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ORIGINAL ARTICLE

Comparison of the properties of mortars containing expanded clay, vermiculite, and rubber residue

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Abstract

Lightweight mortars are indicated for services that require low specific mass composites. There are several lightweight aggregates available on the market. Waste rubber from tires is a low-density waste option that can be used as lightweight aggregate. The rubber waste when used in mortar reduces its density, in addition to bringing benefits from an environmental point of view. In this research, the mechanical behavior, and physical properties of mortars in which the natural fine aggregate contents were replaced by mixtures in different proportions of rubber, expanded vermiculite, and expanded clay were investigated. For the analysis of the properties of the composites, they were submitted to tests of dynamic modulus of elasticity, damping, compressive strength, flexural strength, coefficient of capillarity, density, and determination of ultrasonic wave transmission velocity. All tested mortars met the requirements of the Brazilian standard, being indicated for laying and covering walls and ceilings, in addition to having excellent acoustic and damping performance.
Keywords: alternative materials, construction materials, mortars.

INTRODUCTION

Civil construction has greatly impacted the environment, with the extraction of raw materials and inadequate disposal of waste. However, it is one of the socioeconomic sectors that most generate jobs, whether direct or indirect [1]. The incorporation of alternative materials and residues in the production of cementitious composites is one of the ways to develop a sustainable material and adapt to the new needs of society [2, 3]. In this way, researchers have sought to understand the influence of the use of different materials in cementitious composites, such as rubber from waste tires [4], blast furnace slag residues [5], expanded polystyrene [6], expanded vermiculite [7], expanded clay [8], and steel fibers [9, 10]. The addition of rubber waste in cement composites improves their acoustic and thermal performance. However, it increases their porosity and reduces mechanical strength. Studies report that these effects can be minimized using superplasticizers and by treating the rubber surface [2, 11].

Expanded clay and vermiculite reduce the self-weight of cementitious matrices. Studies show that to minimize the loss of mechanical strength of composites, pre-saturation of these lightweight aggregates at the time of production is suggested [12, 13]. There is also an increase in the void ratio and an improvement in the acoustic and thermal performance of the composite when using expanded clay and vermiculite [8, 14, 15]. Recent studies show that, in cementitious composites with rubber, expanded clay, or vermiculite, the absorption of the impact energy is influenced both by the porosity of the cementitious matrix and by the transition zone between aggregates and the paste matrix [9, 8, 16, 17]. Within this context, this research evaluates properties in the fresh and hardened states of mortars containing rubber residues, expanded clay, and vermiculite.

EXPERIMENTAL

Materials: the reference mix proportion studied was 1:2.48:0.60 (by mass). The materials used were CPV-ARI, a high initial strength cement, natural sand of quartz origin, and potable water. Natural sand was replaced by a mixture of rubber residue without surface treatment (the rubber residue was obtained through the tire retreading process, using the material that passed through a 1.2 mm sieve and retained in a 0.6 mm sieve, used in levels of 25-35%) with expanded vermiculite (hydrated silicate containing predominantly iron, magnesium, potassium, and aluminum, used in a level of 30%), or expanded clay (lightweight aggregate composed of silica, alumina, and compounds containing iron, magnesium, potassium, and lower levels of other minerals, used in a level of 30%). For the mixes with expanded vermiculite, it was necessary to incorporate a superplasticizer (S.P.) additive, based on polycarboxylate polymer. Regarding expanded clay, before it was placed in the mixer, it was saturated in water for 24 h, as clay is porous and absorbs water [3]. The physical characteristics of the materials used in this study are presented in Table I and the particle size distributions in Fig. 1. The fineness modulus and maximum size results for sand, rubber, and expanded clay were obtained using particle size analysis tests [18]. For vermiculite, the test followed the specifications of the ABNT NBR 11355 standard [19]. The

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sand density results were obtained by means of a test in accordance with ABNT NBR 16916 [20]. The vermiculite density was determined with an adapted method based on the ABNT NBR 16605 [21]. The proportions of the mixes developed are shown in Table II.

