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Durability of lightweight masonry mortars made with white recycled polyurethane foam

C. Junco, J. Gadea, A. Rodríguez, S. Gutiérrez-González, V. Calderón *

Departamento de Construcciones Arquitectónicas e Ingenierías de la Construcción y del Terreno, Universidad de Burgos, c/Villadiego s/n, 09001, Spain

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ABSTRACT

Masonry mortars made with Portland cement, sand, water and white recycled polyurethane foam from industrial waste are examined in this study. Different mixtures were firstly prepared through the substitution of different amounts of sand by equivalent volumes of polyurethane and then, with different ratios of cement/aggregates. The comparative study was carried out on the effect that different ageing tests have on the mechanical properties of these mortars under flexion and compression. For this purpose, the samples were exposed to different corrosion and hardness tests: resistance to dry heat, hot water, salt spray test and Kesternich testing. After ageing, a small reduction in compressive strength was observed. However, in all the samples, the strength values were sufficiently high to consider that these types of recycled materials remain practically unaffected when compared with the reference specimens. Finally, alkali-silica reaction tests were performed to determine the chemical stability of these mortars.

1. Introduction

Since their discovery, polyurethanes have assumed great commercial importance, to such an extent that they have shown the most rapid global growth of all types of polymers. This is due to their versatility, given that they are formulated and processed in very different forms: thermostable thermoplastics, soft and hard elastomers, lining, fibres, flexible, rigid and semi-rigid foams, etc. Among all these possibilities, polyurethane foams are used in the construction industry as insulating materials, where this property depends on their density and their internal air cavities. Although the weight of these materials is relatively low, the values are generally compatible with acceptable mechanical properties [1,2]. The inclusion of compounds such as polyurethane foams as a recycled and reusable material in substitution of varying amounts of aggregates is therefore of great interest in the production of new construction mortars. The subsequent study of their properties and the analysis of their durability are fundamental to test the behaviour that these compounds will have over time.

At present, different aggregates are used in mortars to replace or combine with cement [3]. So, many lightweight materials are used as aggregates in mortars [4] with lower densities and better workability, although generally without replacing the aggregate or the cement, which gives rise to higher water/conglomerate ratios than those needed in conventional mortars [5,6]. Besides, polyurethane is a lightweight material that is potentially much more flexible and hydrophobic than other traditional lightweight materials [7], such as perlite, expanded glass or hollow micro-spheres, which may be useful to control subsequent water absorption rates.

Other researchers have reported on the positive influence of aggregates on mortar durability [8,9], but specific references relative to their manufacture and the determination of stability over time of aggregate with recycled polyurethane foams or another recycled polymers are scarce [10–12].

The aim of this paper is to determine the properties of different blends containing cement-polyurethane-sand for the production of lightweight mortars containing recycled foams from polyurethane and assess their durability through various accelerated ageing tests in accordance with current norms.

2. Materials and methods

2.1. Raw materials

In this study, ordinary Portland cement type CEM I 42.5 R with a density 3065 kg/m^3 was used for mortar mixes. The chemical composition is shown in Table 1, as per Standard EN 197-1 [13].

River sand, sieved between 0 and 4 mm with a density 2600 kg/m^3 was used. The particle size distribution was obtained as per Standard EN 13138 [14].

White polyurethane foam waste (PU foam) was obtained from the destruction of panels used in the refrigeration industry. The waste was crushed to a particle size of between 0 and 1 mm before being used as an aggregate substitute.

* Corresponding author. Tel.: +34 947 259436; fax: +34 947 259478.
E-mail address: vcalderon@ubu.es (V. Calderón).

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Table 1
Chemical composition of cement.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	Loss of ignition	Others
Cement (%)	60.40	21.30	6.10	4.00	1.50	1.30	0.40	2.30	2.00	0.70

The apparent density of the polyurethane panels before crushed was 43 ± 2 kg/m^3, measured on 10 panels (20 × 10 × 0.8) cm^3. The real density of the foam after triturating, analysed by the picnometer method described in EN 13138, was 1083 kg/m^3. Its chemical composition was obtained by CHNS elemental analysis with a LECO CHNS-932 analyzer, and by X-ray diffraction incorporated in scanning electron microscopy, the method with which the images were acquired (Fig. 1).

