Use of expanded polystyrene waste as a substitute for natural sand in coating mortars: evaluation of physical and mechanical properties

Utilização de resíduos de poliestireno expandido como substituto da areia natural em argamassas de revestimento: avaliação das propriedades físicas e mecânicas

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ABSTRACT
The incorporation of waste in the production of materials for civil construction has been the subject of studies for some time. In this context, coating mortars containing expanded polystyrene (EPS) waste arise as an alternative to replace natural aggregates. The main objective of this study was to develop coating mortar with EPS waste as a substitute for natural sand, using different percentages of substitution (0%, 10%, 20%, 30%, 40% and 50%). The characterization of the specimens was carried out through tests of compressive strength, flexural tensile strength, tensile bond strength, density in the fresh state and density in the hardened state (wet and dry), air void, water absorption, shrinkage and thermal conductivity. The results showed that the material met the standards in relation to strength properties, adherence for internal coatings and presented low thermal conductivity compared to the reference material.

Keywords: coating mortar, eps waste, physical properties, mechanical properties.

RESUMO
A incorporação de resíduos na produção de materiais para a construção civil vem sendo objeto de estudos há algum tempo. Neste contexto, as argamassas de revestimento contendo resíduos de poliestireno expandido (EPS) surgem como uma alternativa para substituir os agregados naturais. O objetivo principal deste estudo foi desenvolver argamassa de revestimento com resíduos de EPS em substituição à areia natural, utilizando diferentes percentuais de substituição (0%, 10%, 20%, 30%, 40% e 50%). A caracterização dos corpos de prova foi realizada através de ensaios de resistência à compressão, resistência à tração na flexão, resistência à tração na aderência, densidade no estado fresco e densidade no estado endurecido (úmido e seco), vazios de ar, absorção de água, retração e condutividade térmica. Os resultados mostraram que o material cumpriu as normas em relação às propriedades de resistência, aderência para revestimentos internos e apresentou baixa condutividade térmica em comparação com o material de referência.

Palavras-chave: Argamassa de revestimento, resíduos de eps, propriedades físicas, propriedades mecânicas.
1 INTRODUCTION

The quality and performance of buildings has become an increasingly present demand in the construction industry. The efficiency of the construction sectors in the thermal insulation of buildings has increased year after year, with a relentless search for materials that can meet the minimum requirements of performance standards (Adamczyk & Dylewski, 2017; Schiavoni et al., 2016). These materials can be developed from wastes that possess essential characteristics such as low thermal conductivity, high mechanical strengths, high durability, low density, among others (Li et al., 2022).

The use of energy in buildings is related to both the construction process and the occupation of the dwelling, affecting the thermal, acoustic, and lighting comfort of the property. By using materials with high performance in thermal insulation, it is possible to achieve savings of up to 7% in the energy consumed to provide thermal comfort. Therefore, it is essential to invest in building materials that can improve the energy efficiency of buildings, resulting in benefits for both the environment and the owners' budget (Yang & Lee, 2015).

A type of material used in civil construction that plays a fundamental role in the efficiency of buildings is mortar. The performance of coating mortars can significantly reduce the internal temperature of buildings, decreasing the thermal conductivity of this material and the absorption of solar radiation on the facades (Passos & Carasek, 2018). The use of alternative materials in mortars, such as lightweight aggregates (such as expanded vermiculite (Rashad, 2016), expanded polystyrene (Prasittisopin et al., 2022), expanded clay (Rashad, 2018), and others) contributes to the reduction of thermal conductivity and consequently increases energy efficiency, reducing the energy consumption of buildings.

The scarcity of natural materials has led to an increase in the use of waste as raw material for the development of new materials. Among these wastes, expanded polystyrene stands out, whose use in the manufacture of construction materials has been studied by several researchers (Adhikary & Ashish, 2022; Brooks et al., 2018; del Río-Merino et al., 2022; Ferrández et al., 2022; Maaroufi et al., 2021; Zhang et al., 2019).

EPS has high demand in various sectors, such as automotive (for finishing), electronics (for insulation and protection in transportation), health (for insulation and protection in transportation), packaging (for food) and construction (for precast slabs, linings and insulation),
among others. Due to its numerous applications, the world production of EPS in 2020 was around 5 million cubic meters (Milling et al., 2020; Silva et al., 2020).

The disposal of EPS waste has been considered an environmental threat, because this material is not biodegradable and can take hundreds of years to decompose in nature. Moreover, despite being 100% recyclable, in Brazil the recycling rate of this material does not exceed 40% of its total volume (Morais & Vidigal, 2021).

