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Thermal coating with rigid recycled polyurethane foam as a partial substitute of limestone aggregate

Recubrimiento térmico con espuma rígida de poliuretano reciclado como sustituto parcial de agregado calizo

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Abstract

This research presents the results of an experimental study about the effect of the rigid recycled polyurethane foam used as a partial substitute of limestone aggregates in the elaboration of cement-based coating, with the objective of reducing the consumption of natural aggregate by replacing it with a recycled material and reducing the thermal conductivity of the coating. The rigid recycled polyurethane foam was crushed to be used as a partial substitute of the fine limestone aggregate in proportions of 15, 20 and 25% in volume, maintaining a cement:sand ratio of 1:3., and its mechanical, physical and thermal properties were evaluated. The mortar of coating with 20% of substitution of recycled polyurethane foam by limestone aggregate, presented a better physical-mechanical and thermal behavior to a laboratory level; therefore, so it was used in real conditions as an exterior coating in a construction prototype elaborated with a wall of blocks and exposed to environmental conditions for a year. The results demonstrated that the modified coating improved its thermal performance by decreasing the interior temperature of the prototype by around 15% compared to the traditional coating, with a difference of 0 to 1.5 °C low, thus maintaining it for most of the year and with relative humidity without significant changes.

Mortar coating, Thermal properties, Limestone aggregate, Rigid polyurethane foam

Resumen

Esta investigación presenta los resultados de un estudio experimental sobre el efecto de espuma rígida de poliuretano reciclada utilizada como sustituto parcial de agregado calizo en la elaboración de recubrimiento base cemento, con el objetivo de reducir el consumo de agregado natural al sustituirlo por un material reciclado y disminuir la conductividad térmica del recubrimiento. La espuma rígida de poliuretano reciclada fue triturada para ser utilizada como sustituto parcial de agregado fino calizo en proporciones de 15, 20 y 25% en volumen, manteniendo una relación cemento:arena de 1:3, y sus propiedades mecánicas, físicas y térmicas fueron evaluadas. El recubrimiento con 20% de sustitución de espuma de poliuretano reciclada por agregado calizo, presento mejor comportamiento físico-mecánico y térmico a nivel laboratorio, por lo que fue utilizado en condiciones reales como recubrimiento exterior en un prototipo de edificación elaborado con muros de block y expuesto a condiciones ambientales durante un año. Los resultados demostraron que el recubrimiento modificado mejoró su desempeño térmico disminuyendo la temperatura al interior del prototipo alrededor de un 15% comparado con el recubrimiento tradicional, con una diferencia de temperatura de 0 a 1.5°C menor, manteniéndola así durante casi todo el año y con humedad relativa sin cambios significativos.

Mortero de recubrimiento, Propiedades térmicas, Agregado calizo, Espuma rígida de poliuretano

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Introduction

Due to the constant climatic changes, new problems arise that require as a solution to reduce the consumption of natural resources, as well as to improve the thermal performance of the materials commonly used in construction, these possible solutions range from the addition of a new material to the replacement of the materials commonly used, in the elaboration of coating mortars (Ponton-Giraldo, 2022; Quiro trujillo, 2022). The term mortar refers to the paste mixture composed of cement, water and fine aggregate, sometimes with additives, which is used in the bonding of bricks for the elaboration of masonry walls or as a covering for the latter. Polyurethane (PU) rigid foam, on the other hand, is a highly spatially cross-linked, thermosetting, hard thermoplastic synthetic material.

At the usual densities for thermal insulation, the foam contains only a small part of the volume of solid matter (with a density of 35 kg/m³), only 3% of the volume is solid matter (Oushabi *et al*., 2017). PU is a material widely used in different sectors, mostly in the construction, refrigeration, automotive and textile industries. PU products in the form of high or low density foam have a wide range of applications. However, due to the high worldwide production and disposal of polyurethane foam from various origins, there is a need for post-use waste disposal processes.

Yang *et al*., 2012, suggests in their research that the most effective means of environmentally friendly disposal is physical recycling, which basically consists of shredding the waste by changing only the physical form as the particles have no reactive activity, leading to a simpler method of operation and a more active application (Yang *et al*., 2012). In the new trends of replacement and addition of building materials, the use of recycling to reincorporate disused materials into the construction process takes a very important role and new recycling methods emerge (Buitrago-Bonilla & Sarmiento-Rodríguez, 2022; Vargas, 2022). For polyurethane foam it is important to employ an effective recycling method due to its properties such as durability, high density, non-flammable, hydrophobic and it is a potential option to be used as a partial substitute for fine limestone aggregate in coating mortars.

