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Impact of Exposure to High Temperatures on the Mechanical Properties of EPS Waste Mortars

Impacto da Exposição a Altas Temperaturas nas Propriedades Mecânicas de Argamassas com Resíduos de EPS

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Abstract

When mortars with added EPS are exposed to high temperatures, such as in fire situations, there is a change in the mortar's properties due to the chemical decomposition of the binders. Understanding these changes is of fundamental importance for evaluating coatings when they are subjected to situations of risk to users, since they result in irreparable losses in the properties of the mixture. This study aims to evaluate the properties and their losses by means of mass loss, flexural tensile strength and compressive strength tests and image analysis using a digital optical microscope. The specimens were exposed to different temperatures: 25 °C, 300 °C, 500 °C and 700 °C, with a required fire resistance time of 30 minutes. The results show a drop in mass and mechanical strength as the percentage of natural aggregate replaced by EPS waste increases. The images analysed show a change in colour and a decrease in the cement paste as the temperature rises, starting at 500 °C. The study revealed that the exposure temperature has a greater contribution to the effects on mechanical strength and loss of mass.

Keywords: Coating mortar; EPS; Mass loss; Mechanical strength.

Resumo

Argamassas com adição de EPS, quando expostas a altas temperaturas, como em situações de incêndio, observa-se uma alteração nas propriedades das argamassas, devido à decomposição química dos aglomerantes. O entendimento dessas alterações é de fundamental importância para a avaliação de revestimentos quando submetidos a situações de risco para os usuários, uma vez que resultam em perdas irreparáveis nas propriedades da mistura. Este estudo visa avaliar as propriedades e suas perdas por meio de ensaios de perda de massa, resistência à tração na flexão e resistência à compressão e análise de imagens por meio de um microscópio ótico digital. Os corpos de prova foram expostos a diferentes temperaturas: 25 °C, 300 °C, 500 °C e 700 °C, com um tempo de resistência ao fogo requerido de 30 minutos. Os resultados demonstram uma queda nas massas e resistências mecânicas à medida que aumenta o percentual de substituição do agregado natural pelo resíduo de EPS. Nas imagens analisadas, observa-se uma mudança de coloração e uma diminuição da pasta cimentícia com o aumento da temperatura, a partir dos 500 °C. O estudo revelou que a temperatura de exposição possui uma maior contribuição nos efeitos sobre as resistências mecânicas e perda de massa.

Palavras-chave: Argamassa de revestimento; EPS; Perda de massa; Resistência mecânica.

1 Introduction

Cladding mortars play an important role in fire situations, as one of their functions is to insulate sealing and structural elements (FORMOSA *et al.*, 2011; RAMÍREZ *et al.*, 2020). Insulation time is essential if the heat is to heat up the structures and cause the buildings to collapse. The minimum TRRF (required fire resistance time) required for residential buildings with up to 5 floors by the Fire Brigade is 30 minutes (BARROSO; FERREIRA; DE LIMA, 2020; MACHADO *et al.*, 2022).

Jimenez *et al.* (2006) emphasise that mortar protection is fundamental for structural elements. They note that structural steel suffers a considerable loss of load-bearing capacity when exposed to temperatures of 500 ºC. Sayadi *et al.* (2016) describe that the addition of EPS to cement paste results in a reduction in density and loss of mechanical resistance at high temperatures.

In Brazil, there are no specific standards for mortars in fire situations. However, for concrete, there is the NBR 15200 standard (ABNT, 2012), which specifies the loss of mechanical resistance in terms of percentage of concrete mass, according to the temperature and time of exposure to fire. This standard will serve as a parameter for this study in order to verify the similarity in behaviour between concrete and mortar in high-risk situations. The same standard describes characteristic resistance losses of 15%, 40% and 70% at temperatures of 300 ºC, 500 ºC and 700 ºC, respectively, with a fire exposure time (TRRF) of 30 minutes, as specified in Machado *et al.* (2022). Foreign standards, such as EN 1366-4 (BRITISH STANDARDS, 2021) and BS 476 (BRITISH STANDARDS, 2011), quote resistance times ranging from 20 to 240 minutes within the temperature range considered.

The results presented by Ramírez *et al.* (2020) in their study on the fire resistance of conventional mortars, with an average temperature of 700 ºC, show a loss of tensile strength in flexion of 92.80%, going from an initial value of 6.67 MPa to 0.48 MPa after exposure to fire. As for compressive strength, a decrease of 30.25 per cent was observed, falling from 29.68 MPa to 20.70 MPa after the same period of exposure. The quality and performance of buildings has become increasingly demanding in the construction sector. The efficiency of construction systems for the thermal insulation of buildings has been improving every year, driven by the incessant search for materials capable of meeting the minimum requirements established by performance standard NBR 15.575 (ABNT, 2013). This standard clarifies the comfort and quality criteria of the building in each of its construction systems.

