CEMENTITIOUS MATRICES WITH LIGHT AGGREGATE BASED ON POLYESTER WASTE AND LAMINATED PVC EXTRUDED WITH POLYSTYRENE

USO DE AGREGADO LEVE À BASE DE RESÍDUOS DE POLIÉSTER E LAMINADO DE PVC EXTRUSADOS COM POLIESTIRENO EM MATRIZES CIMENTÍCIAS

USO DE AGREGADO LIGERO A BASE DE RESIDUOS DE POLIÉSTER Y LAMINADO DE PVC EXTRUSADOS CON POLIESTIRENO EN MATRICES CEMENTICIAS

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ABSTRACT
Waste generation from diverse sectors of the economy has given rise to studies related to consumption and disposal of several associated products. The traditional shoe making sector in the state of Rio Grande do Sul (Brazil) is no exception and has a need to implement sustainable actions for the re-use of raw material waste. The objective of this study was to develop a light aggregate based on polyester waste and laminated PVC extruded with recycled polystyrene for use in cementitious matrices. A reference mortar was prepared with a mix ratio of 1:3 (cement: quartz sand) and water/cement ratio (w/c) of 0.48. Additionally, 4 mortars were prepared with light aggregate replacement contents of 25 %, 50 %, 75 % and 100 % in volume with respect to quartz sand. Properties evaluated were consistency in the fresh state and compressive strength, density, water absorption and porosity in the hardened state. It was determined that consistency decreased as light aggregate substitution content increased. Similarly, decreases in compressive strength and density were noted with increasing light aggregate substitution content. On the other hand, water absorption, porosity and void index increased in conjunction with the decrease in density as substitution content increased.

KEYWORDS
Shoe making industry; waste; light aggregate

RESUMO
A geração de resíduos provenientes dos diversos setores da economia tem gerado estudos e pesquisas relacionados ao consumo e descarte dos mais variados produtos. Neste contexto, inserem-se as indústrias do setor calçadista, tradicionais no Estado do Rio Grande do Sul (Brasil), as quais têm a necessidade de buscar ações sustentáveis no reaproveitamento das sobras de matérias-primas da produção de calçados. Este trabalho teve como objetivo produzir um agregado leve à base de resíduos de poliéster e laminado de PVC extrusados com poliestireno reciclado e utilizá-lo em matrizes cimentícias. Foram preparadas argamassas referência com traço, em massa, de 1:3 (cimento: areia quartzosa) e relação água/cimento (a/c) de 0,48. Outras quatro argamassas foram preparadas com teores de substituição da areia quartzosa, em volume, pelo agregado leve, em 25%, 50%, 75% e 100%. No estado fresco, foi determinado o índice de consistência das argamassas. No

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estado endurecido, as amostras foram submetidas a ensaios de resistência à compressão, densidade, absorção de água e porosidade. A consistência das argamassas reduziu com o aumento do percentual do agregado leve nas argamassas. Da mesma forma, o aumento do percentual do agregado leve conduziu a uma diminuição da resistência à compressão e da massa específica das amostras. Por outro lado, o aumento do percentual do agregado leve conduziu a aumentos da absorção de água, da porosidade e do índice de vazios, indicando que a densidade da argamassa diminuiu com o aumento da substituição de areia quartzosa pelo agregado leve.

PALAVRAS-CHAVE
Indústria calçadista; resíduo; agregado leve

RESUMEN
La generación de residuos provenientes de diversos sectores de la economía ha impulsado estudios e investigaciones relacionados con el consumo y la eliminación de una amplia variedad de productos. En este contexto, se encuentran las industrias del sector del calzado, tradicionales en el estado de Rio Grande do Sul (Brasil), las cuales enfrentan la necesidad de implementar acciones sostenibles para reutilizar los desechos de materias primas provenientes de la producción de calzado. Este trabajo tuvo como objetivo producir un agregado ligero a base de residuos de poliéster y lámina de PVC extruidos con poliestireno reciclado y utilizarlo en matrices cementicias. Se prepararon morteros de referencia con una proporción, en masa, de 1:3 (cemento: arena cuarzosa) y una relación agua/cemento (a/c) de 0,48. Además, se elaboraron otros cuatro morteros con diferentes niveles de sustitución de la arena cuarzosa, en volumen, por el agregado ligero, en proporciones de 25%, 50%, 75% y 100%. En estado fresco, se determinó el índice de consistencia de los morteros. En estado endurecido, las muestras fueron sometidas a ensayos de resistencia a la compresión, densidad, absorción de agua y porosidad. Los resultados mostraron que la consistencia de los morteros disminuyó a medida que aumentó el porcentaje de agregado ligero. De manera similar, el incremento del agregado ligero condujo a una reducción de la resistencia a la compresión y de la densidad de las muestras. Por otro lado, el aumento en el porcentaje de agregado ligero provocó un incremento en la absorción de agua, la porosidad y el índice de vacíos, lo que indica que la densidad del mortero disminuyó con el incremento de la sustitución de la arena cuarzosa por el agregado ligero.

PALABRAS CLAVE
Industria del calzado; residuo; agregado ligero

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1. INTRODUCTION

Waste generated by diverse sectors of the economy has given rise to studies related to the consumption and disposal of several associated products. The traditional shoe making sector in the state of Rio Grande do Sul (Brazil) is no exception and has a need to implement sustainable actions for the re-use of raw material waste.