For example in Thailand, Tantisattayakul *et al*., 2018, reported that for the use of polyurethane rigid foam waste from dismantled refrigerators and its implementation in lightweight concretes, the best method used is physical recycling, with less environmental and energy impact, however, in terms of insulating properties, they suggest that recycling needs to be improved for its implementation to further decrease the environmental impact in terms of energy consumption during the use stage (Tantisattayakul *et al*., 2018).

On the other hand, Gómez-Rojas *et al*., 2019 evaluated the feasibility of using recycled polyurethane foam (PUR) waste from different industries such as refrigeration and automotive, in building materials, specifically incorporated in base-plaster mixtures, where it was reported that, in the case of waste from the refrigeration industry, they presented good thermal behaviour related to the microstructure of semi-closed hexagonal cells. Such behaviour can be exploited for the improvement of building materials if incorporated as thermal insulation. These polymers degraded around 200ºC without chemical and physical changes, they are inherent materials and did not show leaching. Additionally, only these wastes met the standards for combustion and heating value test which is ideal for interior building cladding (Gómez-Rojo *et al*., 2019).

Other studies reported on lightweight mortars have shown that it is possible to reincorporate waste materials such as expanded polystyrene, thermoplastic waste and paper sludge ash, which contribute greatly to the non-overexploitation of stone aggregates if they are used as a partial substitute for aggregate (Corinaldesi *et al*., 2011; Oushabi *et al*., 2017; Parada Rocha, 2022; Saikia & De Brito, 2012). There are also several studies on the incorporation of PUR as a partial replacement of sand for lightweight mortars, determining important mortar characteristics such as workability, density, air content and the evolution of compressive strength as a function of mortar age. Gadea *et al*., 2010, reported that it is possible to replace the fine aggregate by polystyrene particles for the production of lightweight mortars maintaining a particle size between 0 and 4 mm PU, it is important to mention that in most of the studies carried out, the type of aggregate used is river or natural sand (Gadea *et al*., 2010; Harith, 2018).

The partial substitution of polymeric waste in mortars and concretes decreases their physical and mechanical properties. Density decreases with increasing PUR substitution (Gutiérrez-González *et al.*, 2012). Calderón *et al*, 2018, used PUR as a partial substitute for silica sand in cement mortars, in substitution proportions of 50%, 60% and 75% by volume, where long-term durability was determined by elastic behaviour through fracture analysis subjected to repeated cycles of compressive loading and unloading, where they reported that the fatigue capacity and structural properties of mortars with partial PUR substitution were similar to those of mortars with partial PUR substitution, was similar to that of the reference mortars used in most masonry works, which guarantees long-term durability when placed directly into building elements, even suggesting that these mortars with partial substitution of PU rigid foam waste can be an alternative product to lightweight mortars based on the addition of expanded clay (Calderoń *et al.* , 2018).

In most of the research reported in the literature about the partial substitution of PUR by aggregates for mortars, they perform their tests at experimental level in laboratory to evaluate their physical, mechanical and thermal behaviour, however, very few report the behaviour of mortars with partial substitution of PUR, under real circumstances of application, subject to climatic conditions in the outdoors.

In this study, the substitution of fine aggregate by recycled polyurethane foam from refrigerators up to 25% was established as a maximum parameter, parameters suggested in order not to compromise the compressive strength.

The objective is to evaluate the thermal performance of the mortars under real environmental conditions used as exterior wall cladding and to compare the physical-mechanical properties between a traditionally manufactured mortar and a mortar with partial substitution of the limestone aggregate by PUR, and to reduce the thermal conductivity of the cladding mortar.

2. Materials and methods

2.1 Materials

Portland Cement Composite, type I classified as CPC according to the standard (ASTM C 150, 2012), density of 3.05 g/cm3 and volumetric weight of 1216.22 kg/m3 was used. Locally obtained crushed limestone aggregate, particle size 0 to 4.75 mm and density 1648.31349 kg/m3. Recycled rigid polyurethane foam from waste refrigerators (PUR) with a density of 37.20208 kg/m3. The PUR was collected, crushed and sieved, establishing the maximum particle size of 4.75 mm, based on other research on lightweight mortars.

2.2 Characterisation of limestone fine aggregate and PUR

The fine limestone aggregate was characterised by means of particle size, specific gravity and absorption percentage, according to the standards (ASTM C 128, 2001; ASTM C 136, 2020), respectively, where the volumetric weight of the aggregates and PUR was determined. Due to the light weight of the PUR and to facilitate the application process under real conditions, the substitution with fine limestone aggregate was by volume.

