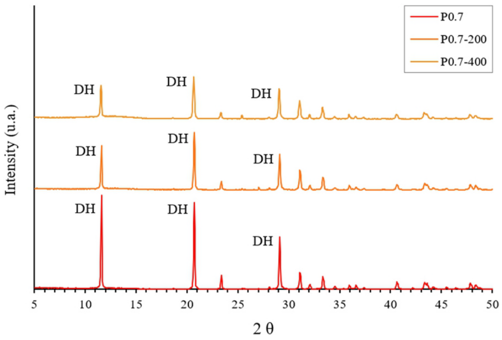

Fig. 9. XRD of the samples P0.7, P0.7–200 and P0.7–400.

21].

3.3. Physico-chemical characterisation

Fig. 9 shows the X-ray diffraction spectra of the reference plaster composites P0.7, P0.7–200 and P0.7–400.

As observed in Fig. 9, all the analysed samples present the characteristic peaks in the plaster composites, corresponding to calcium sulfate dihydrate (DH: $CaSO_4{\cdot}2\ H_2O$), eing indicated in Fig. 9 the most intense peaks, corresponding to 2Θ values of 11.65°, 20.74° and 29.15°. Nevertheless, as the amount of DEW in the composites increases as a partial mass substitution of the original plaster material, the intensity of the peaks reflected in the diffractogram decreases proportionally. This effect can be seen more clearly in Table 4, which shows the decrease in the size of the crystals in each composite.

As can be seen in Table 4, the new plaster composites prepared by replacing the original water/plaster mixture with DEW have a smaller crystal size compared to the reference composite P0.7. Thus, there is a decrease in crystal size relative to the reference composite of 9.79% and 21.85% for P0.7–200 and P0.7–400 respectively.

Below, Table 5 shows the most relevant results obtained from the thermogravimetric analysis (TGA) for compounds P0.7, P0.7–200 and P0.7–400.

As shown in Table 5, the partial replacement of the original plaster material by DEW results in an increase of the total mass loss, with a 6.55% and 11.82% increase compared to the P0.7 sample in P0.7–200 and P0.7–400 composites, respectively. On the other hand, in all the analysed composites, the highest mass loss occurs in the range from 0 °C to 250 °C, corresponding to the transformation of the dihydrate ($CaSO_4$-2 H_2O) into the hemihydrate ($CaSO_4$-1⁄2 H_2O) in an endothermic process. This mass loss is reduced compared to the reference plaster in samples P0.7–200 and P0.7–400 by 1.14% and 1.53%, respectively. Additionally, the plaster composites containing DEW again undergo a second mass loss in an exothermic event in the temperature range 250–550 °C, with P0.7–400 losing the largest proportion of mass in this process. In this case, the maximum mass loss rates are around 390 °C and 480 °C, temperatures that coincide with the combustion of EPS [62]. Finally, in the temperature range of 550–750 °C, the decomposition of calcium carbonate (CaCO3) into calcium oxide (CaO) occurs, with an average mass loss of 1.15% for all compounds.

Table 4
Mean size (D) of the ordered crystalline domains of the samples P0.7, P0.7–200 and P0.7–400.

Sample	Peak position (2θ, degree)	β=FWHM (degree)	Crystallite size D (nm)
P0.7	20.71595	0.12728	66.27
P0.7-200	20.71379	0.14109	59.78
P0.7-400	20.66339	0.16285	51.79

Taking into consideration the results obtained in the TGA and the values collected in the direct real-fire test (Fig. 4), the reference composite P0.7 would have experienced a greater mass loss during the first 5 min of the test, when temperatures reached around 300 °C. On the other hand, P0.7–200 and P0.7–400, composites would have lost a higher amount of mass after 10 min of testing, when temperatures around 450 °C were reached.

Finally, the total carbon analysis has been carried out for the new plaster composites produced. This analysis is highly useful as it allows estimating the amount of CO_2 and CO that could be generated in a fire. For this purpose, a typical room measuring $4 \times 3{\times}2.6\ m^3$ has been considered, where the false ceiling, made of prefabricated panels produced with the materials developed in this research, would be burnt.

In general, carbon in a sample can be present in two forms, inorganic carbon and organic carbon. Inorganic carbon mainly corresponds to carbonates, bicarbonates and dissolved carbon dioxide, while organic carbon is associated with organic matter or compounds. EPS is entirely composed of organic material, therefore, its combustion in the new plaster composites developed would be the main source of CO_2 or CO generation, depending on whether its combustion is complete or incomplete, respectively.

The results obtained in the total carbon analysis are shown in Table 6. The composites analysed were P0.7, P0.7–200 and P0.7–400 since the aim is to determine the impact of introducing DEW into these plaster composites during a fire in terms of emissions. In addition, the inorganic nature of the fibres used would not contribute to the increase in the quantities of CO and CO_2 generated.

From Table 6 it can be observed that total carbon in plaster without additions is very low, mainly due to the presence of $CaCO_3$ [63]. However, as expected, total carbon level raise as the amount of DEW increases while the quantity of plaster material present in the samples decreases. The main increase was reflected in the organic carbon, which increased by up to 15.65% for sample P0.7–400 in comparison to the reference material (P0.7).

Once the total organic carbon of the composites was obtained, the amount of CO_2 and CO that would be generated during a fire if the total combustion of the composites took place was estimated, the results are shown in Table 7.

Both CO_2 and CO emissions calculated in Table 7 increase proportionally with the increment of the quantity of DEW in the composites, with P0.7–400 showing the highest emissions of these gases. The concentration of CO_2 considered hazardous to health is set at levels above 40000 ppm/h [27]; on the other hand, CO is the most dangerous gas arising in fires, and can be lethal at concentrations above 2000 ppm/h [27]. In both cases, neither of the two values considered potentially harmful would be exceeded with any of the compounds developed in this study. Furthermore, it should be noted that the CO_2 and CO values obtained would be generated in the worst-case scenario where all combustion is either complete or incomplete. In this sense, it is usual that, depending on the specific characteristics of the fire (wind, combustible material, etc.), combustion is a combination of both types, resulting in lower emissions of each of these gases.

4. Conclusions

Currently, the international community's efforts towards a more sustainable production model in the construction industry are leading to the development of alternative materials with the incorporation of plastic waste, in which the effect of a fire on people's safety is rarely analysed. In an innovative approach, this study analyses the behaviour in a real fire of plaster composites in which the original raw materials have been partially replaced by EPS in dissolution. Additionally, the influence of incorporating different high-temperature resistant reinforcement fibres is analysed, as well as an evaluation of the potential emissions of toxic gases associated with the combustion of these

Table 5
Summary table of the thermogravimetric analysis of compounds P0.7, P0.7–200 and P0.7–400.

Sample	Total mass loss (%)	Interval (°C)	Máx. temperature (°C)	Partial mass loss (%)	Associated heating effects	Coments
P0.7	21.30	0-250	129.06	19.70	Endothermal	DH to HH
			147.38		Endothermal	HH to anhydrite
		250-550	363.23	-	Exothermal	Anhydrite phase transition
		550-750	642.20; 672.07	1.13	Endothermal	$CaCO_3$ to CaO
P0.7-200	27.85	0-250	129.06	18.56	Endothermal	DH to HH
			143.31		Endothermal	HH to anhydrite
		250-550	387.67; 479.30	7.82	Exothermal	EPS combustion
		550-750	636.77; 666.64	1.17	Endothermal	$CaCO_3$ to CaO
P0.7-400	33.12	0-250	130.42	18.17	Endothermal	DH to HH
			143.99		Endothermal	HH to anhydrite
		250-550	392.42; 480.66	13.64	Exothermal	EPS combustion
		550-750	632.70; 666.64	1.09	Endothermal	$CaCO_3$ to CaO

Note: Calcium sulphate dihydrate (DH); calcium sulphate hemihydrate (HH).

Table 6
Results of total carbon analysis of P0.7, P0.7–200 and P0.7–400 composites.

Sample	Analysed mass (mg)	Total carbon (%)	Inorganic carbon (%)	Organic carbon (%)
P0.7	100	0.49	0.32	0.17
P0.7-200	100	7.87	0.38	7.49
P0.7-400	100	16.22	0.4	15.82

composites. From the results obtained, the following conclusions can be drawn:

- The incorporation of DEW as partial replacement of the original raw materials in plaster composites has resulted in savings of up to 23% in the consumption of these natural resources. This new way of reusing EPS waste is technically feasible and represents a step towards the production of more sustainable alternative materials in the building sector.
- The new plaster composites produced with the addition of DEW showed a significant reduction in their density, this decrease being directly proportional to the amount of residue added. Furthermore, these composites recorded the lowest temperatures during the fire test and did not exhibit cracks after exposure to flames, in contrast to the reference plaster.
- The basalt and glass fibres as reinforcement contributed to mitigate the mass loss experienced by the composites with DEW addition after fire by 1.10% and 1.80% respectively. During the direct real-fire test, it was observed that the composites with basalt fibres presented the highest peak temperatures, while the plaster with glass fibres were the ones that started their cooling process the fastest.
- The flexural strength of the composites decreased drastically after exposure to flame in all cases. However, all plasters with DEW incorporation in replacement of the original raw materials showed higher strengths than the reference without additions. For the glass fibre reinforced composites, the highest residual strengths were observed in those composites without waste incorporation, with plaster P0.7-FV showing 25% higher flexural strength compared to P0.7-400-FV. On the other hand, the addition of DEW in composites with basalt fibres increased the flexural strength by 58% and 16% in composites P0.7-200-BF and P0.7-400-BF respectively.
- The plaster with DEW recorded higher compressive strength compared to the P0.7 reference after fire action, by 85% and 100% for the P0.7-200 and P0.7-400 composites respectively. The incorporation of reinforcement fibres improved these results considerably; however, the addition of DEW was more beneficial in combination with basalt fibres, increasing the strength of the P0.7-BF plaster by 60% with the addition of 200 g of DEW.
- SEM images show that once solidified, DEW adheres to the gypsum crystals, reducing the connections between them, thus reducing the mechanical strength of the composites at ambient temperature. On the other hand, when the material is exposed to high temperatures, the pathways generated after EPS degradation promote the release of the vapour contained in the matrix, increasing the material's residual strength.
- After analysing the crystal size determined by XRD, it was found that the size of the gypsum crystals decreases as the amount of residue added increases, up to 21.85% in the case of the P0.7-400 composite.
- The TGA results indicate that the composites made with DEW as replacement for plaster would have better preserved their integrity during the first 5 min of flame exposure compared to the reference plaster. Once a temperature of around 450 °C was reached, these composites would begin to lose a higher proportion of mass due to the degradation temperature of the EPS.
- During the combustion of the compounds designed in this research, the estimated CO and CO_2 emissions did not exceed the maximum concentrations established by the IDLH standard for both gases in any case.

The limitations of this work include the lack of analysis of other toxic gases emitted in smaller proportions that could also pose a potential danger to people in the event of fire. Additionally, it should be noted that the performance of the direct real-fire test, being a non-standardised test, does not allow for the classification of the material within the European Reaction to Fire classification system. In this sense, it would be valuable to determine the fire resistance using the standardised test included in ISO 834, as well as to carry out a study of the economic feasibility for the development of these materials. Therefore, this opens a line of research that enables other tests such as combustibility, fire rating and large-scale fire response tests which would provide complementary and more detailed knowledge about the fire behaviour of the new plaster composites developed in this research.

Table 7
Estimation of CO_2 and CO emitted in the combustion of false ceiling panels made with P0.7, P0.7–200 and P0.7–400 composites in a typical room of 12 m^2.

Plate	Bulk density (kg/m^3)	Plate mass (kg)	CO_2 emitted (kg)	CO emitted (kg)	CO_2 emitted (ppm)	CO emitted (ppm)
P0.7	1104.56	165.68	1.03	0.66	33.10	21.06
P0.7-200	935.31	140.30	38.53	24.52	1234.94	785.87
P0.7-400	850.17	127.53	73.97	47.07	2370.94	1508.78

CRediT authorship contribution statement

Zaragoza-Benzal Alicia: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ferrández Daniel:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Prieto M. Isabel:** Writing – review & editing, Validation, Methodology. **Atanes-Sánchez Evangelina:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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3.6. Development and characterization of new lightweight waste-based plaster composites for building applications

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Development and characterization of new lightweight waste-based plaster composites for building applications

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ABSTRACT

The development of new environmentally friendly construction materials that incorporate waste as an alternative to traditional raw materials is becoming increasingly important and necessary for the construction sector. Gypsum plasters composites are characterised by their versatility and wide range of applications in precast construction due to their excellent technical performance and low cost. This research presents a new material that incorporates EPS waste in solution and recycled rubber aggregates as secondary raw materials, partially replacing traditional plaster material. In this way, partial mass substitutions of up to 12.5 % have been achieved compared to the reference composites without additions. The results show how the incorporation of EPS in solution allows a more homogeneous integration of the residue in the plaster composite matrix. Although it is true that the incorporation of both residues has slightly reduced mechanical resistance to bending and compression, reaching minimum values of 3.71 MPa and 5.08 MPa respectively, the results obtained greatly exceed the minimum values required by current regulations. On the other hand, in the study conducted with prefabricated false ceiling plates, it has been observed that the combined effect of both residues allows for greater resistance to simple bending than traditional composites, with a reduction in bulk density and thermal conductivity of up to 30.1 % and 26.5 %, respectively. Thus, this work presents a viable alternative for the development of new plaster composites that are more sustainable, lightweight and conducive to advancing towards the industrialisation of the construction sector.

1. Introduction

According to current estimations, the number of end-of-life tyres (ELTs) discarded annually is expected to reach 1.2 billion units by 2030 [1]. Faced with this serious problem, the EU has taken on the challenge of recovering and revaluing this waste to reduce its environmental impact [2]. Traditionally, ELTs have been accumulated in landfills or incinerated for energy recovery [3]. However, it is known that ELTs take about 100 years to decompose [4], generating microplastics during this decomposition process and polluting groundwater and watercourses [5]. On the other hand, when these solid wastes are burned, harmful emissions such as SO_x, NO_x and VOCs are produced [6]. This alarming situation, along with the creation of the European Green Pact, which advocates for industrial

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mobility to improve sustainability [7], has led several researchers to look for different ways of revalorising ELTs for their application in civil engineering and building works [8–10].

Currently, the construction industry is moving towards the integration of circular economy models aimed at reducing the volume of waste generated and mitigating its accumulation in landfills, while also prolonging the lifespan of developed products over time [11]. In this sense, the chemical nature of gypsum composites makes them products with a high degree of recyclability [12], which has prompted several studies using this binder as a base material for the integration of ELT waste and the development of more sustainable building materials, as shown in Table 1.

The necessity to develop new prefabricated materials to reduce the cost of housing construction projects has spurred research focused on gypsum composite materials [28]. In this sense, plasterboard (also known as gypsum board [29]) has enabled a reduction in the time and costs associated with interior cladding execution, improving finish quality while increasing operator productivity and safety [30,31]. The excellent hygrothermal regulation capacity of gypsum materials, traditionally used as cladding materials, makes them ideal for manufacturing panels for false ceilings and interior partitions [32].

