardened state, some of the main properties decrease with the addition of rubber, such as: compressive, tensile, and flexural strength. This is due to the relatively low stiffness of the rubber and the poor bond between the rubber particles and cement paste[7,15,25-27]. The benefits of using recycled rubber are many: reduced unit weight, resulting in a lightweight composite capable of relieving stress on structural systems, in addition to improving the impact absorption capacity, improving ductility and increasing crack resistance capacity[18,24,27-30]. Additionally, using rubber residue in cement composites is related to the material's acoustic properties. Given the concerns related to the negative effects of noise exposure, which may cause sleep disturbances, hearing loss, increased blood pressure tension, decreased performance and irritations (psychological effects) to the building user[31,32]. The construction industry has been studying alternatives to minimize the effects of noise in buildings. Some materials can be used to prevent the passage of noise into environments, such as fibrous materials (glass wool, rock wool), and porous materials such as vermiculite, expanded clay and rubber. Waste from scrap tyre rubber have been used in cementitious composites in order to make them more porous and less dense, aiming at greater energy absorption, causing the sound wave to be dissipated within the material itself[3,21,33,34]. Research conducted by Angelin et al.[34] has led to the conclusion that up to approximately 15% of the sand can be replaced by rubber, maintaining adequate mechanical strength. They also concluded that the best performance of the rubber residue in relation to sound attenuation, occurs in mortars with rubber in the shape of fibers, when compared to the shape of spheroids. In addition, Si et al.[17] found that the speed of sound transmission decreased with the addition of rubber residues in the concrete, presenting a positive effect on ultrasonic transmission and acoustic performance. When studying mortars with 25% and 50% substitution of fine aggregate by rubber fibers[34] they concluded that the increasing percentage of rubber in the mixture provides better acoustic properties, showing an increase in attenuation and a decrease in the speed of propagation of P waves. It's well established that civil construction is one of the most representative sectors in the economy and one of the most energy consuming. Therefore, one of the great challenges of today is the reconciliation between economic development and the minimization of energy consumption[35]. It is known that the replacement of natural sand by rubber residues in mortars, contributes to the trapping of air bubbles in the cementitious matrix, increasing the porosity of the paste and decreasing the density of the mortar[15,34]. Given the concerns related to improvement mortar's thermal properties[33,35], and consequently when they are applied as walls and ceilings cladding, they improve the thermal comfort of buildings. This research helping support a better knowledge and understanding of this eco-friendly material for civil construction with thermoacoustic properties using residues that cause environmental degradation if disposed of incorrectly. The differential of this research is the development of mortars with rubber residues, used for walls and ceilings coating, and improved thermal and acoustic properties in relation to traditional mortars, aiming at a better performance of buildings and the comfort of its users.

Table 1. Physical properties and chemical composition of cement, fine aggregate and crumb rubber.

	Cement	Fine Aggregate	Crumb Rubber
Physical Properties			
Density (g/cm^3)	3.08	2.64	1.15
Unit weight (g/cm^3)	1.03	1.51	0.39
Max. Diameter (mm)	-	2.4	2.40
Fineness modulus	-	1.62	2.82
Chemical Composition (%)			
C	-	-	91.5
Zn	-	-	3.5
O	-	-	3.3
S	-	-	1.2
Na	-	-	0.2
H	-	-	0.2
Ca	-	-	0.1
CaO	63.33	-	-
SiO_2	19.19	-	-
Al_2O_3	5.15	-	-
Fe_2O_3	2.8	-	-
MgO	0.92	-	-
Na_2O	-	-	-
K_2O	-	-	-
Lost on ignition	3.97	-	-
Insoluble residue	0.48	-	-

3. Methodology

3.1. Materials and mixtures proportions

Were produced mortars using high early strength (HES) Portland cement. Table 1 shows the chemical composition and physical properties of cement, natural quartzitic sand and crumb rubber. Figure 1 presents the particle size distribution of natural quartzitic sand and crumb rubber, determined according to ASTM D6913[36]. Figure 2 shows the natural quartzitic sand and crumb rubber particles.