2.3 Specimen dosage

The mixing ratios of the coating mortars with a cement:fine aggregate ratio of 1:3 are shown in Table 1. The mortar mixtures were prepared and classified according to their percentage of fine aggregate substitution as: reference mortar with 0% PUR substitution (CPC), mortar with 15% substitution (C15), mortar with 20% substitution (C20) and mortar with 25% substitution (C25).

Cement: Aggregate				
Properties	**CPC**	**C15**	**C20**	**C25**
Water / Cement	1.07	1.03	1.05	1.04
Fluidity (%)	106	110.9	99.5	103.1
Cement (Kg)	0.42	0.42	0.42	0.42
Fine aggregate (Kg)	1.48	1.26	1.18	1.11
PUR (ml)	0	135	180	225
Water (ml)	321	310	314	311

Table 1 Specimen dosage

2.4 Compressive strength

The compressive strength of the samples made with the different compositions was determined according to the standard (ASTM C 109/C109M, 2002). For the test, seven 5 cm cubes of each composition were prepared. The reference fluidity was taken as 110±5 %, which is recommended for coating mortars. The samples were cured in water under ambient conditions for 28 days. An ELVEC E 659-4 press was used for the test.

2.5 Adhesion between mortar and block Wall

Among the most important characteristics for the coating mortar is the bond strength between the coating and the block wall. Therefore, test tests were carried out based on the standard (ASTM C 1857, 2020), for which it was necessary to adjust to a coating mortar. For the purpose of this research, the objective was to find the value of the pullout strength of the mortar adhered to the surface of the block wall, with the support of a mechanical device to produce the pullout failure shown in the image in Figure 1a. The mortar mixtures in the different substitution compositions were applied directly to the block walls where they were cured for a period of 28 days. Subsequently, they were cut into cylinders attached to the wall with a diameter of 2.82 cm, with a length of 1.5 m. Ten tests were carried out for each mortar composition as shown in the image in Figure 1b.

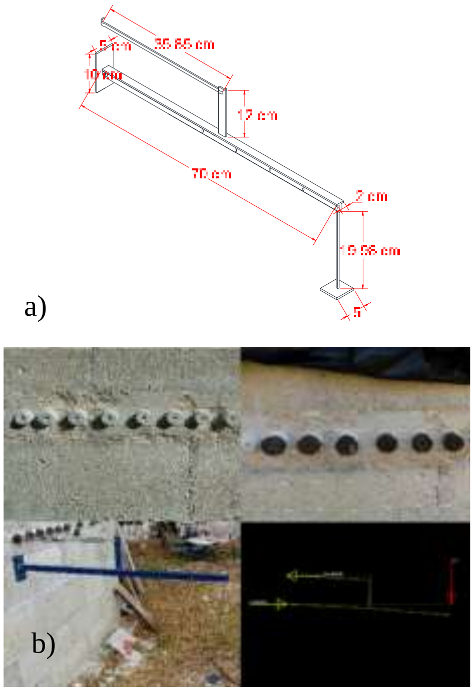

Figure 1 a) (b) Adhesion testing device, (b) Process of testing adhesion of mortar samples on block wall

2.6 Thermal Conductivity and Specific Heat (Cp)

The thermal conductivity study was carried out using a hot plate conductivity meter with guard, based on the standard (ASTM C 177, 2019). Samples of 152 x 127 ± 2 mm cross-section and 25 ± 2 mm thickness were prepared. For each test, a pair of mortar specimens was used, which were traced from vertex to vertex to determine the length of the groove and the thermocouple to be installed in the plate. The resulting dimensions were 76 mm long and 5 mm deep in the centre of each face. Four thermocouples were connected to a 16-channel monitor (Stanford Research System model SR630).

The entire thermal conductivity test process included four runs for each pair of mortar slabs. The first run was performed by supplying the copper resistor with a current of 20 volts for 12 consecutive hours. For the subsequent runs, the voltage was increased to 25, 30 and 35 volts every 24 hours, respectively. The specific heat was determined based on the standard (ASTM C 351, 1999). Initially, the mass and dimensions of each sample to be tested were obtained, which were used in the thermal conductivity coefficient test.

2.7 Prototype construction and monitoring of temperature and humidity under real environmental conditions

Based on the analysis of the results obtained in the laboratory of compressive strength, adhesion and thermal performance of the mortar samples of different compositions CPC, C20, C25 and C30, it was determined that the mortar mixture with PUR substitution classified as C20, presented the best performance, so it was used for the elaboration of the prototypes for in-situ exposure, under real climatic conditions. Two prototypes of blocks for direct placement of the mortar mixtures were made, the reference CPC and C20. Both were applied directly with the specifications of the plan shown in the image in Figure 2, to determine the temperature and relative humidity by means of sensors (HOBO UX100-011 temperature / relative humidity data logger). The construction of the prototypes was carried out with a foundation based on masonry with limestone and dados at the castle foundation points of both prototypes.