Formosa *et al.* (2011) mention in their study that mortars exposed to temperatures above 100 ºC tend to release the free water present in the pores of the mixture. As the temperature rises in the range between 100 ºC and 300 ºC, the water present in the mixture's chemistry is released. When exposed to temperatures above 450 ºC, portlandite decomposes. Wendt (2006) describes that calcium hydroxide dehydration occurs at 480 ºC and is responsible for the change in volume of the mortar. This shrinkage can reach 33%, causing cracks that contribute to a reduction in the mechanical strength of the mixture. In addition, the same author, observed in his study the identification of 6 types of crystalline phases during the heating of cement pastes. Neutron diffraction showed portlandite, ettringite, calcite, calcium oxide, CSH and larnite. The results indicate a decrease in CSH in the mix and the appearance of calcium oxide after the decomposition of the portlandite present in the mortar mix, from 480 ºC onwards.

Understanding the behaviour of mortars under high temperature conditions is of fundamental importance for the safety and durability of structures. As previously mentioned, studies have highlighted the significant effects of heat on the composition and properties of mortars. These studies reveal everything from the release of free and chemical water, through the decomposition of components such as portlandite and calcium hydroxide, to changes in the crystalline phases present in the mixture. Understanding these phenomena is fundamental to mitigating risks such as loss of mechanical resistance, shrinkage and cracking in structures. Therefore, this scientific article seeks to consolidate and expand this knowledge by exploring the thermal effects on the properties of EPS coating mortars, thus providing subsidies for the improvement of construction standards and practices that guarantee the safety and quality of buildings in the face of extreme temperature conditions.

The aim of this study was to evaluate mortars produced with crushed EPS waste by means of exposure tests at temperatures of 300 °C, 500 °C and 700 °C for a set time of 30 minutes. Mass loss and mechanical strengths in flexural tensile strength and compressive strength were evaluated.

2 Materials and methods

The research was conducted using CPII-Z 32 Portland cement, one of the main types used in the region of Passo Fundo, RS for application in mortar coatings. The chemical, physical and mechanical properties were defined by the manufacturer, in accordance with the normative requirements of NBR 16697 (ABNT, 2018) as shown in Table 1.

Table 1. Properties of CPII-Z 32 Portland cement

Properties	Parameters		Unit	Requirement (NBR 16697 (ANBT, 2018))	Cement used (Manufacturer's data)
Chemistry	Magnesium oxide (MgO)		%	-	3.9
	Sulphur Trioxide (SO_3)		%	≤ 4.5	3.5
	Fire loss		%	≤ 8.5	6.6
	Insoluble residue		%	≤ 18.5	16.8
Physics and Mechanics	Fineness	0.075	%	≤ 12.0	10.8
	Pick-up time	Start of grip	Min	≥ 60	240
		End of grip	Min	≤ 600	456
	Compressive strength	03 days	MPa	≥ 10.0	13.53
		07 days	MPa	≥ 20.0	24.88
		28 days	MPa	≥ 32.0	36.4

The hydrated lime used was CH-III hydrated lime, characterised according to data obtained from the manufacturer and data analysed by standard NBR 7175 (ABNT, 2003a) as shown in Table 2.

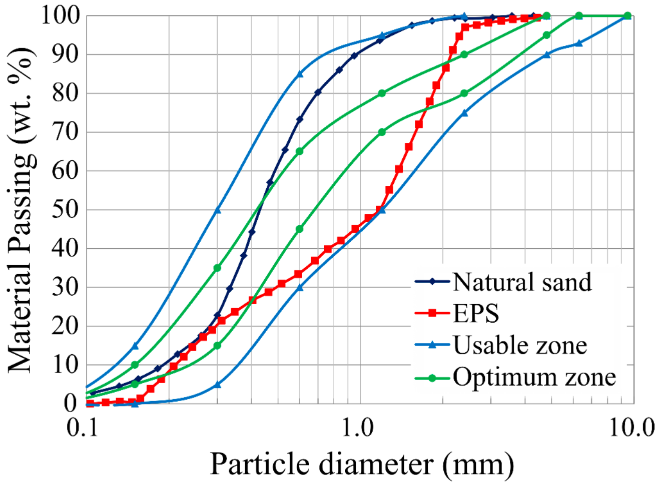
The natural aggregate selected was river sand from the Santa Maria/RS region. The particle size curve of the sand shows a particle size outside the optimum zone of NBR 7211 (ABNT, 2022), but within the usable zone of the same technical standard, as shown in Figure 1.