2.2. Mixtures

The operating procedure for the fabrication of lightweight mortar consisted of manufacturing traditional mortar (a mixture of cement, sand and water) and, then replacing different percentages of sand with crushed PU foam. The cement/aggregate dosage by weight – the aggregate taken as the total quantity of sand and polyurethane in relation to cement – was 1 to 3, 1 to 4 and 1 to 6. Although the initial dosages were considered by weight, different amounts of sand were substituted by an equivalent quantity of polyurethane in volume. The amount of added water was necessary to ensure good workability, fluency and plastic state, in accordance with Standard EN 1015-3 [15]. Three series of lightweight mortar were produced, Series I with a 1/3 relation cement/(sand + -PU), Series II with 1/4 and Series III with 1/6 relation.

2.3. Densities and air void contain

Fresh and hardened density and occluded air were measured according to EN 1015-6 [16] and EN 1015-10 [17] at a temperature of 20 ± 1 °C and a relative humidity of 50 ± 1%.

2.4. Mechanical properties

Flexural strength and compressive strength were tested according to the EN 1015-11 [18] standard, after 7 and 28 days of curing. Three different test specimens were tested under flexion for each composition and six under compression. The test samples measured 40 mm × 40 mm × 160 mm, and the bottom support rollers were separated at intervals of 100 mm. The resulting fragments in this test broke under compression using a load surface of 40 mm × 40 mm.

2.5. Durability test

The tests used to evaluate the durability of the mortar mixtures may be grouped in accordance with their meaning into three blocks. Firstly, the behaviour of those materials in the presence of aggressive atmospheres: salt spray test and sulphur dioxide testing. Taking into account the fact that these materials have been made with polyurethane foams, a second series of accelerated ageing tests used in the construction industry to study PU foam behaviour were performed, such as the test of ageing behaviour in hot water and in hot/dry atmospheres. Finally, the study was completed with alcaline attack in order to determinate alkali-silica reactions and the chemical behaviour of these materials.

2.6. Salt spray test

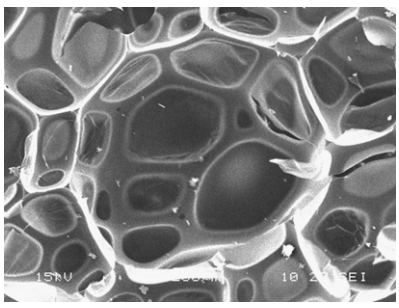
This method is used to evaluate the relative corrosion resistance of mortars exposed to marine or industrial environments by means of a salt spray at a high temperature The test, performed as per ISO 9227:90 [19], involves placing the samples in an enclosed salt spray chamber, filled with a continuous indirect saline mist atmosphere with 50 g/l of a standardized 5% solution of NaCl at 35 °C for 30 days. The major effect of such environments, where temperature is an important factor, is the diffusion of chlorine ions into the cementitious mixtures that can produce detrimental effects.

2.7. Kesternich test

This experiment, described in EN ISO 6988 [20], simulates an industrial atmosphere containing SO_2. Samples are exposed to an atmosphere that over a 24 h cycle passes water vapour saturated in SO_2 at 40 ± 2 °C for 8 h into an air cooled atmosphere held at room temperature for 16 h. In this case, the daily cycle was repeated 15 times. An initial visual inspection of the samples after the test was essential to analyse the expansive reaction, due to the combination in the mortar mass of free lime and silicates with SO_2 and CO_2.

2.8. Water at 105 °C

The aim of this test consist to analyse the degree of resistance when mortars are exposed to boiling water, and is a standard dura-



Element	White foam
C	61.4
O	5.5
N	6.8
H	12.4
Ca	0.0
Others	13.9
Total	100.0

Fig. 1. Scanning electron microscopy and elemental chemical analysis of the polyurethane foam waste.

bility study performed on either open or closed cell polyurethane foam specimens for construction. The operating procedure is given in standard EN ISO 2440 [21], and consists of accelerated ageing under hard humidity conditions. The samples were immersed in water at 105 °C for 3 h in order to test potential hydrolysis of PU foam bonds.

2.9. Dry heat at 140 °C

The test procedure, performed as described in standard EN ISO 2440, consists in ageing under dry heat at 140 °C for 240 h, which are the maximum temperature and period recommended in the standard. Under these conditions, thermal oxidation of the polyurethane could occur, obtaining the result of variations in the molecular weight that are evident in the reduction of mechanical strengths and a change in colour. Intense oxidation, especially at high temperatures, could lead to deterioration of the polymeric chain and the loss of carbon monoxide and water.