The environmental impact of economic activity occurs from the generated amount of polluting waste and limited re-use of excess raw materials during both manufacture and post-use. These materials tend to be disposed in sanitary or industrial landfills (Alves and Barbosa, 2013; Soares and Araújo, 2016; Albanio and Tatsch, 2016) and present a contamination risk to soil and groundwater (FLACH *et al.*, 2017). Trein (2015) also noted another environmental problem in industrial centers: often waste incineration is not a recommended option due to the release of toxic gases so excess waste has to be disposed in sanitary landfills.

According to Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE), only 4 % of waste is recycled in Brazil (ABRELPE, 2020). Studies have determined that recyclable wastes were mostly plastic (16.8 % amounting to 13.8 million t/year), paper and cardboard (10.4 % amounting to 8.57 million t/year), glass (2.7 %), metals (2.3 %) and multilayered packaging (1.4 %). The remaining 5.6 % comprised textile, leather and rubberized recyclable waste (ABRELPE, 2020; AGÊNCIA BRASIL, 2022).

According to the 2019 yearly activity report from Associação Brasileira das Indústrias de Calçados (ABICALÇADOS, 2019), there were over 6 thousand shoe making businesses in Brazil. The shoe making sector represented 4 % of gross national product (GNP) with gross revenue of R$21 billion in 2018 for a production of 944 million pairs of shoes. This placed Brazil as the 4th largest shoe maker in the world and Rio Grande do Sul as the 2nd major shoe making state in the country accounting for 20.1 % of the total in 2018. Within Rio Grande do Sul, the Vale do Rio dos Sinos region produced 78.6 million pairs of shoes in 2022 (ABICALÇADOS, 2022). Soares and Araújo (2016) noted that the most common solid waste from shoe making production originated in the steps of cutting, assembly and finishing for a total of approximately 300 t/day.

In parallel, the construction sector has several initiatives related to the management of plastic waste, with re-use being considered the ideal disposal method (ALMESHAN *et al.*, 2020). Hita *et al.* (2018) considered plastic recycling equivalent to a product life cycle extension and adding environmental worth to its use.

The objective of many sustainability studies in civil construction has been the development of alternative materials with lower environmental impact. These were produced from recycled solid waste and used as total or partial replacement of conventional materials. One such material is recycled polymer used in substitution to aggregates in cementitious matrices (Saikia and Brito, 2012; Trein, 2015; Gu and Ozbakkaloglu, 2016; Babafemi *et al.*, 2018; Badache *et al.*, 2018; Bahij *et al.*, 2020). However, the variety of recycling processes affected the characteristics of these substitute aggregates and induced subsequent changes to the properties of cementitious matrices both in the fresh and hardened state.

Schneider *et al.* (2021) evaluated mortars with sand partially replaced with aggregate produced from the non-metallic portion of PCI boards. Results showed decreases in flow table and compressive strength as replacement content increased. Silveira *et al.* (2022) partially replaced quartz sand with wet blue leather waste encapsulated in recycled polypropylene (PP). Results showed a decrease in compressive strength as substitution content increased, peaking at a 93 % decrease in strength with 100 % substitution at 28 days. Similarly, Lansing (2018) tested light extruded PP aggregate recycled from textile waste and observed a decrease in strength and specific mass as well as an increase in porosity and water absorption with increasing substitution content.

On the other hand, Tutikian *et al.* (2017) replaced sand with light aggregate from ethylene-vinyl acetate (EVA) copolymer waste in substitution contents of 20 %, 40 %, 60 %, 80 % and 100 % in floor mortar beds. Results showed good improvement in sound insulation for all substitution ratios. Similarly, Trein (2015) evaluated the re-use of EVA waste and polyurethane-covered (PU) textile waste as light aggregate in alkali-activated mortars. Chart 01 presents a summary of reference studies that made use of polymer light aggregates and their results.

Results of **Chart 1** denoted that, regardless of the light aggregate used, increased substitution content produced a decrease in cementitious matrix mechanical properties and loss of workability. However, some advantages gained were lower density and increased thermal-acoustic insulation. Thus, the focus of this study was the use of shoe making industry waste as light aggregate. The shoe making process involved several steps that generated several types of wastes which have not been fully considered as substitution material despite being technically and environmentally viable. The light aggregates used in this study were from polyester and laminated PVC extruded with recycled polystyrene. Resulting cementitious matrices properties were evaluated both in the fresh and hardened states for future feasible applications in civil construction projects.

REF.	TITLE.	LIGHT AGGREGATE FROM WASTE (LAW)	SAND SUBST. CONTENT	MAIN RESULTS
TREIN, 2015	Effect of using shoe making industry waste in alkali-activated mortars	EVA and polyurethane-covered (PU) textile waste	10 %, 20 %, 30 % and 40 % by volume	Compressive strength above 1.5 MPa for 40 % LAW content at 28 days. Water absorption and porosity increased as LAW content increased.
KROEFF, 2016	Evaluation of shoe making industry waste use in Portland cement-based cementitious matrices	EVA and polyurethane-covered (PU) textile waste	25 % and 50 % by volume	50 % LAW content deemed ideal for a minimum strength of 1.5 MPa.
TUTIKIAN *et al.*, 2017	Use of light aggregate from recycled shoe making industry waste in mortar bed for sound proofing in residential buildings	Shoe making industry EVA waste	20 %, 40 %, 60 %, 80 % and 100 % by volume	Decrease in compressive and flexural tensile strengths as LAW replacement content increased. But all LAW content mortars had positive increases in sound proofing.
LANSING, 2018	Evaluation of light aggregates from recycled shoe making industry waste incorporated in cementitious matrix	Extruded textile waste (polyester and cotton) with polypropylene (PP)	25 %, 50 % and 75 % by volume	Decrease in compressive strength and specific mass as LAW substitution content increased. Increase in porosity and water absorption as LAW substitution content increased.
BADACHE *et al.*, 2018	Thermo-physical and mechanical characteristics of sand-based lightweight composite mortars with recycled high-density polyethylene (HDPE)	Plastic waste from HDPE tubes	15 %, 30 % 45 % and 60 % by volume	Composite mortars had lower mechanical performance than reference mortar. A 60 % LAW substitution content decreased compressive strength by 38 % with respect to reference mortar.
SILVEIRA *et al.*, 2022	Light aggregate produced from recycled shoe making industry waste for use as partial replacement of river quartz sand in cementitious matrix	Wet-blue leather waste encapsulated in recycled polypropylene (PP)	25 %, 50 %, 75 % and 100 % by volume	Decrease in compressive strength as LAW substitution content increased. Decrease of 93 % in compressive strength for 100 % replacement content at 28 days.

