ENGLSH VERSION...

Performance of plaster composites incorporating rubber tire particles

Rendimiento de compuestos de yeso que incorporan partículas de neumáticos de goma

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Abstract

Gypsum is the oldest synthetic construction material that is known, however it is a material about which there is little knowledge at the level of research, and in this work its study took place by making composites with the incorporation of rubber tires, aiming to obtain an alternative construction material. Thus, the objective was to investigate gypsum-based composites, with a mass incorporation of 5, 10, and 15% of two grades of vulcanized rubber residue from tire retreading processes. The granulometries are referred to as thin (sieve pass-through #0.60 mm) and thick (sieve pass-through #1.19 mm). The composites were investigated in terms of consistency (mini-slump), mass density, water absorption, surface hardness, flexural strength, compressive strength, scanning electron microscopy (SEM), and thermal behavior. The results revealed that rubber incorporation can be attractive in gypsum composites: in which the consistency decreased with the increase of the rubber content and the thick rubber granulometry favored the workability of the composites; the mass density was reduced, mainly with thin granulometry, as the rubber content in the composites increased; the water absorption showed that the high levels of rubber favor the penetration of water in the composites, regardless of the granulometry; the surface hardness showed reduced impact energy provided by the composite with 10% thin rubber; in both flexural strength and compression, the composite with 5% thin rubber showed a similar result to the control composite, while composites with 15% rubber suffered a gradual drop of up to 60 and 40%, respectively; with SEM it was observed that the thin rubber composites had smaller pores, in addition to more effective adhesion between the rubber particles; finally the rubber helps to reduce the thermal amplitudes during the day, mainly with the increase of the particle size and the rubber content.

Keywords: *Gypsum composites; tire rubber; alternative material; physical-mechanical characterization*

Resumen

El yeso es el material de construcción sintético más antiguo que se conoce, sin embargo, es un material sobre el cual hay poco conocimiento a nivel de investigación, y en este trabajo su estudio se realizó haciendo compuestos con la incorporación de neumáticos de goma, con el objetivo de obtener un material de construcción alternativo. El objetivo era investigar los compuestos a base de yeso, con una incorporación en masa de, 5, 10 y 15%, de dos grados de residuos de caucho vulcanizado de los procesos de recauchutado de neumáticos. Las granulometrías se denominan delgadas (paso de tamiz # 0.60 mm) y gruesas (paso de tamiz # 1.19 mm). Los compuestos se investigaron en términos de consistencia (mini-asentamiento), densidad de masa, absorción de agua, dureza de la superficie, resistencia a la flexión, resistencia a la compresión, microscopía electrónica de barrido (SEM) y comportamiento térmico. Los resultados revelaron que la incorporación de caucho puede ser atractiva en los compuestos de yeso: donde la consistencia disminuyó con el aumento del contenido de caucho y la granulometría de caucho grueso favoreció la trabajabilidad de los compuestos; la densidad de masa se redujo, principalmente con granulometría delgada, a medida que aumentó el contenido de caucho en los compuestos; la absorción de agua mostró que los altos niveles de caucho favorecen la penetración de agua en los compuestos, independientemente de la granulometría; la dureza de la superficie mostró una energía de impacto reducida proporcionada por el compuesto con 10% de goma delgada; Tanto en la resistencia a la flexión como en la compresión, el compuesto con 5% de goma delgada mostró un resultado similar al compuesto de control, mientras que los compuestos con 15% de goma sufrieron una caída gradual de hasta 60 y 40%, respectivamente; con SEM se observó que los compuestos de caucho fino tenían poros más pequeños, además de una adhesión más efectiva entre las partículas de caucho; finalmente, el caucho ayuda a reducir las amplitudes térmicas durante el día, principalmente con el aumento del tamaño de partícula y el contenido de caucho.

Palabras clave: Compuestos de yeso; neumático de goma; material alternativo; caracterización fisico-mecánica

1. Introduction

Gypsum is considered to be one of the oldest known binders, with wide use in civil construction due to its physical and mechanical properties combined with low production cost (John and Cincotto, 2007); (Yu and Brouwers, 2012). In Brazil, it is practically used in ceilings, coverings and in partition walls called plasterboard, which has shown high growth due to the ease and speed of installation and molding of the sheets.

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In parallel, one of the main waste generated today is vulcanized rubber from unserviceable tires, which causes damage to the environment due to its inadequate disposal. Studies on the production of cementitious composites incorporated in tire rubber have demonstrated the possibility of this material partially switching aggregates of natural origin, contributing to the environment by replacing it with materials from finite natural sources. With regard to the use of rubber in gypsum composites, (Serna et al., 2012) have investigated the addition of end-of-life tire rubber (ELT) in gypsum pastes. In their study rubber content of 1, 3, and 5% by volume was incorporated with three different particle sizes of 0-1 mm, 1-2 mm, and 2-4 mm. The results were compared with samples of gypsum paste without the addition of rubber, and an increase was observed in the tensile strength of the composites.

(Takaki et al., 2016) studied gypsum composites incorporating rubber particles from tire retread at 5% by mass. The granulometries used were #0.075 mm (thin), #1.19 mm (medium), and #2.38 mm (thick). It was concluded that for the incorporation of 5%, the tire rubber with medium granulometry resulted in the most interesting composite, because it exhibited characteristics that did not relate to the extreme form of the reference composite, while other incorporations presented many results that were inferior to those obtained for plaster without rubber.

(Iucolano et al., 2015) studied composites formed by the gypsum matrix incorporated with abaca fibers subjected to different chemical treatments (with distilled water, NaOH solution and EDTA solution) to modify the surface characteristics and improve the adhesion with the gypsum matrix. The treatments with NaOH and EDTA solutions resulted in a worsening of the mechanical behavior of the composites, while the fibers treated with distilled water provided a better adhesion with the inorganic matrix. The aforementioned authors also observed an improvement in flexion behavior when compared to the reference gypsum matrix. For this test, composites were used in which the fibers went through the treatment process in raw water (Fx) and distilled water (FW_x), in which "x" represents the amount (% by weight) of fibers added in relation to the binder, was used of 1, 2 and 3%. All composites with different percentages had results above the reference trait.

(Medina et. al., 2018) reported that the results found in the literature are considered somewhat inaccurate and several of the technical and practical aspects end up remaining unanswered, which ends up hampering the profitable application of rubber in the construction industry as well as a better knowledge of physical properties, chemical and mechanical properties of rubber, as well as its proper characterization process, these factors being considered necessary for a better use of this residual material. The aforementioned authors also reported that the rubber performance consists largely of the matrix that will be used in the production process and also of the material content to be used, as well as the need for complete characterization of the rubber, as this information is not normally available tire manufacturers and/or recyclers and even the material distributors. In view of the inconvenience of use presented, the same authors mention, in the same way that (Mundo et al., 2018), the hydrophobic condition of tire rubber, responsible for causing attenuation in the connection with the matrix and consequently reduction of mechanical properties, and emphasize that alternatives adopted as mechanical and chemical pretreatments in rubber, prior to its application in composites, it would only increase production costs and not bring about considerable improvements.