The body of the prototypes was made of block walls and the slab was made of joist and vault. Both prototypes had the same dimensions and were placed facing each other in a mirror image, with a separation of 3 m between them. On top of the slab, a 1:3:7 cement:lime:fine aggregate mix was placed with a thickness of 0.05 m and a 1% slope every metre to prevent water stagnation and filtration inside the prototypes. A 0.07 m thick concrete slab with a rustic finish was made inside each prototype.

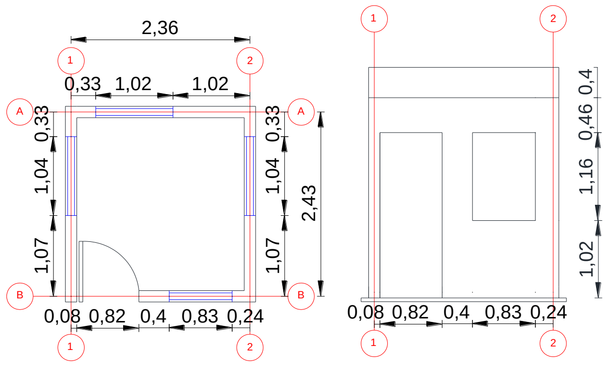

Figure 2 Architectural drawing of prototypes for mortar mix placement and temperature and humidity monitoring

The first prototype was covered with CPC mortar, with a thickness of 0.15 m in a single layer. The walls were previously dampened with abundant water, to prevent part of the moisture in the mixture from being absorbed. The application was carried out on a single day to ensure the same environmental conditions. Alternatively, the coating was applied on the second prototype with C20 mortar at the same thickness. Once the application was completed on both prototypes, the coating was cured in water for 28 days.

According to the standard (ASTM C 1046, 2021), both prototypes must be completely closed, so the windows and doors were sealed with 0.015 m thick wood and the joints as well as the electrical outlets were sealed with polyurethane expanding foam, both inside and outside the prototypes, as shown in Figure 3a and b, exterior and interior, respectively. The monitoring equipment was installed at the centre of each prototype, then closed and sealed to maintain stable conditions inside. The outdoor temperature and humidity sensor (EXT) was installed at a distance of 15 m from the prototypes, using a dht22 sensor measuring temperature between -40 to 125, with an accuracy of 0.5 °C and using a program developed in Arduino software.

Monitoring was carried out under real conditions. Temperature and humidity were recorded every 30 minutes for 24 hours for a period of 12 months both inside and outside the prototypes, thus covering the warm and cold months, to verify the performance of the thermal envelope, also considering that the characteristics of the area have a warm sub-humid climate, where most of the year there are high temperatures and high relative humidity.

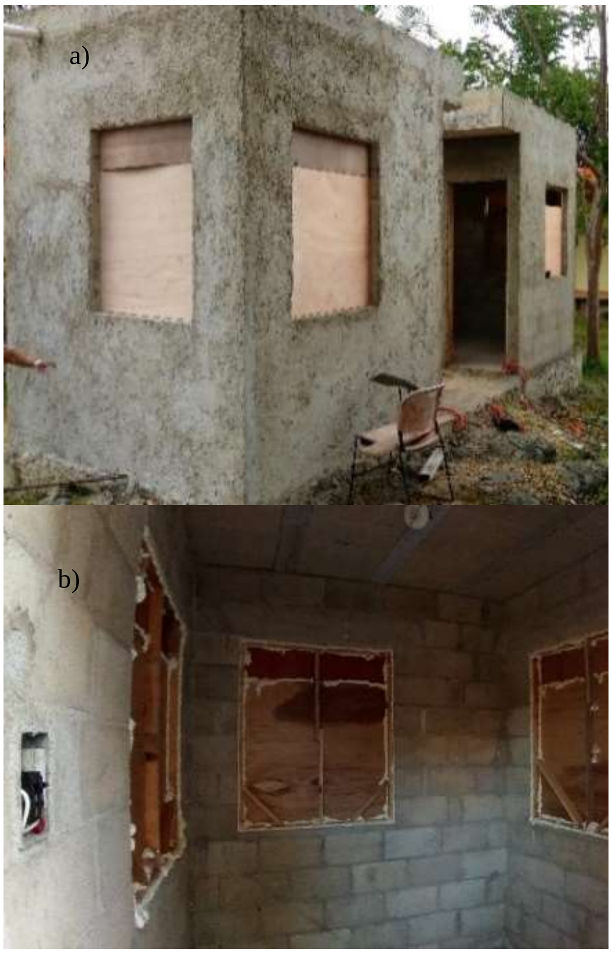

Figure 3 Building prototypes sealed with polyurethane expandable foam. a) Exterior, b) Interior