2.10. Alkali-silica reaction

The behaviour of mortars in the presence of aqueous solutions of sodium hydroxide was tested as per standard EN 146508:98 [22]. This test is intended to determine the existence of potential reactions between the cement and the aggregate and the cement and polymeric foam that substitutes the aggregate in the manufacture of mortars. This reactivity entails the formation of gels that expand in the presence of humidity, revealing cracks and differential movements and with it, a drastic reduction in hardness [23].

This analysis consists in manufacturing three 25 mm × 25 mm × 285 mm mortar specimens for each dosage. The specimens were submerged in a solution of NaOH 1 M at 80 °C temperature, measuring the elongation of each specimen at different ages.

3. Results and discussion

3.1. Fresh state

Table 2 summarizes dosages, water/cement relation, and results of fresh density and occluded air. The paste in contact with the lightweight aggregate seems to be denser than the paste located further away, which seems to be due to the water absorbed by the lightweight aggregate [24], which could reduce or keep the water/cement (w/c) ratio of the surrounding paste.

With regard to the properties in the fresh state, as may be seen from Table 2 for each of the Series, the inclusion of larger amounts of PU foam and the resulting increase in porosity, led to a reduction of the apparent density, which corresponded to a progressive increase in the percentage of occluded air. These parameters were accentuated when the cement/(sand + PU) ratio increased. Thus, when for example the results obtained with a substitution of 100% in the three series were compared, a density 1440 kg/m^3 was observed for dosage 3PU100 of Series I, (cement/(sand + PU) equal to 1/3), whereas 1250 kg/m^3 and 1089 kg/m^3 were obtained for dosages 4PU100 (1/4 ratio) and 6PU100 (ratio 1/6), respectively. Moreover, they do achieve a very interesting progressive reduction in density; the PU100 sample achieving a reduction of around 46% of the reference value 6R.

3.2. Hardened state

With regard to the density results in the hardened state, Table 3, in all cases, a loss of mass in the form of water was observed over time from 7 to 28 days, which appears logical when considering, on the one hand, the progress loss of part of the mixing water by evaporation and, on the other hand, the reduction of free water due to hardening reactions that promote mechanical strengths in the long term. Moreover, due to the compaction of the material and the curing of the test specimens, the apparent densities decreased in relation to the fresh state by about 200 kg/m^3, in all cases.

The densities of the mortars decreased in time due to the water evaporation during the curing process, for each dosage of PU foam. Density decreases as the amount of PU foam increases the selected ratios only achieved densities that allow us to consider these materials as lightweight mortars with regard to their use, having a maximum density of less than 1300 kg/m^3 in the hardened state, according EN 998 standards [25,26].

Concerning mechanical properties, the results, showed in Table 3, illustrate that the progressive replacement of sand for polyurethane entails a reduction in mechanical strengths under both compression and flexion, which was higher as the cement/(aggregate + PU) ratio increased.

The samples showed important variations in terms of mechanical strength in comparison with the reference samples. In the samples made by total replacement of aggregate by PU, it was found that the mechanical strength decreased around 60%, 70% and 80% for Series I, II and III, respectively (Table 4).

The ratio between flexural strength and compressive strength at 28 days is given in Fig. 2 and each series appeared to fit well with those proposed by certain other researchers [27,28]:

$$f_t = k(f_c)^{\acute{\alpha}} \quad (1)$$

The correlation results were calculated with the test results, and the resulting ratio is given in Fig. 2, with a correlation coefficient of $R^2 = 0.96$. It may be observed that all the mortar mixes behave in similar ways.

Table 2
Mix proportions and properties in fresh state of the mortar mixtures.

Series no.	Mix no.	Relation cement/(sand + PU)	Sand replaced by foam in volume (%)	w/c	Fresh density (kg/m^3)	Occluded air (%)
Series I	3R	1/3	0	0.71	2123	4.7
	3PU25	1/3	25	0.71	2012	5.6
	3PU50	1/3	50	0.67	1892	12.8
	3PU75	1/3	75	0.63	1687	14.0
	3PU100	1/3	100	0.62	1439	17.5
Series II	4R	1/4	0	0.94	2096	4.7
	4PU25	1/4	25	0.84	2011	6.8
	4PU50	1/4	50	0.78	1878	7.4
	4PU75	1/4	75	0.77	1532	11.4
	4PU100	1/4	100	0.90	1251	19.0
Series III	6R	1/6	0	1.3	2045	5.1
	6PU25	1/6	25	1.2	1987	6.8
	6PU50	1/6	50	1.2	1792	12.0
	6PU75	1/6	75	1.4	1433	16.0
	6PU100	1/6	100	1.4	1089	30.0

Table 3
Density and mechanical data of tested composites mortars.