Chart 01: Summary of reference studies on the use of polymer light aggregate in cementitious matrices.
LAW: light aggregate from waste.
Source: Authors.

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2. MATERIALS AND METHODOLOGY

The binder used in this study was CPV ARI – RS, a sulfate-resistant, high initial strength Portland cement equivalent to type III Portland cement (ASTM C150, 2021). The chemical oxide composition of CPV ARI – RS is shown in Table 01. The main oxides contained in CPV ARI – RS were CaO (67.97 wt.%) and SiO_2 (15.54 wt.%).

Sand used in the cementitious matrices was natural quartz sand from the Vacacaí river in the state of Rio Grande do Sul, Brazil. Sand was dried in an oven at 105 ºC ± 5 ºC for 24 h and sifted with standardized sieves recommended by standard NBR 17054 (ABNT, 2022). After this preparation, sand was separated into parts matching the granulomety of light aggregate shown in **Table 01**. This sand preparation methodology was applied to minimize the effects of distinct granulometries of sand and light aggregate in the cementitious matrices.

Oxide	wt. %
MgO	1.51
Al2O3	3.73
SiO2	15.54
SO3	3.33
Cl	0.07
K2O	1.16
CaO	67.97
TiO2	0.26
V2O5	0.01
MnO	0.04
Fe2O3	2.77
SrO	0.26
ZrO2	0.01
BaO	0.02

Table 01: Chemical oxide composition of Portland cement CP V ARI - RS determined from X-ray fluorescence (XRF) (in wt.%). L.O.I (Loss on ignition) determined as 3.30 wt.%.
Source: Authors.

Quartz sand density was 2.62 g/cm³ and water absorption was 0.87 % as determined from the procedures of standard NBR 16916 (ABNT, 2021). Hardness in the 0 to 100 Shore D scale was determined as 92.11 in 10 s from the procedures of standard ASTM D2240 (ASTM, 2021) averaged over 9 pressure points. It should be noted that the Shore D methodology of ASTM D2240 (ASTM, 2021) was to determine the hardness of thermoplastics and hard rubbers. Despite not being recommended for ceramic materials, it was used nonetheless in order to offer a direct comparison to the light aggregate.

2.1 Production of light aggregate from polyester and laminated PVC extruded with polystyrene waste.

Light aggregate was produced from polyester and laminated PVC waste. Both wastes were extruded with recycled polystyrene (PS). Polyester and laminated PVC waste were collected from a shoe and hand bag maker located in the state of Rio Grande do Sul, Brazil. Both wastes were generated from cutting processes in the manufacture of these products. Polystyrene used for the extrusion process were sourced from plastic cups and wastes from an injection mold business, namely soles, wedge clogs, insoles and heels. The latter were 50 wt.% polystyrene.

Light aggregate was produced with 20 % shredded polyester and laminated PVC waste and 80 % recycled polystyrene by mass. These proportions were based on Lansing (2018) in order to obtain an aggregate with non-fibrous texture since excessive fiber content would require more water and cause deleterious effects on the mechanical properties of the matrices.

Light aggregate material was homogenized in a mixer and fed to a SEIBT model 25 extruder with 4 kg/h capacity at 22 m/min and 4 heating exit levels (140 ºC, 155 ºC, 170 ºC and 180 ºC). The mixed material was extruded layered at a speed related to mixture homogeneity based on previous studies (Trein, 2015; Kroeff, 2016; Lansing, 2018; Silveira *et al.*, 2022).

Extruded material was cooled by passing through a 4 m long tub with water and compressed air kept at 10 ºC, fed to a granulator machine with a 6 mm sieve and collected in a metal bin with maximum carrying capacity of 500 kg. Granules were aspirated into a USIFER tower dryer model ES 100 with a processing capacity of 100 kg/h. Drying was conducted at 60 °C for 10 min.

Finer granulometries were obtained with a micronizer machine with sieves ranging from 2 mm to 4 mm as in reference studies (Lansing, 2018; Silveira *et al.*, 2022). The final light aggregate contained 75 % of passing material from the 6 mm granulator sieve (**Figure 01a**) and 25 % of passing material from the 2 mm micronizer sieve (**Figure 01b**).