As shown in the literature review summarised in Table 1, the incorporation of ELTs waste improves the thermal and acoustic properties of the resulting composites. It also reduces the water absorption of the analysed plaster materials [14,16,19,20]. On the

Table 1
Review of studies with ELT incorporation in gypsum composites.

Reference	Type of Waste	Studied Incorporation	Application	Main Results
[13]	Rubber: 0–1; 1–2; 2–4 mm	Volume fractions: 1-3-5%	Gypsum Plaster	Decrease in mechanical strength compared to the reference plaster. Increase elasticity modulus of the composites, higher water retention and heterogeneous distribution of the rubber.
[14]	Rubber. 0–0.6; 0.5–2.5; 2.5–4.0 mm	Weight Additions: 30-40-50-60 %	Gypsum Plaster	Thermal performance is improved especially with the fine fraction, reducing density. The elastic nature of the recycled rubber improved the acoustic performance against impact noise.
[15]	Textile Fiber: 2–8; 6–26 mm (length)	Weight Additions: 1-2-3-4%	Gypsum Plaster	Substantial reduction in mechanical strength. The presence of the fibres reduces adhesion to the plaster matrix. Heterogeneity in fibre composition and morphology.
[16]	Rubber. 0–0.6; 0.5–2.5; 2.5–4.0 mm	Weight Additions: 30-40-50-60 %	Gypsum Plaster	There is an increase in total water absorption coefficient, open porosity and capillary water absorption in all composites, being more significant the increase in the finer rubber fraction.
[17]	Rubber: 0.063–0.800 mm	Weight Additions: 5 % (rubber)	Gypsum Plaster	Plaster composites with 12 mm carbon fibre in 1-1.5-2% by weight addition improve the mechanical properties (especially flexural strength) of composites with rubber addition.
[18]	Rubber Fiber: 2.5–10.0 mm (length)	Volume fractions: 3-5-8-15-20 %	Gypsum Plaster	Rubber fibres are added, causing a decrease in mechanical strength, but an increase in toughness and an improvement in the thermal resistance of the gypsum composites.
[19]	Rubber: 0.5-2-5; 4 mm; Textile Fiber	Textile Fiber: 20 g Rubber: 10 % vol.	Gypsum Plaster	ELT waste and $(C_3H_3NaO_2)_n$ additions improve the thermo-acoustic performance, reducing the overall warming potential of traditional composites by 34 % and maintaining zero flame spread in case of fire.
[20]	Textile Fiber: 4–18 mm (length) Expanded Polystyrene	Weight Additions: 1 % Textile fiber EPS 150-300-450 g/kg of gypsum	Gypsum Plaster and EPS solution	Capillary water absorption and total water absorption decreased in the produced plaster composites, along with the water vapour permeability. Thus, good mechanical performance is obtained after moisture-dryness cycling. Its lower density makes it suitable for sustainable prefabricated products, with lower thermal conductivity and higher supply chain efficiency.
[21]	Rubber: 0.60 mm and 1.19 mm	Weight Additions: 5-10-15 %	Gypsum	Higher gypsum-rubber adhesion in the 0.60 mm diameter fraction, presenting a high capacity to maintain the internal temperature during the coldest periods, although lower mechanical resistance.
[22]	Rubber: 0–0.50 mm	Weight Additions: 14.5 % and 46.6 %	Gypsum	There is a decrease in density and mechanical strength. In addition, these residues reduce the effectiveness of gypsum coatings in protecting building and structural elements against fire.
[23]	Rubber: 2–8 mm	Volume fractions: 10-20-30-40-50 %	Gypsum Plaster	Classified as lightweight material according to ACI 213R-87, with reduced capillary absorption, thermal conductivity and diffusivity compared to traditional plaster composites, and can be used in prefabrication according to Algerian specifications standard (DTR C3.2).
[24]	Rubber Crumbs: 0.315–5.000 mm	Weight Additions: 5-10-100 %	Semi-aqueous Gypsum	Replacing sand with rubber in quantities: 5-2.5 mm (6 %); 2.5–1.25 mm (29 %); 1.25–0.63 mm (29 %) and 0.63–0.315 mm (7 %), increases the sound absorption coefficient by 31 % compared to the control sample.
[25]	Rubber tyre chips: 0.063–2.000 mm	Weight Addition: 5-10-15 %	Gypsum	Compositions of 400 kg/m^3 sand with the addition of rubber and gypsum in a proportion of 5-10-15 % by weight improve the stability and compressive strength of peat soils.
[26]	Textile fibers: 108.2–12469.1 μm	Weight Addition: 1-2-3%	Gypsum	The addition of ELT textile fibres and crushed cork to reduce the density of gypsum blocks allows to increase the fracture energy and to have optimal compressive strengths.
[27]	Rubber: 2.5–4 mm	Weight Addition: 9–18 %	Gypsum	Recycled mineral wool fibres were used to improve the mechanical strength of rubber-lightened gypsum composites, reducing thermal conductivity and developing prefabricated blocks.

Table 2
Main results obtained in studies with EPS waste incorporated in gypsum-based materials.

Reference	Studied Incorporation	Main Results
[38]	EPS aggregates: 1-2-3% by weight	Using gypsum and plaster binders, the configurations analysed exceeded the mechanical resistance requirements set out in UNE-EN 13279-2.
[39]	EPS aggregates, 0.5-1.0-1.5 lb. additions	The produced composites showed their suitability to produce sound reflection plates especially for low frequencies (250 Hz).
[40]	EPS Particles 0–3 mm: 20-40-60-80 % by volume	A tragacanth solution of 0.5–1.0-1.5 % by weight is added to the gypsum composites with EPS, reducing the thermal conductivity and mechanical resistance. The material is conceived as a decorative plaster.
[41]	EPS aggregates, addition of 120-450-1100 g	The EPS waste is thermally treated to reduce its volume and increase its density, achieving compressive strengths of 136 kPa, density of 194 kg/m^3 and thermal conductivity of 60.4 mW/m·K.
[42]	EPS aggregates: 0–80 % with increments of 10 % by volume	The thermal and acoustic resistance of gypsum composites increases progressively as the percentage of EPS waste added increases.
[43]	EPS aggregates: 4-5-10-15 % by weight of gypsum	Four configurations of prefabricated lightweight gypsum blocks were designed for use as high ductility partitions.

other hand, the inclusion of rubber residues reduces mechanical flexural and compressive strengths. This creates a heterogeneous matrix that reduces the ductility of the precast products, with better performance of gypsum composites with incorporations of granular rubber in a fine fraction of diameter less than 0.60 mm [13,15,21,22]. However, while these studies are relevant for ELT waste recovery, revalorisation and recycling, as the industrialisation of the sector advances, it is essential to evolve towards more sustainable solutions that allow the development of more efficient modular components and increase the circularity of construction products.

In this research, the addition of ELT rubber waste is combined with thermal insulation residues derived from External Thermal Insulation Composite Systems (ETICS). The utilisation of ETICS in existing residential buildings has witnessed rapid expansion in recent decades due to increasingly stringent energy efficiency requirements [33]. In installed ETICS, polymeric expanded polystyrene (EPS) insulation has been used in preference [34]. This insulation type offers advantages such as low cost compared to other insulations, as well as a low density that facilitates its handling and improves its thermal resistance [35,36]. However, its recycling process is complex due to the number of impurities in the EPS waste (adhered mortar, dust, fungi, etc.), which makes it necessary to include cleaning stages for its physicochemical recycling [37]. An alternative approach involves thermal treatment of these high calorific value wastes, which leads to large greenhouse gas emissions and a strong environmental impact [34].

Some authors have used shredded EPS waste as a secondary raw material to produce gypsum composites of lower density and thermal conductivity, as shown in Table 2.

However, no study has been found that explores the combined effect of including waste from ELT and EPS in the production of plaster materials. Thus, as an innovative contribution of this study, a new plaster composite incorporating dissolved EPS waste is presented to enhance the integration of this plastic waste in the matrix, as well as the incorporation of ELT rubber powder. The aim is to conduct a physicochemical and mechanical characterisation to explore potential applications of these novel materials, thereby advancing towards greater sustainability of construction products.

2. Methodology

This section presents the methodology used to conduct this research work. To this end, this section includes the materials used, the sample preparation process and the experimental programme describing the characterisation tests performed.

2.1. Materials

The following raw materials were used to produce the new plaster composites developed in this research: gypsum plaster, water, rubber aggregates from ELT, EPS wastes and universal solvent.

Gypsum plaster used as a binder material, it is characterised by its high purity and quality [44]. The most relevant characteristics of the E−35 Iberyola plaster (supplied by the company Placo Saint-Gobain) are shown in Table 3.

Water from the Canal de Isabel II (Madrid, Spain) was used for the mixing of the composites. This is drink water which has been successfully used in other research works [19,20,27], and is characterised by a hardness of 26.85 mg/l $CaCO_3$, a total chlorine content of less than 0.96 mg/l and a pH of 8.38 [48].

Rubber aggregates from ELT, with an average diameter between 0 and 0.8 mm and mixed morphology (acicular and angular). These composites were supplied by the non-profit organisation SIGNUS Ecovalor, S.L. (Madrid, Spain). Their main characteristics are presented in Table 4.

On the other hand, these rubber aggregates have the following percentage chemical composition: ketone extract (10–20 %), polymers (40–55 %), natural rubber (21–42 %), carbon black (30–38 %), ashes (3–7%) and sulphurs (0–5%).

EPS wastes from facade rehabilitation using ETICS in the Community of Madrid and supported by the Housing Rehabilitation and Urban Regeneration Plan [49]. The EPS waste obtained was manually shredded to obtain pieces with a diameter of less than 5 cm. Its characteristics include a low thermal conductivity of 0.035 W/m·K, bending strength of more than 200 kPa and density of 28–30 kg/m^3.

Universal solvent obtained from volatile hydrocarbons. It is a colourless, non-water soluble compound, whose main characteristics are [50]: density at 20 °C (ASTM D 1298/4052) 0.812 ± 0.020 g/cm^3, vapour pressure 85.5 mmHg and flash point of -8 °C.

Table 3
E–35 Iberyola plaster properties according to EN 13279-1 and provided by the manufacturer [45,46].

Thermal conductivity (W/m·K)	0.30	**Particle size (mm)**	0–0.2
Water vapour diffusion (μ)	6	pH	>6
Purity index (%)	92	**Flexural strength (MPa)**	3.0
Fire performance EN 15824: 2009 [47]	A1	**Global Warming Potential (kgCO$_2$/kg)**	0.25

Table 4
Properties of rubber aggregates from ELT used for the preparation of the new plaster composites.

Density (kg/m^3)	Humidity (%)	Textile Material (%)	Ferromagnetic Material (%)	Others (%)
1100–1127	<0.75	<0.50	<0.1	<0.25

2.2. *Sample preparation*

For the plaster composites mixing process, the techniques and methods described in the current standard EN 13279–2:2014 [51] have been used. This process is shown schematically in Fig. 1.

As can be seen in Fig. 1, on the one hand, a slurry is obtained as a result of mixing the EPS waste and universal solvent in a 1:2 ratio by weight with a final bulk density of 650 ± 10 kg/m^3. On the other hand, the plaster powder, pre-mixed with recycled rubber aggregates, is kneaded with water. In this way, by incorporating the slurry into the liquid mixture of the plaster compound, a more homogeneous mixing process is achieved; enhancing the integration of the EPS residue into the matrix. The water/plaster ratio by weight was determined using the shaking table method, resulting in a paste consistency of 165 ± 5 mm, which in turn corresponded with a final water/plaster ratio of 0.7. Finally, it should be noted that the specimens were cured for seven days under laboratory conditions (23 ± 2 °C and 50 ± 5 % relative humidity), and 24 h before being tested, they were placed in an oven at a temperature of 40 ± 2 °C and 50 ± 5 % relative humidity. This process favours the evaporation of the solvent that did not evaporate during the exothermic reaction of the setting of the plaster composites. It is worth highlighting that the elaboration process shown in Fig. 1 has been originally designed to produce the new gypsum composites analysed in this research work, so that this methodology can be replicated by other researchers interested in the development of new gypsum materials with improved physical and mechanical properties.

Table 5 displays the weight dosages used for the development of the new plaster materials, indicating the partial substitution by weight of the original raw materials (plaster and water) with the incorporated residues for each compound manufactured. It should be noted that the quantities listed in Table 5 correspond to the required proportions to produce a series of three standardised prismatic RILEM specimens of 40 × 40 × 160 mm^3. In addition, Fig. 2 shows a cross-section of the samples produced in which the matrices of the different plaster composites can be seen. Thus, the good integration between the matrix of the composite with and without the addition of EPS slurry and the rubber aggregates from ELT can be observed.

The reincorporation of secondary raw materials into the manufacturing process of new, more sustainable construction materials is a key challenge today, as it is estimated that the global solid waste generation will reach 7 Mt by 2025 [52]. For this reason, as shown in Table 5, achieving the replacement of up to 12.5 % by weight of the original plaster raw material in the composites developed in this

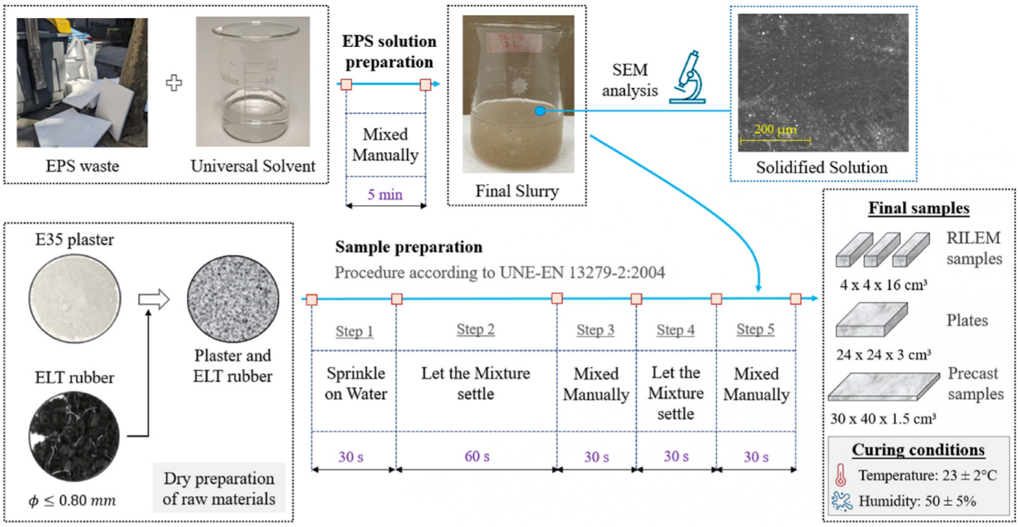


Fig. 1. Preparation process of the new developed plaster composites.

Table 5
Weight proportions used to produce the plaster composites.