Table 2. Properties of lime

Properties	Parameters		Unit	Requirement (NBR 7175 (ABNT, 2003b))	Hydrated lime CHIII Used (Manufacturer's data)
Chemistry	Carbon dioxide (in the factory)		%	≤ 13.00	11.53
	Unhydrated calcium magnesium oxide		%	≤ 15.00	14.06
	Total non-volatile oxides		%	≥ 88.00	93.52
Physics	Fineness	0.600	%	≤ 0.50	0.47
		0.075	%	≤ 15.00	14.88
	Water retention		%	≥ 70.00	75.00
	Incorporating sand		%	≥ 2.2	3.00
	Plasticity		%	≥ 110.00	114.50

The natural aggregate selected was river sand from the Santa Maria/RS region. The particle size curve of the sand shows a particle size outside the optimum zone of NBR 7211 (ABNT, 2022), but within the usable zone of the same technical standard, as shown in Figure 1.

Figure 1. Particle size curve of sand and crushed EPS



The EPS waste used in the study was collected in the city of Passo Fundo. It was type F fire-retardant EPS from electronic product packaging. Type F EPS, when in contact with high temperatures (above 100 ºC), tends to shrink or melt and inhibit the spread of fire (TITTARELLI *et al.*, 2016). The waste was processed with a knife mill at 2-minute intervals and sieved until it reached a particle size that passed the 2.36 mm diameter sieve. The particle size of the EPS waste used can be seen in Figure 1. Figure 2(a) shows the raw EPS and Figure 2(b) shows the crushed EPS.

Figure 2. (a) EPS in natura and (b) crushed EPS

(a) (b)

Production of the mortar began after a preliminary experiment to check and analyse the mix found in the literature, in a ratio of 1:1:6 (cement, lime and sand) by volume. After separating and classifying all the materials in separate containers, a 250 ml plastic beaker and a 0.01g precision electronic scale were used to measure the materials.

The experimental matrix can be arranged according to the order of the tests that were carried out, with 3 test specimens (40x40x160 mm) per design: relative mass, compressive strength and flexural tensile strength. A total of 72 mortar specimens were developed, divided into 6 mixes, with different percentages of replacement of fine aggregate with EPS waste. The mix used as a reference for the experiment was 1:1:6 (cement: lime: small aggregate), with portions (10%, 20%, 30%, 40% and 50%) of the small aggregate (natural sand) being replaced by crushed EPS waste (<2.26 mm). The materials used in volume are shown in Table 3.

Table 3. Experimental matrix

Dash	Cement (volume)	lime (volume)	Natural sand (volume)	EPS (volume)	a/A ratio (mass)	Index of consistency
RF	1	1	6	-	1.0	240 ± 10 mm
E10	1	1	5.4	0.6	0.95	240 ± 10 mm
E20	1	1	4.8	1.2	0.90	240 ± 10 mm
E30	1	1	4.2	1.8	0.85	240 ± 10 mm
E40	1	1	3.6	2.4	0.80	240 ± 10 mm
E50	1	1	3	3	0.75	240 ± 10 mm

a/A = ratio of water (a) to binder (A).

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

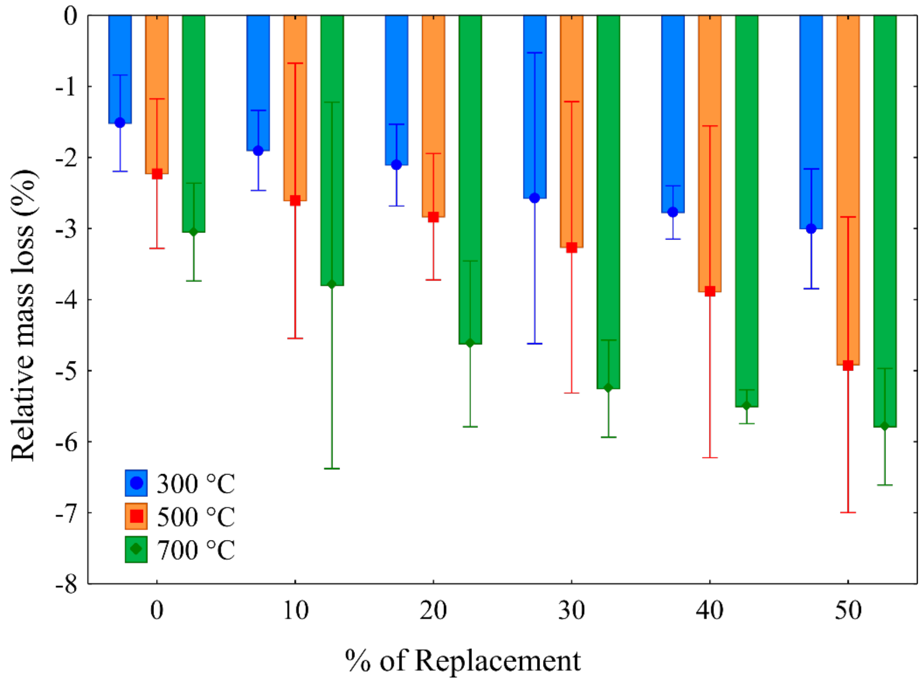
To check the effect of temperatures in fire situations, the specimens were exposed to three temperatures, 300 ºC, 500 ºC and 700 ºC using a muffle furnace. The masses of each specimen were measured before and after exposure. An exposure time (TRRF) of 30 minutes was determined for these tests, as specified in Machado et al. (2022). Cooling was carried out at room temperature (25 °C) for 6 hours. After checking for loss of mass, the specimens were sent for destructive tests of flexural tensile strength and compressive strength.