3. Results and discussion

A coating mortar that is applied outdoors under real climatic conditions must maintain its consistency and workability during the entire application time. To achieve the required flowability, the amount of water had to be higher due to the high degree of absorption of limestone material (Trejo-Arroyo *et al*., 2019) and due to the type of use of the mortar, so the water-cement ratio reached values greater than one.

As for the volumetric weight values of both fine aggregate and polyurethane foam were determined to ensure that each sample is as accurate as possible to the next, with the same substitution ratio, which were 37.20 kg/m3 and 1648.31 kg/m3, respectively.

The results of the compressive strength of the mortars are presented in the graph in Figure 5. The reference mortar, CPC, achieved an average value of 30.86 MPa. The trend showed that the compressive strength of the mortars decreases with increasing PUR substitution. The strength of mortar C15 decreased by 10.5% with respect to the reference mortar, reaching an average value of 27.62 MPa. In the case of mortar C20, the strength decreased by 21.55%, with an average value of 24.21 MPa and finally in the case of mortar C25 the strength decreased by 24.97%.

Despite the 21.55% decrease in compressive strength in mortar sample C20, it was the mortar considered with the best response to be exposed under real conditions, as it does not significantly compromise its mechanical properties. An overlay mortar must withstand a compressive strength greater than 20 MPa, thus benefiting the lowest aggregate consumption natural limestone.

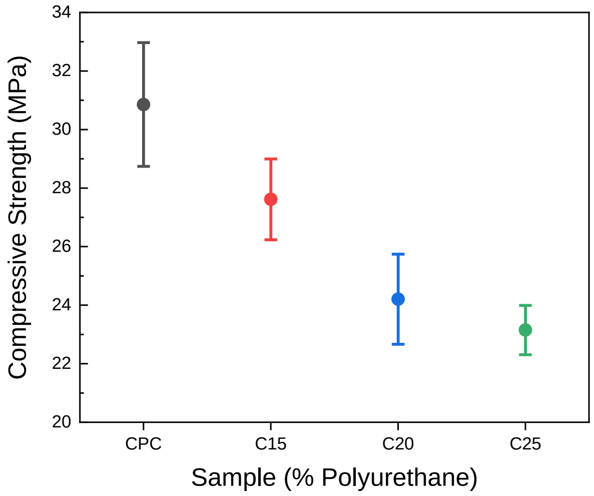

Figure 4 Compressive strength of mortar samples with partial replacement of fine aggregate by PUR

As for the bond strength results, the reference mortar CPC achieved an average value of 11.0461 kg/cm2, as shown in Table 2. These values were obtained after dividing the applied force by the effective contact area of the mortar cylinders with the failure device.

Based on the bond strength obtained from the CPC sample, a decrease in strength of the mortar with 15% PUR substitution of 25.24% was observed. For the case of the C20 and C25 mortars the strength improved considerably compared to the C15 mortar and remained in a stable range with respect to the CPC reference mortar. It is important to mention that, with the addition of the polyurethane foam in the mortar mix, the friction during the placement of the coating in real conditions was considerably reduced and the final finish presented better visual and textural characteristics.

It is also important to highlight that the compressive strength and the adhesion strength between the block and the covering mortar are the most important characteristics of any building envelope, which provides the durability of the material in place and allows it to perform its function correctly, both related, because if one decreases the other is affected, a covering with very high resistance but that does not stay in place due to lack of adhesion, does not work correctly, in the same way a covering that remains adhered, but when hitting it detaches is not considered functional either.

Mortar	σ (kg/cm^2)	Compressive strength (MPa)
CPC	11.046	30.86
C15	8.257	27.62
C20	11.371	24.21
C25	10.694	23.15

Table 2 Results mechanical properties

In the SEM micrograph of Figure 5a, the interaction zone between the cementitious matrix and a PUR particle can be observed. The microstructure of the PUR particles shows a homogeneous interconnected network of pores inside walls with sizes of approximately 50 to 150 µm. According to (Gómez-Rojo *et al.*, 2019) it corresponds to a closed cell type structure in which gas is occluded inside the cells, characteristic of a rigid polyurethane foam type. The mechanical properties can be correlated by the presence and amount of PUR.