	Sample	Plaster (g)	Water (g)	Rubber (g)	Slurry (g)	Raw Material Saving (%)
Series 1	P0.7	1000	700.0	–	–	–
	P0.7–1%	990	693.0	17.0	–	1.0
	P0.7–1.5 %	985	689.5	25.5	–	1.5
	P0.7–2%	980	686.0	34.0	–	2.0
	P0.7–2.5 %	975	882.5	42.5	–	2.5
Series 2	P0.7-EPS	900	630.0	–	170	10.0
	P0.7-EPS-1%	890	623.0	17.0	170	11.0
	P0.7-EPS-1.5 %	885	619.5	25.5	170	11.5
	P0.7-EPS-2%	880	616.0	34.0	170	12.0
	P0.7-EPS-2.5 %	875	612.5	42.5	170	12.5

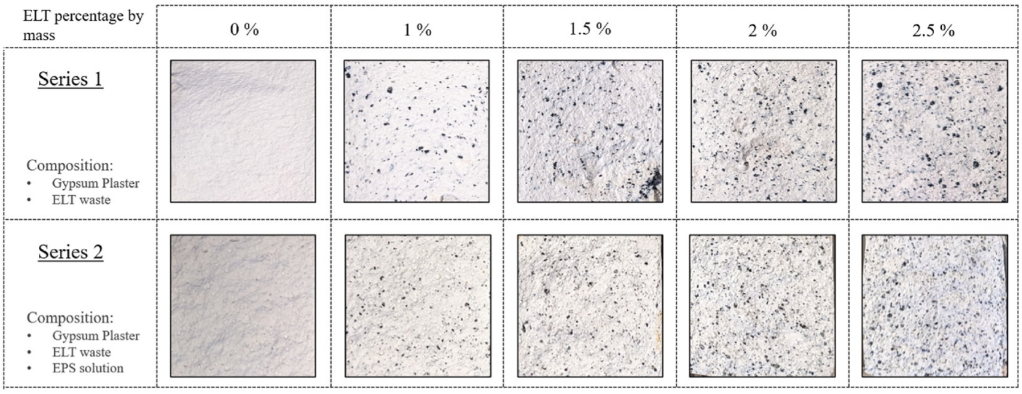


Fig. 2. Cross-section of the different plaster composites produced in this research.

research represents progress towards incorporating circular economy criteria in the building sector. This percentage gains particular significance within Spanish context, where the volume of municipal solid waste generated annually is approximately 22 million tonnes, of which only 43.3 % is recovered [44]. On the other hand, Fig. 2 shows how the incorporation of the EPS waste in solution during the mixing process generates a compact and homogeneous matrix, with no significant visual differences between series 1 and series 2. This innovative process for the recirculation of construction waste represents a step forward in the development of more sustainable plaster composites with a similar finish to traditionally used materials.

2.3. *Test methods*

During the development of the experimental campaign proposed for this research, physicochemical and mechanical characterisation tests were carried out on the produced plaster composites. The different phases of this experimental programme, together with the tests included in each of the stages, can be seen schematically in Fig. 3.

In a first phase, physicochemical characterisation tests of the composites were carried out by X-ray diffraction (XRD) and thermogravimetric analysis (TGA). For these analyses the sample is taken from the centre of one-half of a sample resulting from a flexural test. The sample is taken from the fractured face of the sample, ground in an agate mortar and sieved to a particle size of 0,3 mm. XRD was performed using a Siemens Krystalloflex D5000 with a Cu-Kα graphite monochromator. The diffraction angles analysed were between 5° $\leq 2\theta \leq$ 60° measured every 0.04° and a time of 4 s per step. Once the diffractograms were obtained, the average size of the ordered crystalline domains in the sample could be determined with the following equation:

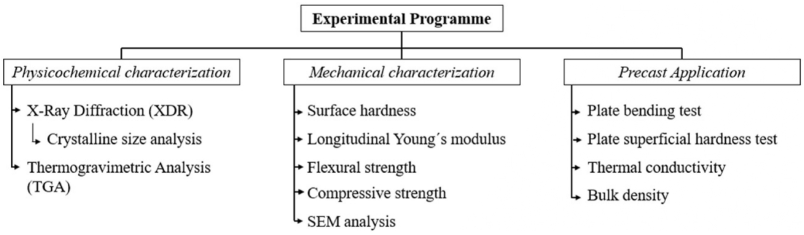


Fig. 3. Schematic breakdown of the experimental programme.

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

where D is the average crystallite size (nm), k is the Scherrer constant taken as 0.94, λ is the wavelength of the Cu-Kα radiation (1.54056 Å), β is the Full Width at Half Maximum (FWHM) of the X-ray peak in radians, and θ is the Bragg angle also in radians [53]. The FWHM was calculated using the most intense peak of calcium sulphate dihydrate at $2\theta = 20.742°$. This parameter provides information about the microstructure of a sample, and how the setting process of the gypsum develops.

On the other hand, a TA Instruments SDT Q600 was used for the TGA analysis, using a heating rate of 10 °C/min from room temperature up to 1000 °C, in a pre-filtered air atmosphere with a flow rate of 100 ml/min. A sample mass of approximately 40–50 mg is analysed. This analysis provides information about the composition of the samples and also corroborate that the chemical reactions related to the setting of the gypsum composites have been carried out correctly. Therefore, it is an indirect measure of the quality and repeatability of the preparation process of the tested samples incorporating different components in solid phase (plaster and rubber) and in liquid phase (EPS solution).

Subsequently, a mechanical characterisation was conducted and the following tests were carried out:

- *Surface hardness* using Shore C hardness tester and following the recommendations outlined in the UNE 102042:2023 standard [54]. Standardised samples of 40 × 40 × 160 mm^3 are used, taking five measurements on two plane-parallel longitudinal faces of the sample. This determination is carried out on a total of three samples (30 measurements per sample). The measuring points are positioned along the longitudinal axis, with a minimum separation of 20 mm between points and between the hardness tester and the ends of the prismatic sample.
- *Longitudinal elasticity* modulus using ultrasonic equipment, consisting of two sensors (transmitter and receiver) connected to the Ultrasonic Tester E46. A transmission frequency of 50 kHz was used, taking readings of the time of passage in the longitudinal direction of the samples. Three readings were taken per dosage, using prismatic samples measuring 40 × 40 × 160 mm^3.
- *Mechanical resistance to bending and compression* obtained according to the current UNE-EN 13279–2:2014 standard [51]. Tests were conducted using an IBERTEST press model AUTOTEST 200-10SW on standardised prismatic samples measuring 40 × 40 × 160 mm^3. To determine the flexural strength, a total of six samples of each dosage were tested, applying a loading speed of 10 N/s until the sample broke. On the other hand, the compressive strength was determined on the 12 semi-metrics obtained from the bending test, using a progressive loading speed of 20 N/s.

Additionally, with the aim of completing this mechanical characterisation, a scanning electron microscopy (SEM) analysis has been carried out. This test was performed with the aid of a Jeol JSM-820 microscope operating at 20 kV and equipped with Oxford EDX analysis. Samples for analysis were obtained in such a way as to ensure an unmodified surface of the compounds. The sample was then coated with a superficial coating of conductive gold using a Cressington 108 metalliser.

Finally, a study was conducted to explore the potential applications of the new plaster composites developed for the manufacture of prefabricated panels for false ceilings. In this part of the experimental programme, the following tests were carried out:

- *Plate bending test* was carried out on 400 × 300 × 15 mm^3 plates using a Proeti, S.A. For the tests, the recommendations of standard EN 12859:2011 [55] were followed. A total of three plates of each dosage were tested.
- *Impact hardness on plates* was determined according to standard EN 12859:2011 [55], measuring the diameter produced by a 50 mm diameter steel ball falling on the plate from a height of 50 cm. Five measurements were taken per plate.
- *Thermal conductivity* was obtained by the thermal box method using 300 × 300 × 30 mm^3 samples. Measurements were recorded with the aid of thermocouples placed on the surface of the plate forming the wall of the thermal box, recording the measurement for 24 h under stationary conditions with a thermal jump between parallel faces of 40 ± 2 °C [56].
- Bulk density: determined according to the procedure given in UNE 102042:2023 [54], using the weight and volume of prismatic specimens of 40 × 40 × 160 mm^3.

3. Results and discussion

In this section, the results obtained from the different tests conducted and their discussion are presented, following the order established in the experimental programme.

3.1. Physico-chemical characterisation

Fig. 4 shows the results obtained for the X-ray diffraction test, taking the samples with and without EPS solution, with ELT rubber percentages of 0 % and 2.5 % by weight.

After analysing Fig. 4, it can be seen that all the composites analysed, regardless of the type of waste added, exhibit diffraction peaks corresponding to gypsum dihydrate ($CaSO_4 \bullet 2H_2O$), being the three most intense ones those corresponding to diffraction angles of $2\Theta = 12°$, 21° and 29° [57]. This diffractogram also allows the assessment of the decrease in the crystallite size of the processed samples with the increase in recycled raw material content. The results of this analysis for the four composites studied are presented in Table 6.

Thus, Table 6 shows how the crystallite size decreases in the samples with partial substitution of the original plaster material by secondary raw materials. Compared to the reference composite P0.7, decreases of 15.6 % (P0.7–2.5 %), 11.4 % (P0.7-EPS) and 22.3 % (P0.7-EPS-2.5 %) are observed [58]. The decrease in crystalline size may result in a less dense packing of the crystals, which could

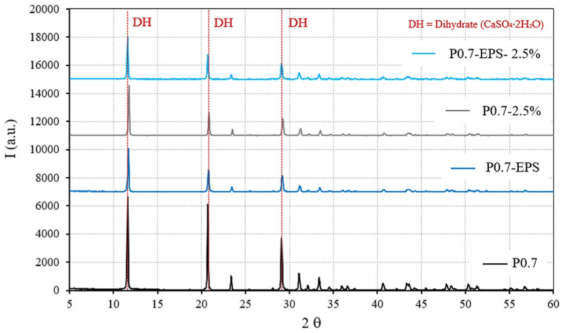


Fig. 4. Diffractogram corresponding to composites P0.7, P0.7-EPS, P0.7–2.5 % and P0.7-EPS-2.5%-.

Table 6
Mean size (*D*) of the ordered crystalline domains of the samples P0.7, P0.7–2.5 %, P0.7-EPS and P0.7-EPS-2.5 %.

Sample	Peak Position (2Θ, degree)	β = FWHM (degree)	Crystallite Size (nm)
P0.7	20.71596	66.75	64.73
P0.7–2.5 %	20.85505	54.23	54.63
P0.7-EPS	20.79303	55.45	57.34
P0.7-EPS-2.5 %	20.71774	48.38	50.30

result in a lower mechanical properties compared to the reference composite and also the lower density and therefore lighter weight of the composites. On the other hand, Table 7 presents the results obtained for the thermogravimetric analysis of the samples, highlighting the temperatures, partial mass losses and associated thermal events.

Hence, Table 7 shows that replacing more plaster with recycled raw material leads to an increase in the total mass loss of the composite materials developed. This mass loss compared to the reference (P0.7) increases by 5.08 %, 6.01 % and 10.1 % for the composites P0.7–2.5 %, P0.7-EPS and P0.7-EPS-2.5 %, respectively. However, there are similarities in all the cases analysed. Thus, the highest mass loss always occurs through an endothermic event at temperatures below 250 °C corresponding to the transition from DH to HH and subsequently from HH to anhydrite [59]. The results of the thermogravimetric analysis correlate with the XRD analysis, which also shows the presence of dihydrate. This corroborates that the chemical reactions related to the setting of the gypsum composites have been carried out correctly.

Table 7
Results of Thermogravimetric Analysis (TGA) of the samples P0.7, P0.7–2.5 %, P0.7-EPS and P0.7-EPS-2.5 %.

Sample	Total Mass Loss (%)	Interval (°C)	Maximum Temp. (°C)	Partial Mass Loss (%)	Associated Heating Effect	Comments[a]
P0.7	21.58	<250	129.18 144.64	19.800	Endothermic	DH to HH HH to anhydrite
		250–550	360.48	–	Endothermic	Anhydrite phase transition
		550–700	641.54677.18	1.224	Endothermic	$CaCO_3$ to CaO
P0.7–2.5 %	26.66	<225	129.18 139.93	18.160	Endothermic	DH to HH HH to anhydrite
		225–600	–	7.118	Exothermic	Rubber combustion
		600–700	639.52 668.43	1.160	Endothermic	$CaCO_3$ to CaO
P0.7-EPS	27.59	<250	129.18 141.95	18.480	Endothermic	DH to HH HH to anhydrite
		250–550	388.72 480.84	7.964	Exothermic	EPS Combustion
		550–700	635.49 664.40	1.120	Endothermic	$CaCO_3$ to CaO
P0.7-EPS-2.5 %	31.66	<225	131.19 143.30	17.170	Endothermic	DH to HH HH to anhydrite
		225–600	377.96 471.42 563.54	13.28	Exothermic	EPS + Rubber Combustion
		600–700	637.50 665.07	0.311	Endothermic	$CaCO_3$ to CaO

[a] DH = Dihydrate ($CaSO_4 \cdot 2H_2O$); HH = Hemihydrate ($CaSO_4 \cdot 1/2H_2O$).

In the case of the reference compound P0.7, a second endothermic event is obtained at a temperature close to 360 °C, corresponding to the transition from anhydrite α to anhydrite β, which does not entail partial mass loss. However, this second thermal event is masked in the composites with added plastic waste (EPS solution and ELT rubber), since in them, in the same temperature range, an exothermic event occurs, which also causes a loss of mass as a consequence of the (exothermic) combustion of the secondary raw materials, rubber and EPS, both of organic nature. For the sample containing only EPS solution, this second mass loss occurs at around 388 °C, with a lower mass loss at around 480 °C, due to the combustion of the polystyrene [60].

In the case of ELT rubber composites, the mass loss occurs progressively from 250 °C to 600 °C, presenting different stages according to the complex chemical nature of the rubber residues [61,62]. It is observed that this second mass loss of the composites increases proportionally to the recycled raw material content, being higher for the P0.7-EPS-2.5 % sample (13.28 % mass loss by combustion). Finally, the third and last thermal event observed in all the composites is endothermic and corresponds to the thermal decomposition of $CaCO_3$ present in the plaster. This reaction produces CaO at temperatures above 635 °C.

3.2. Mechanical characterisation

Regarding the mechanical characterisation of the new plaster composites developed, Table 8 shows the results obtained for the surface hardness and the longitudinal elasticity modulus determined by ultrasound technique.