3 Results and discussions

3.1 Relative mass loss

The results of mass loss at different temperatures are shown in the graph in Figure 3. These results reveal a greater loss of mass in test specimens with a higher concentration of EPS residue and at higher temperatures. However, this loss of mass was below the results found in recent studies on fire-resistant mortars (FORMOSA *et al.*, 2011; JIMENEZ; DUQUESNE; BOURBIGOT, 2006; RAMÍREZ *et al.*, 2020). This can be attributed to the use of natural aggregates in the mix, due to the better packing of the particles and, above all, the insertion of EPS waste, which is characterized as fire retardant.

Figure 3. Relative mass loss as a function of the percentage of natural aggregate replaced by EPS and exposure to different temperatures



Through the analysis of variance and Tukey's test, it can be said that the factors (% replacement and temperature) have a significant influence on the mass loss of the mortars developed. It can be seen that temperature is the factor with the greatest influence on mass loss, with a contribution of around 77.5%. These results can be corroborated by the ANOVA shown in Table 4.

Table 4. ANOVA for relative mass loss

Factors	Sum of squares	Degree of freedom	Mean squares	F value	P-value	Contribution (%)
% of replacement	25.459	5	5.092	11.557	0.0000	9.6
Temperature (°C)	204.674	3	68.225	154.852	0.0000	77.5
Interaction	12.830	15	0.855	1.941	0.0419	4.9
Error	21.148	48	0.441			8.0
Total	264.111					100.0

As the temperature rises, there is an acceleration in the decomposition of the EPS, which results in greater porosity in the mortar matrix. This not only compromises the structural integrity of the material, but also increases the loss of mass due to the volatilization of the EPS components and the formation of voids in the mortar. At extremely high temperatures, such as 700 °C, the degradation of the EPS is even more pronounced, leading to rapid deterioration of the mortar and a significant loss of mass.

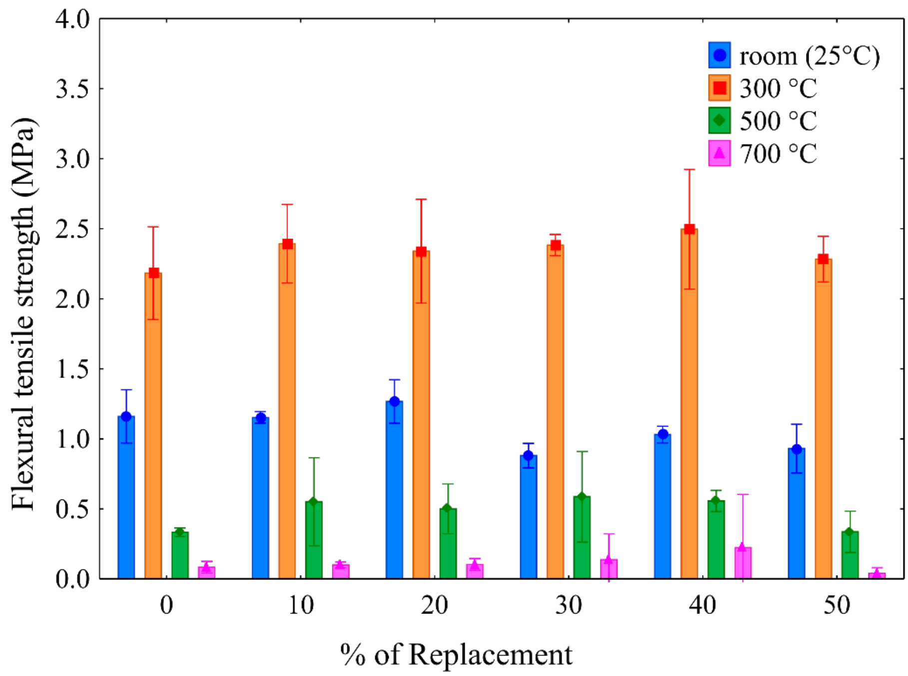
3.2 Flexural tensile strength

The flexural tensile strength results after exposure to high temperatures of 300 ºC, 500 ºC and 700 ºC can be seen in Figure 4. Analyzing the mechanical flexural tensile strength results at 300 ºC reveals an increase in strength in all proportions of natural aggregate replaced by EPS waste. The results showed significant improvements of 87.93%, 106.03%, 88.70%, 167.41%, 145.09% and 145.16%, corresponding to the proportions of 0%, 10%, 20%, 30%, 40% and 50%, respectively. This is due to the EPS melting at a temperature above 220 °C leading to better adhesion between the EPS particles and the surrounding mortar matrix, thus increasing the flexural tensile strength.