The surface of the polyurethane particles has a smooth texture as seen in the image in Fig. 5b, which is inferred to reduce the adhesion with the cementitious paste, in addition to its hydrophobic nature.

The contact surface between the PUR particles and the cementitious mix was analysed and the analyses suggest that the mortar paste coats the polyurethane particles with little adhesion, so that as the percentage of PUR substituted by the limestone aggregate increases, the mechanical resistance tends to decrease.

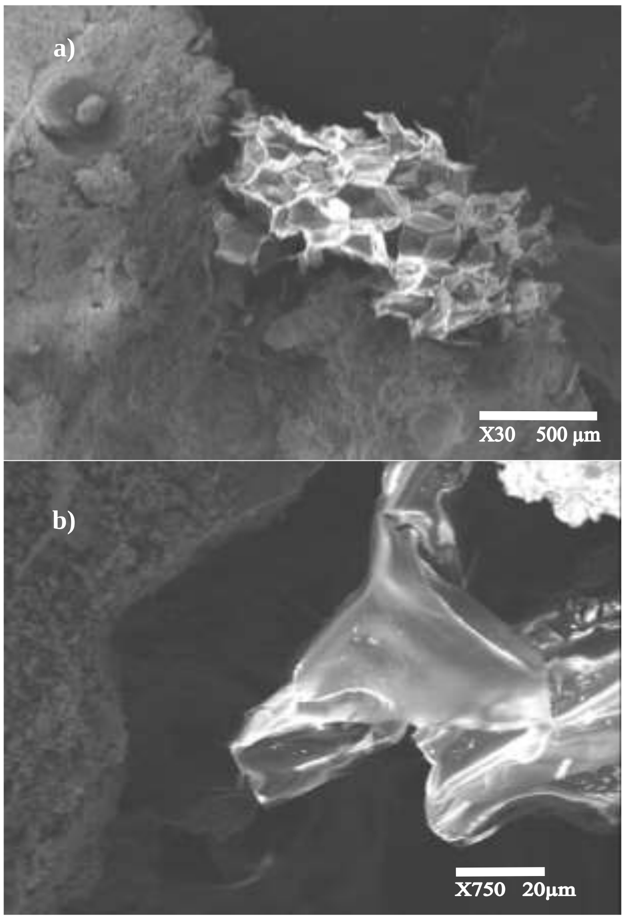

Figure 5 Micrographs obtained by SEM. a) PUR particle surface, b) contact surface between the polyurethane particle and cementitious paste

The results of the thermal conductivity and specific heat tests are presented in Table 3. The general trend indicated that, the higher the amount of fine aggregate substitution by polyurethane foam, the thermal conductivity coefficient tends to decrease, with this trend becoming narrower from 20% PUR substitution onwards. It is important to mention that the thermal conductivity is low but not within the range of the best commercial insulating materials, however, it was decreased compared to traditional coating mortars. In the case of specific heat, it increased with increasing PUR substitution, indicating that more heat is required to raise its temperature; the C15 and C20 mortar samples presented very similar values.

Type of mortar	Thermal conductivity (W/m °C)	Specific heat (kJ/kg °C)
CPC	1.733	0.721
C15	1.711	0.754
C20	1.460	0.752

Table 4 Thermal conductivity results

Figure 6 shows the graph corresponding to the temperature data recorded throughout the year, both for the outside temperature (EXT) and inside the prototypes with the CPC and C20 mortar coating envelope. The months recorded with the highest temperatures were from May to August and it was observed that the EXT temperature was higher than inside both the CPC and C20 prototypes. In September, the EXT temperature started to decrease due to weather conditions, increased rainfall and the arrival of autumn-winter. In addition, the heat flow inside both prototypes also started to decrease, however, as the prototypes were closed and sealed, the temperature remained higher compared to the outside.

If the EXT temperature is compared with the inside temperature of the CPC prototype, the difference is recorded in the order of 0 to 1.8ºC. Comparing the outdoor EXT temperature with the indoor temperature of the C20 prototype, the difference was recorded in the order of 0 to 2.5ºC, which, according to the conditions of the area, of warm sub-humid climate, high temperatures most of the year and high RH, it is noted that a difference of more than 2ºC is very significant which will considerably improve the conditions inside a building.

On the other hand, the results suggest that, in the lowest temperature months recorded, the thermal envelope works in the opposite direction, retaining the temperature inside in both prototypes CPC and C20, however, comparatively the prototype with mortar C20 recorded the lowest temperature in the order of 0 to 1.5ºC during almost the whole year.