First of all, it should be noted that the previous results were taken into account for organize this study, in which 20% of the rubber content was used to replace with sand[2,34,37]. In addition, it is important to note that the main focus of this investigation is the development of mortars with rubber residues, used for walls and ceilings coating, and improved thermal and acoustic properties in relation to traditional mortars. Table 2 shows the proportion of the mixtures. CP00 indicates the reference mixture, i.e., without the addition of crumb rubber. Mixtures CP05, CP10, CP15 and CP20 represent mixtures with partial replacement of sand by rubber in 5, 10, 15 and 20%, respectively. The mortars consistency index was set at 222 ± 5 mm, with the water/cement ratio varying from 0.63 to 0.64.

Table 2. Mixture proportions (in mass).

Mixture	CP00	CP05	CP10	CP15	CP20
Cement	1.00	1.00	1.00	1.00	1.00
Sand	3.00	2.85	2.70	2.55	2.40
Crumb Rubber	-	0.07	0.13	0.20	0.26
w/c	0.64	0.63	0.63	0.64	0.64

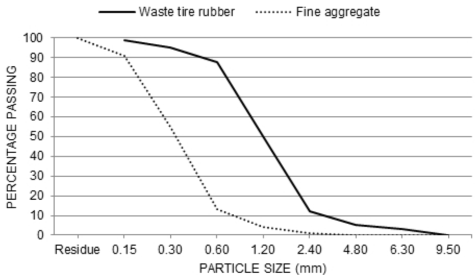

Figure 1. Particle size distribution of natural quartzitic sand and crumb rubber.

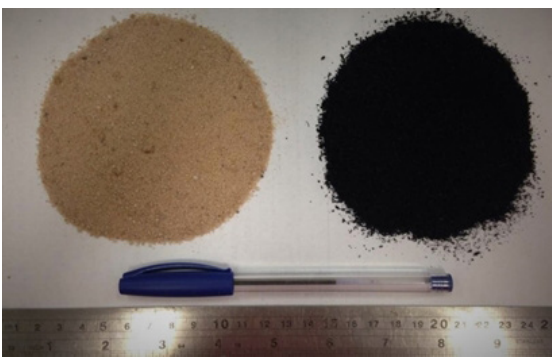

Figure 2. Image of natural quartzitic sand and crumb rubber.

3.2. Tests carried out in the fresh and hardened states

Physical, mechanical, thermal and acoustic analyzes were performed to evaluate the influence of the increase of crumb rubber in mortars used for walls and ceilings coating. In the fresh state were performed water retention, and the mass density and incorporated air content, following the prescriptions of the standards ASTM C1506[38] and EN1015-6[39], respectively.

In the hardened state, the prismatic specimens with 40 × 40 × 160 mm were mechanically tested for flexural tensile strength and compressive strengths, at 7 and 28 days. The recommendations of the ASTM C348[40] and C349[41] standards were followed, respectively. Mass density in the hardened state was measured, as specified by ASTM C642[42]. Besides that, efficiency factor (EF) relating the compressive strength-to-mass density ratio has an important role to designate the cement compounds performance, as described in Equation 1.

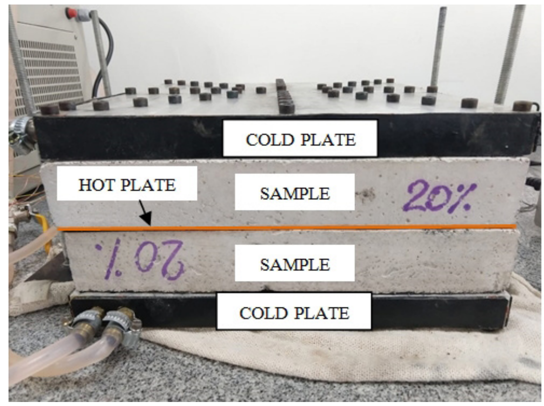

Figure 3. Plate assemble system for the thermal conductivity test.

$$EF = \frac{fc}{\rho} \quad (1)$$

where the unit for EF is given in MPa.dm^3/kg, “fc” is the compressive strength (MPa) and “ρ” is the mass density (kg/dm^3).