When exposed to a temperature of 500 ºC in the flexural tensile test, there was a reduction in strength in all proportions of the test specimens. The greatest loss of strength is seen in the reference mix with 0% EPS, with a drop of 71.55%, while the smallest drop is seen in the proportion of 30%, with a loss of strength of 33.70% compared to room temperature.

The results of the flexural tensile test, after exposure to a temperature of 700 ºC, show an even more marked decrease, with a loss of strength of 93.10%, 91.37%, 91.93%, 84.26%, 78.43% and 95.69%, for the proportions of 0%, 10%, 20%, 30%, 40% and 50% EPS, respectively.

Figure 4. Flexural tensile strength as a function of replacement percentage for different exposure temperatures



With percentages of 0%, 10%, 20%, 30%, 40% and 50% of EPS, it is possible to observe a reduction in the cementitious paste covering the aggregates at higher temperatures. This behaviour has been described by some authors (FORMOSA *et al.*, 2011; WENDT, 2006), with a greater loss occurring between 500 °C and 700 °C. This loss can be attributed to the decomposition of portlandite, resulting in an increase in porosity and a reduction in the mortar's mechanical strength.

In the range between 300 °C and 500 °C, there are no significant differences in the porosity and coverage of the paste on the aggregates, only a lighter colouring of the paste. From 500 °C up to 700 °C, a reddish-grey colour is observed, attributed to the release of the ferrous constituents present in the aggregates, as described by authors in their studies (FORMOSA *et al.*, 2011; WENDT, 2006). The EPS is decomposed in the moulds, generating voids with higher proportions in the traces with greater insertion of the residue.

The analysis of variance for flexural tensile strength is shown in Table 5. For this result, it is possible to state, with 95% confidence, that there is evidence that the temperature and replacement percentage factors influence the flexural tensile strength results. In this case, the temperature factor was also the most influential with a predominant contribution of 97.5%.

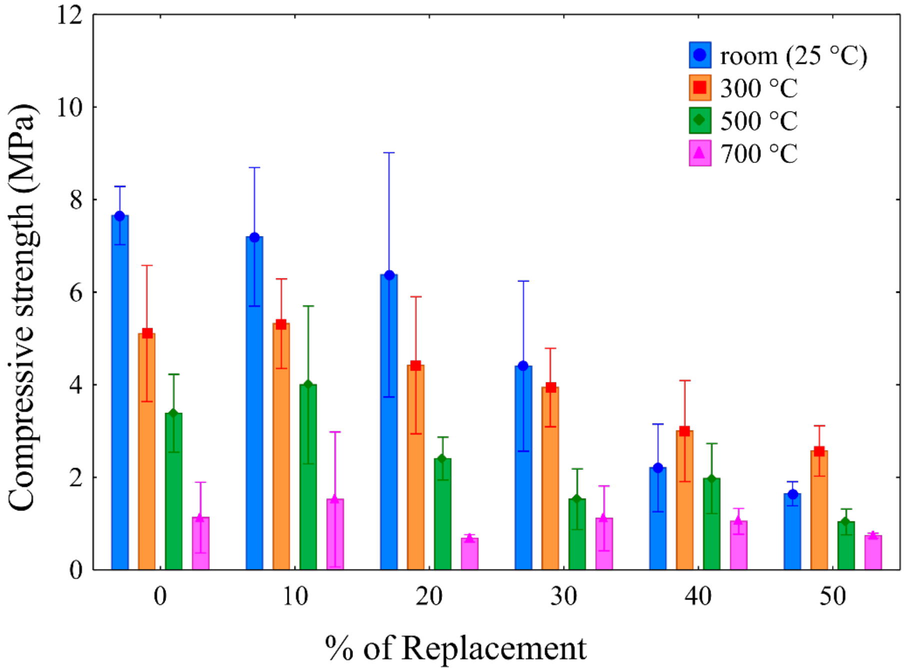
Table 5. ANOVA for the flexural tensile strength results

Factors	Sum of squares	Degree of freedom	Mean squares	F-value	P-value	Contribution (%)
% of replacement	0.302	5	0.060	5.303	0.0006	0.6
Temperature (°C)	51.766	3	17.255	1516.402	0.0000	97.5
Interaction	0.453	15	0.030	2.653	0.0053	0.9
Error	0.546	48	0.011			1.0
Total	53.067					100.0