Mixing and molding: to obtain a homogeneous mixture, a mixer with a capacity of 18 L and two sets of speeds (low speed, 140 rpm, and high speed, 285 rpm) was used. To homogenize the mixtures, the dry materials were first mixed manually in a bowl. After homogenizing the dry materials, the mixer was turned on at a low speed, around 70% of the total water was incorporated (at this point the expanded clay was incorporated), and then a mixing time of 4 min was recorded. In the mixtures that used an additive, it was incorporated and then 30% of the water was added, and another 4 min of mixing was recorded until the end of the mixing process [22]. Once the mortar was properly mixed, 60 prismatic test specimens measuring 40x40x160 mm were molded. The metal molds received a thin layer of mineral oil to facilitate later removal from the mold. The molds were filled in two layers, on a compacting table. After 24 h, the mortars were de-molded and submerged in water (20-25 ºC) in a humidity chamber until they reached the age required for the tests.

Table I - Physical characteristics of materials.

Material	Maximum size (mm)	Fineness modulus	Density (kg/dm^3)
Cement	-	-	3.10
Natural sand	2.40	2.30	2.66
Rubber*	2.44	3.83	1.16
Expanded vermiculite	4.80	4.05	0.45
Expanded clay	4.80	2.32	1.40
Superplasticizer	-	-	1.12

** rubber used passed a 1.2 mm sieve and retained in a 0.6 mm sieve.*

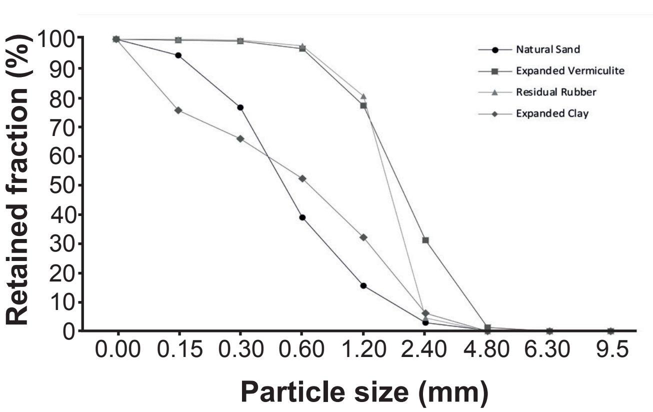

Figure 1: Granulometric curves of the aggregates used.

Testing methods: after the mixing process, in the fresh state of the mortars, a test was carried out to determine the consistency index [23], through a mortar spreading test using the consistency table. The diameter of the spread was measured using a caliper. At the curing ages of 7 and 28 days, destructive and non-destructive tests were performed. Six specimens of each mortar composition were molded for destructive tests and three for non-destructive tests. Compressive and flexural strengths were performed using an electromechanical press (Emic), with a load capacity of 600 kN, according to the specification of ABNT NBR 13279 [24]. In the flexural strength test, the prismatic specimens (40x40x160 mm) were placed on two supports, and a constant load was applied to the center of the specimen, at a rate of 50±10 N/s until rupture. The flexural strength of the 3-point bending test was calculated by:

$$R_f = \frac{1.5\ F_f.L}{40^3} \qquad \text{(A)}$$

where R_f is the flexural tensile strength (MPa), F_f is the load applied vertically at the center of the prism (N), and L is the distance between supports (mm). The compressive strength test used halves of the ruptured specimens, with a loading rate of 500±50 N/s being applied to the specimen until rupture, calculated according to the specification of ABNT NBR 13279 [24] by:

$$R_c = \frac{F_c}{1600} \qquad \text{(B)}$$

where R_c is the compressive strength (MPa), F_c is the maximum applied load (N), and 1600 is the section area of the test piece considered square (40x40 mm). The specific gravity (ρ_{max}) was obtained by weighing (m) and measuring the width (l), height (h), and length (c) of the specimen and calculated according to the specification of ABNT NBR 13280 [25] by:

Table II - Mix proportions of the mortars (kg/m^3) and a fresh state property (consistency).