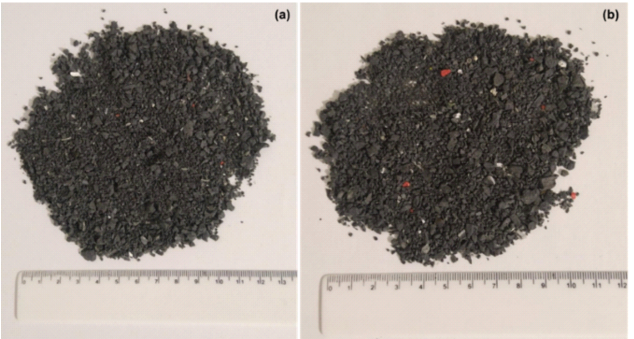

Figure 01: Materials of the light aggregate of this study: (a) granules produced by the granulator; (b) granules produced by the micronizer.
Source: Authors.

Table 02 presents the granulometry of the light aggregate of this study. Based on the composition and the criteria of standard NBR 17054 (ABNT, 2022), the fineness modulus of the light aggregate was determined as 4.18.

Sieve size (Normal series, in mm)	% retained	accumulated % retained
2.36	36	36
1.18	51	88
0.60	8	96
0.30	3	98
0.15	1	100
< 0.15	0	100

Table 02: Granulometry of light aggregate used in this study processed with granulator and micronizer.
Source: Authors.

Besides granulometry, light aggregate real density was determined as 0.87 g/cm³ and water absorption as 5.08 % with procedures of standard NBR 16916 (2021). The procedure used to determine water absorption was adjusted to a drying temperature of 70 ºC instead of 105 ºC. This was needed to avoid softening of the thermoplastic in the aggregate. Hardness in the 0 to 100 scale Shore D was determined as 54.22 Shore D with 10 s over 9 pressure points as per standard ASTM D2240 (ASTM, 2021).

2.2 Mixing and preparation of cementitious matrices

The reference matrix (M0) contained 0 % light aggregate content and was prepared with a mix ratio of 1:3 (cement: sand) and a water/cement (w/c) ratio of 0.48 based on standard NBR 7215 (ABNT, 2019). In order to keep most factors constant, only sand substitution content by volume was considered while mix ratio and w/c ratio were kept the same for all matrices. The substitution matrices and their respective substitution contents were: M25 (25 %), M50 (50 %), M75 (75 %) and M100 (100 %) by volume. Considering that the densities of quartz sand and light aggregate were 2.62 g/cm³ and 0.87 g/cm³, respectively, the mass of light aggregate for each matrix was determined from equation (1):

$$M_{ag} = \frac{M_{sand}}{\gamma_{sand}} \times (\%\ substitution\ content) \times \gamma_{ag} \qquad (1)$$

Where:
M_{ag} = mass of light aggregate;
M_{sand} = mass of quartz sand;
= density of quartz sand;
= density of light aggregate.

Standard NBR 7215 (ABNT, 2019) prescribed standardized sand with 4 granulometries to be used, each corresponding to a proportion of 25 %. For this study, this standard was adapted to use sand with 6 granulometries (2.36 mm; 1.18 mm; 0.6 mm; 0.3 mm; 0.15 mm and < 0.15 mm) in the same proportions found for the light aggregate so that both would match. A visual comparison of the granulometries of both aggregates is shown in **Figure 02**.

Matrix preparation started with cement and water being homogenized in an EMIC model AG-5 mechanical mixer with 5 L capacity for 1 min at high speed. Aggregates (quartz sand and light aggregate) were added and further mixed for 1 min at low speed. The axle was scraped to remove any adhered material and the matrix further mixed for 3 min at high speed. Mixing times were adapted from previous studies (KROEFF, 2016; LANSING, 2018 and SILVEIRA *et al.*, 2022).

Mortars were poured in prismatic cubic molds measuring 50 mm x 50 mm x 50 mm in 2 layers. Each layer was consolidated by applying 30 impacts over 30 s with a flow table apparatus in a similar fashion as the flow table test of standard NBR 13276 (ABNT, 2016). After consolidation of the second layer, the mortar top surface was smoothed out. Samples were covered with a plastic film and allowed to rest for 48 h prior to demolding. Demolded samples, shown in **Figure 03**, were stored in a saturated solution of calcium hydroxide in accordance with standard NBR 5738 (ABNT, 2015) until evaluated for compressive strength, density, water absorption and porosity.

Table 03 presents the materials and composition of the cementitious matrices of this study, namely M0, M25, M50, M75 and M100.

Figures 02 and **03** are shown respectively in the next page.

Cementitious matrix	% LAW	Cement	Sievesize (Normal series, inmm)	Quartz sand	LAW	Water (mL)	w/c ratio	Cement consumption (kg/m³)
		Mass (g)		Mass (g)	Mass (g)			
M0	0	500	2.36	545.70	0.00	240	0.48	510.63
			1.18	770.25	0.00			
			0.6	121.20	0.00			
			0.3	39.00	0.00			
			0.15	18.00	0.00			
			<0.15	5.85	0.00			
M25	25	500	2.36	409.28	45.30	240	0.48	510.63
			1.18	577.69	63.94			
			0.6	90.90	10.06			
			0.3	29.25	3.24			
			0.15	13.50	1.49			
			<0.15	4.39	0.49			
M50	50	500	2.36	272.85	90.60	240	0.48	510.63
			1.18	385.13	127.89			
			0.6	60.60	20.12			
			0.3	19.50	6.48			
			0.15	9.00	2.99			
			<0.15	2.93	0.97			
M75	75	500	2.36	136.43	135.90	240	0.48	510.63
			1.18	192.56	191.83			
			0.6	30.30	30.18			
			0.3	9.75	9.71			
			0.15	4.50	4.48			
			<0.15	1.46	1.46			
M100	100	500	2.36	0.00	181.90	240	0.48	510.63
			1.18	0.00	256.75			
			0.6	0.00	40.40			
			0.3	0.00	13.00			
			0.15	0.00	6.00			
			<0.15	0.00	1.95			

Table 03: Materials and composition of cementitious matrices containing distinct light aggregate substitution contents.
LAW: light aggregate from waste.
Source: Authors.