For (Sofi, 2018), who studied tire rubber incorporated in concrete in terms of durability aspects, given the performance of water absorption and penetration tests, evidencing its influences when used as partial replacement of the fine aggregate (rubber fiber) and cement (rubber powder), from 0 to 20%, with multiple strokes of 2.5%. The results showed that the amount of water absorbed by test specimens with chemical attack (acids), in all ages (28, 56 and 84 days), was higher than the feature called reference. The aforementioned author also pointed out that at the end of the test (84 days of absorption) the specimens that contained the highest rubber content (20%) were those that showed high degrees of degradation, and this fact is considered to result from the appearance of micropores in the surroundings of the rubber surface, a fact that provided greater water penetration with consequent agents that degrade the material.

Accordingly, the incorporation of synthetic fibers and residues in the production of gypsum-based composites has been investigated to improve their physical and mechanical properties and produce more lightweight, resistant, and economical materials.

The objective of this study was to investigate gypsum-based composites with a mass incorporation of 5, 10, and 15% of two grades of vulcanized rubber residues from the tire retreading process, with granulometry that will hereinafter be referred to as thin (#0.60 mm through the sieve) and thick (#1.19 mm through the sieve). The investigation was conducted with regard to mini-slump tests, mass density, water absorption, surface hardness, flexural strength, compressive strength, scanning electron microscopy (SEM), and thermal behavior.

2. Materials and Methods

2.1 Materials

The tire rubber, from the retreading of truck tires, was selected and characterized in different granulometric bands, passing through the # 1.19 mm and # 0.60 mm mesh sieves, hereinafter referred to as thick (enlarged form, fiber type) and thin (powdered rounded form), respectively. With the characterization from the NBR NM 45 (ABNT, 2006), Archimedes Theorem and NBR NM 248 (ABNT, 2003), the density value of 1.15 g/cm³ was obtained, unit weight of 0.39 g/cm³ for thick rubber and 0.32 g/cm³ for thin rubber.

Construction plaster without additives was used for coating, and was essentially composed of β-hemidate. This gypsum had a compressive strength higher than 12 MPa, density of 2.62 g/cm³, unit weight of 0.71 g/cm³, and a pale white color.

Construction plaster is used in superplasticizing composites that are mainly used in the production of concrete. In cement composites, this product offers a reduction in the amount of kneading water and allows high initial strengths, while reducing the carbonation process. The superplasticizer has a density of 1.07 kg/l, pH 4.0-6.0, and is basically composed of a polycarboxylate solution in an aqueous medium.

2.2 Production of composites

Ten composites were produced, including the control (without rubber), which served as a reference for comparing parameters. The rubber incorporation was 5, 10, and 15% (by mass), which is equivalent to 14.20, 24.80 e 33.10% (by volume), based on (Sofi, 2018), (Serna et al., 2012) and (Takaki et al., 2016), who used of 3 to 20% of rubber content in cement composites. The adopted water/gypsum ratio was 0.40. The addition of superplasticizer was 0.50% in relation to the plaster mass. (Table 1) lists the fabricated composites.

Table 1. *Composition of fabricated composites.*

Composites	Identification	% Plaster	Rubber (by mass)	Rubber (by volume)
1	Control	100	—	—
2	C1(5-0)	95	5% thin	14.20% thin
3	C2(0-5)	95	5% thick	14.20% thick
4	C3(10-0)	90	10% thin	24.80% thin
5	C4(0-10)	90	10% thick	24.80% thick
6	C5(15-0)	85	15% thin	33.10% thin
7	C6(0-15)	85	15% thick	33.10% thick
8	C7(7.5-7.5)	85	7.5% thin + 7.5 thick	19,85% thin + 19,85% thick
9	C8(10-5)	85	10% thin + 5% thick	24.80% thin + 14.20% thick
10	C9(5-10)	85	5% thin + 10% thick	14.20% thin + 24.80% thick

It is worth mentioning that the composites C7 (7.5-7.5), C8 (10-5) and C9 (5-10), as shown in (Table 1), had levels of rubber incorporation that added the two particle sizes adopted in the work, with the purpose of to verify their influence on the produced composites.

(Table 2) shows a schematic schedule involving all the parameters of the experiments, as well as the number of specimens that were manufactured and used for each test.

Table 2. *Scheme of variables to be analyzed in the experimental program and number of specimens tested by composite.*

% Tire Rubber	*Number of composites produced*	*Tests performed by composite*	*Age (days)*	*Number of specimens*	*Total number of specimens (per composite)*
5, 10 e 15	*10*	*Consistency*	*0*	—	*16*
		Flexural strength	*28*	*4*	
		Compressive strength	*28*	*3*	
		Water absorption	*28*	*2*	
		Surface hardness	*28*	*2*	
		Mass density	*28*	*4*	
		Thermal behavior	*>28*	*1*	

2.3 Experimental program tests

The consistency (mini slump) of the composites was observed by conducting a mini-slump test according to (Kantro, 1980), who measured the workability conditions of the material through its fluidity/plasticity. The mass density (specimens with dimensions of 400 x 300 x 15 mm), water absorption (specimens tested for 120 minutes submerged, with dimensions of 300 x 300 x 15 mm), flexural strength (specimens tested on a Pavitest press - model C1006 - capable of reading small loads, with dimensions of 400 x 300 x 15 mm), and surface hardness (specimens with dimensions of 400 x 300 x 15 mm) tests were based on NBR 14715-2 (ABNT, 2010). The compressive strength test was conducted according to NBR 12129 (ABNT, 2019), using cubic specimens of dimensions 50 x 50 x 50 mm, molded in metallic form and tested in a Heckert press (100 ton capacity).

The SEM assay was made from the fragments of ruptured test specimens in the compression strength test, the small fragments were placed in beakers with acetone, so that it could interrupt the hydration process of the plaster, this process took one hour. Then they were removed from the beaker and left in an oven for two hours, so that the acetone used evaporated. After the hydration of the plaster was interrupted, the specimen fragments were prepared for microscopy, and since the plaster is not a metallic and conductive material, it was necessary to cover it with a thin layer of gold, using the Sputerring Quorum equipment, to that the electron beam incident on the material was conducted in such a way as to produce the images generated in this test. It was used Carl Zeiss Microscope, model EVO LS15, from the Department of Physics and Chemistry of FEIS/UNESP, Ilha Solteira, Brazil.

The thermal behavior test method used by (Santos, 2008) was adapted to the analysis of thermal behavior in a housing unit produced from plaster and expanded polystyrene (EPS) composites. The test specimens of the water absorption tests were used, in which the procedure involved the use of 10 simple K type thermocouples and a Minipa thermohygrometer, model MT-240, 10 styrofoam supports, made of 4.5 cm thick to support the plasterboard. The test consisted of placing a thermocouple inside the styrofoam supports for each studied composite, these served to read the temperature measurement every 15 minutes, for 7 days, from 8:00 am to 8:00 pm. The external temperature was measured using the thermohygrometer every hour. To read the temperatures, the Arduino software serial monitor was used, with the time interval programming used for the measurements. The results were analyzed by reading the external temperatures throughout the day and comparing them with the temperatures inside each created environment.

3. Results and Discussions

3.1 Consistency (mini-slump)

Generally, a variation in consistency according to the incorporated rubber content was observed. The obtained results were non-linear because the composites with a rubber incorporation of 15% had a higher consistency than those with an incorporation of 10%. (Figure 1) shows the average consistency graph obtained for the composites.