3.3 Compressive strength

The mechanical compressive strength results obtained after exposure to high temperatures are shown in Figure 5. The tests carried out without exposure to high temperatures showed that by increasing the amount of EPS in the mortar to replace the natural aggregate, the compressive strength decreased. For the temperature of 300 °C, the compressive strength results presented indicate a loss of strength with increasing temperature, along with an increase in the amount of residue inserted into the mix, in the proportions of 0%, 10%, 20% and 30%. On the other hand, there is an increase in strength for the proportions of 40% and 50% at 300 °C, compared to the ambient temperature of 25 °C, with increases of around 28.20% and 52.97% respectively. The greatest drop in resistance recorded in the test was observed at 10%, resulting in a reduction of 25.28%.

Figure 5. Compressive strength as a function of the percentage of replacement for different exposure temperatures



In the compressive strength results at 500 °C, the reference mix showed a higher strength compared to room temperature, with an increase of 31.51%. On the other hand, the other traits showed a drop in strength, attributed to the fragility of the residue in withstanding high temperatures. The greatest loss was seen in the test with a 60.03 per cent reduction in the replacement ratio with 20 per cent EPS.

At a temperature of 700 °C, in the compression test, all the moulds showed losses in their mechanical strength, with the greatest loss occurring with the 20% proportion, which recorded approximately 88.72% of its strength in relation to room temperature.

The analysis of variance (Table 6) shows that temperature and replacement percentage influence compressive strength. Temperature is still the factor that contributed most to the variation in strength, i.e. the higher the exposure temperature, the lower the compressive strength, with the exception of the 40% and 50% traits at 300 °C, which showed higher strengths than the reference traits.

Table 6. ANOVA for the flexural tensile strength results

Factors	Sum of squares	Degree of freedom	Mean squares	F value	P-value	Contribution (%)
% replacement	87.19	5	17.438	31.170	0.0000	28.0
Temperature (°C)	151.97	3	50.656	90.548	0.0000	48.8
Interaction	45.32	15	3.022	5.401	0.0000	14.6
Error	26.85	48	0.559			8.6
Total	311.34					100.0

3.4 Image evaluation

In the macrographs recorded with a digital magnifying glass, it is possible to see the different internal behaviours of the mortars exposed to different heating temperatures recorded for the 0% proportion in Figure 6. As the temperature rises, there is an increase in porosity due to a decrease in mass, attributed to cement decomposition in the portlandite, as well as a change in colour due to the release of elements present in the natural aggregate. In the other traces, seen in Figure 7, with 10% replacement, in Figure 8, for 20% replacement, in Figure 9, for 30% replacement, in Figure 10, for 40% replacement and in Figure 11, for 50% replacement, the same behaviour is observed, but with an increase in pores, due to the melting of the EPS residue (>220 °C), and the higher the proportion of EPS, the greater the porosity of the mixture exposed to high temperatures.

Figure 6. Mortar without EPS and exposed to temperatures of (a) 300 °C, (b) 500 °C and (c) 700 °C

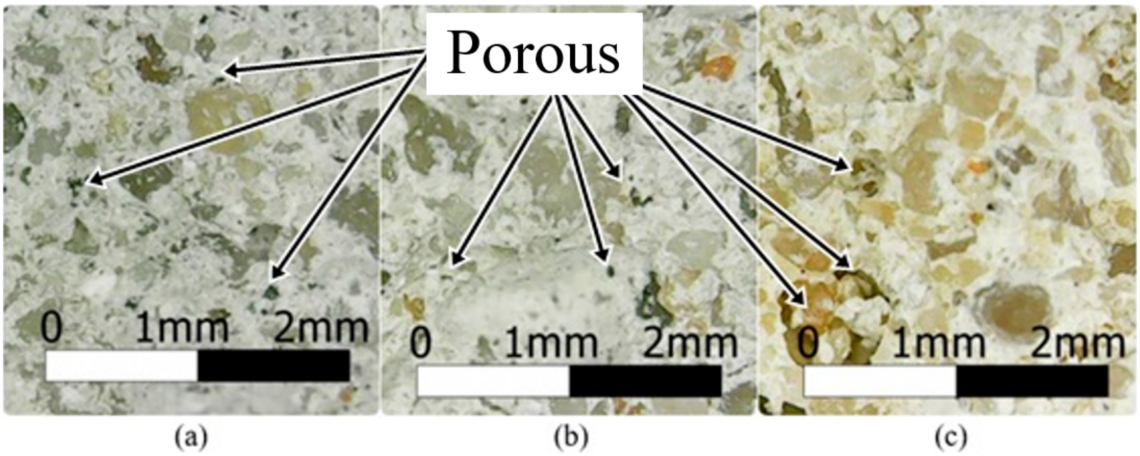


Figure 7. Mortar with 10% EPS and exposed to temperatures of (a) 300 °C, (b) 500 °C and (c) 700 °C