Mix	Cement	Water	S.P.	Natural sand	Residual rubber	Expanded vermiculite	Expanded clay	Consistency (mm)
M-0R-0EV-0EC	539	323.4	0	1336.72	0	0	0	320.0
M-25R-30EV-0EC	539	323.4	2.69	601.52	145.73	67.84	0	237.0
M-35R-30EV-0EC	539	323.4	2.69	467.85	204.02	67.84	0	212.0
M-25R-0EV-30EC	539	323.4	0	601.52	145.73	0	211.06	329.0
M-35R-0EV-30EC	539	323.4	0	467.85	204.02	0	211.06	298.0

$$\rho_{max} = \frac{m}{l.h.c} 1000 \quad (C)$$

To obtain the capillarity index [26], the specimens were weighed after sanding one of the sides. The sanded face was placed in contact with water in a box for a period of 10 and 90 min. After each time, they were weighed again. The capillarity coefficient (C) is equal to the average value of the mass difference at 10 min (m_{10}) and 90 min (m_{90}), according to:

$$C = m_{90} - m_{10} \quad (D)$$

The propagation velocity of the ultrasonic wave [27] was obtained by an ultrasonic pulse emitter and receiver (US Lab, Agricef; power of 700 W, resolution of 0.1 μs) coupled to each base of the cylindrical test piece, using longitudinal wave transducers at a frequency of 45 kHz. The ultrasonic wave velocity was obtained by:

$$V = \frac{d}{t} \quad (E)$$

where d is the height of the specimen (mm) and t is the time (s) the ultrasonic wave travel the distance d. The test carried out to determine the dynamic modulus of elasticity and damping used the method of natural vibration frequencies. For this, the test was carried out using the impulse excitation technique, which equipment (Sonelastic) had a sensor capable of capturing the acoustic response of the test piece when subjected to a short-term mechanical impact. Using computational software, it was possible to identify the natural frequency of the fundamental flexural vibration of the specimen, thus allowing the calculation of the dynamic modulus of elasticity and the damping factor [28-31]. To better understand the properties, the microstructure of the mortars was analyzed using a scanning electron microscope (SEM, VEGA3, Tescan). The mortar samples tested were metalized with two layers of gold to improve their electronic conduction. The SEM was configured with a 10 kV energy beam, a 500 pA current, and a working distance of 10 mm.

RESULTS AND DISCUSSION

Properties of mortars in fresh and hardened states: for the characterization of fresh mortars, the consistency index was evaluated, which results are shown in Table II. It was observed that when expanded vermiculite was incorporated into the mortars, these presented a reduction in the consistency of 26% to 34% for the M-25R-30EV-0EC and M-35R-30EV-0EC mortars, respectively, even when using superplasticizer. However, the increase in consistency in composites with vermiculite [32, 33] and expanded clay [3] is also reported by other researchers. The loss of consistency of the mixtures is also attributed to the use of rubber, a similar fact reported in other studies [34, 35].

The density and capillarity coefficient results of the laying and coating mortars are presented in Table III. The density results allowed us to observe that, according to the increasing rubber content, in the mixes with expanded vermiculite, the decreases in specific mass were 26% and 32%. In mixtures with expanded clay, the decreases were 35% and 38%. Similar reports are found elsewhere [3, 36-38]. The capillary coefficient for the mixes with expanded clay showed higher values than the data for the mixes containing vermiculite. The rubberized mortars presented a reduction in the capillarity coefficient with the increase in the percentage of rubber residues when compared to the reference mix. This behavior was expected, since the insertion of rubber waste, despite promoting an increase in the number of voids present in the mixtures, has hydrophobicity as its main characteristic, which limits the percolation of water through the pores [15].

Table III - Density results and mortar capillary coefficients after 28 days.