For the thermal conductivity test, according to ABNT NBR 15220:2005[43], at 28 days, specimens with 300.5 × 300.5 × 45 mm were made to analyze mixtures CP00, CP10 and CP20. This thermal conductivity test, using the protected hot plate method, consists of a system composed of two cold plates made of aluminum, one lower and one upper, with 305 × 305 × 25 mm, connected by hoses to a thermostated bath and, two mortar plates. Between the mortar slabs, a hot plate made of kapton was installed, with a resistance of 9.8Ω and a guard ring that surrounds the hot plate, with a resistance equal to 42.9Ω, both connected to a source of direct current. Furthermore, in order for the faces of the plates remain in perfect contact with each other, two metal supports were used that stabilize the structure without pressing it. Figure 3 illustrates the plate assemble system. Thermal conductivity was calculated according to Equation 2.

$$q = -k.\ A.\left(\frac{\Delta_T}{\Delta_x}\right) \quad (2)$$

where q is the heat, k is the thermal conductivity of the material, A is the area perpendicular to heat, ΔT/Δx is the thermal gradient.

The mixtures CP00, CP10 and CP20 were submitted to the ultrasound test, at 28 days, to obtain the acoustic attenuation and speed of sound propagation, according to the standard ASTM C597[44], using 40 × 40 × 160 mm prismatic specimens

(Figure 4a and Figure 4b). Waves of 1 MHz were emitted, the initial and final amplitude (A_i and A_f) was provided by the equipment, in percentage, so that it was possible to measure the compression waves (P). It was necessary to fix the gain values, which were adjusted according to the waves emitted by the pulsator, since the amplitude varied significantly between the samples. For the measurement of shear waves (S), it was necessary to adjust the gain values for each sample, the amplitude values also varied between them. The coefficient of acoustic attenuation of the specimen has been found by the Equation 3.

$$\acute{a} = -\frac{20}{h}\log\left(\frac{A_f}{A_1}\right) \quad (3)$$

where α is the attenuation coeficiente, A_i is the initial amplitude (dB), A_f is the final amplitude (dB), h is the height of the sample (cm).

The speed of wave propagation was calculated using the Equation 4:

$$V = \frac{L}{t} \quad (4)$$

where V is the speed of propagation of the ultrasonic wave (mm/μs), L is the distance between the transducer coupling points (mm), t is the time recorded by the equipment (μs).

The microscopy test was performed for all mixtures, at 28 days, using the LEO 430i Scanning Electron Microscope (SEM), to better understand the microstructure of mortars. The samples went through the carbon metallization process and were analyzed with the operating conditions: a) electron beam energy: 20 kV, b) beam current: between 500 pA (images) and 6000 pA (microanalysis) and, c) working distance: 19 mm. The samples to analyze the micrographs were obtained from small fragments of specimens of the concrete prepared.

4. Results and Discussions

4.1. Fresh properties

The results of the fresh state test are displayed in Table 3.

It has been found a reduction in the values of mass density of 5.55%, 11.16%, 13.48% and 17.09% of the mixtures CP05, CP10, CP15 and CP20, respectively, in comparison to CP00. This reduction in mass density occurs because the unit mass and specific mass of the crumb rubber are lower than that of natural sand and also because the rubber waste incorporates air in the mixtures as a result of its geometry and irregular surface[4,45,46].

ASTM C270[47] recommends that the maximum content of incorporated air in mortars be 14%. The studied mortars showed incorporated air between 2 and 12%, *i.e.*, below 14%. According to Canova et al.[48] values above 16% of incorporated air in the mortar can reduce the tensile adhesion resistance on the substrate. Other studies report similar levels of incorporated air, since the use of rubber fibers as an aggregate increases the porosity of the cementitious matrix due to the greater air entrainment of the irregular surface of the rubber fibers[31,46,49].