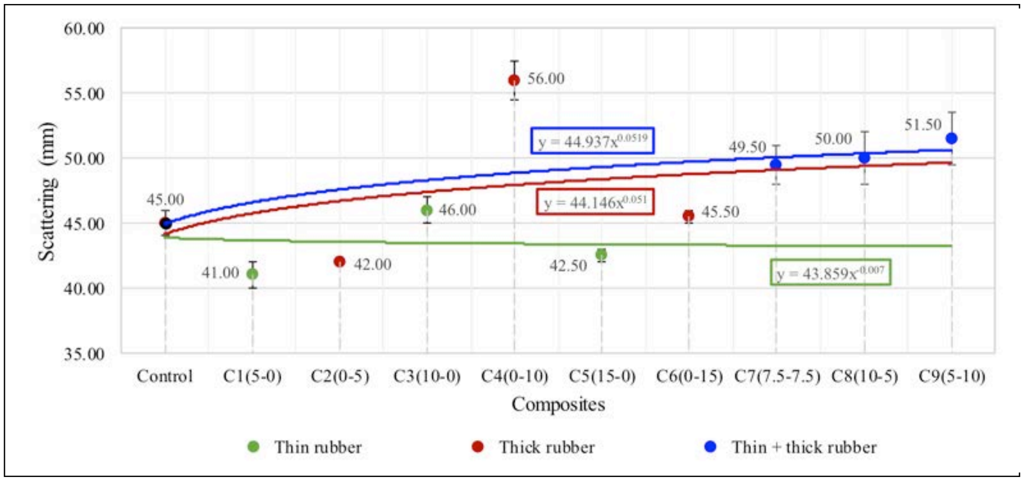

Figure 1. *Consistency graph.*

Amongst the composites containing only one of the two granulometries (C1 to C6), it was observed that those containing thick rubber, namely C2(0-5), C4(0-10), and C6(0-15), corresponded to the highest results, and exhibited a better spreading of the paste in comparison with the results obtained by the thin rubber. It was also verified that composite C4(0-10) with a 10% incorporation of thick rubber exhibited the highest mean spread amongst all investigated composites.

For the composites that contained the two rubber granulometries in different ratios, composite C7(7.5-7.5) exhibited the lowest scattering amongst the three, but was still higher by 10% in comparison with the scattering observed for the control composite. However, the composite with the highest thick rubber content, namely C9(5-10), had the highest consistency, with an increase of slightly more than 14%.

The composites with an incorporation of 5% were the most consistent, followed by those with a rubber incorporation of 15%. The highest scattering was obtained by composites containing 10% of rubber, as was observed for the two investigated granulometries.

This is similar to the results obtained by (Takaki et al., 2016), because the composites produced with a rubber incorporation of 5% and particle sizes of #0.075 mm, #1.19 mm, and #2.38 mm led to an increase in the average size of the composites as the granulometry of the incorporated rubber increased. It is worth mentioning that the authors used various different factors, such as the gypsum type, ratio w/g (0.60), and superplasticizer.

3.2 Mass Density

In this assay almost all rubber-containing composites had a lower average density than the control, which may be related to the low density of the rubber particles in comparison with the gypsum. It was also observed that with the increase in the incorporation of rubber content, the density became lower. This can be attributed to the small air layers around the rubber particles, which contributes to the reduction of the composites' mass density. A graph showing the average density of the fabricated composites is presented in (Figure 2).

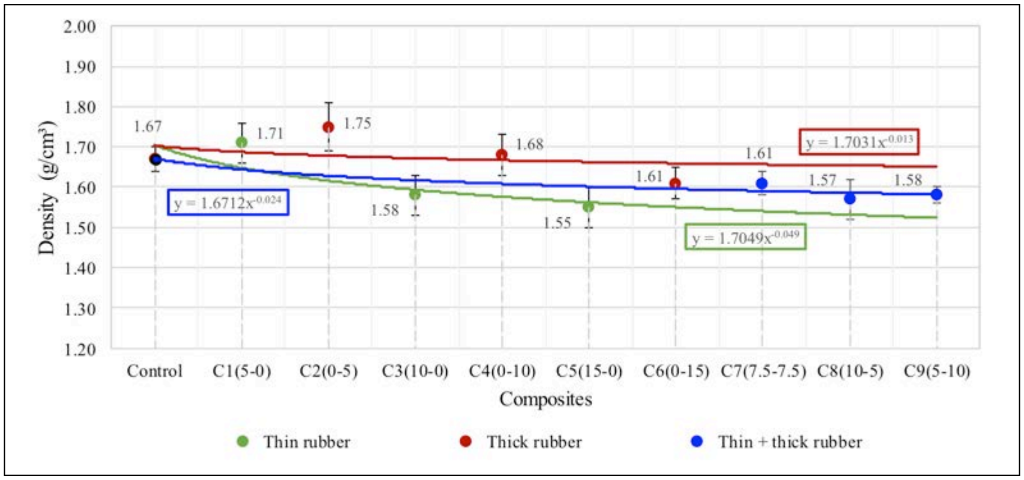

Figure 2. *Mass density graph.*

It was observed that composites C1(5-0) and C2(0-5), which had the highest consistencies, also had the highest densities, with an increase of 2.40% relative to the control for composite C1, and an increase of 4.80% relative to the control for composite C2. However, composite C4(0-10) had practically the same density as the control, whereas all other fabricated composites had lower density than the reference.

Amongst the investigated rubbers, it was observed that the thick granulometry had the highest density averages in comparison with the thin granulometry, for all investigated ratios and composites C1(5-0), C2(0-5), C3(10-0), C4(0-10), C5(15-0), and C6(0-15). This demonstrates that the thinner grit resulted in a lighter material, for presenting a lower unit weight (0,32g/cm³) when compared to thick rubber (0,39 g/cm³). Amongst the three percentages, the best result was achieved for composite C5(15-0), with an average density of 11.20% lower than the control.

The same results have been reported by (Serna et al., 2012), who observed that rubber particles added to the gypsum matrix cause the partial replacement of gypsum paste with rubber, which results in an average weight loss between 1.50 and 2.50% in relation to the reference samples. This difference in weight was greater in samples with a lower ratio of water/gypsum paste, and higher when more rubber was added. Moreover, the presence of rubber in the samples led to a smaller decrease in weight in seven days, in comparison with the reference samples.

3.3 Water Absorption

In the water absorption test, the observed tendency was the same as that in the consistency test: the composites with a rubber incorporation of 5%, namely C1(5-0) and C2(0-5), absorbed less water amongst all investigated composites. The graph of the mean absorption is shown in (Figure 3).

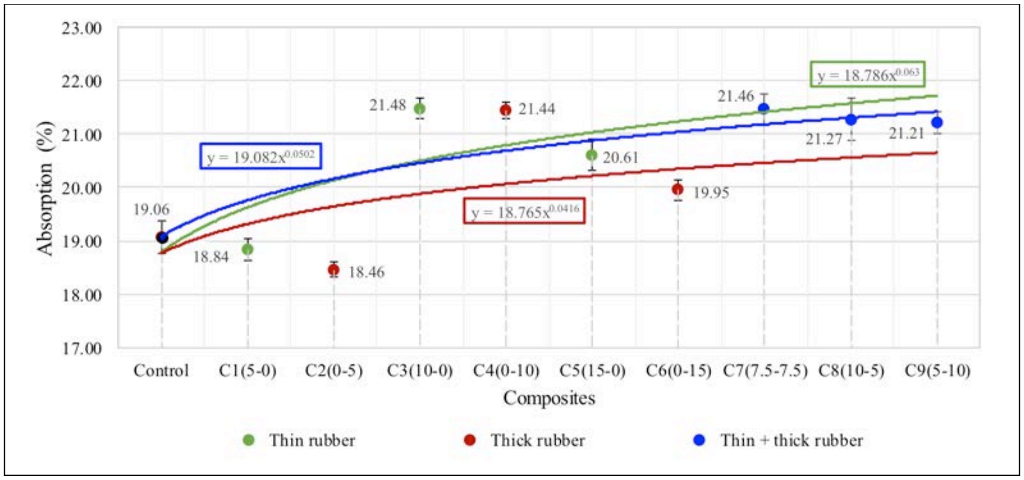

Figure 3. *Absorption graph.*

The composites with a rubber incorporation of 5% exhibited the lowest water absorption amongst all investigated composites. A significant difference was not observed between the two granulometries, because the thin rubber had an absorption of 18.84% while the thick rubber had a slightly lower absorption of 18.46%.