Mix	Density (kg/m^3)	Capillary coefficient (g/dm^2.min$^{1/2}$)
M-0R-0EV-0EC	2147±38	3.9±0.1
M-25R-30EV-0EC	1603±28	1.4±0.4
M-35R-30EV-0EC	1477±29	1.2±0.2
M-25R-0EV-30EC	1399±23	3.2±0.4
M-35R-0EV-30EC	1348±25	2.0±0.2

Table IV shows a reduction in compressive strength with increasing rubber content, 75% and 78% for mixtures with expanded vermiculite, and 77% and 80% for mixtures with expanded clay. According to ABNT NBR 13281 standard [39] for compressive strength, all mixes were classified as P5 (value between 5.5 and 9.0 MPa) with the exception of the reference mix which was classified as P6 (value greater than 8.0 MPa). This was probably due to the lower rigidity of lightweight aggregates compared to natural sand. According to others [40, 41], this fact is associated with: a) lower density of light aggregates compared to natural sand; and b) increased porosity of the mixtures. Following the behavior found for the compressive strength results, the flexural strength also showed a reduction of 57% to 46% for mortars containing expanded vermiculite and a reduction of 51% to 63% for mortars with expanded clay (Table IV). According to ABNT NBR 13281 [39] for flexural strength, all mixes were classified as R6 (value greater than 3.5 MPa) with the exception of M-35R-0EV-30EC which was classified as R4 (value between 2.0 and 3.5 MPa). This fact was also associated with the higher void ratio provided by the incorporation of rubber waste into the mixtures [3, 14, 40, 41]. A reduction in the dynamic modulus of elasticity was also observed for mortars with increasing rubber contents, containing (Table IV): a) expanded vermiculite, in the range of 75% to 82% for the longitudinal modulus and 76% to 82% for the flexural mode; and b) expanded clay, a reduction from 69% to 77% for the longitudinal modulus and from 70% to 79% for the flexural mode. This behavior

Table IV - Results in compressive strength, flexural strength, and elastic dynamic modulus.

Mix	Compressive strength (MPa)		Flexural strength (MPa)		Elastic modulus (GPa)	
	7 days	28 days	7 days	28 days	Longitudinal 28 days	Flexural 28 days
M-0R-0EV-0EC	26.5±2.2	34.0±0.9	6.2±0.2	7.3±0.3	22.4±0.7	22.9±1.0
M-25R-30EV-0EC	6.9±0.7	8.6±0.4	1.9±0.7	3.1±0.1	5.6±0.3	5.6±0.3
M-35R-30EV-0EC	6.7±0.4	7.6±0.3	3.2±0.5	3.9±0.3	4.1±0.1	4.2±0.2
M-25R-0EV-30EC	5.2±0.9	7.9±1.1	2.4±0.4	3.6±0.3	6.9±0.2	6.8±0.2
M-35R-0EV-30EC	5.6±1.0	6.8±0.6	2.3±0.2	2.7±0.5	5.1±0.2	4.9±0.1

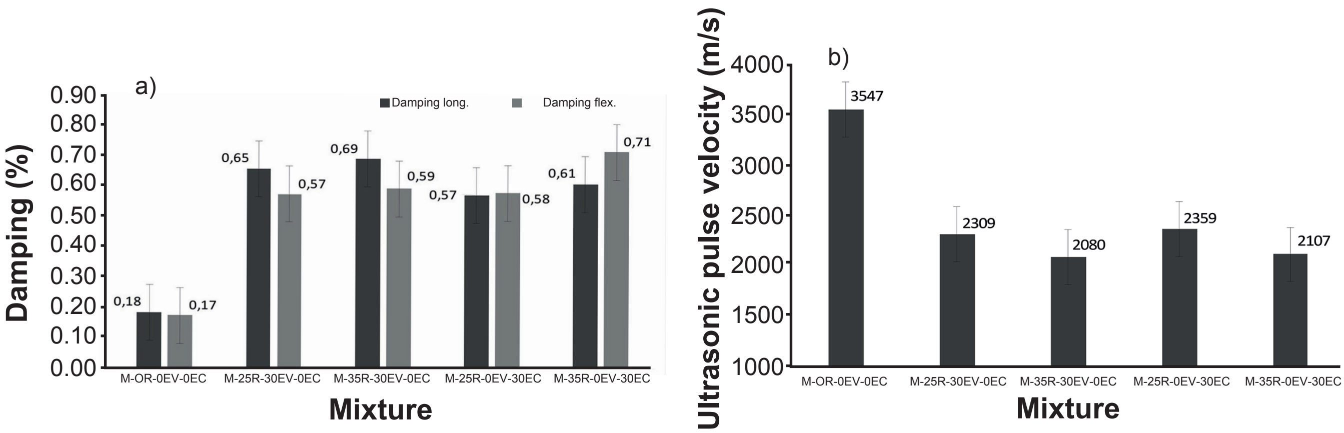

Figure 2: Results of damping factor (a) and ultrasonic pulse velocity (b), at the age of 28 days.