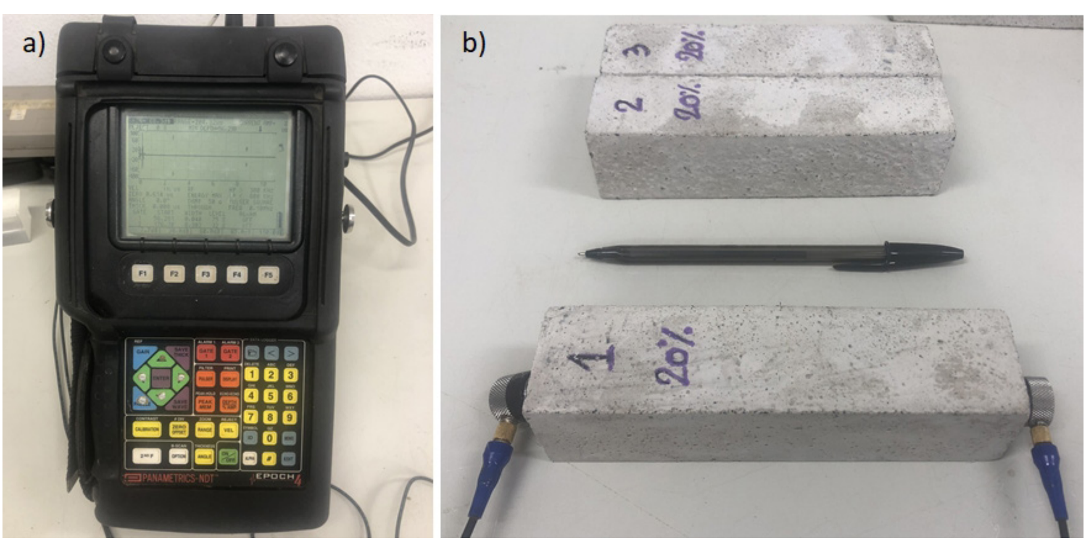

Figure 4. Ultrasound test (a) Equipament (b) Prismatic Specimens.

Table 3. Results of the fresh state test of mixture mortars.

Mixtures	CP00	CP05	CP10	CP15	CP20
Mass Density (kg/m³)	2,175	2,054	1,932	1,882	1,803
Incorporated Air (%)	2	6	10	10	12
Water Retentivity (%)	95	93	93	94	91

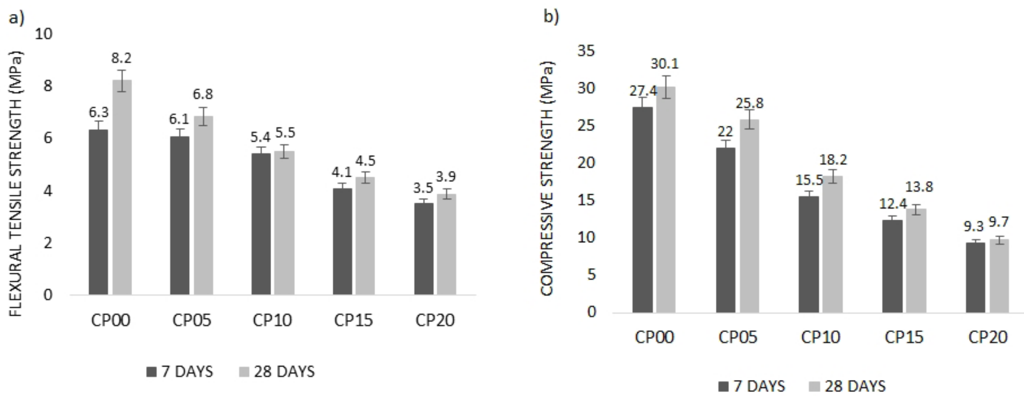

Figure 5. Experimental results of (a) flexural tensile strength and (b) compressive strength, at 7 and 28 days.

In all mortars mixtures studied, water retention was greater than 90%, classified as U5 according to ABNT NBR 13281:2005[50], a positive factor for coating mortars, since water retention guarantees its workability and productivity[51,52]. This increase in water retention can be justified by the SEM images that illustrate a greater porosity in the mixtures, justifying the high water retention in its fresh state. The high water retention rates were also verified by other authors when studying rubberized mortars[46,48].

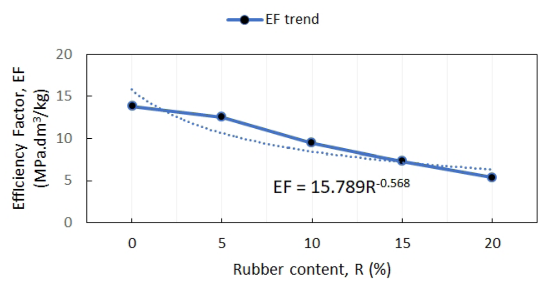

Figure 6. Experimental results of efficiency factor.