Series no	Mix no.	Density (kg/m^3)		Flexural strength (MPa)		Compressive strength (MPa)	
		7 days	28 days	7 days	28 days	7 days	28 days
Series I	3R	2100	2035	5.0	5.28	15.9	23.69
	3PU25	1783	1678	3.37	4.88	14.9	20.5
	3PU50	1658	1550	2.84	3.62	12.9	18.6
	3PU75	1489	1311	2.80	3.39	12.8	16.00
	3PU100	1310	1250	1.82	2.1	7.19	10.23
Series II	4R	2030	2008	3.45	5.28	13.11	18.22
	4PU25	1765	1631	3.38	4.85	10.76	18.00
	4PU50	1690	1520	3.40	4.59	10.00	17.63
	4PU75	1325	1168	3.00	3.12	9.00	14.16
	4PU100	1110	917	1.03	1.4	3.65	5.44
Series III	6R	1998	1996	3.24	3.07	9.84	10.64
	6PU25	1880	1545	2.51	2.32	7.55	8.57
	6PU50	1677	1465	2.40	2.41	5.21	7.89
	6PU75	1240	1005	2.29	1.12	3.85	4.21
	6PU100	854	734	0.61	0.74	1.52	1.78

Table 4
Decrease in mechanical resistances in relation to reference samples when the replacement of aggregate by PU is total.

	Flexural strength (%)		Compressive strength (%)	
	7 days	28 days	7 days	28 days
Series I	63	60	55	57
Series II	70	73	72	70
Series III	81	76	84	83

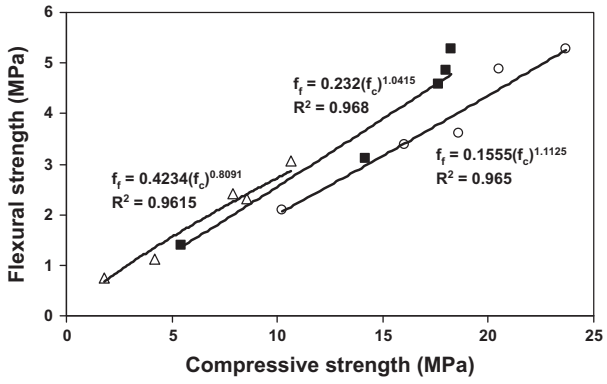


Fig. 2. Correlation between flexural strength and compressive strength at 28 days. ○ Series I, ■ Series II, Δ Series III.

3.3. Durability test

Following the ageing tests, a visual inspection of the reference specimen surfaces confirmed the degree of deterioration, and the comparative study was conducted of the effect that these tests have on the mechanical properties under both flexion and compression [29,30]. Each result represents the average of three measurements performed on three samples of the same composition. All the mechanical experiment were carried out under laboratory conditions, at 20 ± 5 °C and with 60 ± 10% relative humidity.

The mechanical strengths under compression were compared before and after each of the reference tests. All the data obtained were very similar. As an example, the Series 1 values are shown in Fig. 3, where it may be seen that despite submitting the samples to the various accelerated ageing tests, the mechanical strengths under flexion and compression were maintained without significative variations with respect to the specimens with the same dosages that were not subjected to any climatic test (referred to as the reference specimens).