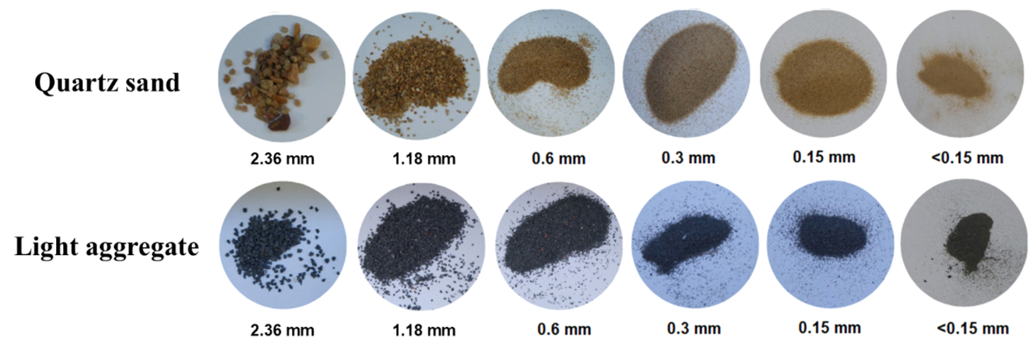

Figure 02: Visual granulometric comparison between quartz sand and light aggregate.
Source: Authors.

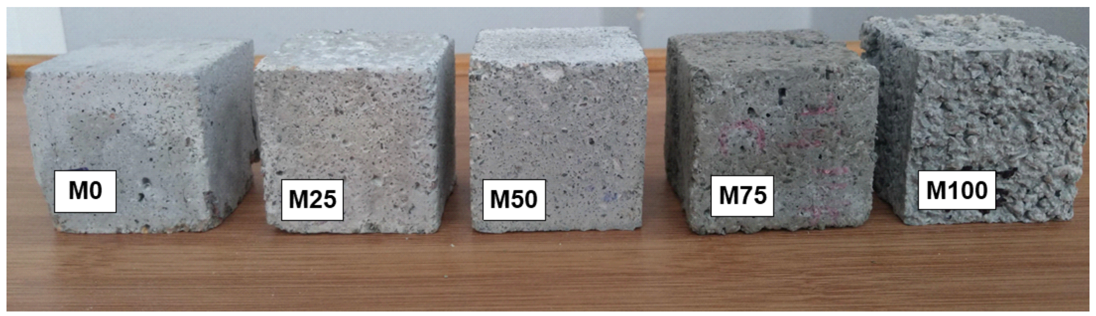

Figure 03: Cubic samples (50 mm x50 mm x50 mm) of each cementitious matrix tested.
Source: Authors.

2.3 Cementitious matrix consistency analysis

Workability of all mortars was evaluated with a flow table test in accordance with the procedures of standard NBR 13276 (ABNT, 2016). The truncated conic mold was filled with 3 layers of mortar of approximately same height. The first, second and third layers were tamped 15 times, 10 times and 5 times with a tamping rod, respectively, for consolidation. The mold was lifted vertically and the table raised and dropped freely 30 times in 30 s in accordance to the procedures of standard NBR 13276 (ABNT, 2016). The consistency index was then calculated as the average of 3 measured diameters.

2.4 Mechanical characteristics

Axial compressive strength was evaluated at 7 days and 28 days of age. Testing was conducted with an Instrom universal testing machine, model1500 HDX at Laboratório de Materiais de Construção Civil (LMCC-UFSM). Testing was conducted with a load of 1 kN/s and, at each age, 4 test bodies were used for each matrix.

2.5 Physical characteristics

Water absorption, void index and real density of all mortars were evaluated af 28 days with equations (2), (3) and (4) based on the procedures of standard NBR 9778 (ABNT, 2009):

Water absorption (%):

$$Ab = \frac{m_{sat} - m_s}{m_s} \times 100 \quad (2)$$

Void index (%):

$$Vi = \frac{m_{sat} - m_s}{m_{sat} - m_i} \times 100 \quad (3)$$

Real density (g/cm³):

$$\rho_r = \frac{m_s}{m_s - m_i} \times 100 \quad (4)$$

where:
msat: mass of water-saturated sample after immersion and boiling;
ms: mass sample dried in an oven at (105 ± 5) ºC;
mi: mass of saturated sample immersed in water after boiling.

3. RESULTS AND DISCUSSION

Consistency index and compressive strength results are presented in **Table 04**. The M0 reference matrix, with no substitution, yielded a higher consistency index than all other matrices with light aggregate content. These results were attributed to higher absorption and angular shape of the light aggregate when compared to quartz sand. The effects of these characteristics were noted in several studies that made use of polymer-based materials in cementitious matrices. For example, Lansing (2018) observed that light aggregate from polyester and cotton waste extruded with polypropylene had a negative effect in the workability of cements. Silveira (2020) also observed decreased workability attributed to the hygroscopic characteristics of the light aggregate over quartz sand. Finally, Hartmann (2019) noted that the laminated shape of light aggregate grains produced greater interlocking between them.