The composites that were incorporated with 10% of rubber presented the highest absorption results, and there was little difference between those that incorporated thin rubber C3(10-0) – 21.48% water absorption, and those that incorporated thick rubber C4(0-10) – 21.44% water absorption. In comparison with the results obtained for the control, the composites with an incorporation of 10% had an absorption that was approximately 2.30% higher than that observed in the control.

However, it was not possible to consider the higher water uptake as a result of rubber incorporation, because the highest addition was 15% for composites C5(15-0), C6(0-15), C7(7,5-7.5), C8(10-5), and C9(5-10), which had lower absorption in comparison with C3(10-0) and C4(0-10) with an incorporation of 10%. In addition to the consistency test observations, the composites with an incorporation of 10% of rubber exhibited greater workability than the composites incorporating 15% of rubber.

Everything indicates, however, that since rubber does not absorb water, it accumulates at the interfaces between gypsum paste and rubber particles or also in micropores, as also observed by (Sofi, 2018), which are created in the presence of rubber.

For gypsum composites with an incorporated dry coconut fiber blanket, (Cunha et al., 2013) observed that fiber incorporation led to an increase in water absorption. This suggests that, for a sample with a higher fiber volume, a higher absorption is justified by the high ability of th fibers to absorb water in their central region.

(Magalhães, 2009) reported similar results after investigating gypsum composites incorporating bamboo, sisal, and coconut fibers with and without the use of superplasticizer. The incorporation ratios were 2 to 8% and varied according to the type of fiber used. The composites with superplasticizer obtained the lowest results in the water absorption test, i.e., between 15 and 23%. The best composite performance was achieved by the incorporation of sisal fiber. For composites containing superplasticizer, the w/g factors were between 0.40, 0.45, and 0.50. For the control gypsum, with the incorporation of the three fibers and without the addition of superplasticizer, the absorption rates varied between 22% and 48%, while the composite incorporating sisal fiber absorbed the least amount of water.

3.4 Surface Hardness

By conducting a surface hardness test, it was possible to verify the contribution of rubber to the plaster composites. The results revealed that smaller deformations occurred after the impact of the steel sphere. Therefore, the surface hardness increased. However, there is no clear relationship between the increase in the rubber incorporation ratio and the reduction in the amount of dents. (Figure 4) shows the mean amount of dents as a graph obtained by the surface hardness test.

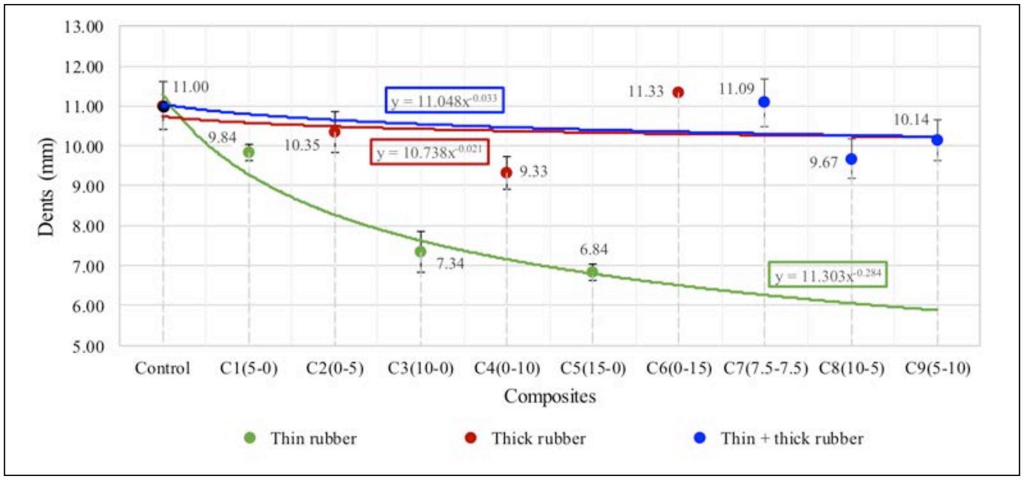

***Figure 4.** Surface hardness graph.*

For thin rubber, with the increase of rubber incorporation in composites C1(5-0), C3(10-0), and C5(15-0), the rubber started contributing to the decrease of dents, which increased the surface hardness by 10.60, 33.32, and 37.86%, respectively.

However, the same was not observed for the thick rubber, which led to an improvement for the first two percentages in composites C2(0-5), C4(0-10), and C6(0-15). The dents were reduced and the surface hardness was increased by 6.05% (on average) for composite C2(0-5), and by 15.19% for composite C4(0-10). However, for composite C6(0-15), the dents increased in comparison with the control, and this reduced the surface hardness by 3%.

It was verified that there did not exist much variation amongst the composites that incorporated a ratio of each rubber granulometry. Additionally, the results for composite C7(7.5-7.5) were very similar to the results obtained for the control, with an increase of only 0.77% in the average size of dents. Moreover, composite C8(10-5) had the smallest dents amongst the three, with a decrease of 12.14% in its dimension, in comparison with the control, which resulted in greater superficial hardness.

It is worth noting that out of all tested composites, only two plates were broken during the launching of the steel sphere. The first plate was that of composite C5(15-0), which had the highest surface hardness; the second plate was that of composite C7(7.5-7.5), which had the second lowest surface hardness. The two plates broke for different reasons: composite C5(15-0) had almost imperceptible dents and the ball had to be thrown more than once to obtain the results; composite C7(7,5-7,5), which had the most dents, ended up breaking when the sphere was launched for the third time.

Something similar has been reported by (Takaki et al., 2016), and suggests that all composites, except those containing 5% rubber with medium particle size had at least one specimen that broke in one of the steel ball bearings and generated cracks. For both the thin rubber plate and the control plate, the ruptures occurred in the bodies that had the lowest average density; that is, the bodies with the greatest surface hardness.

(Kern et al., 2000) investigated gypsum matrix composites with an incorporation of shoe buttresses in the percentages of 10, 15, 20, and 25%. They observed that the gypsum matrix without the incorporation of residue always ruptured suddenly at the first fall of the sphere. The composites incorporating residue had higher ductility and exhibited considerable plastic deformation, particularly those with the highest incorporation ratios.

3.5 Flexural Strength

By conducting a flexural strength test, we were able to verify that the rubber exerted significant influence in the specimens. As the content of rubber incorporation increased, the strengths obtained by the composites were reduced, differently from that found by (Iucolano et al., 2015) who used abaca fibers (Musa textiles) in the plaster matrix, as can be seen in (Figure 5).