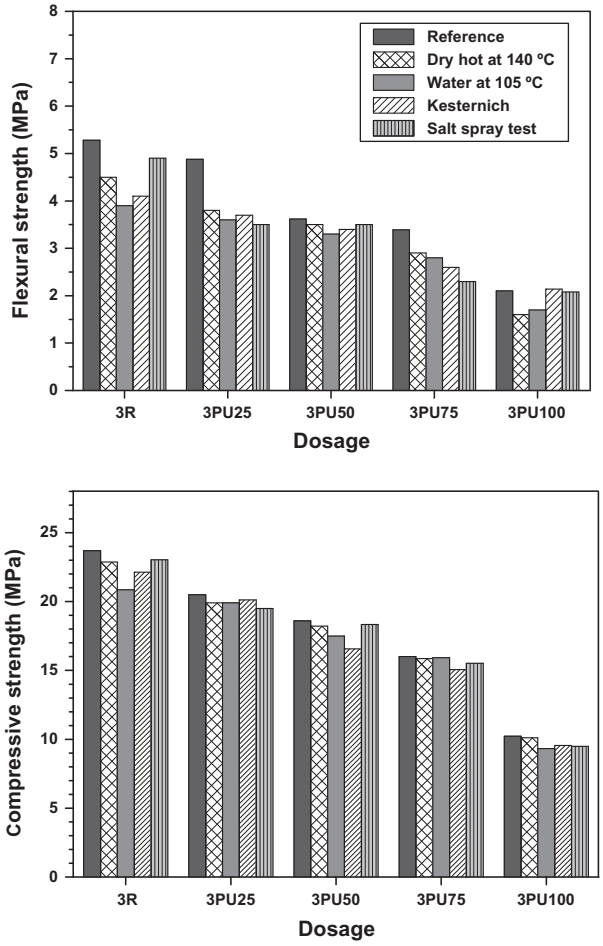


Fig. 3. Flexural strength and compressive strength before and after durability tests for Series I and 1/3 dosage.

Scanning Electron Microscopy (SEM) analysis of the studied samples in the salt spray test and Kesternich chamber test (Fig. 4) confirmed the deposition of salts on the surface, which was probably due to the presence of soluble salts in both tests. This

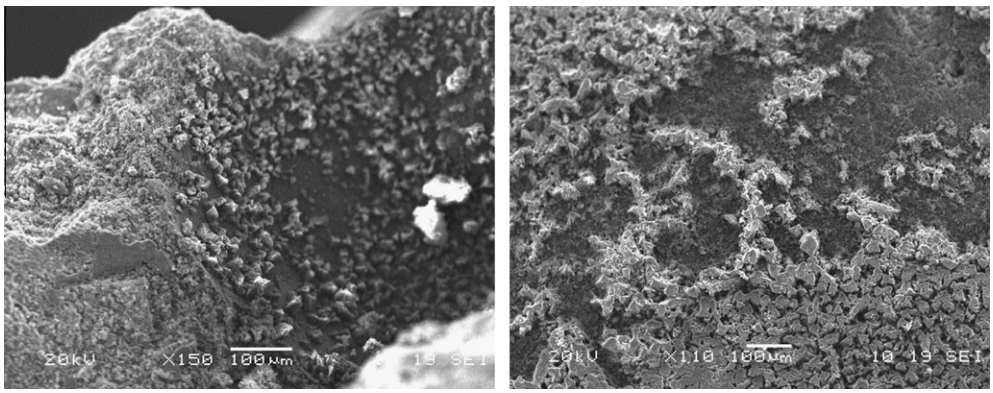


Fig. 4. Salt deposition: kesternich test (left) and salt spray test (right).

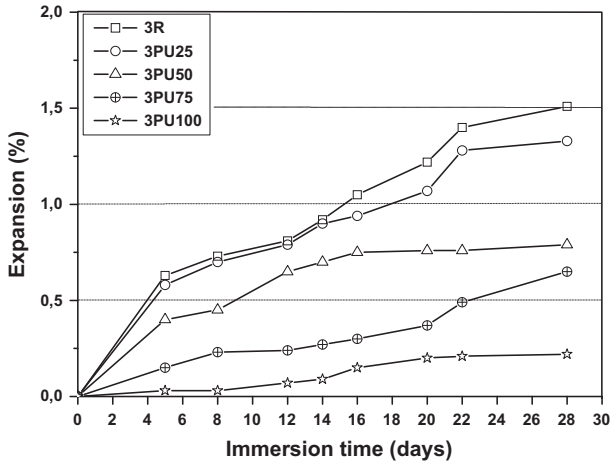


Fig. 5. Percentage of expansion of mortars versus time exposed to an immersed solution of Na_2SO_4 at 80 °C.

deposition leads to the appearance of efflorescence that changes the colour of the specimens [31] and leaves the properties of the blend unaffected with regard to their strength, which means it is considered an esthetic rather than a structural fault.

The behaviour concerning alkali-silica reaction is based on lineal expansion of the mortars, which was evaluated at 14 and at 28 days, should not exceed 0.1% and 0.2%, respectively, in order to consider the samples as non-reactive.