On the other hand, there have been attempts to incorporate non-conventional aggregates to develop lightweight construction materials in order to improve thermal efficiency. In this context, it can be observed that the use of small amounts of EPS replacing fine aggregate in mortar composition reduces thermal conductivity. For example, the study conducted by Tasdemir et al. (2017) presented results pointing to a reduction of the order of 85% (from 0.45 W/m.K to 0.067 W/m.K) for lightweight concretes. Dixit et al. (2019) also evidenced the reduction of thermal conductivity through the use of EPS in mortars.

With the intention of contributing to studies on more efficient materials and sustainable application of waste, this work had as main objective to evaluate the properties of coating mortars developed with the partial replacement of natural aggregate by EPS waste.

2 MATERIALS AND METHODS

2.1 MATERIALS

The binder materials used were cement CPII Z-32 and hydrated lime CHIII. The CPII Z-32 cement has an addition of pozzolanic material, varying from 6 to 14% of its mass, and its fineness is less than or equal to 12%, which ensures lower permeability, ideal for linings, and a slower hydration, providing an increase in mechanical strength.

Hydrated lime was used to confer greater workability, decrease water absorption, and reduce the voids in the mortar. In addition, it was employed to increase mortar plasticity, allowing greater deformations without the formation of cracks, and to retain more water during mixing, which provides better adhesion in coating mortars.

The natural aggregate used was river sand (Figure 1(b)), whose particle size curve can be observed in Figure 1(a). The natural sand presents a fineness modulus and density of 3.10 and 1530 kg/m³, respectively. The EPS waste was collected in the city of Passo Fundo, RS, Brazil. The raw EPS, which can be seen in Figure 1(c), was washed with water to remove impurities.
(dust, organic waste, among others). It was then ground and sieved with a 2.36 mm sieve, as seen in Figure 1(d). In Figure 1(e), it is possible to observe the enlarged image of the processed residue particles, which present irregular shapes and rough texture, potentially enhancing adherence with the cementitious paste. The EPS particle size curve can be seen in Figure 1(a). The processed EPS waste has a fineness modulus and density of 2.55 and 12 kg/m$^3$, respectively.

Figure 1. (a) Granulometric curve for natural sand and EPS; (b) Natural sand macrography; (c) EPS waste; (d) EPS processed; and EPS macrography.

2.2 EXPERIMENTAL PROCEDURES

The mixing of the materials was performed according to the specification of the standard NBR 16541 (ABNT, 2016). Previous experiments were performed to determine the proportions of materials for the coating mortar with addition of EPS waste. A 1:1:6 mixture (cement, lime and sand) by volume was used. The amount of water was added by adjusting the consistency index to 240 ± 10 mm.

Initially, the dry materials (cement, lime, sand) were mixed with a mechanical mixer until they were homogenized. Sequentially, water and EPS were added to the dry materials and mixed for 3 minutes at a speed of 140 rpm. Figure 2(a) shows the EPS added to the mortar and Figure 2(b) shows the homogenized EPS after kneading the mixture.
The experimental matrix with the experimental composition of the mortar mixtures can be seen in Table 1.

Table 1. Composition of the experimental mixtures.

<table>
<thead>
<tr>
<th>Description</th>
<th>C (m³)</th>
<th>L (m³)</th>
<th>NS (m³)</th>
<th>EPS waste (m³)</th>
<th>W/C (Mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF – 0%</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>E10 – 10%</td>
<td>1</td>
<td>1</td>
<td>5.4</td>
<td>0.6</td>
<td>0.95</td>
</tr>
<tr>
<td>E20 – 20%</td>
<td>1</td>
<td>1</td>
<td>4.8</td>
<td>1.2</td>
<td>0.90</td>
</tr>
<tr>
<td>E30 – 30%</td>
<td>1</td>
<td>1</td>
<td>4.2</td>
<td>1.6</td>
<td>0.85</td>
</tr>
<tr>
<td>E40 – 40%</td>
<td>1</td>
<td>1</td>
<td>3.6</td>
<td>2.4</td>
<td>0.80</td>
</tr>
<tr>
<td>E50 – 50%</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0.75</td>
</tr>
</tbody>
</table>

RF – reference; W/C – water/cement; NS – natural sand; C – cement; L - lime

2.3 CHARACTERIZATION OF THE MORTARS

The characterization of mortars is essential to ensure the proper performance of the material in civil construction. In the case of mortar with EPS, different tests are performed to evaluate its physical and mechanical properties, such as density in the fresh state, density in the hardened state (dry and saturated), air void, water absorption, compressive strength, flexural tensile strength, tensile bond strength, shrinkage and thermal conductivity.

The determination of the density in the fresh state was performed according to the specifications of standard NBR 13281 (ABNT, 2005b) The mortar was placed in a cylindrical container with known dimensions and its mass was measured using a precision scale with 0.01g resolution. The fresh density was calculated by dividing the mass by the volume of the container.
The properties of water absorption by immersion, air void and densities (dry and saturated) were determined according to NBR 9778 (ABNT, 2009) for an age of 28 days.