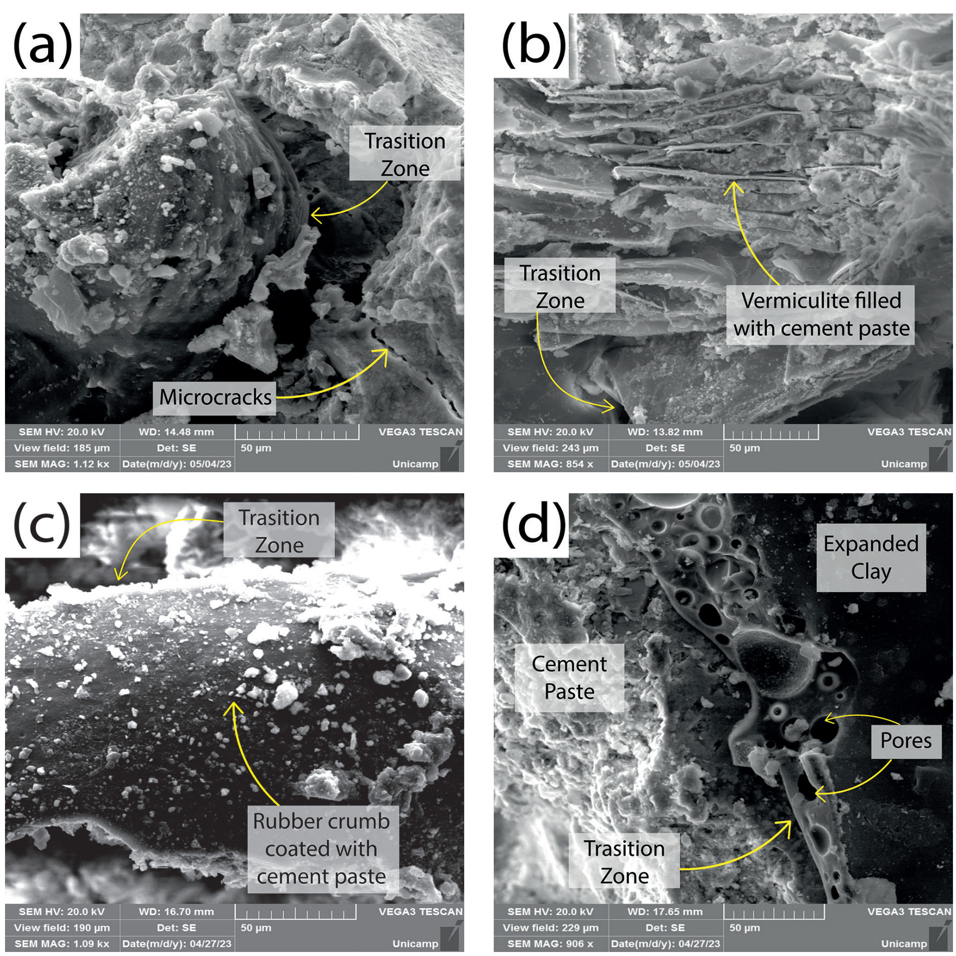

Figure 3: SEM micrographs of mortar samples: a) M25R-30EV-0EC; b) M35R-30EV-0EC; c) M25R-0EV-30EC; and d) M35R-0EV-30EC.