The results of the expansion for Series 1 may be seen in Fig. 5, in which reactivity falls as the amount of sand replaced by PU foam increases, yielding non-reactive sample in which all of the sand was substituted. Therefore, a greater presence of PU foam diminishes the possibility of alkaline reactivity and, therefore, of expansion in the medium to short term of the mortars, which means increased dimensional and structural stability over time.

After the attack the surfaces were studied by SEM, with the aim of examining possible changes that justify the expansion of the samples [32–34]. It was possible to confirm, after observing fragments of the mortar specimens, that the increased volume obtained in the mortar bars method was due to the appearance of calcoalkaline gels (smooth and thick) produced in the alkaline attack. As an example, one of the thick calcoalkaline-type gels may be seen in Fig. 6, found in the mortars that underwent expansion, which demonstrates that they might potentially be reactive in the alkaline environments. The X-ray dispersion analysis indicates that these formations are basically composed of silica and calcium oxides, sodium and potassium, which are the elements that form the expansive gels.

The bars of mortar method is generally simple and reliable in order to determine the reactivity of siliceous aggregates. Although due to the complexity of these types of alkali-aggregate processes it is convenient to complement this test with a preliminary petrographic analysis, an analysis of surface reactivity, and a study of the environmental conditions. With all these parameters it will be possible to predict with certainty and in a safely way whether or not an aggregate will be reactive in the presence of alkaline solutions. In other words, consider all the parameters to know if the aggregate will be alterable and likely to react with the interstitial phase of the mortar or concrete.

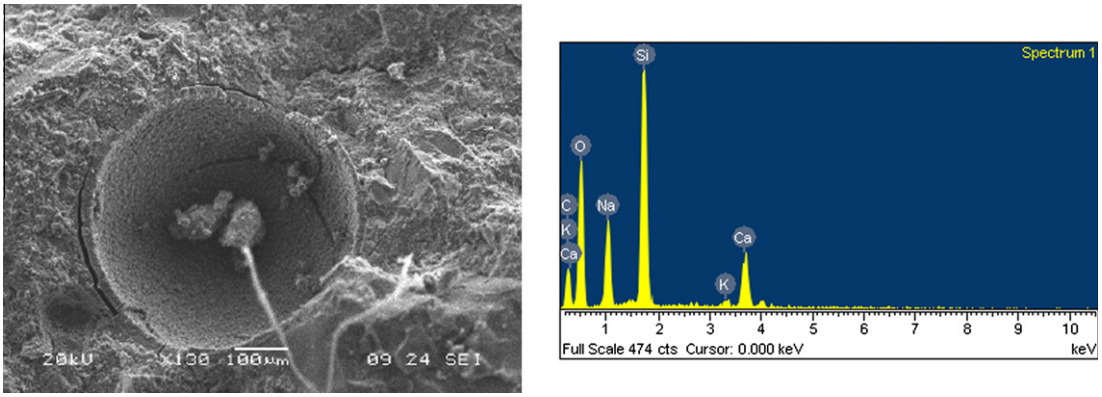


Fig. 6. Left: thick calcoalkaline gel obtained after mortar specimens attacked by hot NaOH. Right: X-ray SEM graphic.

4. Conclusions

The results of this research prompt us to draw the following conclusions and considerations:

- The preparation of lightweight mortars with white polyurethane foam from the refrigeration industry would contribute, on the one hand, to the re-assessment of a waste product that is generated in large quantities and on the other, to savings in significant amounts of sand.
- This type of masonry mortar can incorporate large quantities of PU foam, depending on the use that will be made of it, which means that up to 100% of the aggregate may be replaced by PU foam.
- The lightweight PU foam mortars are useful for improving workability in general, reducing the quantity of water needed for a good consistency, which can be useful in applications, such as rendering, since the lighter mortar has higher workability and covering capacity.
- The conventional mortars analysed in this study had an acceptable density both in the fresh and in the hardened state, as per current norms. Density became progressively lower with the inclusion of PU foam. PU foam may excessively reduce some characteristics of the lightweight mortars, most notably mechanical strength.
- In general, lightweight mortars exhibit similar behaviour to conventional mortars when resisting different aggressive environments. In all cases, even in the most aggressive standardized tests for the determination of the durability of panels of polyurethane used in construction, it was confirmed that the mechanical strengths, under both flexion and compression, remained practically unaffected.
- However, the tests of alkali-silica reactivity determined that the aggregates used in this study are likely to react with the alkalis present in the pore solution, and that the reactivity of the composite falls in proportion to the amount of aggregate substituted by PU foam.

Acknowledgements

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