The compressive strength and flexural tensile strength tests were performed by molding four specimens per mix, with dimensions 40x40x160 mm, manually compacted and broken at an age of 28 days, in accordance with the standard NBR 13279 (ABNT, 2005a). The compressive strength test was performed using a hydraulic press EMIC model PC 100 C (EMIC-PC100C, Instron, Norwood, MA, USA). In turn, the Instron EMIC EL 2000 universal testing machine was used for the flexural tensile strength test.

To verify the traction adherence, the coating mortar was applied to a wall built with 6-hole bricks, measuring 14x19x11.5 cm. Between the coating and the substrate a 1:2.5 (cement and sand) roughcast was applied until the substrate was completely covered. The coating mortar was applied three days after the application of the rough cast, using a wooden template to ensure a thickness of 2.5 cm and regularization of the surface. After 27 days, circular cuts were made in the coating and the metallic particles were glued with epoxy glue. The pull-out test was performed, at age 28 days, using a manual torque equipment, according to the specifications of NBR 13528 (ABNT, 2010).

For the shrinkage test, three specimens were molded per mix, with dimensions of 25x25x285 mm. The dimensions were measured at ages 1 and 28 days, using a digital equipment with 0.01 mm precision, according to the specifications of the standard NBR 15261 (ABNT, 2005c). The specimens for the thermal conductivity test were made with dimensions of 300x100x30 mm. The determination of thermal conductivity was obtained by means of the surface hot wire technique. This technique has already been validated as a variant of the parallel hot wire in previous works (Favaretto et al., 2017; Lermen et al., 2019, 2021) and is characterized by being a direct method that detects transient temperature. The experimental system is composed of two multimeters to determine the electric current and voltage, two parallelepiped-shaped specimens, a hot wire (0.5 mm diameter kanthal) connected to a power source, four temperature sensors (NTC), and a data acquisition system. The temperature sensors were calibrated for a range from 0°C to 100°C.
3 RESULTS AND DISCUSSIONS

3.1 DENSITY IN THE FRESH AND HARDENED STATE, WATER ABSORPTION AND AIR VOID

Figure 3 presents the density in the fresh state, dry and saturated density as a function of the substitution of natural aggregate by EPS waste. As expected, there was a reduction in density with increasing percentage of substitution. This trend can be explained by the physical characteristics of EPS waste, such as its low density, reduced surface energy and hydrophobicity. These factors favor the formation of voids, especially in the paste/waste interface region, which makes the mortar with EPS more porous and aerated (Petrella et al., 2020).

![Figure 3: Densities in the fresh state, saturated hardened state, and dry hardened state as a function of the percentage of substitution of natural sand by EPS waste.](chart)

A difference in density was observed between the specimens in the fresh state and in the saturated hardened state when there was substitution of more than 30% of EPS in the mortar. This difference can be attributed to the evaporation of water present in the mixture during the curing process, in addition to the formation of voids due to mortar shrinkage. It is important to note that void formation is a phenomenon that can occur during mortar curing, and that can be intensified by increasing the percentage of EPS in the mixture.

The results presented in Figure 4 indicate that the use of EPS waste contributes to the increase of voids present in the microstructure of the mortar. An increase in the air void is...
observed as more waste is incorporated, which results in a higher water absorption capacity and, consequently, in more permeable mortars when compared to the reference mortar.

Figure 4: Water absorption and air void as a function of the percentage of substitution of natural sand by EPS waste.

Adding EPS to mortar promotes void formation due to its closed cell structure and its ability to float in the liquid mortar mixture. When EPS is added to mortar, it is distributed evenly in the mixture, and during the hardening process, the EPS particles are expanded by mixing and heating water, leaving a network of voids in their place. This results in increased porosity and reduced density of the mortar, which can lead to better thermal and acoustic insulation, but can also make the mortar more permeable. Therefore, the addition of EPS in mortar should be carefully studied to ensure that the resulting permeability is suitable for the specific application (Prasittisopin et al., 2022).

3.2 COMpressive STRENGTH AND FLEXural TENSILE STRENGTH

The results of compressive strength and flexural tensile strength of the coating mortars with different levels of EPS were evaluated at 28 days, and their averages are presented in Figure 5. As expected, it was observed that the mechanical strength of the mortars decreases as the proportion of EPS replacing natural sand increases. The addition of EPS can be a satisfactory solution to reduce the density of the products, however, its incorporation usually affects the mechanical characteristics of the composites produced, since the lightweight polymeric aggregate does not present the same mechanical strength as its substitutes. Furthermore, the small
air bubbles enclosed within the EPS macromolecules form small non-absorbent voids that are susceptible to failure at the paste/EPS interface (Dixit et al., 2019; Passos & Carasek, 2018).