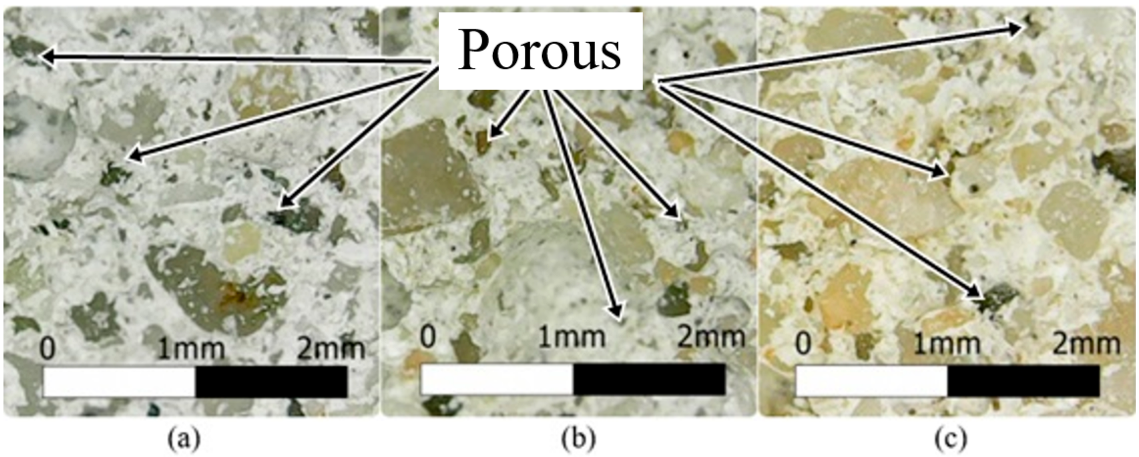
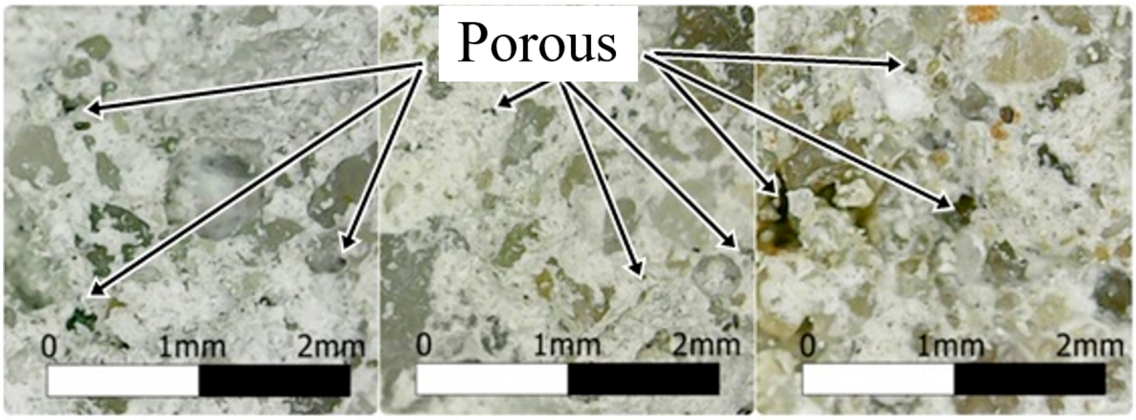
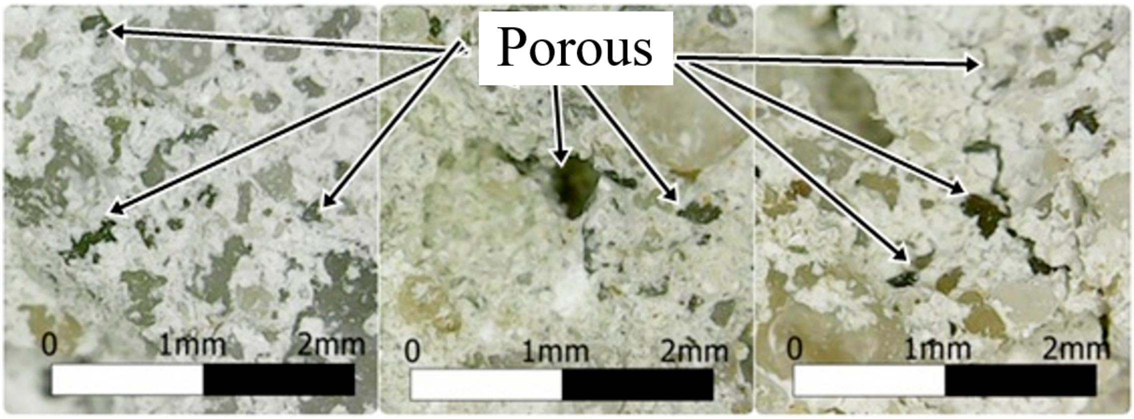