Cementitious matrix	% LAW	Average consistency index (mm)	Average compressive strength and standard deviation (MPa)	
			7 days	28 days
M0	0	254	36.04 ± 2.34	43.35 ± 1.63
M25	25	221	17.10 ± 2.72	20.89 ± 1.69
M50	50	184	11.32 ± 0.52	14.14 ± 0.49
M75	75	169	8.03 ± 0.62	8.82 ± 0.31
M100	100	156	6.29 ± 0.36	6.03 ± 0.14

Table 04: Average consistency index and compressive strength of cementitious matrices of this study with different light aggregate substitution content.
Source: Authors.

On the other hand, Zhang *et al.* (2021) observed substantial increases in the workability of a cementitious matrix with added polymers due to greater water retention and entrained air. Aattache, Soltani and Mahi (2017) noted that mortars with polymer content tended to be more porous, requiring more mixing water to maintain workability and, consequently, changed the characteristics of the mixture. Average compressive strength results of matrices with respect to light aggregate substitution content are also shown in the graph of **Figure 04** alongside standard deviation bars. Strength at 7 days varied between 36.04 MPa (M0) and 6.29 MPa (M100) while at 28 days varied between 43.35 MPa (M0) and 6.03 MPa (M100).

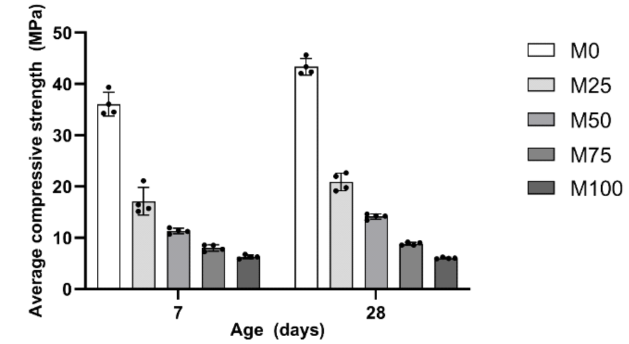

Figure 04: Average compressive strength and standard deviation bars for cementitious matrices with different light aggregate substitution content.
Source: Authors.

A statistical ANOVA (analysis of variance) was conducted to determine the effect of light aggregate substitution content (0 % 25 %, 50 %, 75 % and 100 %) and age (7 days and 28 days) on the compressive strength of the cementitious matrices. The ANOVA had a double factor for compressive strength due to the substitution contents with a 95 % confidence level. Data were evaluated for normality with a Shapiro-Wilk test and found to follow a normal distribution (∝< 0.05). The subsequent ANOVA and its results are shown in **Table 05**.

ANOVA results indicated significant statistical difference between all 3 factors: age, substitution content and age x substitution content. Therefore, a post hoc Tukey test was conducted to identify factors with significant differences and the results are shown in **Table 06**.

Comparing the results of **Table 06**, non-significant differences in compressive strength were observed between contents of 50 %, 75 % at 7 days and 75 % and 100 % at both 7 days and 28 days. Similar results were obtained in other reference studies. Lansing (2018) did not identify significant differences in compressive strength for cementitious matrices with 50 % and 75 % light aggregate content in all ages of the study (7 days, 28 days, 63 days and 91 days). Similarly, Silveira (2020) obtained no significant differences between the ages of 7 days and 28 days for matrices with light aggregate substitution contents of 25 %, 50 %, 75 % and 100 %.

	SUM OF SQUARES	DEGREES OF FREEDOM	AVERAGE OF SQUARES	CRITICAL F	CALCULATED p-VALUE
AGE	83.45	1	83.45	F(1,30) = 42.82	P < 0.0001***
CONTENT	5827	4	1457	F(4,30) = 747.6	P < 0.0001***
AGE X CONTENT	69.33	4	17.33	F(4,30) = 8.893	P < 0.0001***
RESIDUAL	58.46	30	1.949		

Table 05: ANOVA (analysis of variance) of the effects of light aggregate content (0 % 25 %, 50 %, 75 % and 100 %) and age (7 days and 28 days) on the compressive strength of cementitious matrices.
Critical F = tabulated F value for p = 0.05
Calculated p-value = reference value
****** significant values***
Source: Authors.

Age (days)	LAW content comparision (%)									
	0 - 25	0 - 50	0 - 75	0 - 100	25 - 50	25 - 75	25 - 100	50 - 75	50 - 100	75 - 100
7	SD	SD	SD	SD	SD	SD	SD	ND	SD	ND
28	SD	SD	SD	SD	SD	SD	SD	SD	SD	ND

Table 06: Tukey test significance analysis of light aggregate content with respect to age for compressive strength of cementitious matrices.
Source: Authors.

Calixto *et al.* (2017) observed that axial compressive strength was not significantly affected when up to 15 % of sand was replaced with expanded polystyrene (EPS). However, substantial decreases in strength were noted for a substitution content of 40 %, attributed to the hydrophobic characteristic of EPS. Bahij *et al.* (2020) also observed decreases in strength of cementitious matrices incorporating polymer aggregates. This was attributed to a lack of adhesion between polymer aggregate and Portland cement paste, characteristic lower rigidity strength of polymer when compared to natural aggregates and increased entrained air content. Zhou and Brooks (2019) also pointed out that another factor contributing to the decrease in compressive strength was the lower density of substitute light aggregates when compared to conventional ones such as gravel and sand.

Overall, it could be concluded that higher light aggregate content led to decreases in compressive strength which affected other mechanical properties of the cementitious matrix. According to Záleská *et al.* (2018) and Bahij *et al.* (2020), the decrease in strength was related to factors such as lower density of light aggregate when compared to quartz sand and low adhesiveness between the surface of light aggregate and cement paste. Polymer-based light aggregates also presented a trend of decreased compressive strength with increasing replacement content. In the case of replacing sand with vermiculite (a light conventional mineral aggregate), Sinhorelli (2019) obtained decreases in mortar compressive strength between 56 % and 63 % for replacement contents between 60 % and 80 %. Similarly, results of this study also pointed to 52 % and 67 % decreases in compressive strength for matrices M25 and M50, respectively.