4.2. Hardened properties

The values of the flexural tensile and compressive strength are shown in Figure 5a and Figure 5b.

The results presented showed a decrease in these properties in mixtures containing crumb rubber compared to the reference mixture, *i.e.*, without rubber. It's well known that decrease is due to the rubber low rigidity and the large volume of pores incorporated into the mixtures, influencing the mechanical strength performance of mortars[7,19,34,46,53,54]. Comparing the flexural tensile and compression resistance, there is a tendency for a greater decrease in the compressive strength when compared to the flexural tensile strength, with the exception of the CP05 mixture, which presented, at 28 days, a reduction 16.81% in the flexural tensile strength and 11.42% in the compressive strength. This fact can be explained due to the elastic capacity of the rubber, causing less interference in the tensile performance[46,48].

Although the mortars studied in this work showed a decrease in flexural tensile strength, all samples met the requirements of ABNT NBR 13281:2005[50], being classified as R6, that is, with values above 3.5 MPa, and classified as P6, with values above 8.0 MPa for the compressive strength. Hence can be applied for walls and ceilings coating.

The results of mass density are shown in Table 4.

Mortars in the hardened state show a tendency for lower density values in relation to mortars in the fresh state, due to the loss of mass caused by the evaporation of water and chemical reactions in the healing process[22,37,46,55]. The decrease in mass density in the hardened state, in relation to the reference mixture, corresponds to 4.37% for the CP05 mixture, 10.63% for the CP10 mixture, 14.31%

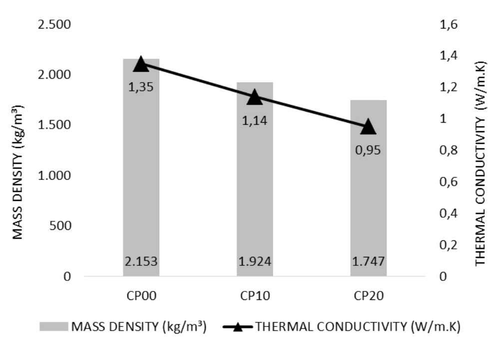

Figure 7. Thermal conductivity in relation to mass density.

Table 4. Experimental results of mass density from the examined mortars.

Mixture	Density (kg/m³)
CP00	2,153
CP05	2,059
CP10	1,924
CP15	1,845
CP20	1,747

for the CP15 mixture, 18.86% for the CP20. The decrease in the density of the rubberized mortar is directly associated with the rubber particles.

In Figure 6 is an analysis of the efficiency factor as a function of the rubber content in the mixture. The trend of decreasing is observed with the increase in the rubber content described as EF = 15.789 R-0.568.

Figure 7 shows the results obtained in the test for the determination of thermal conductivity.

As shown in Figure 7, a decrease in thermal transmittance of approximately 16% and 29% was identified, respectively, for mixtures CP10 and CP20, when compared to the reference mixture. Less dense materials are not good conductors of heat, as the heat flow dissipates in the porous structure of the material. Another factor that helps in low thermatic transmittance is the fact that rubber is an insulating material, *i.e.*, a poor conductor of energies[23,33,36,53,56]. Angelin et al.[34] observed that the rubber, in finer granulometry, increases the thermal insulation of cementitious compounds, due to the increase in the adhesion of the rubber with the matrix. These characteristics of rubberized mortars demonstrate the possibility of their use in walls and ceilings coverings in order to improve the thermal comfort of the environments. Studies show that as the sample density decreases, its thermal transmittance also decreases. The mortars studied also showed a decrease in their mass density, which corroborates the decrease in thermal transmittance. Kazmierczak et al.[46] found a significant reduction in thermal transmittance in mortars with 2%, 4% and 6% replacement of sand by crushed rubber, using the procedures described in ASTM C177[57], method equivalent to ABNT NBR 15220:2005[43], attributing this result to the low density of the rubberized mortars and the low thermal conductivity of the rubber. Letelier et al.[58], replaced 10% and 15% of sand by rubber residue and obtained an average reduction of 26% and 41% respectively, using to determine the thermal conductivity, the procedure of the thermal needle probe according to the ASTM D5334-08[59] standard.