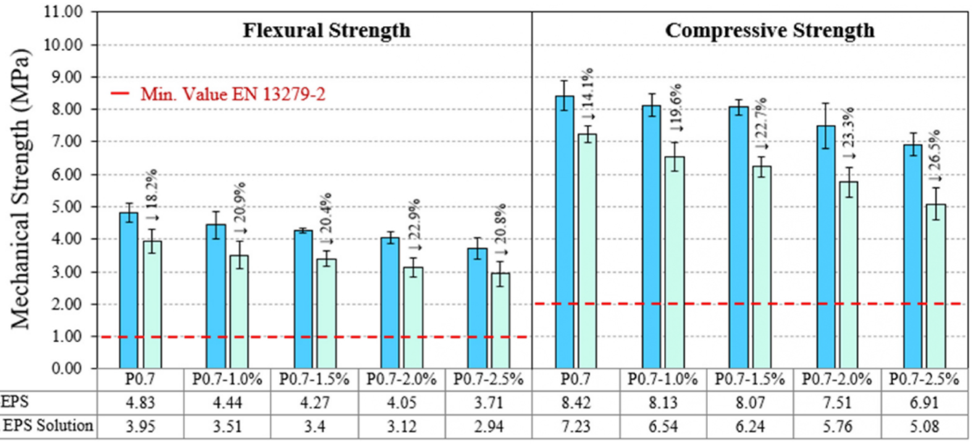
As can be seen in Table 8, the surface hardness of the developed composites decreases as the content of the added secondary raw materials increases. As can be observed, the elastic nature of the ELT rubber waste decreases the surface hardness, a phenomenon that has been contrasted by other authors who have worked with waste from polymeric materials with these characteristics [14,17]. On the other hand, composites with EPS solution incorporation have a lower Shore C hardness, as a consequence of the lower content of plaster material and the reduced surface hardness of EPS [38]. In line with these results, a progressive decrease in MOEus has been obtained for the plaster composites as the recycled raw material content increases, being lower in the composites with the addition of EPS solution. These results, in agreement with those obtained by other researchers [63], lead to a progressive decrease in mechanical strength as the original plaster is replaced by the recycled materials. The maximum decrease in surface hardness and MOEus compared to the reference composite P0.7 has been 17.0 % and 36.4 %, respectively, for the composite P0.7-EPS-2.5 %.

Fig. 5 shows the results obtained for flexural and compressive strength. The results have been separated by test type and based on whether or not they contain EPS solution in the plaster composite matrix. The minimum value established by the EN 13279-2 standard for these composite materials has been included, which is set at 1 MPa and 2 MPa for flexural and compressive strength, respectively [51].

As can be seen in Fig. 5, the plaster mix substitution by ELT rubber leads to a progressive reduction in the mechanical strength of the composites as the proportion of the waste increases in the dosages. Specifically, the lowest strengths were obtained in the P0.7–2.5 % plaster, with a decrease of 23.19 % and 17.93 % for flexural and compressive strength, respectively. These effects have been observed

Table 8
Results for Shore C surface hardness and modulus of elasticity by ultrasounds (MOEus).

Surface hardness (Shore C units)			MOEus (MPa)		
Sample	Non-EPS	With EPS solution	Sample	Non-EPS	With EPS solution
P0.7	79.30 ± 0.17	76.43 ± 1.76	P0.7	12459.4 ± 255.3	8772.2 ± 348.4
P0.7–1.0 %	78.80 ± 0.46	67.20 ± 0.78	P0.7–1.0 %	10727.1 ± 651.4	7358.6 ± 99.3
P0.7–1.5 %	78.50 ± 0.10	64.53 ± 1.89	P0.7–1.5 %	10781.9 ± 187.9	6852.9 ± 281.9
P0.7–2.0 %	77.17 ± 0.85	63.70 ± 0.46	P0.7–2.0 %	9995.5 ± 180.4	6298.3 ± 221.6
P0.7–2.5 %	74.93 ± 0.68	63.40 ± 0.53	P0.7–2.5 %	9335.0 ± 140.7	5581.8 ± 208.1



	P0.7	P0.7-1.0%	P0.7-1.5%	P0.7-2.0%	P0.7-2.5%	P0.7	P0.7-1.0%	P0.7-1.5%	P0.7-2.0%	P0.7-2.5%
■ Non-EPS	4.83	4.44	4.27	4.05	3.71	8.42	8.13	8.07	7.51	6.91
□ With EPS Solution	3.95	3.51	3.4	3.12	2.94	7.23	6.54	6.24	5.76	5.08

Fig. 5. Results for the flexural and compressive strength of the elaborated plaster composites.

in composites where rubber residues and other polymers have been used in gypsum matrices [13,64]. On the other hand, the incorporation of EPS dissolution in gypsum and rubber composites generates a further decrease in strength. While in flexural strength, this reduction is around 20 % on average, in compressive strength, the impact is greater as the amount of rubber in the mixtures increases, varying between 19 % and 26 %. The results obtained show how the combination of dissolved EPS with ELT rubber mainly affects the compressive behaviour of the plasters. However, all the composites produced in this research far exceeded the minimum values indicated in the EN 13279-2 standard [51].

In general terms, the main drawback derived from the incorporation of secondary raw materials in gypsum composites is the decrease in their mechanical strength, as can be seen in Fig. 5. For this reason, some authors opt to use reinforcing fibres to improve ductility and increase the breaking strength, as well as to reduce the water/plaster ratios in order to develop more compact composites with higher compressive strength. However, both techniques have their complexity, since in the first case it is necessary not only to ensure an adequate dispersion of the fibres in the matrix but also to obtain an optimum percentage of addition by weight, while in the second strategy it is necessary to maintain the workability of the samples by reducing the water/conglomerate ratio through the use of plasticisers that seriously increase the cost of the final product [65]. Therefore, it is interesting to know the relative position of the composites developed in this research with respect to the compressive and flexural strength values obtained in other studies in the literature dealing with the recycling of ELT and EPS. This comparative discussion is presented in Fig. 6, where the excellent mechanical behaviour obtained in the composites developed in this work is reflected.

As can be seen in Fig. 6, the values obtained for the flexural and compressive strengths of the composites designed in this work are comparatively higher than those obtained by other researchers. Thus, it is shown how the integration of the dissolved EPS waste in the original plaster composite matrix improves the mechanical properties of the gypsum composites with the incorporation of ELT rubber waste. The mechanical properties of the materials designed in this research have only been surpassed by those gypsum composites that have been reinforced by the incorporation of synthetic fibres [17,20]. Thus, in a potential application of these composite materials for the development of industrialised construction products, it would be interesting to analyse the impact of incorporating reinforcement fibres in the matrix, such as glass, polypropylene, basalt or carbon fibres.

Finally, in order to gain a deeper understanding of the internal microstructure of the new composites developed, SEM analysis has been carried out and it is presented in Fig. 7. For this analysis, the two samples with the highest rubber recycled aggregate content, i.e. P0.7–2.5 % and P0.7–2.5%-EPS, were selected. These samples were chosen under the criteria of being the ones with the highest recycled raw material content in each of the series, with and without EPS solution. On the other hand, after analysing different areas, the most representative images obtained at 20, 250 and 1000 magnifications were selected. In this way, the greatest possible information was gathered about the matrices of the composites analysed.

As can be seen in the image with lower magnification of the P0.7–2.5 % composite, Fig. 7(a) shows how some ELT aggregates are well integrated, while others present some defects at the bond interface, which would explain the reduction in the mechanical properties of the composites. On the other hand, some pores produced during setting can be seen. For the same number of increments in Fig. 7(b) corresponding to the P0.7-EPS-2.5 % sample, a higher porosity caused by the addition of the EPS solution can be observed. These pores contribute to reduce the final bulk density of the composites and decrease their mechanical strength. As the number of magnifications increases for the P0.7–2.5 % sample, in Fig. 7(b), the integration of the ELT rubber residue in the composite matrix is observed in detail, which was already observed out by Herrero del Cura in his doctoral thesis [66]. Small pores caused by the

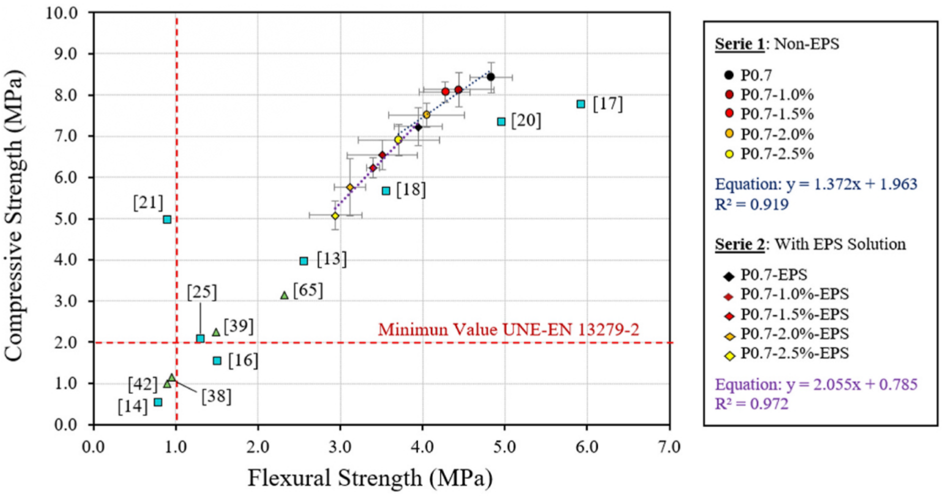


Fig. 6. Compressive strength vs Flexural strength for the new plaster composites developed in this work (Serie 1 and Serie 2) and comparison to the literature. Where [13]: Gypsum with 5 % wt. ELT rubber (0.6–2.5 mm) [14]; Plaster with 34 % vol. ELT rubber (0–0.6 mm) [16]; Plaster with 50 % wt. ELT rubber (2.5–4 mm) [17]; Plaster with 5 % wt. ELT rubber (0.06–0.8 mm) and carbon fiber [18]; Plaster 20 % vol. ELT rubber fiber (2.5–10 mm) [20]; Plaster with 1 % wt. textile fiber and EPS solution [21]; Gypsum with 15 % wt. ELT rubber (0.6–1.2 mm) [25]; Gypsum mortar with 50 % sand and 50 % ELT rubber (0–1 mm) [42]; Gypsum with 80 % vol. EPS waste [38]; Gypsum with 3 % wt. EPS waste [39]; Gypsum with 60 % vol. EPS waste [65]; Gypsum with 3 % wt. XPS waste.

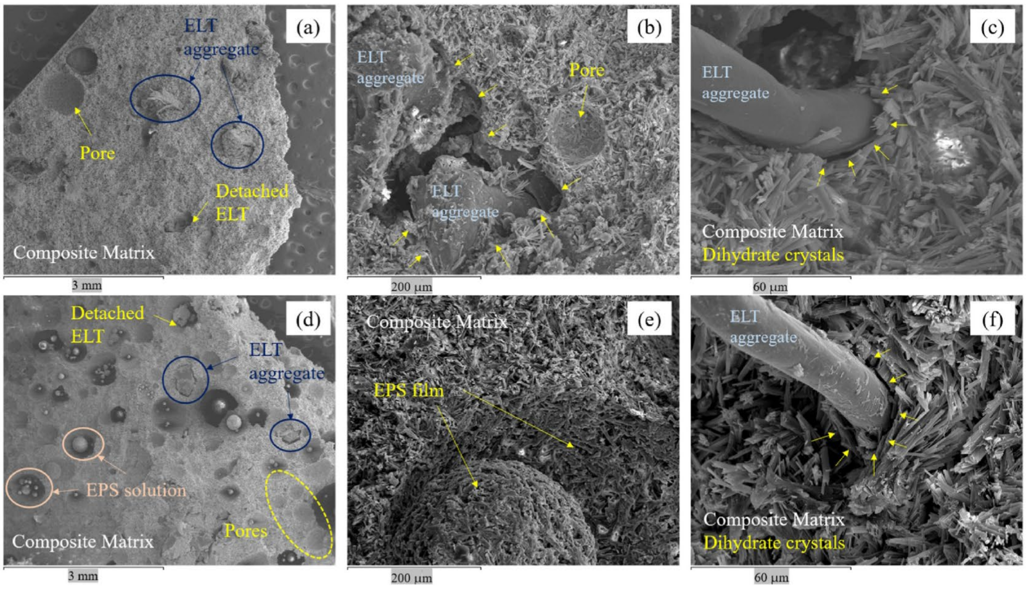


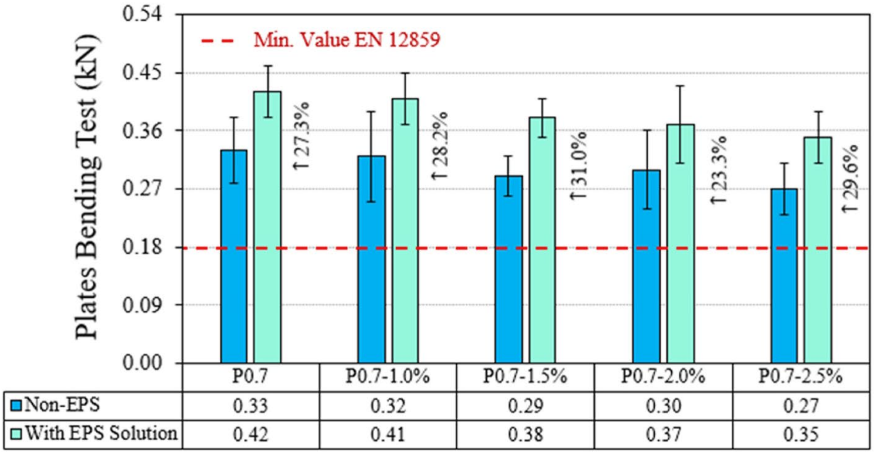
Fig. 7. SEM analysis, for samples P0.7–2.5 % (a, b, c) and P0.7-EPS-2.5 % (d, e, f). Magnifications × 20 (a, d), × 250 (b, e) and × 1000 (c, f).

evaporation of the free kneading water are also shown. In Fig. 7(c) the formation of the dihydrate crystals is shown ($CaSO_4 \bullet 2H_2O$), with their characteristic acicular morphology [59], around the waste (ELT granulate). Finally, for the compound with the highest amount of residue added, sample P0.7-EPS-2.5 %, upon magnification at × 250 magnifications (Fig. 7(e)), the formation of a plastic film coating the dihydrate pores as a consequence of the solidification of the added EPS can be seen [67].

In addition, the presence of EPS causes the dihydrate crystals to agglomerate into spheres, driven by the solidification of the EPS once the solvent has evaporated. The formation of these spheres may result in the discontinuity of the three-dimensional matrix of the composite formed by the dihydrate crystals, and may explain the lower mechanical properties of composites incorporating EPS compared to those without it. On the other hand, Fig. 7(f), shows again how around the ELT rubber particles the gypsum crystals in the matrix develop again in an appropriate way, even though traditional plaster material has been partially replaced by EPS solution. However, it is true that the crystallite size was reduced as confirmed by the physicochemical analysis (Table 6), with respect to the sample without additions.

3.3. Application for the development of precast products

In the third phase of the characterisation of the newly developed plaster composites, their feasibility for the development of sustainable building precast products, especially designed for the production of ceiling panels, has been analysed. The application of these gypsum-based precast elements is widely used in the building industry [65]. However, the urgent need to find solutions to reduce



	P0.7	P0.7-1.0%	P0.7-1.5%	P0.7-2.0%	P0.7-2.5%
Non-EPS	0.33	0.32	0.29	0.30	0.27
With EPS Solution	0.42	0.41	0.38	0.37	0.35

Fig. 8. Maximum ultimate load for the plate bending test on the plaster composites.