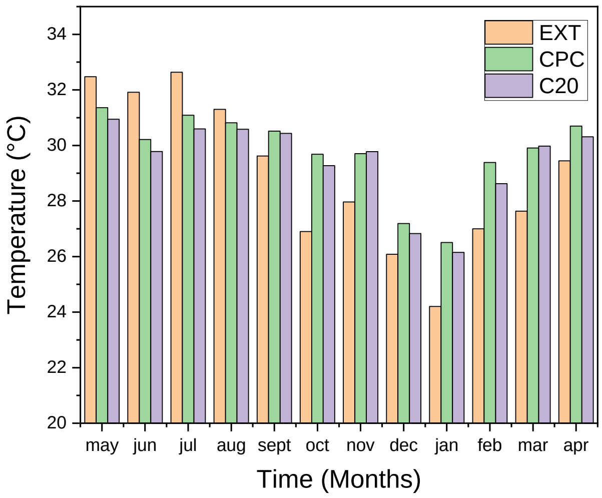

Figure 6 Average temperature record per month, exterior (EXT) and interior of the prototypes with the envelope of CPC and C20 mortar

Regarding humidity, the results of the outdoor (EXT) and indoor data recording of both prototypes with CPC and C20 mortar coating are shown in Figure 7. It shows the monthly average of the three different sensors for the same period of 12 months, it is remarkable how the humidity increases in the months where, in general, rains are more common, it is important to mention that the exterior EXT humidity was lower in the sunniest and warmest months, however, as the months become more rainy, the exterior humidity increased more than the interior of both prototypes, the recording of the humidity inside the prototypes was very similar, only differences between the two were of the order of 0. 5 %, highlighting that unlike the commercial thermal insulators installed in slabs or formwork, this C20 mortar coating did not increase the interior humidity concentration significantly.

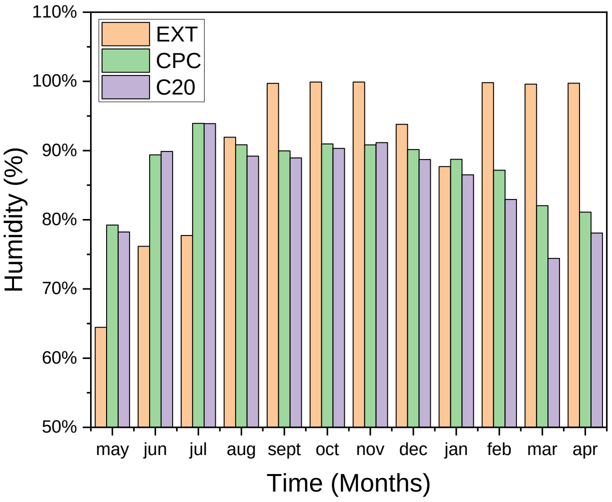

Figure 7 Average humidity record per month, exterior (EXT) and interior of the prototypes with the CPC and C20 mortar envelope

Figure 8a and b shows the average values per month of the minimum and maximum temperature recorded, respectively, for both prototypes CPC and C20. As shown in the graphs, the year-round behaviour of the temperature inside the C20 prototype remained below the minimum temperature recorded in the CPC prototype, both in the minimum and maximum temperature record throughout the year, maintaining a difference between 0 to 1.5°C below. These results suggest that, under real exposure conditions, the modification of the coating mortar mix with the substitution of PUR for limestone aggregate effectively lowers the temperature inside a building.