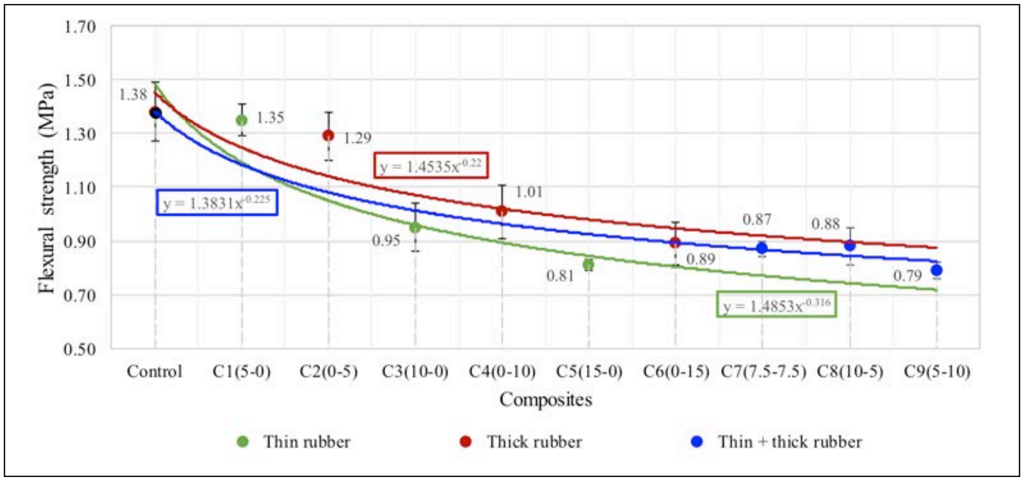

Figure 5. *Flexural strength graph.*

It is worth mentioning that the maximum resistance supported by the specimen before suffering damages is important to be observed to determine the value of the maximum load supported by the composite before compromising its proper performance, in this way the results for composites C1(5-0) and C2(0-5) were very similar to the results obtained for the control. Composite C1(5-0) had a difference of 2.60% relative to the control, whereas the difference of composite C2(0-5) was 7%.

Composites C5(15-0) and C9(5-10) had the greatest difference in relation with the control; the results obtained were 41.50% and 42.80%, respectively, which is lower than that the results obtained for the control.

It is important to note that only in the composites with an incorporation of 5%, namely C1(5-0) and C2(0-5), the thin rubber had the highest mean. However, relative to the composites with an incorporation of 10 or 15%, namely C3(10-0), C4(0-10), C5(15-0), and C6(0-15), the thick granulometry achieved the best results.

Amongst the composites containing one of the two rubber granulometries, the composite that exhibited the lowest decrease in resistance was again composite C8(10-5) (36,30% below the control), followed by composite C7(7,5-7.5) (37.20% below the control). Finally, composite C9(5-10) had the lowest average amongst all composites.

During the flexural strength tests, it was observed that the rubber helped in maintaining the integrity of the test specimen. Therefore, after the test, the plates did not separate completely as in the case of the control composite.

Something similar was observed by (Raghavan et al., 1998) during the flexion testing of mortar specimens incorporating rubber tire. They verified that, after the failure of the mortar matrix, the pieces of the rubber supported the cracking and prevented the total rupture of the specimen.

The average decrease of the composites was between 8.30% (with 5% of rubber) and 41.60% (with 15% of rubber). Apparently, this was caused by the lower adhesion between the gypsum paste and the rubber particles, which was observed through SEM.

(Oliveira et al., 2012) investigated plaster composites incorporating EVA, and analyzed their mechanical behavior by conducting a flexural strength test. The authors concluded that, because of the adhesion problems between the gypsum paste and EVA, the composites exhibited lower strength in comparison with the control. Additionally, as the EVA percentage and w/g ratio increased, the strength of the investigated composite decreased.

(Serna et al., 2012), who investigated gypsum and rubber tire composites to improve the elastic behavior of gypsum, observed that the incorporation of rubber caused a decrease in the resistance to gypsum flexion. The

resistance decreased proportionally with the incorporation of rubber between 10.40% (with 1% rubber) and 19.90% (with 5% rubber). The authors attributed this reduction in force to the lack of adhesion between the rubber particles and the gypsum matrix.

For (Takaki et al., 2016), who used three different retreading rubber granulometries, the incorporation of rubber contents at 5% (mass) resulted in plasterboard flexural strengths superior to those of the control composite, that is, the composite with medium rubber (# 1.19 mm) enabled an increase of 21.60%, whereas the composite with thin rubber (# 0.075 mm) showed an increase of 7.60%, and the composite with thick rubber (# 2.38 mm) allowed an improvement of 5.10%.

3.6 Compressive Strength

Generally, composites with incorporated rubber tire exhibit lower compressive strength in comparison with a control, as can be seen in (Figure 6).

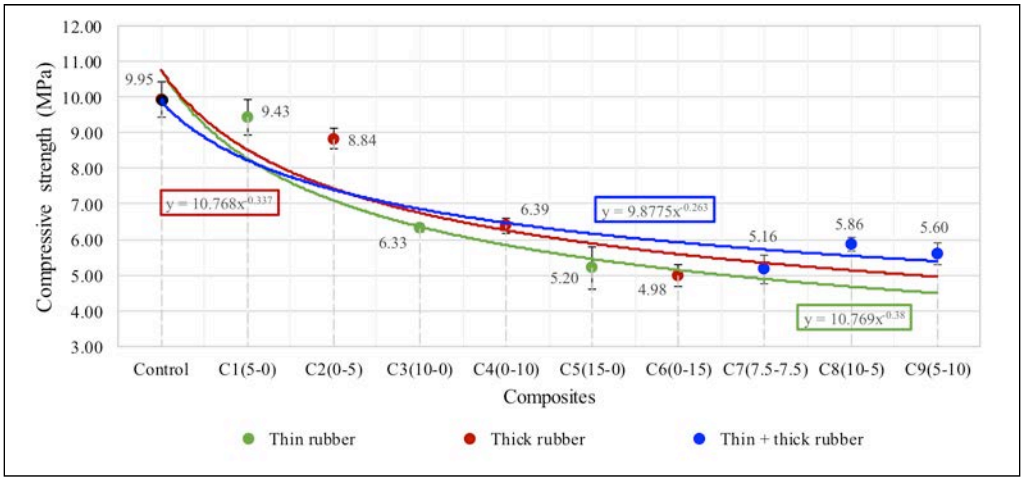

Figure 6. *Compressive strength graph.*

This test being important because it can shorten and break the composite, as well as ensure that it does not easily deform and ensure adequate dimensional accuracy when required by compression efforts, the composite that came closest to the control was C1(5-0), whose compressive strength was 5.20% lower (on average) than that of the gypsum paste control. The result for composite C2(0-5) was also satisfactory because it revealed that this composite had a resistance of 8.84 MPa, which is considered suitable for use considering that the plaster does not have a structural function.

By comparing the used rubber granulometries, it was observed that the composites containing thick rubber had the lowest strength. This was particularly the case for composite C6(0-15), for which the lowest results were 49.90% lower than the control, on average.

Amongst the investigated percentages, it was possible to verify that as the rubber incorporation increased, the resistance exerted by the test specimens decreased, because the results for all specimens containing 15% of rubber were lower by 40% (on average) in comparison with the mean obtained for the control.