Table 9
Impact hardness test on plates. Results for footprint diameter in millimetres.

Sample	Non-EPS		With EPS solution	
	Footprint (mm)	Comments	Footprint (mm)	Comments
P0.7	14.5 ± 0.6	Broken	15.3 ± 0.8	Non-Broken
P0.7–1.0 %	15.0 ± 0.7	Broken	15.7 ± 0.6	Non-Broken
P0.7–1.5 %	14.0 ± 0.4	Non-Broken	15.0 ± 0.7	Non-Broken
P0.7–2.0 %	14.7 ± 0.7	Non-Broken	15.3 ± 0.6	Non-Broken
P0.7–2.5 %	14.8 ± 0.5	Non-Broken	15.3 ± 0.4	Non-Broken

the consumption of non-renewable raw materials and to recover waste materials has driven the development of new, more efficient and technically feasible construction systems [27]. In this section, Fig. 8 shows the results obtained for the plate bending test.

In the results presented in Fig. 8, it is especially noteworthy that all the composites produced with partial replacement of the original plaster material by EPS solution showed a higher breaking strength in the simple bending test on plates. In fact, the P0.7-EPS sample showed a breaking load up to 27.3 % higher than the traditional P0.7 plaster. This is a breakthrough for the building sector, as it implies that composites with the incorporation of secondary raw materials in partial substitution of the original composites can achieve optimum strengths to be competitive in the market. Furthermore, it underscores the importance of conducting tests on composites at scales close to the real ones, as behaviour can sometimes differ depending on the geometry and size of the samples [27].

On the other hand, the progressive incorporation of granular waste from ELT has followed a similar trend to that obtained in Fig. 5, with the maximum breaking load decreasing as the mass content of rubber waste increased. This effect has been observed by other researchers who have worked with plastic waste in plaster composites, such as electrical cable waste [68], polycarbonate waste [69] or rubber fractions from ELTs larger than 2 mm [23].

Table 9 compiles the results obtained for the impact hardness test on prefabricated plaster plates. It includes both the diameters of the footprint produced after the impact of the steel ball on the surface of the plate, as well as annotations indicating the final state of the precast plate after the test.

From the analysis of Table 9, it can be deduced that the composites with the addition of EPS waste solution showed a higher deformation after impact, which is reflected in a larger footprint diameter. These results, in line with those obtained for the Shore C surface hardness, reflect the higher deformation energy absorption capacity of these composites with the addition of secondary raw materials. Likewise, the P0.7 and P0.7–1% samples did not pass the test, since due to their higher brittleness they broke after impacting the steel ball on their surface, as shown in Fig. 9. Thus, the incorporation of lightweight aggregates is beneficial for impact attenuation, as observed by Álvarez et al. in their study with plasters and additions of natural expanded aggregates [70].

Finally, it is necessary to know the thermal conductivity and its relationship with the bulk density of the composites developed in this research. These two physical properties are directly related to the final energy efficiency of the plaster composites and their potential application as lightweight prefabricated products in buildings. The results obtained for the materials developed are shown in Fig. 10.

As shown in Fig. 10, the addition of granulated rubber from ELT reduced the thermal conductivity progressively as the amount of residue increased, with values up to 15.17 % lower compared to the reference plaster (P0.7). This effect has already been observed in previous studies by other researchers [14]. Likewise, by incorporating dissolved EPS in the mixtures to replace the plaster mix, the thermal conductivity of the composites experienced an even more notable decrease, reaching reductions of up to 26.53 % in the P0.7-EPS-2.5 % composite with respect to the plaster without additions. It should be noted that, although it is true that recycled rubber from ELT in combination with dissolved EPS increases the thermal resistance of conventional plasters, the results obtained show that dissolved EPS is the addition that has the greatest impact on reducing the thermal conductivity of the hardened plaster material.

On the other hand, the thermal conductivity is strongly linked to the bulk density of the composite materials [20]. Fig. 11 shows how the density of the composites decreased proportionally to the amount of recycled rubber added. Likewise, the incorporation of the EPS solution instead of traditional plaster material significantly reduced the density of the composites, obtaining values on average 17.53 % lower than those obtained with the addition of rubber alone. The lowest density was obtained in the P0.7-EPS-2.5 % composite, with a reduction of about 30 % compared to the reference sample (P0.7).

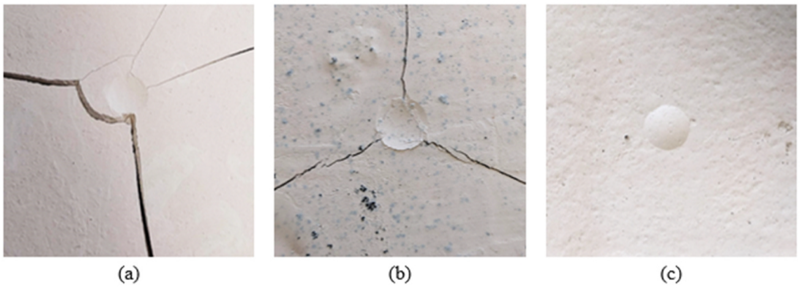
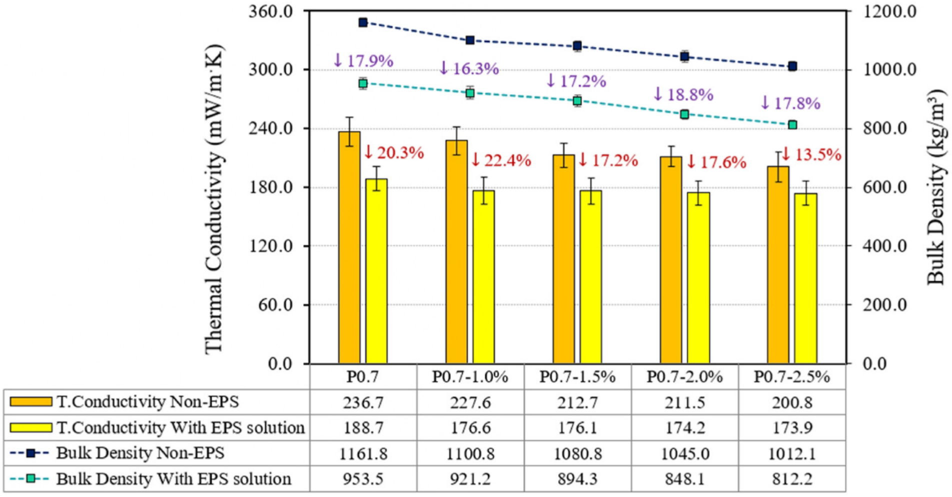

(a) (b) (c)

Fig. 9. Footprint left on specimens after impact hardness testing on plates: (a) P0.7; (b) P0.7–1%; (c) P0.7-EPS-1%.



	P0.7	P0.7-1.0%	P0.7-1.5%	P0.7-2.0%	P0.7-2.5%
▨ T.Conductivity Non-EPS	236.7	227.6	212.7	211.5	200.8
▨ T.Conductivity With EPS solution	188.7	176.6	176.1	174.2	173.9
--■-- Bulk Density Non-EPS	1161.8	1100.8	1080.8	1045.0	1012.1
--■-- Bulk Density With EPS solution	953.5	921.2	894.3	848.1	812.2

Fig. 10. Results for thermal conductivity and bulk density of the prepared plaster materials.

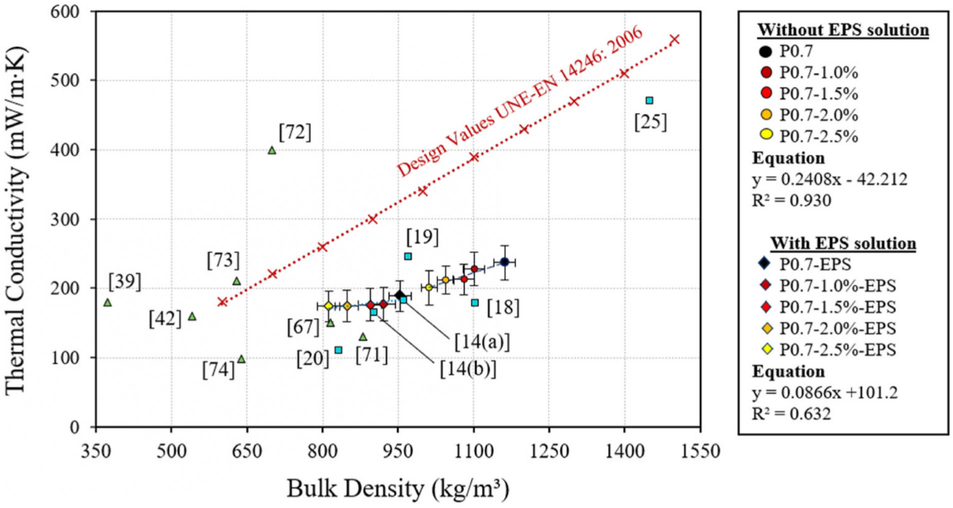


Fig. 11. Thermal conductivity vs Bulk density for the new plaster composites developed and comparison to the literature. Where [14]: (a) Gypsum with 40 % wt. ELT Rubber (2.5–4 mm), (b) Gypsum with 40 % wt. ELT rubber (0–0.6 mm) [18]; Plaster with 15 % vol. Rubber Fibre (2.5–10 mm) [19]; Plaster with 16.4 % ELT rubber (2.5–4 mm) and ($C_3H_3NaO_2$)$_n$ [20]; Plaster with 1 % wt. Textile Fibre and EPS solution [25]; Gypsum Mortar with 50 % ELT rubber and 50 % dune sand [39]; Gypsum with 60 % vol. EPS waste [42]; Gypsum with 60 % vol. EPS waste [67]; Plaster with 17.6 % wt. EPS solution [71]; Plaster with triturated XPS waste [72]; Gypsum with triturated EPS and ceramic waste aggregates [73]; Gypsum with 1.5 % wt. EPS waste [74]; Gypsum with 40 % vol. EPS waste and 1 % wt. tragacanth.

Thus, Fig. 11 shows how all the composites developed in this research present optimal values for the design of plaster prefabricated elements in accordance with EN 14246:2006 [75]. Furthermore, although it is true that other existing composites in the literature have a lower density and thermal conductivity compared to the plaster composites analysed, when analysing Fig. 6, we observe that the mechanical strengths of these are lower than those obtained for the materials studied in this research. This fact places the new composites in a situation of competitive advantage in product differentiation, where a material with good thermal performance has been obtained, lightened and with adequate mechanical strength for use in construction.

3.4. *Critical reflection and implications for industry*

In recent decades, the building sector has been immersed in a process of industrialisation that is moving towards the development and application of new prefabrication techniques and systems [76–83]. This transition makes it possible to move towards more responsible production models that make it possible to reduce the generation of waste on site, although it is true that newly developed systems must comply with the specifications set out in the current regulations and the relevant quality standards [84]. In this work, new composites have been developed with partial replacement of the original plaster material by secondary raw materials for use in buildings. Figs. 12 and 13 show a qualitative analysis of the most relevant properties obtained for the composites analysed.

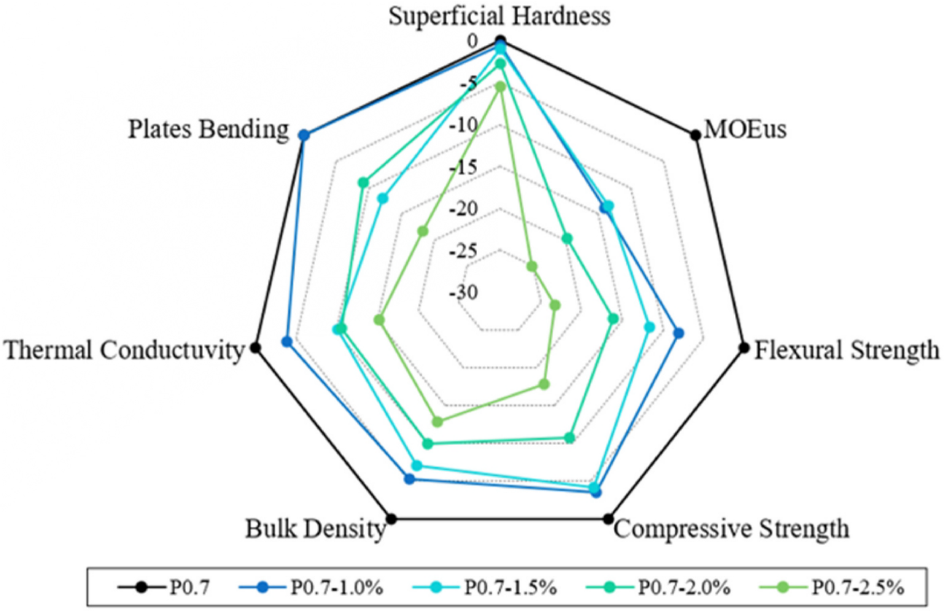


Fig. 12. Visual comparative analysis of the physical-mechanical properties for plaster composites without EPS solution.

While it is true that, in all the cases included in Figs. 12 and 13, there is a percentage decrease in mechanical strength as the added recycled material content increases, at no point did the values fall below those stipulated by current regulations. Thus, not only are more environmentally sustainable products obtained with a replacement of the original raw material by up to 12.5 % in mass, but progress is also made towards their possible commercialisation. The plaster composites produced are lighter, easier to transport and offer a sustainable alternative to traditional prefabrication systems.

On the other hand, to complement the information included in Figs. 12 and 13, an analysis of variance (ANOVA) is included in Table 10. The following factors have been considered: (A) type of dosage, with and without EPS solution, (B) percentage of recycled rubber aggregate added. For each property, the basic assumptions of the model were tested: independence, homoscedasticity and normality of the residuals. For the interpretation of Table 10 it is noted that a p-value below the significance level ($\alpha = 0.05$) can be considered statistically significant for that property analysed and factor involved.

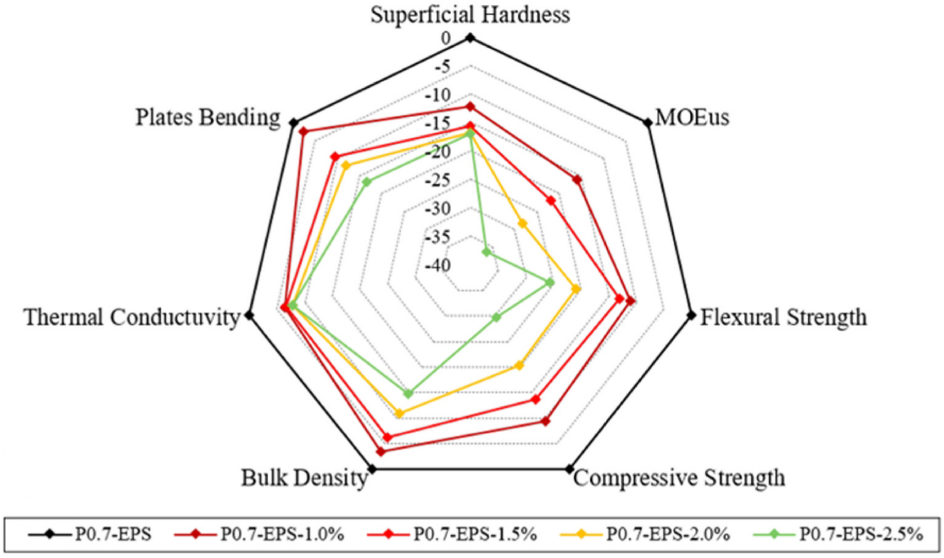


Fig. 13. Visual comparative analysis of the physical-mechanical properties for plaster with EPS solution.