Figure 8. Mortar with 20% EPS and exposed to temperatures of (a) 300 °C, (b) 500 °C and (c) 700 °C



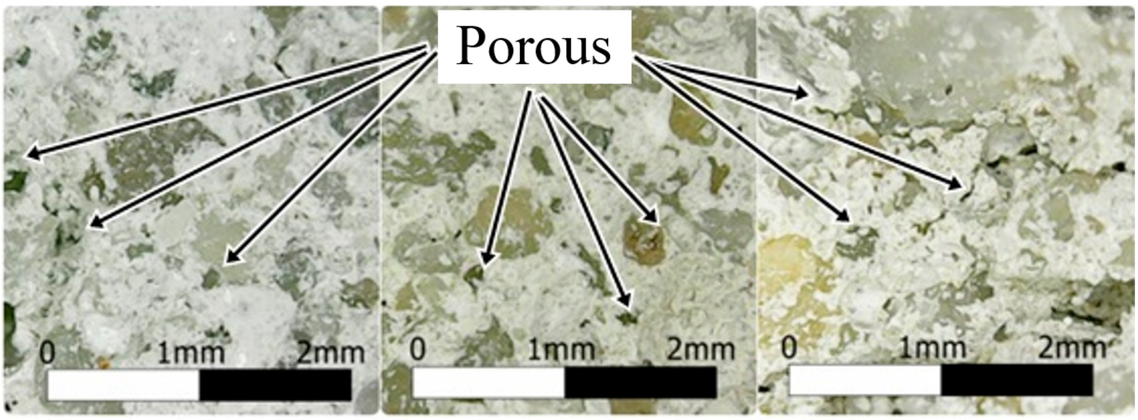
(a) (b) (c)

Figure 9. Mortar with 30% EPS and exposed to temperatures of (a) 300 °C, (b) 500 °C and (c) 700 °C



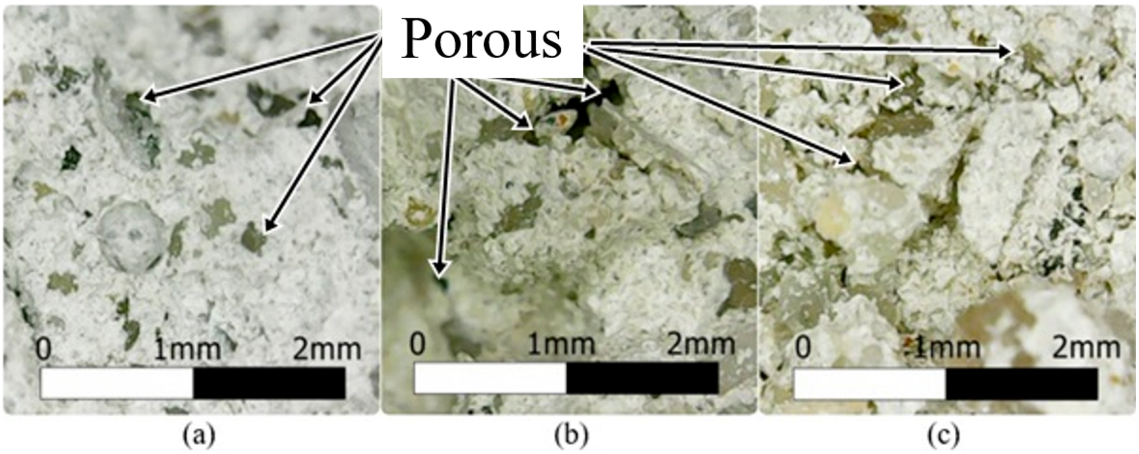
(a) (b) (c)

Figure 10. Mortar with 40% EPS and exposed to temperatures of (a) 300 °C, (b) 500 °C and (c) 700 °C



(a) (b) (c)

Figure 11. Mortar with 50% EPS and exposed to temperatures of (a) 300 ºC, (b) 500 ºC and (c) 700 ºC



4 Conclusions

This study evaluated the influence of different temperatures and percentages of replacement of natural aggregate with EPS waste on the mechanical and physical properties of mortars. Based on the results obtained, the following conclusions can be drawn:

- EPS mortars exposed to high temperatures suffer significant losses in mass and mechanical resistance.
- The chemical decomposition of the cement paste is observed especially after 500 ºC, contributing to the drop in strength.
- The melting of EPS particles at temperatures above 300 ºC, due to their low melting temperature, increases the porosity of the mixture.
- These changes in the composition of the mortar result in more pronounced drops in the mechanical resistance to flexural tensile strength and compressive strength.

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