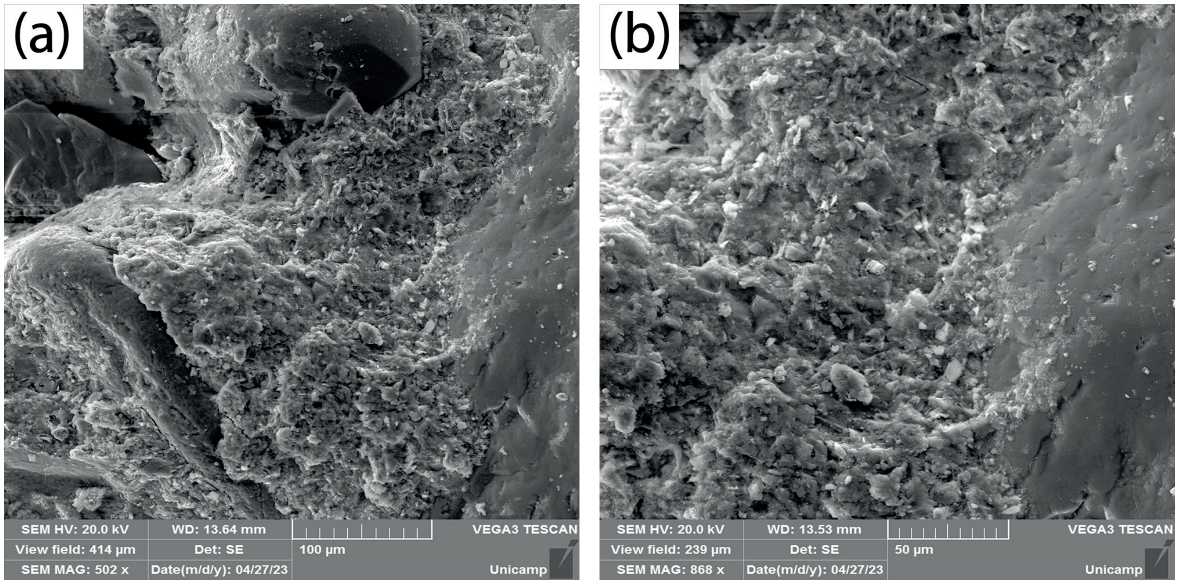

Figure 4: SEM micrographs of reference mortar sample M-0R-0EV-0EC at different magnifications.

was mainly due to the rubber residue, which weakened the cementitious matrix, which favored the appearance of cracks and stress accumulation, associated with the low modulus of elasticity of rubber, expanded vermiculite, and expanded clay [35, 36, 41].

Fig. 2a presents the damping factor results for the studied mortars. It was verified that the energy absorption capacity by the internal structure of mortars increased with increasing rubber content, whether associated with expanded vermiculite or expanded clay. For M-35R-30EV-0EC, the damping factor increased by 383% for longitudinal and 347% for flexural mode, and for M-35R-0EV-30EC the damping factor increased by 339% for longitudinal and 418% for flexural mode. These levels provide the material with better performance when subjected to dynamic loads. Similar behavior was reported by Moustafa and Elgawady [42] for the replacement of 30% of fine aggregate with rubber waste which resulted in a 30% increase in the damping factor. In Fig. 2b reductions of ultrasonic wave transmission velocity are observed for all mortars containing rubber compared to the reference mix of 35% and 41% for the mixes M-25R-30EV-0EC and M-35R-30EV-0EC, and 34% and 40% for the M-25R-0EV-30EC and M-35R-0EV-30EC mixes, respectively.

The images in Fig. 3 explain the results obtained in these tests showing the increase in pore content in mortars containing increasing levels of rubber, vermiculite, and clay compared to the reference mix. This trend was also observed by other researchers [37, 43-45]. In the M25R-30EV-0EC mix (Fig. 3a), there was an increase in the number of pores, microcracks, and points where the rubber was surrounded by products of cement hydration with a well-defined and highlighted transition zone of the cementitious paste [15]. For M35R-30EV-0EC (Fig. 3b), there was a structure with an increase in the transition zone between the paste solids. For the M25R-0EV-30EC (Fig. 3c), an evident transition zone between the rubber and the cementitious paste, the main characteristic of this residue [34], was observed. Fig. 3d for M35R-0EV-30EC highlights the presence of pores, the transition zone, and the glassy characteristics of the expanded clay wall [3]. Fig. 4 shows a dense and homogeneous structure for the M-0R-0EV-0EC mix, with no visible transition zones, corroborating the mechanical strength values found.