Table 10
Analysis of variance (ANOVA) for the different properties analysed: p-value obtained for each factor studied.

Factor	MOEus (MPa)	Surface hardness (Shore C Units)	Flexural strength (MPa)	Compressive strength (MPa)	Plates bending test (kN)	Thermal conductivity (mW/m·K)	Bulk density (kg/m^3)
A	3.52E-19	4.82E-18	2.90E-07	9.66E-11	1.04E-04	6.88E-08	7.90E-19
B	1.01E-12	1.68E-11	1.66E-04	4.43E-07	1.70E-01	3.10E-02	7.56E-12

The suitability of these plaster composites for the production of prefabricated components has also been analysed and understood as complete or semi-complete components. These components can be assembled *in situ* for the development of construction systems, reducing not only the volume of waste generated as a result of the execution process but also reducing on-site manufacturing times [85]. All developed composite materials exceeded the minimum breaking load value set by the regulations, and even incorporating EPS solution in the plaster composite matrix, the flexural strengths of the ceiling panels were improved while reducing their density and thermal conductivity. This is a key advantage of these prefabricated systems, as they could help mitigate greenhouse gas emissions by reducing energy consumption in buildings, which currently for European residential buildings is currently around 41 % of total energy consumption [86].

Compared to traditional construction technologies, prefabrication increases productivity, improves the safety of operators and the quality of the final product and helps reduce noise in cities. It reduces the need for manpower, improves the schedules' predictability and reduces dust levels [87,88]. Finally, it is worth highlighting how the replacement of the original plaster material by secondary raw materials helps mitigate the environmental impact associated with obtaining plaster binder in the supply phase, as reported by Romero-Gómez et al. in their study [84].

4. Conclusions

In this research, a physicochemical and mechanical characterisation has been conducted on a new plaster composite with the addition of rubber powder from ELT in combination with EPS waste in solution. The incorporation and revaluation of these secondary raw materials as a substitute for natural resources has made it possible to achieve a more sustainable material, in line with the circularity objectives imposed for construction products by the European Commission and other international organisations. The following conclusions can be drawn from the results obtained:

- The reuse of recycled materials in this research has allowed a reduction in the use of original raw materials by up to 12.5 % in the production of plaster composites.
- The results show a decrease in the surface hardness of the composites, ranging from 15.3 % to 17.0 %; however, a greater capacity for absorbing deformation energy was observed, resulting in more elastic and impact-resistant plaster composites.
- The secondary raw materials demonstrated good integration with the plaster matrix. Specifically, the addition of EPS solution generated significant porosity in the samples, reducing the longitudinal elasticity modulus by up to 36.4 % in the most unfavourable case. Nevertheless, a fairly cohesive matrix was maintained in all cases.
- It has been observed how the crystallite size is reduced in the composites produced with the addition of secondary raw materials, affecting their mechanical strength to a certain extent. Nevertheless, microscopic analyses show an adequate formation of the dihydrate crystals, although the crystallite size was smaller compared to the plaster without additions.
- Mechanical strengths in prismatic samples were affected as the added recycled material content increased, however, they still showed values above those set by the current regulations. It is worth noting that all the composites showed a higher flexural strength in plates than the plaster without additions, with the P0.7-EPS composite obtaining the best results, showing a 27.3 % higher strength than the reference sample (P0.7).
- Likewise, the composites produced obtained a lower thermal conductivity and density. In such a way that in the P0.7-EPS-2.5 % sample, the values obtained for these properties decreased to 26.53 % and 30.09 % respectively, compared to the traditional plaster. These results, combined with the good mechanical performance obtained, position the composites developed in this research as a highly interesting alternative to produce prefabricated plates and panels with a higher circularity and sustainability index.

In summary, this research contributes to the development of new sustainable construction materials, manufactured under circular economy criteria and with good physico-chemical and mechanical properties. Additionally, it is committed to the industrialisation of the building sector and the development of more efficient and technically viable prefabricated building materials. As limitations in this research, it is worth highlighting the absence of a broader experimental campaign to assess the behaviour of the new composites under the effects of water and humidity, as these are some of the most destructive agents in plaster and can decisively affect the durability of prefabricated products made with this material. In this sense, future lines of research could explore the behaviour of these composites in environments with a high humidity index, as well as the analysis of the performance of these new materials with the addition of different reinforcement fibres to enhance their mechanical resistance. In line with this issue, it would be interesting to carry out a study by means of mercury or helium porosimetry in order to know in more detail the size of the pores and their distribution in each sample. These results have strong repercussions on the mechanical properties and thermal behaviour of the plaster composites, which is why it is a complementary analysis of great relevance. Finally, it should be noted that in future work it would be interesting to seek alternative methods for dissolving EPS that are more environmentally friendly and do not compromise the economic profitability of these newly developed compounds.

Patents

The lightweight plaster composite presented in this research has been registered as innovative and original material at the Spanish Patent and Trademark Office (OEPM), with registration number ES 2 933 873 B2 and patent grant date 31 October 2023 [89].

CRediT authorship contribution statement

Alicia Zaragoza-Benzal: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Ferrández:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Paulo Santos:** Writing – review & editing, Validation, Methodology, Formal analysis. **Evangelina Atanes-Sánchez:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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3.7. Upcycling EPS waste and mineral wool to produce new lightweight gypsum composites with improved thermal performance

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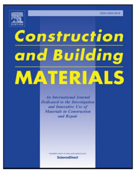

Upcycling EPS waste and mineral wool to produce new lightweight gypsum composites with improved thermal performance

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Lightweight steel frame wall

ABSTRACT

Energy efficiency and waste management are crucial for sustainability of construction sector. In this research, a new gypsum composite material is presented in which traditional raw materials have been partially replaced by thermal insulation waste from facades energy retrofitting projects, using an innovative process to recover this waste. Consequently, a novel lightweight gypsum composite has been developed with a replacement of up to 14.7 % by weight of the original material with EPS waste, adding mineral wool as reinforcement fibres (0.375 % wt.). Thus, thermal behaviour analysis of these new composites has been conducted, both material itself and of its performance as part of a real construction system, including finite element analysis of the construction system. In addition, the physicochemical, physical and mechanical characterisation of the new composites has been carried out. Results show that the developed new material has a density 20.3 % lower than the traditional gypsum composite, resulting in a 30.4 % reduction in thermal conductivity. Furthermore, the use of these new lightened gypsum composites as finishing boards in lightweight steel frame (LSF) wall systems reduces the overall thermal resistance of the wall by up to 10.6 % with just 25 mm thickness. On the other hand, the mechanical resistance of this new material exceeds the reference values established by current standards, ranging between 4.18 and 1.87 MPa for flexural strength and between 7.87 and 4.27 MPa for compressive stresses. Additionally, the developed composites have shown a reduction in both total and capillary water absorption compared to traditional gypsum by 19.6 % and 40.0 % respectively, enhancing the material's durability and its excellent thermal properties throughout its lifespan.

1. Introduction

Buildings constitute the main energy consumer, with households being the sector with the highest energy demand, only behind the transport industry [1]. In this context, the EU has developed a legislative framework through the Energy Efficiency Directive and the Energy Performance of Buildings Directive, to achieve climate neutrality and total decarbonisation of the building stock by 2050 [2,3]. According to 2021 data, in the EU 64.4 % of energy consumption in dwellings is allocated to space heating [4]. Therefore, in order to achieve the ambitious goal set by international organisations, it is essential to optimise the thermal performance of building envelopes through the improvement of exterior insulation systems.

New insulation materials in construction have favoured structures like Lightweight Steel Frame (LSF) walls being considered an interesting option from the standpoint of energy demand and sustainability. These prefabricated systems offer lower embodied energy compared to traditional solutions, speed and higher quality in execution, easy maintenance, suitability for envelope modernisation, flexibility and modulation, and great recyclability and reusability [5–7]. However, the high thermal conductivity of steel studs can lead to the appearance of thermal bridges if they are not carefully designed and executed [8], which can increase the thermal transmittance of the enclosure by 28–41 % [9–11].

Several researchers have studied how to avoid these thermal bridges in different ways (increasing the number of insulation layers [12], perforating the studs [13]; different profiles morphologies [14]). However, the incorporation of Thermal Break Strips (TBS) on the contact

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surface of the stud has proven to be the most efficient solution. Employing this latter solution, Larbi *et al.* [15] analysed the mechanical and thermal behaviour of a system composed of a rigid PVC layer and acoustic insulation in metal structures. Their numerical simulations demonstrated how this solution achieved reductions of up to 65 % in thermal bridging. Similarly, Tkalčić *et al.* [16] incorporated PVC pieces, which separated the steel structure from the rest of the system layers, resulting in 33 % improvements in the thermal resistance of the walls. Conversely, Andersons *et al.* [17], synthesised and characterised high-density PU foams with biobased polyols, which showed similar performance to commercial options. Another alternative is the use of aluminium reflective foils on the inner layer of the insulation in configurations where an intermediate air layer is introduced [9,18]. In these cases, the low emissivity of aluminium foils reduced the impact of thermal bridges by up to 19 %, even exceeding the performance of solutions with aerogel strips on steel studs [18]. It is worth noting the increasingly frequent use of TBS composed of recycled materials, such as cork or rubber from end-of-life tyres (ELT), which, in addition to being able to reduce the thermal transmission of steel studs by up to 32 %, are solutions with a strong focus on sustainability and circular economy [19]. It is worth noting that the revalorisation of plastic waste is becoming a key resource to produce more sustainable construction materials [20,21]. This situation allows not only to comply with current European guidelines on emissions, energy efficiency and natural resources, but also to be consistent with the fact that the construction sector is one of the largest waste generators in the EU [22].

In recent years, public administrations have provided incentives for the energy refurbishment of buildings since around 75 % of buildings constructed in the EU do not comply with current energy efficiency regulations [23,24]. The most commonly used method for energy retrofitting of façades so far has been External Thermal Insulation Composite Systems (ETICS) due to their good thermal performance, low density, high durability and cost-effectiveness [25]. The large amount of square metres of ETICS executed each year generates significant quantities of waste of these materials. This situation has led many researchers to focus on the development of strategies for reusing and valorising these materials. Particularly, the use of EPS waste stands out as one of the most used insulators in the installation of ETICS due to its low price, low specific weight and low thermal conductivity [26], which has encouraged its use as a light addition or light filler in concretes, mortars and plasters with improved thermal behaviour [27].

The case of gypsum or plaster-based composites is particularly interesting from a sustainability perspective, as their production requires less energy, and they can be easily recycled while retaining their original properties [28]. In the following Table 1, several research studies have been compiled, where waste from different thermal insulation materials used in construction have been incorporated into gypsum composites. Since several of these studies have evaluated the effect of other types of additions, only composites without the incorporation of insulation waste have been considered as a reference, thus the behaviour of these types of additions can be analysed individually in each case.

Firstly, it should be considered that the low addition percentages contemplated in the different studies are due to the low characteristic density of the insulating materials, which can range between 28 kg/m^3 and 70 kg/m^3 [38]. This influences the low specific weight of the composites produced [39], except for composites with added sands.

In all cases, thermal conductivity (λ) is considerably reduced with addition of thermal insulation waste. In general terms, the greatest reductions in the thermal conductivity of the composites were obtained with the addition of shredded PUR and EPS waste. However, of all the composites analysed, the lowest values are linked to the addition of EPS thermal insulation residues. On the other hand, the addition of mineral wool is more aimed at improving the mechanical flexural strength of gypsum composites, as it is incorporated during mixing as fibres, while at the same time conferring certain thermal properties on these gypsum-based materials. These types of cladding composites have great potential in terms of the energy efficiency of buildings, as the thermal conductivity of the cladding can account for up to 75 % of the total thermal performance of facade [11]. In addition, the low densities of these materials make them a very interesting product for use in industrialised systems such as LSF walls.

The main objective of this research is to study a new lightweight gypsum composite, partially replacing traditional raw materials with construction and demolition waste (CDW). A physico-chemical and mechanical characterisation of the material was conducted, incorporating innovative EPS waste from façade rehabilitation and mineral wool fibres as reinforcement. In addition, its thermal behaviour was evaluated in a real construction system (LSF wall), testing recycled rubber strips as thermal break systems. Finally, the results obtained were compared and validated with 2D simulations conducted using THERM software. Overall, this study seeks to delve into the implementation of strategies based on circular economy and sustainability in the

Table 1
Compilation of studies on gypsum/plaster composites and thermal insulating waste.

Study	Addition	Compounds	Density (kg/m^3)	ΔDensity (%)	λ (W/m·K)	Δ λ (%)
[29]	Reference	Gypsum A + 10 % Paper waste + 0.28 % Surfactant (porous agent)	820	_	0.33	_
	Insulation waste addition	EPS 1 %	750	−8.5	0.27	−18.2
[30]	Reference	Gypsum B1 + 20 % Recycled gypsum	670	_	0.51	_
	Insulation waste addition	24 % EPS + 8 % Recycled gypsum	370	−44.8	0.18	−64.7
[31]	Reference	Gypsum A + 65 % Standard sand	1920	_	1.80	_
	Insulation waste addition	10 % PUR	930	−51.6	0.21	−88.3
[32]	Reference	Gypsum B1 + 29 % Ceramic waste	1310	_	0.40	_
		Gypsum B1 + 22 % Concrete waste	1230	_	0.36	_
	Insulation waste addition	12 % Ceramic waste + 0.52 % EPS	1030	−21.4	0.28	−30.0
		8.4 % Concrete waste + 0.28 % EPS	1030	−16.3	0.33	−8.3
[33]	Reference	Gypsum A	990	_	0.26	_
	Insulation waste addition	1.1 % EPS + 1.6 % XPS	710	−28.3	0.15	−42.3
[34]	Reference	Gypsum B1 + 17.7 % Rubber	860	_	0.18	_
	Insulation waste addition	17.7 % Rubber+ 0.12 % Mineral wool	840	−2.3	0.16	−11.1
[35]	Reference	Gypsum B1	1030	_	0.33	_
		Gypsum B1 + Glass powder	1410	_	0.38	_
	Insulation waste addition	1.1 % EPS	610	−40.8	0.23	−30.1
		1.1 % XPS	890	−13.6	0.29	−12.1
		27.7 % Glass powder + 1.2 % Mineral wool	1300	−7.8	0.33	−13.2
[36]	Reference	Gypsum A	1480	_	0.30	_
	Insulation waste addition	0.74 % PUR	880	−38.0	0.19	−36.7

Note: All quantities refer to the percentage by weight of the total materials used in each investigation. Gypsum A: Calcium sulphate-based binder > 90 %; Gypsum B1: Binder with calcium sulphate content > 50 % and calcium hydroxide content < 5 %, according to UNE-EN 13279–1 [37]. λ – Thermal conductivity.

construction sector, with a strong commitment to energy efficiency and responsible use of resources.