For the rubber incorporation of 5%, the results reported by (Serna et al., 2012) are smaller than the results obtained by this study, because the reduction obtained by the previous study was 20% (w/g = 0.60), 26% (w/g = 0.70), and 29% (w/g = 0.80) in relation to the control, whereas, in this study, the maximum reduction was 11%.

(Fuzaro et al., 2015), who have also investigated the compressive strength of gypsum composites incorporating tire residues, reported that there were significant differences in the statistical data obtained for all treatments. Additionally, the treatment that obtained the best results was that of plaster without the incorporation of rubber. However, by analyzing the treatments wherein rubber content was added to gypsum, they verified that the *treatment with a rubber incorporation of 5% obtained a higher normal tension to compression value, while the treatment with a rubber incorporation of 15% obtained a lower value.*

(Oliveira et al., 2012) fabricated gypsum composites with EVA residues, w/g ratio of 0.80, and incorporation ratio of 15%. They obtained a compressive strength of 3.20 MPa, which is a lower value in comparison with plaster composites incorporating 15% of rubber, and a compressive strength of 4.97 MPa.

3.7 Scanning Electron Microscopy

By conducting a SEM test, we verified various aspects of the investigated composites, such as the crystallization of gypsum and the adhesion between the gypsum paste and the rubber particles.

The images in the sequence show the comparison of different types of gypsum crystallization. In the gypsum paste control (Figure 7A), the formation of crystals with more prismatic, elongated, and well defined forms was observed. For the same magnification observed by the microscope, a different crystallization for the plaster composites with tire rubber was observed. For the composites containing thin rubber (Figure 7B), the plaster crystallization was slightly less prismatic and defined, but still elongated. For the composites containing thick rubber (Figure 8A), the gypsum crystallization was much less elongated and defined in comparison with the other two composites. Thus, prismatic shapes were not observed in this paste. For the composites containing two types of rubber (Figure 8B), the gypsum crystallization was the most different amongst those already discussed: the shapes were not defined, there was a lot of irregularity in the paste, and many voids were observed.

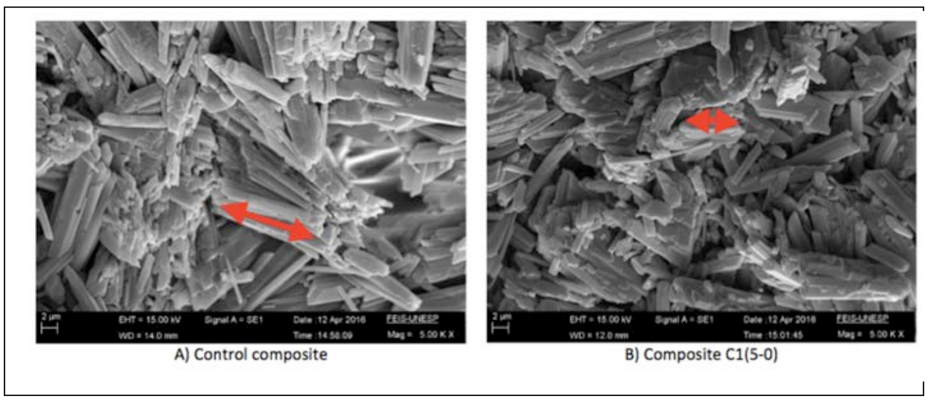

Figure 7. *Different types of gypsum paste crystallization.*

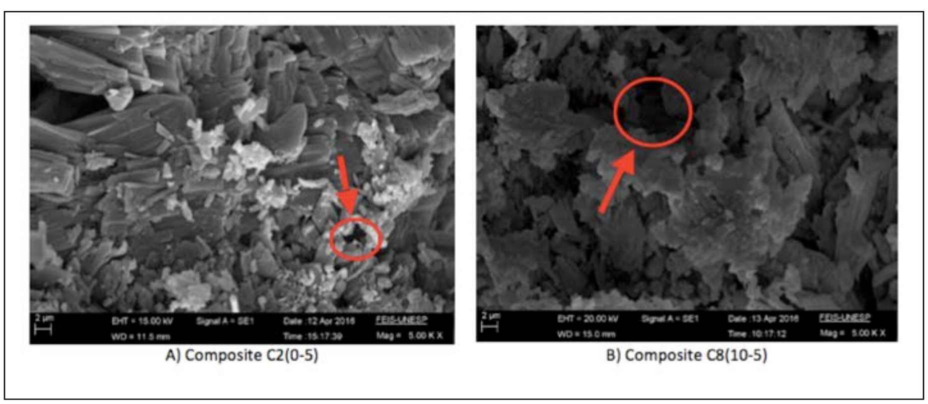

Figure 8. *Different types of gypsum paste crystallization.*

Everything indicates that this difference in the crystallization of plaster paste is due to the contamination of other materials that are present in the silo where the rubber is stored or on the floor from which the waste was collected, which may be steel particles, sand or other material, since between the rubber and the plaster paste do not present a chemical reaction that justifies such a change.

To compare the adhesion of gypsum paste with rubber, the same magnification was used in the microscope test. The adhesion between the gypsum paste and the thin rubber (Figure 9A) exhibited the best integration between the two, and had few voids in the interface of these two materials. In the gypsum paste containing thick rubber (Figure 9B), the adhesion occurred more subtly because a void was present at the interface of the two materials, and this prevented the uniformity of the material. For the gypsum composite incorporating two rubber granulometries (Figure 9C), the material was slightly more uniform, with some voids present, but with less space present in the interface.

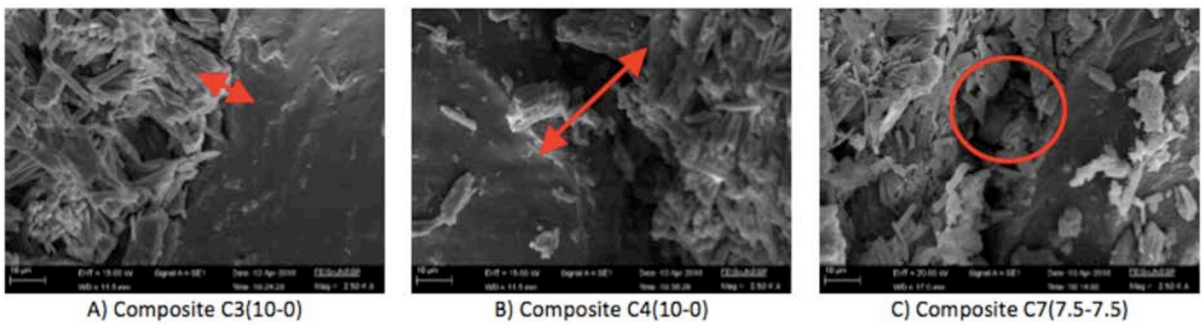

Figure 9. *Different types of adhesion between gypsum paste and rubber particles.*

3.8 Thermal Behavior

Gypsum as a vertical sealing element has an important performance in the behavior and thermal insulation of the environments, therefore, analyzing the performance of the studied composites regarding this property was relevant in this work. The results will be presented in the form of a graph comparing the percentages and particle sizes studied.

Generally, the variation of temperature between the investigated composites was not great. Specifically, a variation of ±2°C was observed in comparison with the external temperature. The graphs corresponding to the thermal test of composites C1 to C6 are shown in (Figure 10), (Figure 11), and (Figure 12).