Physical characteristics of water absorption, void index (porosity) and real density were evaluated at 28 days. Real density results are shown in **Figure 05(a)** with respect to substitution content while the relation between compressive strength and density is shown in **Figure 05(b)**.

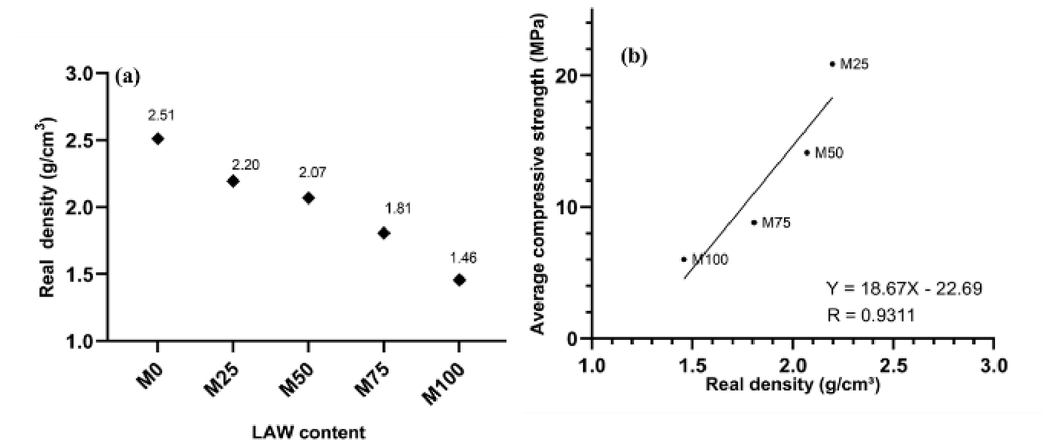

Figure 05: (a) Real density (g/cm³) of cementitious matrices with respect to light aggregate replacement content at 28 days and (b) relation between compressive strength and real density at 28 days.
Source: Authors.

Figure 05a shows that real density of the cementitious matrix decreased with increasing light aggregate substitution content. This was related to the lower density of light aggregate (0.87 g/cm³) when compared to quartz sand (2.62 g/cm³). The same results were obtained by Soares (2016), Lansing (2018) and Bahij *et al.* (2020). Silveira (2020) noted that density had the opposite behavior as water absorption and porosity of the matrices as light aggregate substitution content increased. Lv *et al.* (2015), Gupta, Chaudhary and Sharma (2016) and Angelin *et al.* (2019) reported the same behavior with the use of ground tire rubber and deemed it to be a result of the characteristics of the recycled aggregate. In the case of rubber, its hydrophobic properties were combined with surface air entrainment to increase void spaces. Finally, Záleská *et al.* (2018) also observed a reduction in density with the use of polypropylene (PP) waste.

Figure 05b shows that replacing sand with light aggregate decreased both real density and compressive strength. Matrix M50 had an 18 % decrease in real density and 67 % in compressive strength when compared to the reference M0 matrix. Furthermore, matrix M100 had a 42 % decrease in real density and 86 % in compressive strength when compared to the reference M0 matrix. The decrease in compressive strength with respect to real density is non-linear as demonstrated by the trend line and correlation coefficient of $R^2 = 0.9311$. It should be noted that the trend line calculation did not include the reference M0 matrix due to its outlier behavior. Sharper decreases in strength were observed between matrices M0 and M25 (52 %) than M25 and M50 (32 %), M50 and M75 (38%) and M75 and M100 (32 %). This indicated that, in addition to aggregate type, aggregate real density was also a contributing factor to the decrease in strength.

Average water absorption and porosity for the cementitious matrices of this study at 28 days are shown in **Figure 06.**

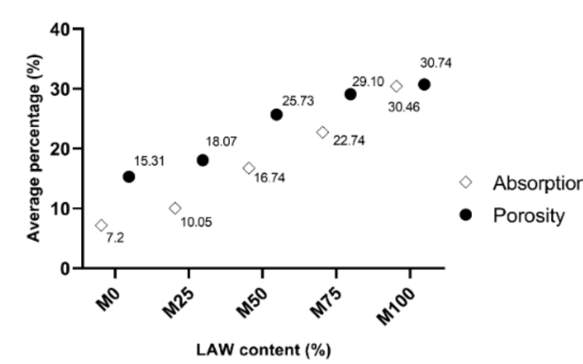

Figure 06: Average water absorption (%) and porosity (%) of the cementitious matrices with light aggregate substitution content at 28 days.
Source: Authors.

Figure 06 shows a direct relation between increased substitution content and increases both water absorption and porosity in the cementitious matrices. It should be noted that water absorption was related not only to porosity but also to pore size and connectivity. At 25 % substitution content, a 40 % increase in water absorption was noted with respect to the reference M0 matrix. Subsequent substitution content increases of matrices M50, M75 and M100 resulted in water absorption increases of 133 %, 216 % and 323 %, respectively, with respect to reference matrix M0. Silveira (2020) related this behavior to the higher water absorptivity of light aggregate compared to quartz sand. That was indeed confirmed as the light aggregate of this study had an absorptivity of 5.08 % while quartz sand was 0.87 %. Silveira (2020) also detected the presence of entrained air in the cement paste-aggregate interface. Mello (2011) also observed increased water absorption in cementitious matrices with recycled high-density polyethylene (HDPE) due to higher entrained air with respect to a reference matrix. In this case the increased water absorption was attributed to increased porosity in the cement paste. Moayeri, Ashrafi and Beiranvand (2016) determined that light aggregates absorbed 5 % to 25 % of water with respect to its dry mass depending on pore characteristics. Liu, Chia and Zhang (2011) proposed a workaround for the increased absorption of light aggregates in building construction that involved pre-wetting based on the specific water absorptivity of the aggregate.