2. Materials and Methods

2.1. Materials

The material used as a binder in this research was gypsum class A according to UNE-EN 13279–1 [37], more than 92 % of which is calcium sulphate ($CaSO_4$). The main properties of this material were provided by the manufacturer (Placo Saint-Gobain, Madrid, Spain): particle size between 0 and 0.2 mm, thermal conductivity 0.3 W/m•K, fire reaction Euroclass A1, flexural strength greater than 3.5 MPa and pH lower than 6.

During the mixing process, drinking water from the Canal de Isabel II (Madrid, Spain) was used, with low hardness and free of impurities or salts, according to Directive (EU) 2020/2184 of the European Parliament and of the Council [40].

As secondary raw materials, graphite polystyrene waste solution (GPWS) was used as a partial substitute for the original composite (plaster and water), and reinforcement fibres from glass mineral wool waste (GMWW) were employed. The GPWS was made from the dissolution of graphite polystyrene (GPS) waste used as thermal insulation in energy rehabilitation works on façades. The waste was collected directly on site and manually crushed into fragments of less than 5 cm in diameter to facilitate the dissolution process. As a reference, the main characteristics of this type of material are shown in Table 2. On the other hand, the solvent used for the preparation of the GPWS was ethyl acetate ($C_4H_8O_2$), whose characteristics are shown in Table 2. Recent research has studied the effect of ethyl acetate as a more environmentally friendly solvent in the chemical recycling of EPS waste due to its low toxicity [41–43]. The ethyl acetate used in this research was supplied by the company Nazza (Madrid, Spain). The density of the GPWS produced is 836.4 kg/m^3, with a graphite polystyrene/ethyl acetate mass ratio of 2:1.

The GMWW used in this study, obtained from panels used in façade insulation, was manually cut to fibre lengths of approximately 12 mm, as shown in Fig. 1(a) and (b). Several studies have obtained good results with fibres of this length, and it is also the size commonly used in commercial gypsum composites [44,45]. Table 3 lists the properties of commercial glass mineral wool commonly used in refurbishment work. Additionally, Fig. 1(c) shows a scanning electron microscopy (SEM) image of the fibres, where the surface morphology of the fibres and their average diameter (6–9 µm) can be observed.

2.2. Material characterisation

2.2.1. Mineralogical characterisation

To analyse the impact of replacing the original gypsum material with GPWS, a study was conducted by using X-ray diffraction (XRD) for the physicochemical characterisation. The process of grinding and sieving the samples required for this test precludes the preservation of GMWW fibres of the compounds, so exclusively the diffraction patterns of the samples without the incorporation of fibres were obtained. The test scope covered diffraction angles between 5° $\leq 2\theta \leq$ 60°, with a frequency of 0.04° and a speed of 4 s per step. The test was performed using a Siemens Krystalloflex D5000 with a Cu-Kα graphite monochromator. The determination of the crystalline composition of the samples was carried out using the International Centre for Diffraction Data Powder Diffraction Files (ICDD PDF) database. Additionally, the mean crystal size of the samples was obtained using the Debye-Scherrer equation:

$$D = \frac{k \cdot \lambda_w}{\beta \cdot \cos\theta} \tag{2}$$

where, D is the mean size of the crystallite (nm), k is the Scherrer constant taken as 0.94, λ_w is the wavelength of the Cu-Kα radiation (0.154056 nm), β is the Full Width at Half Maximum (FWHM) of the X-ray peak in radians and θ is the Bragg angle in radians [47]. The value for FWHM is the one corresponding to the most pronounced peak of calcium sulfate dihydrate ($2\theta = 20.742°$).

Table 2
Main properties of the materials used to make the GPWS.

Graphite polystyrene				
Density (kg/m^3)	Thermal conductivity (W/m•K)	Fire reaction (Euroclass)	Compressive strength (MPa)	H_2O absorption (kg/m^2)
18–20	0.032	E	0.07	<0.5
Ethyl acetate				
Purity (%)	Density at 20 °C (kg/m^3)	Water content (%)	Ethanol content (%)	Boiling point (°C)
>99.5	900	<0.05	<0.2	77

2.2.2. Physical-mechanical characterisation

In the physical-mechanical characterisation, the total water absorption, open porosity and capillary water absorption were determined, as well as the surface hardness, flexural and compressive strength of the composites. Additionally, scanning electron microscopy (SEM) images of the composites were obtained. The tested samples were dried in a laboratory oven at a temperature of 40 ± 2 °C and relative humidity of 50 ± 5 %, for 24 hours, until a constant mass was achieved prior to testing.

The total water absorption was obtained by adapting EN 14617–1:2013 [48] standard. Samples of 40×40×160 mm^3 were placed in a container with water, ensuring that their surface remained at least two centimetres below the water level for two hours weighing the samples before and after the test. The process was repeated until the difference between two consecutive measurements was less than 0.1 %, obtaining the amount of water absorbed by the material in relation to the dry weight of the samples.

The open porosity was determined by adapting the EN 1936:2007 standard [49], using 40×40×160 mm^3 samples and an electronic balance with a precision of 0.01 g. The values for this property were obtained by applying the following equation:

$$\rho_o = \frac{m_s - m_d}{m_s - m_h} \times 100 \tag{3}$$

where m_s is the mass of the sample saturated in water, m_d is the mass of the dried sample and m_h is the mass of the sample immersed in water, all expressed in grams.

Bulk density of the samples was obtained following the indications of UNE 102042:2023 standard [50], with three prismatic samples of 40×40×160 mm^3 for each dosage elaborated. For this purpose, the mass of the samples was obtained using an electronic laboratory scale with an accuracy of 0.01 g, while the dimensions were measured with a calliper with 0.01 mm precision.

The determination of the capillary water absorption coefficient was carried out by adapting EN 1925:1999 [51] standard. The test was performed by vertically immersing the 40×40×160 mm^3 prismatic samples of each compound 3 ± 1 mm in water, placing them on a grid so that they were separated one centimetre from the bottom of the container. During the test, the samples weights were recorded at certain time intervals (0, 1, 3, 5, 10, 15, 20, 30 and 40 min), obtaining the increase in mass per unit area as a function of time.

The surface hardness of the composites was obtained according to the recommendations described in the UNE 102042:2023 standard [50], using a Shore C hardness tester. The test was conducted on two opposite longitudinal faces of 40×40×160 mm^3 RILEM standardised samples, taking 5 measurements on each face, using a total of three samples for each dosage.

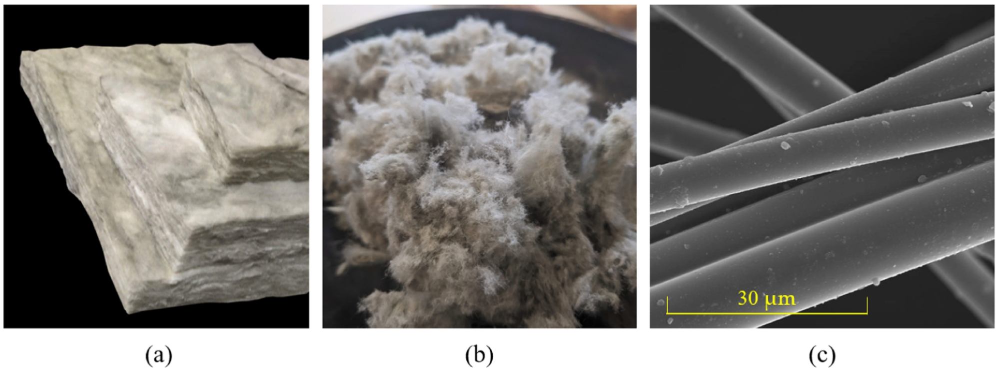

(a) (b) (c)

Fig. 1. (a) Recovered mineral wool insulation board waste; (b) GMWW fibres used in the production of the composites; (c) SEM image of GMWW fibres (magnifications ×2000).

Table 3
Main properties of the recycled glass mineral wool [46].

Density (kg/m^3)	Thermal conductivity (W/m·K)	Fire reaction (Euroclass)	Compressive strength (MPa)	H_2O absorption (kg/m^2)
70–120	0.036	A1	0.02	< 1

On the other hand, the flexural and compressive strength tests were performed according to EN 13279–2:2014 [39] standard. Both tests were carried out using an IBERTEST AUTOTEST 200–10SW equipment, applying a progressive load until the specimens failed. For each dosage, the flexural strength was determined by testing six samples, while the compressive strength was measured on the twelve half-specimens resulting from the flexural strength test.

The SEM images were captured with a TESCAN Vega 4 microscope (high/low vacuum) operating at 20 kV with colour cathodoluminescence and two Bruker EDX detectors (30 and 60 mm^2). These images provide insight into the internal microstructure of the gypsum composite materials, which influences their physico-mechanical behaviour. The samples were coated with a thin layer of gold with a Cressington 108 auto evaporator, ensuring proper conductivity of the electron beam.

2.3. *Thermal performance*

In order to analyse the thermal properties of the newly developed gypsum composite material, as well as to evaluate its performance when integrated in the LSF wall system, the following tests have been carried out: guarded hot plate method, heat flow meter (HFM) method and finite element simulations in THERM software.

2.3.1. *Guarded hot plate method*

The guarded hot plate method was used to determine the thermal conductivity of the plaster composites produced for this research, according to UNE-EN 12664 standard [52]. The 15×15×3 cm^3 samples used were tested at temperatures of 10 °C, 25 °C and 40 °C using a λ-Meter EP500e equipment (Dresden, Germany). Once a steady regime was reached, the test was prolonged up to 90 minutes for each of the indicated temperatures. The results correspond to the thermal conductivity value at a temperature of 10 °C according to the regression line obtained from the measurements taken at the different temperatures (10 °C, 25 °C and 40 °C).

2.3.2. *Heat flow meter (HFM) method*

The influence on the total thermal resistance of new gypsum composites in a load-bearing LSF wall has been determined using the modified heat flow meter (HFM) method [53], as suggested by Rasooli and Itard in their study [54]. With this method, the *U-value* is obtained by the heat flux produced through the wall when it is placed between two chambers at different temperatures once a steady regime is reached. One of these chambers was regulated to a temperature of 5 °C (cold chamber), with the assistance of an Electrolux refrigerator (Model ERT 6658) attached to the chamber, while the other was maintained at 40 °C (hot chamber) using a 70 W electrical resistance. Between the two chambers the LSF wall to be tested was placed, with dimensions of 1030 × 1060 mm^2, consisting of: oriented strand board (OSB) (e =12 mm); commercial C90 × 43 × 15 × 1. 5 mm (web x flange x lip return x thickness) cold-formed steel studs; a mineral wool insulation layer (e = 90 mm); two gypsum plasterboards (e = 25 mm, total), as shown in Fig. 2. The centre-to-centre distance of the vertical steel studs was 400 mm.

In each of the chambers, a fan was installed to prevent air stratification, along with a radiation screen on each side of the wall, at a distance of 10 cm and leaving a free space of 5 cm between the perimeter of the screen and the interior walls of the chambers. The test was conducted with 400 × 180 × 25 mm^3 samples for each of the newly designed gypsum composites. These plates were placed by cutting an opening in the gypsum plasterboard layer to match the size of these plates. They were arranged so that one side of the plate rested on the central steel stud (where a thermal bridge is located) and the other side on the existing insulation layer between profiles, as shown in Fig. 2.

The heat flow between both wall surfaces was measured using four heat flux meters, Hukseflux HFP01 model (accuracy ± 3 %), placing one over the area in contact with the steel stud and another over the cavity area, both on the hot and cold sides (Fig. 3). Additionally, the surface temperature of the gypsum plates, the air temperature near their surface, and the interior temperature of the climatic chambers were recorded using type K (1/ 0.315) PFA insulated thermocouples (class 1 precision).

Furthermore, in this work, a wall configuration with TBS made of recycled end-of-life tyre (ELT) rubber, 50 mm wide and 10 mm thick, has been implemented. These TBS were placed along the cold face of the steel studs since, in a real construction scenario, this arrangement would be the most appropriate to prevent interstitial condensation in the wall. Both configurations can be observed in the cross-section displayed in Fig. 2. The thicknesses and thermal conductivities of each layer composing the wall are shown in Table 4.

The global average surface-to-surface thermal resistance (R_{global}) was determined by the weighted *R-value* obtained in the two measurement zones of the wall (stud and cavity), according to the equation:

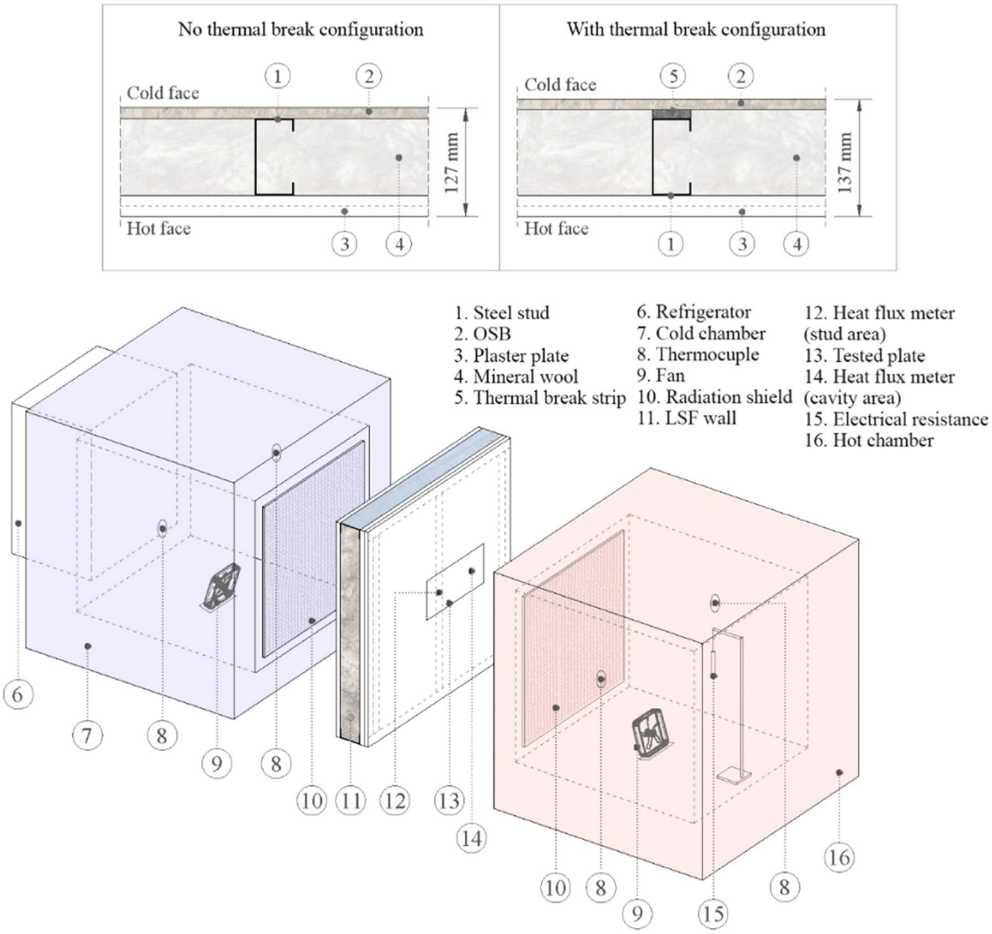


Fig. 2. Diagram of the test setup to measure the thermal resistance of a LSF wall with a finish composed of the developed gypsum materials.