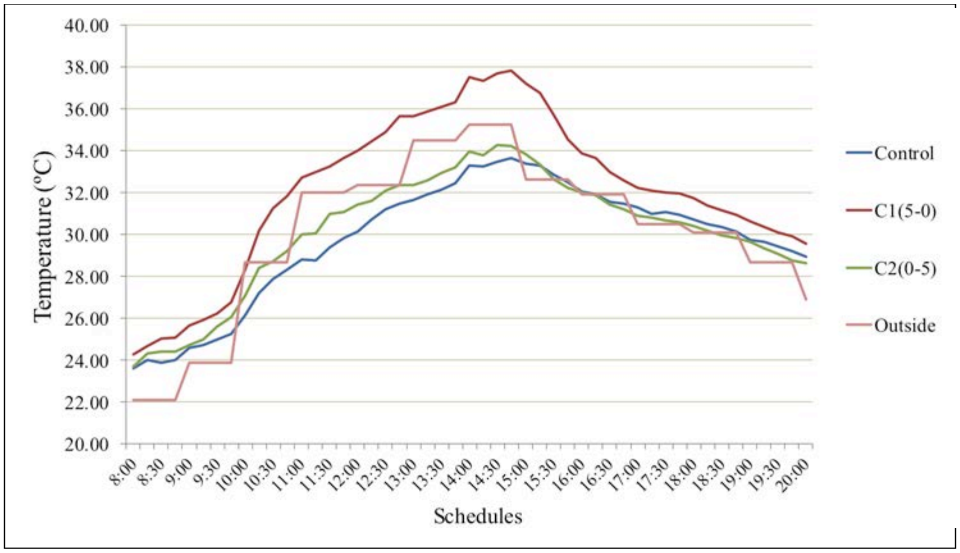

Figure 10. *Graph of thermal behavior for composites with 5% of rubber.*

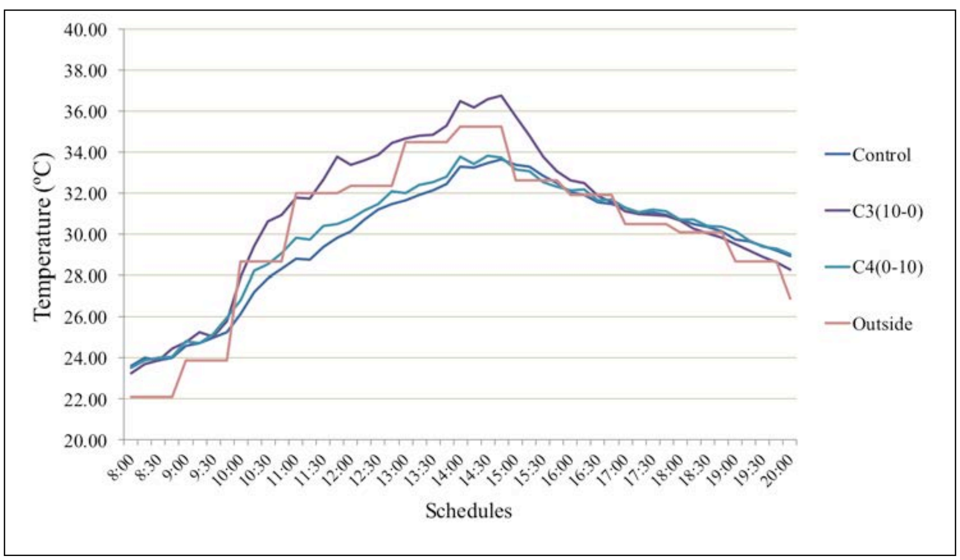

Figure 11. *Graph of thermal behavior for composites with 10% of rubber.*

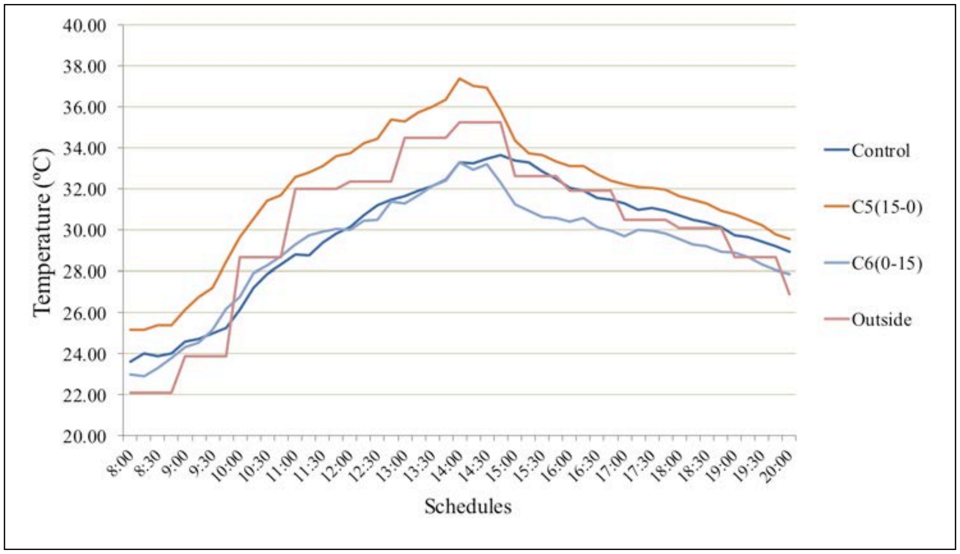

Figure 12. *Graph of thermal behavior for composites with 15% of rubber.*

As can be seen, the three graphs have various points in common. The first one is until 10:00 a.m.; the external temperature is lower than that of the interior environments formed by the composites, with a difference of ± 3°C; that is, even at the lowest temperature, the composites were able to maintain the internal temperature between 23°C and 25°C.

In the time range between 10:00 and 15:00, when the temperature was higher, the external temperature increased by approximately 11°C, and was accompanied by an increase in the internal temperature, which occurred in a different manner. For the composites containing thin rubber, namely C1(5-0), C3(10-0), and C5(15-0), the internal temperature was higher than the external temperature by ± 2°C, reaching approximately 37°C. Thereby, it was observed that the thin rubber contributed to the internal heating of the created environments, a characteristic that is not useful in Brazil because, for the majority of days in a year, the temperature is mostly high and retaining heat to withstand such low temperatures is not required.

However, composites incorporating thick rubber, namely C2(0-5), C4(0-10), and C6(0-15), exhibit interesting thermal behavior, as evidenced by the obtained results which are similar to those obtained for the control composites in many analyzed times. The plaster had the characteristic of good thermal insulation, owing to its porous structure. Thus, it was verified that the thick rubber did not interfere significantly with its properties.

For composites with thin rubber, it was observed that all had temperatures higher than those presented by the control composite and the external temperature. Those with incorporation of 5 and 15% rubber were the ones that had the highest temperatures internally, with values above 37ºC, which is not considered comfortable from the internal point of view of an environment.

The C1 (5-0) composite showed the highest thermal amplitude among the three composites, with a difference of about 13ºC between the lowest and the highest temperature reached throughout the day, a fact that can cause discomfort due to the wide variation in temperatura.

The composite that contained 10% of incorporation, C3 (10-0), showed slightly lower temperatures at some times throughout the day, and only a difference of ± 1ºC from the outside temperature in the period of most intense heat. In comparison with the control composite, C3 (10-0) showed some points of overlap between 08:00 and 09: 30h and between 17:00 and 20: 00h, but in the period of greater insolation the difference between them is ± 3ºC, exceeding the internal temperature of the control.