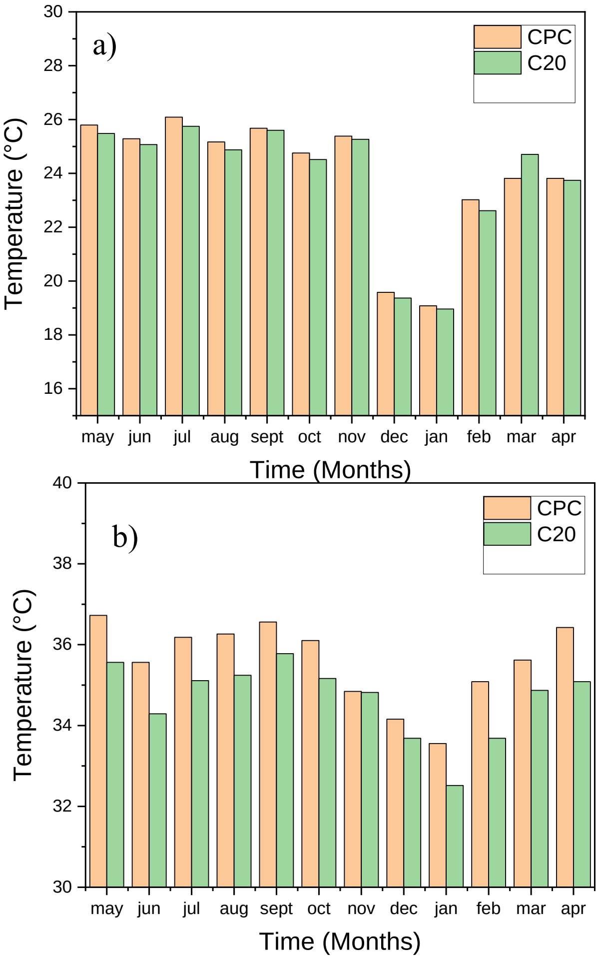

Figure 8 Annual average temperature record. a) Minimum temperature, b) Maximum temperatura

As for relative humidity, the results are presented in the graphs in Figure 9. The average values obtained per month of humidity in both prototypes CPC and C20 are shown, both for the minimum and maximum values, humidity remained constant in both prototypes with differences of less than 0.5 %.

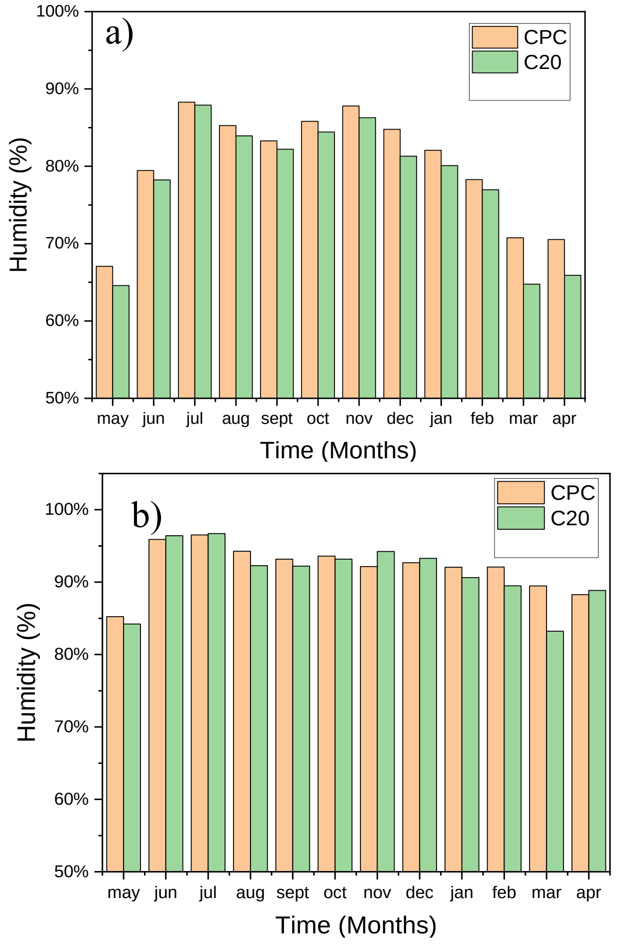

Figure 9 Annual average humidity record, a) Minimum humidity and b) Maximum humidity

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Conclusions

Covering mortars with different percentages of substitution of recycled polyurethane rigid foam (PUR) for fine limestone aggregate were characterised by means of different techniques, in order to evaluate their thermal performance when exposed to weathering under real environmental conditions with high temperatures and high relative humidity most of the year. The results indicated that with increasing PUR substitution content, the compressive strength decreased.

However, from the experimental laboratory tests, it was determined that the coating mortar with 20% partial substitution was the one that obtained the best conditions to be applied in-situ as the envelope of a prototype building and to be exposed to weathering under real climatic conditions. The compressive strength of the C20 mortar was 24.21 MPa and with a bond strength between the facing mortar and the block wall of 11.3710 kg/cm2, very similar to the traditional mortar, which does not compromise the mechanical properties and integrity of the structure.

Regarding the thermal conductivity of the mortar slabs, the results indicated that by increasing the substitution content of PUR for limestone aggregate, the thermal conductivity decreased by 15% compared to that of the traditional mortar, and the specific heat increased, indicating that more energy is required to increase the temperature. The mortar topping envelope with PUR substitution by 20% fine limestone aggregate exposed to real environmental conditions reduced the temperature inside the prototype building by about 1.5°C during most of the year while keeping the humidity constant. Future work could focus on the thermal performance and durability of the mortar with partial replacement of fine aggregate by recycled polyurethane rigid foam applied on the interior walls or roofs as thermal insulation for energy savings in buildings.

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