Regarding average values of porosity, Figure 06 shows a similar increase as light aggregate substitution content increased. Matrix M25 presented an increase in porosity of 18 % with respect to reference matrix M0. Similarly, matrices M50, M75 and M100 had increases of 68 %, 90 % and 101 %, respectively, with respect to reference matrix M0. These results matched Hwang, Kim and Ann (2015), Blazy and Blazy (2021) and Miah *et al.* (2023) which observed similar increases in porosity with the use of recycled industrial materials such as steel, polypropylene and Asian areca palm nut fibers as light aggregate substitutes for sand.

Soares (2016) reported a porosity of 17 % for a cementitious matrix that replaced 50 % of treated commercial river sand with light aggregate by volume. This value was close to the 18 % of the M25 matrix of this study and demonstrated the effect of the type of aggregate on porosity. Soares (2016) also verified that increased porosity and decreased density from light aggregate substitution produced an increase in water absorption. This indicated that the increase in porosity was not the single main contributor to the decrease in compressive strength and the type of aggregate should also be considered. In the case of this study, the polymer-based light aggregate had less rigidity than quartz sand as confirmed by the hardness test results of 92.11 Shore D and 54.22 Shore D for quartz sand and light aggregate, respectively.

Figures 06 and **07** show water absorption increases of 23 % and 30 % for matrices M75 and M100, respectively. This was due to the higher waster absorption of the light aggregate (5.08 %) when compared to quartz sand (0.87 %). This result was related to compressive strength values of matrices M75 and M100 which had no significant variation at 7 days and 28 days. Similar results were obtained by Lansing (2018) for matrices with 50 % and 75 % light aggregate content and porosity around 25 %.

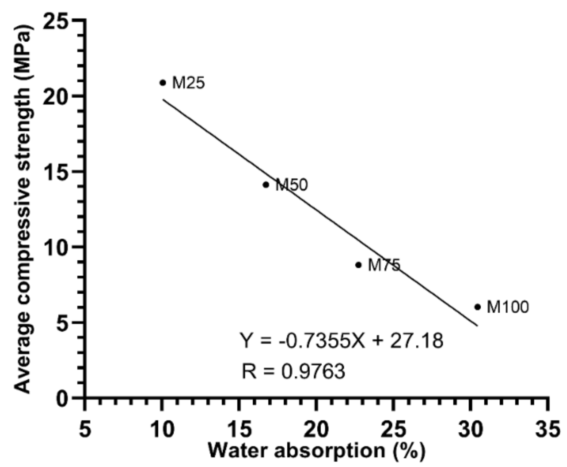

Figure 07: Relationship between average compressive strength and water absorption ot the cementitious matrices with light aggregate substitution content at 28 days.
Source: Authors.

Figure 07 shows that increases light aggregate substitution content increased water absorption and decreased compressive strength in the cementitious matrix. The decrease in strength was approximately linear with respect to water absorption as shown by the trend line and correlation coefficient of $R^2 = 0.98$. Once again the trend line did not include the outlier reference M0 matrix data point. These results indicated that porosity and, by extension, water absorption were predominant factors in the decrease of strength as substitution content increased. Koksal, Gencel and Kaya (2015) pointed to a strong correlation between porosity, water absorption and density in that, as porosity increased, density decreased and water absorption increased with carryover effects of decreasing mechanical properties.

4. CONCLUSIONS

Results of this study confirmed that light aggregate from polyester and laminated PVC extruded with polystyrene affected fresh and hardened state properties of cementitious matrices based on Portland cement. The following conclusions were drawn:

- In the fresh state, increased substitution of quartz sand with light aggregate markedly decreased workability, as confirmed through flow table tests. The 100 % substitution content of matrix M100 produced a decrease of around 61 % in mortar consistency index with respect to the reference M0 matrix.
- In the hardened state and through statistical analysis, it was determined that increased substitution of quartz sand with polymer-based light aggregates decreased compressive strength of the cementitious matrices.
- Increased substitution of quartz sand with light aggregate increased water absorption and void index and decreased real density of the cementitious matrices.

Results of this study demonstrated that light aggregates produced from polyester and laminated PVC extruded with polystyrene could be used to replace quartz sand in civil construction as long as the replacement content was not too high. For example, matrix M50 at 28 days had a compressive strength above 14 MPa, real density 18 % lower and water absorption of over 100 % higher than the reference mortar. Consequently, the use of such matrix would be adequate only for situations in which the mortar was not responsible for the integrity of the system such as filling cavities or normalizing surfaces

Future extensions to this study would continue the analysis of the use of this cementitious matrix as acoustic and thermal insulation as well as economic viability.

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AL: formal analysis, visualization and writing - review & editing.

ASV: conceptualization, funding acquisition, methodology, project administration, supervision, visualization and writing - review & editing.

PMA: resources and writing - review & editing.

LCR: resources and writing - review & editing.

Conflict declaration: nothing to declare.