With the joint incorporation of rubber and clay and expanded vermiculite, an increase in pores and microcracks was noted, resulting in a less compact structure, with evidence of the transition zone, mainly due to the presence of rubber residue, which has a hydrophobic characteristic. This evidence explained: a) a reduction of mechanical properties for mixes with increasing rubber content; b) a decrease in wave propagation velocity, indicating a trend towards improved acoustic performance for mortars with rubber, vermiculite, and clay; and c) the influence of the microstructure on the damping factor of the material.

CONCLUSIONS

From the evaluation of the properties in the fresh and hardened state of the mortars produced, it can be concluded that, in its fresh state, the rubber residue was the component that most influenced the reduction of the consistency of the mixtures. In the hardened state, the decrease in density values and the increase in pore content significantly affected the mechanical properties of rubber mortars, both for those containing vermiculite and clay. For the mixes with increasing rubber content, the reduction of these properties was: a) for the vermiculite mix, there was a reduction of 75% to 78% for compressive strength, 57% to 46% for flexural strength, and 75% to 82% for dynamic modulus of elasticity; and b) for the clay mixture, a reduction of 77% to 80% was observed for compressive strength, 51% to 63%

for flexural strength, and 70% to 79% for dynamic modulus of elasticity. However, the increase in porosity in rubber mortars positively affected properties such as damping and acoustic performance of the material. Environmental and technical gains resulting from the use of rubber residues in mortars were verified, together with the decrease in their densities, showing that such mortars are a material option to be applied in construction elements that demand greater damping and good acoustic properties.