Figure 5: Compressive strength and flexural tensile strength as a function of the percentage of substitution of natural sand by EPS waste

The 30% content of EPS waste is a transition point for the change of category of the coating mortars, according to the classification established by NBR 13281 (ABNT, 2005b). Regarding compressive strength, mixtures with more than 30% of EPS belong to the P2 category, while mixtures with lower contents are classified as P5 category. Regarding flexural tensile strength, the same content (30%) is a point of category change, because up to this limit the mortars are classified as category R2 and above this limit they are classified as category R1.

The results show a great potential of the residue as a partial substitute for natural aggregate, and EPS when inserted in proportions of up to 20%, has a similarity of results within the standard deviation of the results obtained. Some variations in results can be seen in some studies (Brás et al., 2013; Silva et al., 2020) directly attributed to the voids content of the mixture, which tend to weaken the mixture in the bond zone between the paste and the aggregate, acting on the compressive strength.

3.3 TENSILE BOND STRENGTH

In Figure 6, the average result of tensile bond strength of the coating mortar with and without waste is presented. As expected, the intrinsic properties of EPS negatively affected the
bond tensile strength results. The higher the EPS content, the lower the bond strength and the higher the probability of defects, thus increasing the chances of material fracture. Regarding the failure mode, for all mixtures, the failure mode was of the cohesive type, occurring inside the mortar, which was expected, since these mortars present low density values and therefore do not stress the mortar/substrate interface throughout their service life. This observation was also made by authors (Passos & Carasek, 2018).

Figure 6. Tensile bond strength as a function of the percentage of substitution of natural sand by EPS waste

![Graph showing tensile bond strength as a function of percentage of EPS waste substitution.]

It can be observed that, regarding the classification of the mortars containing EPS waste, most of them are in class A2, with the exception of the mixture containing 10% of substitution, which, as well as the reference mortar, is in class A3 (ABNT, 2005b).

3.4 DIMENSIONAL VARIATIONS (SHRINKAGE TEST)

Figure 7 presents the shrinkage analysis of mixtures with and without EPS waste through the linear dimensional variation of the lining mortars. It was found that the mortar with 10% EPS waste showed a behavior closer to that of the reference mortar in terms of shrinkage, while the other formulations had greater dimensional variation. This is due to the increase of imperfections in the microstructure of the composite with increasing amount of waste, which leads to greater loss of moisture to the environment and consequent reduction of volume, causing shrinkage. In addition, the presence of EPS aggregate interferes with the deformation capacity of mortars,
increasing the chance of movement of the arrangement as the percentage of substitution increases, which increases the risk of shrinkage cracking (Brooks et al., 2018; Passos & Carasek, 2018).

Figure 7. Shrinkage as a function of the percentage of substitution of natural sand by EPS residue.

3.5 THERMAL CONDUCTIVITY

The results obtained by the thermal conductivity test are presented in Figure 8. The heat conduction in materials is directly related to the microstructural and compositional characteristics of the composite, since the conduction mechanism is associated with the combination of vibrational waves and electron movement. In the substitution of natural sand by EPS waste, there is a change in the characteristics of the composite, making it lighter and with a higher pore volume fraction. With this, there is a change in the heat conduction mechanism, being smaller in the more porous mixtures. With regard to the thermal performance of buildings, porous materials are favorable for thermal insulation, because they have low conductivity.
Figure 8. Thermal conductivity as a function of the percentage of substitution of natural sand by EPS residue.

The thermal performance of a building can be significantly affected by the type of material used. Porous materials are more favorable for thermal insulation due to their low conductivity. Regarding mortars, the standard NBR 15220-2 (ABNT, 2022) establishes a reference value of 1.15 W/mK for conventional mortar. Based on these parameters, it can be stated that mixtures containing EPS replacement are able to offer satisfactory thermal performance.

4 CONCLUSION

The coating mortar developed with the addition of EPS waste replacing natural sand showed satisfactory results in relation to the different properties evaluated, i.e., the technical indicators met the minimum requirements established by current standards.

The results of this study show that it is feasible to use EPS waste in coating mortars in all the percentages evaluated. However, we highlight the mix with 20% EPS waste, which presented properties without significant changes when compared to the reference mix, besides having low density, compressive strength and flexural tensile strength with low variation. Regarding durability, there is a higher water absorption and air void in the mortars with EPS residue when compared to the reference mortar. However, it is important to note that there was a significant improvement in thermal properties. As for adherence, the results met the normative requirements for the use of internal coverings.
Finally, the study indicates that mortar with EPS waste can be considered a viable and sustainable option for civil construction, providing both economic and environmental benefits.

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REFERENCES