The results of the acoustic attenuation test of mixtures CP00, CP10 and CP20, for compression and shear waves, are shown in Figure 8a and Figure 8b.

As for the compression waves, in percentage terms, the mixture CP00 to CP10 showed an increase in attenuation of ~ 12%, while the mixture CP10 to CP20 of ~ 13.2%. In relation to shear waves, there was an increase in attenuation from CP00 to CP10 of ~ 6.2%, and from CP10 to CP20 around 18.15%. The most representative increases were observed for the CP20 mixture. This behavior was also observed by Angelin et al.[34], who reported that, in rubberized composites, there is a gain in damping waves, compared to composites produced with conventional aggregates. It can be analyzed by Figure 8a and Figure 8b, that the attenuation of the shear waves is greater than for the compression waves, as described by Eiras et al.[60]. Therefore, rubber favors an increase in acoustic attenuation, ensuring better performance of the studied mortars. The increase in acoustic attenuation, when rubber is added to the mortar, can be explained by the spreading and absorption of the increased P and S waves in the mortar, since there is a greater presence of water and air in the composites (Table 3). Letelier et al.[58], using the ultrasound method, obtained a decrease in the propagation speed of sound waves in rubberized mortars of 15% for the mixture with 10% rubber, and 28% decrease in the mixture with 15% of rubber, in relation to the reference mixture. The decrease in the propagation speed of sound waves in rubberized mortars is justified by the increase in voids present in the mixture, causing the sound wave to dissipate, losing speed. According to the mass density tests in the hardened state and the SEM images, the mortars showed an increase in porosity, contributing to reduce the speed of propagation of ultrasonic waves, providing better acoustic attenuation. This effect was also observed by Albano et al.[61], Ghizdăveț et al.[31], Flores Medina et al.[32], Kurz et al.[45] and Angelin et al.[34], corroborating the favorable acoustic property of rubberized mortars.

To analyze the transition zone (TZ) between cement matrix and rubberized aggregate, mortar fragments were collected for microstructural test. In the reference mortar image (Figure 9a), it is possible to verify a dense and compact paste with a low amount of pores and micro-cracks, which justifies the greater mechanical behavior, and lower voids for these mixtures compared to the others.

Additionally, in Figure 9b to Figure 9f, it is possible to observe that there is a discontinuity in the TZ lines, which shown that the adhesion between the crumb rubbers particles and the cement matrix is low, which can be justified by the hydrophobic nature of the rubber[62]. This evidence justifies the decrease in resistance and these results are in line with those reported by Long et al.[54], Gupta et al.[63] and Angelin et al.[64]. As well the rough texture and lamellar shape of the rubber[9,65] resulting in a less compact structure.

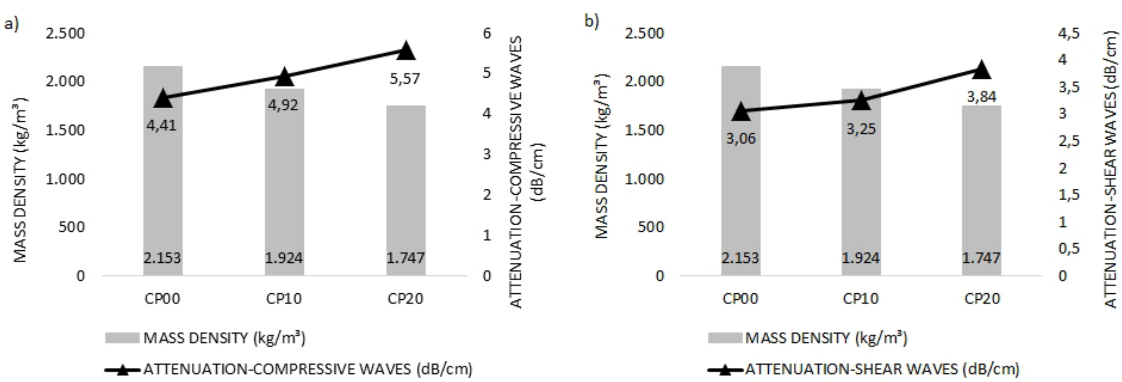

Figure 8. Sound attenuation in relation to mass density.