The different coloration of the specimens with thin granulometry can help to justify this increase in temperature, since they present a more grayish color and everything indicates that the darker the coloration, the more heat the material absorbs and consequently passes into the environment.

Regarding thick rubber, it is clear that, unlike what happened with composites with thin rubber, those incorporated with 5 and 10% - C2 (0-5) and C4 (0-10) - showed the highest results temperature and many of them similar to each other, but in this case they were very similar to the control and, consequently, provided a good thermal insulation.

In the period of lowest temperature, between 08:00 and 10:00, the three composites presented about ± 2°C more than presented externally. However, in the hottest period of the day, the fact is reversed and composites with thick rubber have ± 3°C less than externally, managing to maintain a more comfortable temperature inside.

Amongst all investigated ratios, the most interesting result was obtained for composite C6(0-15), because this composite had the mildest temperatures in the period between 12:00 and 20:00, with a difference of ±3°C in comparison with the control composite or the external temperature, which helps in thermally insulating the environment.

As for the aesthetic aspect, it was observed that the composites with thick rubber showed a lighter color, reflecting more the incident rays and thus absorbing less heat.

Composites C7, C8, and C9 exhibited intermediate thermal behavior amongst the composites that contained only one granulometry. The graph corresponding to the evolution of the average temperature throughout the day is presented in (Figure 13).

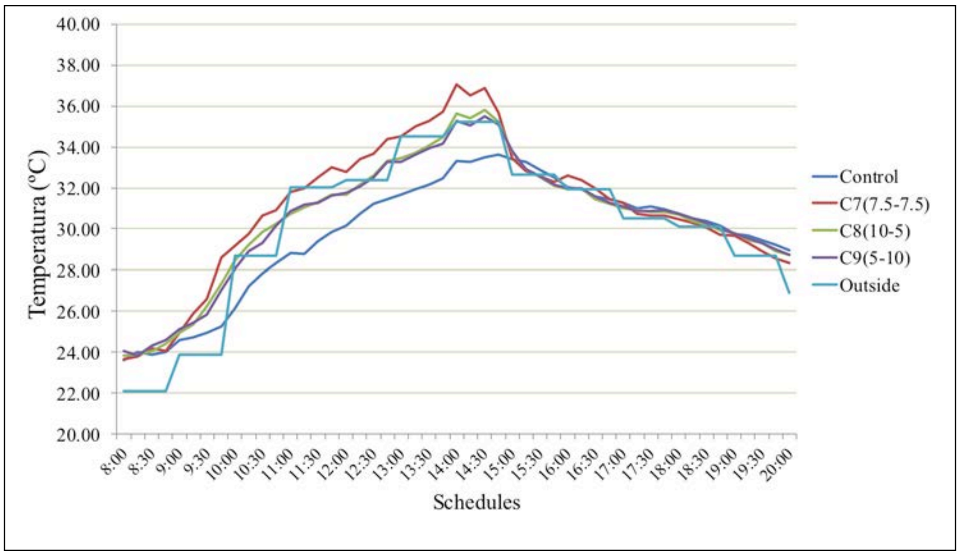

Figure 13. *Thermal behavior of composites C7 to C9.*

Composites C7 (7.5-7.5), C8 (10-5) and C9 (5-10) showed intermediate thermal behavior between composites that had only one of the particle sizes incorporated. Generally, C7(7.5-7.5) had higher temperatures reaching up to 37°C, as was also the case for the composites incorporating 5 and 15% of thin rubber. Therefore, the contribution of this granulometry to internal heating was greater, and can also contribute to more discomfort if we think in terms of the built environment. C7(7.5-7.5) was still the composite with the greatest thermal amplitude of ±13°C during the day, which does not contribute to the desired insulation of the environment.

The results for composites C8(10-5) and C9(5-10) were approximately the same throughout the day. By 15:00, the results were between the results obtained for the composite control and those obtained for C7(7.5-7.5). Thus, the results corresponded with the external temperature. The different percentages of thin and thick rubber did not lead to any differences in the results.

At 15:00 and until the end of the test (20:00), all rubber composites had temperatures similar with the control and external temperature, which does not contribute to the desired insulation of the environment.

By building a small housing unit, (Santos, 2008) was able to better analyze the effect of temperature and direction of view on each face (North, South, East, and West), which resulted in differences of 6°C to 7°C (between the temperature of the internal wall and the external temperature) for facades that had a lot of insulation (North and West), and a difference of ±4°C between the external temperature above the building and the temperature just below the slab.

(Santos, 2008) also noticed that for the walls that were in the shade, the temperature values were approximately the same. However, there was a significant difference for the walls exposed to the sun (reaching up to 7°C), which demonstrates the suitable thermal resistance of the composite based on plaster with incorporated EPS.

In this study, it was observed that the thick granulometry made the largest contribution to the insulation and comfort of the environment, mainly with a rubber incorporation of 15%. It was also observed that the difference in the temperature variations between the interior and the exterior did not exceed ±3°C.

4. Conclusions

The following conclusions were drawn from this study:

a) *By conducting a consistency test, it was verified that the composites with 5% of rubber had the highest consistencies. As the rubber content increased, the workability of the paste also increased, particularly for composites with an incorporation of 10%. The thick rubber had the highest workability amongst all investigated ratios.*
b) *For the mass density test, the best performance was observed for the composites with the highest incorporation ratio (15%), which resulted in lighter materials. Amongst the investigated granulometries, the thin rubber contributed the most and had the lowest densities amongst the three investigated ratios.*
c) *With regard to water absorption, it was verified that the composites with 5% of rubber had the lowest absorption, even in comparison with the control composite. Amongst the investigated ratios, the incorporation of 10% had the highest absorption, while the composites with an incorporation of 15% exhibited a subtle decline. In this test, the thick rubber absorbed less water of the three ratios.*
d) *By conducting a surface hardness test, it was observed that the rubber composites exhibited a mean amount of dents that was smaller than that of the control, which makes the dents nearly imperceptible. The best results were obtained for composites with an incorporation of 10%. Additionally, the thin granulometry had a more prominent role in impact resistance.*
e) *By conducting a flexural strength test, we observed an improvement in the performance of composites with 5% of rubber, and particularly for those incorporating the thin particle size. As the percentage of rubber increased, it was verified that the resistance to flexion gradually decreased to 60%.*
f) *By conducting a compressive strength test, it was found that the composites with 5% of rubber provided the best results. In particular, the thin granulometry obtained results very close to those obtained for the control. Additionally, the resistance tended to reduce excessively for ratios above 5%.*
g) *By using SEM, it was observed that the composites incorporating thin rubber exhibited gypsum paste crystallization in a more prismatic and elongated manner. Moreover, smaller pores and better adhesion between the rubber particles and the paste was observed.*
h) *The thermal behavior test obtained interesting results with regard to visualizing the specimens' performance relative to the heat transfer into the created environment and the provided insulation. Thereby, it was observed that the composites with thick rubber content had the lowest thermal amplitudes during the day, particularly the specimens with an incorporation of 15%, which demonstrates the ability of this composite to transmit little of the heat received during the hottest period of the day, and its ability to maintain the internal temperature during colder periods.*

Thus, the use of tire rubber in the production of plasterboard can become an attractive incentive to recycle this industrial waste. Moreover, it can enable the production of a new composite that is appropriate for civil engineering construction.

5. Acknowledgment

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