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REFERENCES

[1] A.P.S. Schiller, F.P. Pinz, M.N. Kurz, C.M. Paliga, A.S. Torres, Res. Soc. Dev. **11**, 13 (2022) e405111335668.
[2] P.C. de Assis Neto, L.P.B. Sales, P.K.S. Oliveira, I.C. da Silva, I.M.S. Barros, A.F. da Nóbrega, A.M.P. Carneiro, Buildings **13**, 3 (2023) 823.
[3] A. Becker, C.T. Ozaki e Silva, R.C.C. Lintz, L.A. Gachet, Mater. Today Proc. **65** (2022) 1222.
[4] A.F. Angelin, R.C.C. Lintz, W.R. Osório, L.A. Gachet, Constr. Build. Mater. **257** (2020) 119573.
[5] C.S.G. Penteado, B.L. Evangelista, G.C.S. Ferreira, P.H.A. Borges, R.C.C. Lintz, Amb. Const. **19** (2019) 21.
[6] G.S. Araujo, L.C. Iwamoto, R.C.C. Lintz, L.A. Gachet, ACI Mater. J. **118** (2021) 79.
[7] M. Karatas, A. Benli, H.A. Toprak, Constr. Build. Mater. **221** (2019) 163.
[8] A.E.M.S. Fontes, K.C. Cabral, W.R.M de Souza, A.E. Martinelli, K.E.S. Fontes, Amb. Const. **22** (2022) 299.
[9] M.H. Gazoni, "Concreto com agregado reciclado reforçado com fibras de aço: revisão da literatura e avaliação de modelos analíticos", M.Sc. dissert., Univ. Fed. São Carlos, S. Carlos (2022).
[10] H.L. Herscovici, D. Roehl, E.S. Sanchez Filho, Ibracon Struct. Mater. J. **12** (2019) 288.
[11] R.A. Assaggaf, M. Maslehuddin, S.U. Al-Dulaijan, M.A. Al-Osta, M.R. Ali, M. Shameem, Case Stud. Constr. Mater. **16** (2022) e00881
[12] K. Naveenkumar, P.A. Suriya, R. Divahar, S.P. Sangeetha, M. Jayakumar, Mater. Today Proc. **46** (2021) 5885.
[13] A.V. Rodrigues, S.R. Bragança, Cerâmica **69**, 389 (2023) 6.
[14] L.S. Batista, F.M. da Silva, L.A. Gachet, R.C.C. Lintz, ACI Mater. J. **119** (2022) 129.
[15] A. Gomes, R.C.C. Lintz, L.A. Gachet, in proc. 64° Congr. Bras. Cerâm., Ass. Bras. Cerâm., S. Paulo (2020).
[16] X. Cai, L. Zhang, W. Pan, W. Wang, Q. Guan, S. Zhai, L. Liu, Y. Zhang, Constr. Build. Mat. **331** (2022) 127.
[17] X. Mei, Q. Sheng, Z. Cui, M. Zhang, D. Dias, Soil Dyn. Earthq. **165** (2023) 107718.
[18] ABNT NBR NM 248, "Aggregates: sieves analysis of fine and coarse aggregates" (2003).
[19] ABNT NBR 11355, "Expanded vermiculite: particle size analysis, test method" (2015).
[20] ABNT NBR 16916, "Fine aggregate: determination of density and water absorption" (2021).
[21] ABNT NBR 16605, "Portland cement and other powdered materials: determination of the specific gravity" (2017).
[22] ABNT NBR 16541, "Mortars applied on walls and ceilings: preparation of mortar mixture for tests" (2016).
[23] ABNT NBR 13276, "Mortars applied on walls and ceilings: determination of the consistency index" (2016).
[24] ABNT NBR 13279, "Mortars applied on walls and ceilings: determination of the flexural and the compressive strength in the hardened stage" (2005).
[25] ABNT NBR 13280, "Mortars applied on walls and ceilings: determination of the specific gravity in the hardened stage" (2005).
[26] ABNT NBR 15259, "Mortars applied on walls and ceilings: determination of water absorption coefficient due to capillary action" (2005).
[27] ABNT NBR 15630, "Mortars applied on walls and ceilings: determination of elastic modulus by the ultrasonic wave propagation" (2009).
[28] ABNT NBR 8522-2, "Hardened concrete: determination of elastic and deformation modulus, part 2: dynamic modulus of elasticity by the method of natural frequencies of vibration" (2021).
[29] ASTM E1876, "Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration" (2015).
[30] ASTM C215, "Standard test method for fundamental transverse, longitudinal, and torsional resonant frequencies of concrete specimens" (2014).
[31] L.B. Otani, A.H.A. Pereira, "Technical-scientific information", ITC-07/ATCP (2017).
[32] K.H. Mo, H.J. Lee, M.Y.J. Liu, T.C. Ling, Constr. Build. Mater. **179** (2018) 302.
[33] J. Liu, Y. Zhuge, X. Ma, M. Liu, Y. Liu, X. Wu, H. Xu, Case Stud. Constr. Mat. **16** (2022) e01038.
[34] P.L. Mwyyappan, S.D.A. Selvasofia, M. Asmitha, S.J. Praveena, P. Simika. Mater. Today Proc. **74**, 4 (2023) 985.
[35] A. Habbib, U. Yuldirim, O. Eren, Constr. Build. Mater. **246** (2020) 118502.
[36] A.S. Sidhu, R. Siddique, Constr. Build. Mat. **345** (2022) 128412.
[37] H. Wang, Y. Wu, B. Cheng, Case Stud. Constr. Mater. **16** (2022) e00803.
[38] S. Dora, R.B. Barta, K.M. Mini, Constr. Build. Mater. **392** (2023) 131903.

[39] ABNT NBR 13281, "Mortars applied on walls and ceilings: requirements" (2005).
[40] R.A. Assaggaf, M.R. Ali, S.U. Al-Dulaijan, M. Maslehuddin, J. Mater. Res. Tech. **11** (2021) 1753.
[41] F. Ren, J. Mo, Q. Wang, J.C.M. Ho, Constr. Build. Mater. **343** (2022) 128049.
[42] A. Moustafa, M.A. Elgawady, Constr. Build. Mater. **93** (2015) 249.
[43] B.S. Mohammed, M. Adamu, M.S. Liew, Case Stud. Constr. Mater. **8** (2018) 380.
[44] Q. Ma, Z. Mao, M. Lei, J. Zhang, Z. Luo, S. Li, G. Du, Y. Li, Ceram. Int. **49**, 11A (2023) 16951.
[45] A. Kashani, T.D. Ngo, P. Mendis, J.R. Black, A. Hajimohammadi, J. Clean. Prod. **149** (2017) 925.
(Rec. 26/06/2023, Rev. 20/09/2023, Ac. 20/10/2023)