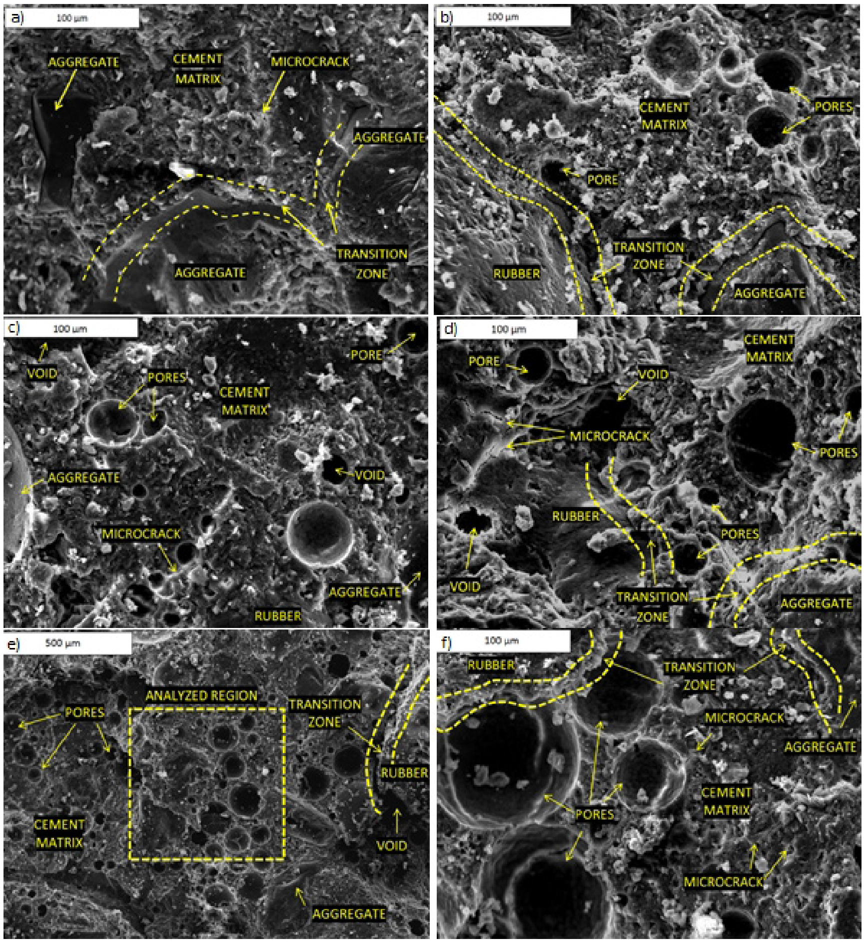

Figure 9. Typical SEM images.

Furthermore, with increasing levels of rubber residues incorporation in the mixtures, there is an increase in the quantity and dimensions of pores and microcracks. It's also worth noted that the amount of voids also acts significantly in relation to the acoustic performance of the materials. On the other hand, less dense materials are not good conductors of heat, as the heat flow dissipates in the porous structure of the material.

5. Conclusions

The use of rubber waste from unserviceable tires in the partial replacement of the fine aggregate in walls and ceilings coating mortar showed satisfactory results in relation to the properties of the mortar in the fresh and hardened state.

Based on the results obtained, it can be concluded that replacing fine aggregate with rubber reduces the specific mass of the mortar and increases the values of incorporated air, making it lighter and more workable.

Flexural tensile strength and compressive strength decreased, as well as elastic modulus. Providing a more flexible mortar, easy to apply, better ductility and resistance to cracking.

There was a reduction in thermal conductivity of 16% and 29% for mortars with 10% and 20% of rubber, respectively, in relation to the reference mixture. This characteristic of rubberized mortars, when used as a coating for walls and ceilings, can provide a better thermal performance in the building, making it difficult to exchange heat between the internal and external environments.

The rubber influenced the porosity of the mortar, increasing the void ratio and with that, the speed of ultrasonic transmission and the propagation of P and S waves decreased, providing the rubberized mortars with an improvement in sound attenuation, due to the loss of energy of the ultrasonic wave .

The replacement of fine aggregate by rubber waste proved to be favorable to mortars for coating walls and ceilings, as they showed improvements in heat transmittance and attenuation of sound waves, maintaining the physical and mechanical parameters required by ABNT NBR 13281:2005.

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