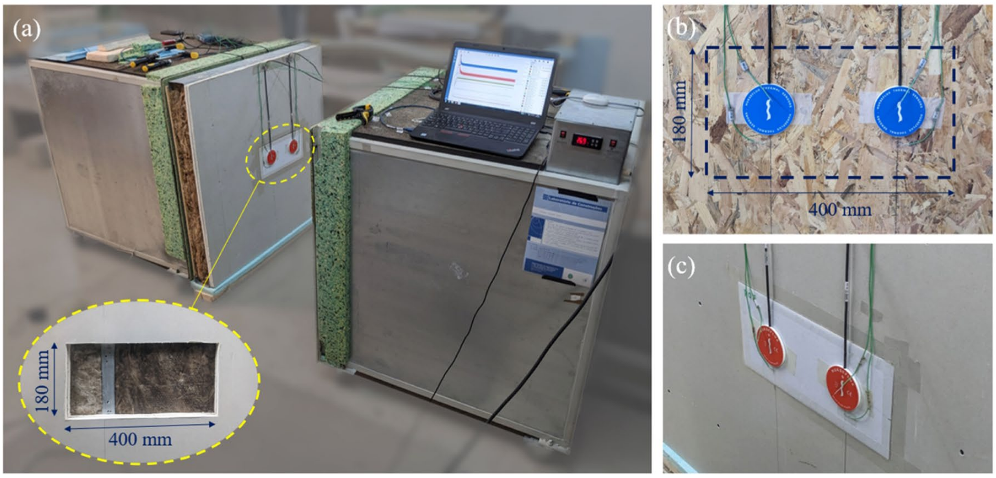


Fig. 3. Test setup to obtain the thermal resistance of a LSF wall construction system. (a) Equipment to conduct HFM method test; (b) heat flux sensors and thermocouples on the cold side of the wall; (c) heat flux sensors and thermocouples on the hot side.

Table 4
Thickness and thermal conductivity of the layers composing the LSF wall.

Material	d (mm)	λ (W/(m·K))	Source
OSB panel	12.00	0.81	Measured*
Mineral wool insulation	90.00	0.04	[55]
Steel stud	90.00	50.00	[56]
Recycled rubber strips	10.0	0.122	[57]

[*] Measured according to methodology outlined in Section 2.2.1.

$$\frac{1}{R_{global}} = \frac{1}{R_{stud}}\frac{A_{stud}}{A_{global}} + \frac{1}{R_{cav}}\frac{A_{cav}}{A_{global}} \tag{1}$$

where, A_{global} is the total area of the LSF wall (m^2), A_{stud} is the area of influence of the steel stud (m^2) and A_{cav} is the remaining cavity area of the LSF wall (m^2). For the influence of the steel stud, the specifications of the ASHRAE zone method [58] were followed. Regarding the local thermal resistances (R_{stud} and R_{cav}), they were calculated taking into account only measurements with an absolute difference of less than 10 % compared to the immediately preceding time measurement (1 hour interval), as specified in ASTM C1155–95 [59].

2.3.3. Numerical finite element simulation

After obtaining the thermal resistance of the tested LSF walls, the results were compared and verified by 2D finite element numerical simulations performed using THERM software. For this purpose, the horizontal section of the LSF wall was modelled with the length of the steel studs spacing (400 mm). The simulations were conducted with and without the rubber TBS (Fig. 2). The thicknesses and thermal conductivities presented in Table 4 were used for the simulation. Likewise, a maximum error in the calculation of the *R-value* of 2 % and a maximum of 100 iterations were set. The boundary conditions of the model (environment air temperatures and surface thermal resistance) were set according to the average values recorded during the HFM method test, resulting in surface thermal resistance values between 0.9 and 0.10 m^2•K/W. This method of obtaining and verifying the thermal resistance of LSF walls has been used by other authors, thus corroborating the suitability of the method for this type of analysis [19,60].

2.4. Sample preparation process

In the sample preparation, firstly, the optimum amount of recycled GMWW reinforcement fibre in the gypsum composites was determined. For this purpose, standardised RILEM samples measuring 40 × 40 × 160 mm^3 were produced according to standard EN 13279–2:2014 [39]. The recycled GMWW fibres were dry-mixed together with the binder to achieve a homogeneous distribution during mixing. The water/gypsum ratio was obtained according to the shaking table method (EN 13279–2:2014 [39]), resulting in a ratio of 0.7 by mass. Once this initial series of samples was prepared, their physical and mechanical characterisation was conducted following the recommendations of standard EN 13279–2:2014 [39], the results of which are shown in Table 5.

As shown in Table 5, the progressive addition of MW fibres produces a slight decrease in density while gradually increasing the mechanical strength as the fibre content increases. However, beyond a 0.5 % fibre addition, the strengths begin to decrease, although they still remain above the values obtained by the reference, as corroborated in other studies [34]. In this research, the addition of 0.375 % MW fibres has been estimated as the most suitable option, as it has shown the best results against bending stresses, together with a good compressive strength.

Once the optimum amount of fibre was established, the final gypsum composites were prepared, the dosages of which are given in Table 6. The specifications of standard EN 13279–2:2014 [39] were followed throughout the mixing process, dispersing the fibres in the dry gypsum powder and incorporating the GPWS in the last stage of the process, as illustrated in Fig. 4.

As can be seen in Table 6, there has been a progressive replacement of the gypsum mix (water and gypsum) with GPWS, aiming to reduce the use of natural raw materials through the incorporation of secondary raw materials. Specifically, savings of up to 14.7 % have been achieved in the use of traditional materials compared to the reference gypsum composite (P0.7). After the mixing and elaboration of the samples, the different samples were stored in laboratory conditions for 7 days at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5 % (these conditions were controlled with support of a ThermoPro TP50 thermohygrometer.).

3. Results and discussion

3.1. Material characterisation of composites

3.1.1. Mineralogical characterisation

In the physicochemical characterisation, X-ray diffraction (XRD) and crystalline size determination of the compounds P0.7 (Ref.), P0.7–125 and P0.7–250 have been carried out, which are shown in Fig. 5 and Table 7, respectively.

As shown in Fig. 5, the main intensity peaks in all the analysed composites appear approximately at the 2θ position of 11.60°, 20.70° and 29.10°, corresponding to the mineral calcium sulphate dihydrate ($CaSO_4 \cdot 2\,H_2O$), the principal component of construction gypsum [37]. The incorporation of GPWS causes a decrease in the intensity of these peaks as the amount of the secondary raw material in the samples increases, being more significant in the P0.7–250 compound. This reduction in the amount of dihydrate structures leads to smaller crystal

Table 6
Dosages by weight of the newly developed gypsum composites.

Nomenclature	Gypsum A (kg/m^3)	Water (kg/m^3)	Recycled MW fibres (kg/m^3)	GPWS (kg/m^3)	Raw material savings (% *)
P0.7 (Ref.)	1302.1	911.5	—	—	—
P0.7–125	1206.4	844.4	—	162.8	7.4
P0.7–250	1110.5	777.5	—	325.5	14.7
P0.7-F	1302.1	911.5	8.3	—	—
P0.7–125 F	1206.4	844.4	8.3	162.8	7.4
P0.7–250 F	1110.5	777.5	8.3	325.5	14.7

[*] Note: Raw material savings compared to traditional gypsum compounds (water and gypsum).

Table 5
Dosages and physical and mechanical characterisation of composites with incorporation of MW fibres.

Nomenclature	Recycled MW fibres (%)	Gypsum A (kg/m^3)	Water (kg/m^3)	Bulk density (kg/m^3)	Flexural strength (MPa)	Compressive strength (MPa)
P0.7 (Ref.)	—	1302.1	911.5	1080.21±15.43	4.09±0.19	8.00±0.35
P0.7–0.125 %	0.125	1302.1	911.5	1074.22±4.40	4.35±0.23	8.42±0.41
P0.7–0.250 %	0.250	1302.1	911.5	1069.92±4.35	4.70±0.21	8.51±0.18
P0.7–0.375 %	0.375	1302.1	911.5	1067.97±10.36	5.09±0.29	8.78±0.26
P0.7–0.500 %	0.500	1302.1	911.5	1061.98±17.92	4.30±0.24	9.03±0.23
P0.7–0.625 %	0.625	1302.1	911.5	1056.38±8.03	4.25±0.18	7.41±0.33

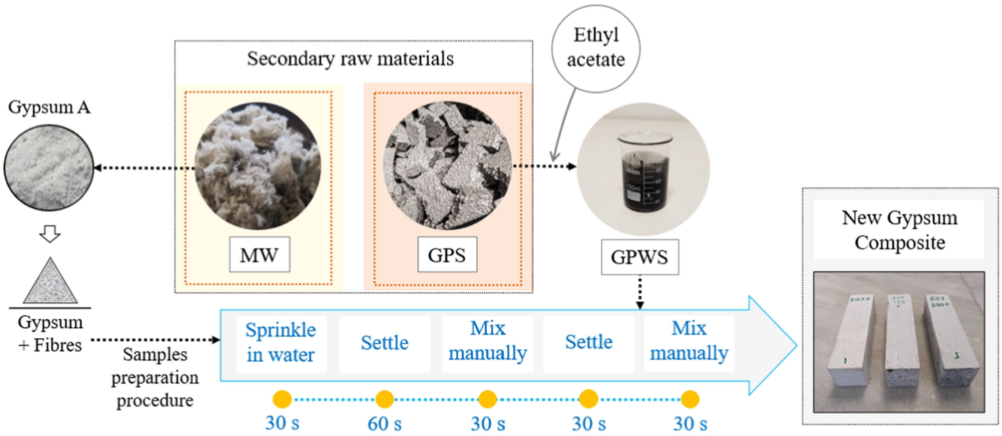


Fig. 4. Description of the production process of the newly developed gypsum composites.

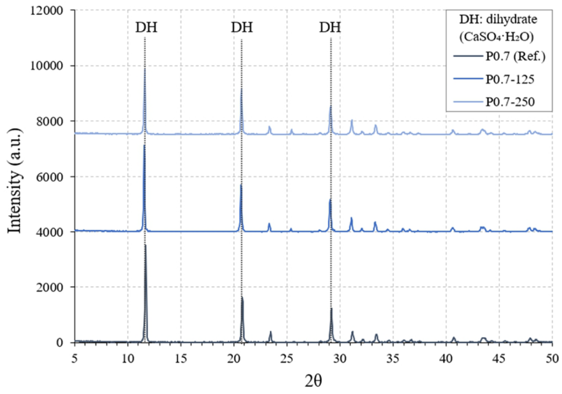


Fig. 5. Diffractogram of P0.7, P0.7–125 and P0.7–250 compounds.

Table 7
Mean size (D) of the ordered crystalline domains of the samples P0.7 (Ref.), P0.7-125 and P0.7-250.

Sample	**Peak position** (2θ, degree)	**β=FWHM** (degree)	**Crystallite size D** (nm)
P0.7 (Ref.)	20.68119	0.15612	54.02
P0.7–125	20.80155	0.15644	53.92
P0.7–250	20.72106	0.17201	49.04

size in the gypsum composites, as shown in Table 7.

The decrease in average crystal size in the P0.7–125 sample is very slight, whereas in P0.7–250 sample this reduction is much pronounced (up to 9.2 % compared to the reference). Similarly, López Pedrajas *et al.* observed that incorporating synthetic EPS particles in suspension altered the formation of gypsum crystals, creating shorter and thicker structures than in gypsum composites without additions [61].

3.1.2. Physical-mechanical characterisation

Fig. 6 below shows the results of the surface hardness, flexural strength and compressive strength tests of the different composites developed in this research.

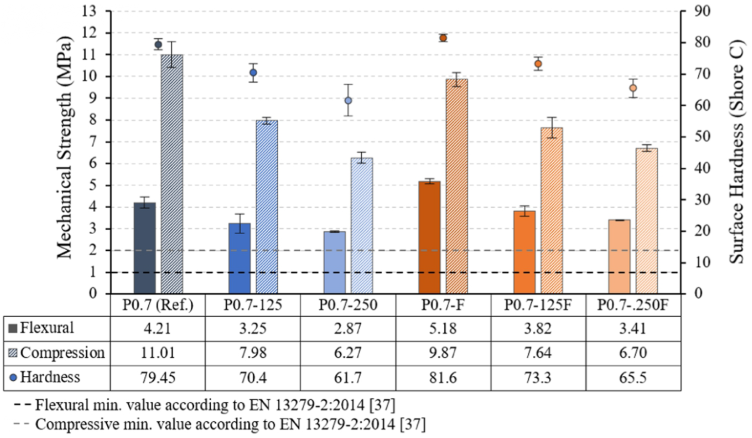
As can be seen in Fig. 6, the surface hardness of the composites decreases as the GPWS addition increases in the composition, reducing by 11.4–22.3 % in P0.7–125 and P0.7–250 compounds respectively. However, the addition of recycled MW fibres increased these values, by 4.1 %-6.2 %. Similar results were obtained by Piña *et al.* [45], using GMWW fibres as reinforcement of cement mortars.

On the other hand, both flexural and compressive strength were also affected by the replacement of gypsum material by GWPS. In both properties, the P0.7–250 composite obtained the lowest strengths, with a decrease of 31.7 % and 43.1 % in flexural and compressive strength, respectively, compared to the reference. It is worth mentioning that the reduction in density is associated with a lower mechanical strength due to the increase in material porosity, which could weaken the internal structure of the composites to some extent [29,62]. Furthermore, it should be noted that the obtained strengths exceeded the minimum values established by EN 13279–2:2014 standard [39] by more than 1.5 MPa for flexural strength and more than 5 MPa for compressive strength, making these composites suitable for use in construction.

In other studies where shredded recycled EPS has been incorporated, the reduction in mechanical strength is directly related to the mechanical strength of the introduced waste itself (which is much lower than that of the gypsum material), as well as to the poor bonding at the waste-matrix interface, negatively affecting the overall strength of the composite [29,63]. However, in the case of this research, this strength decrease is mainly due to the modification experienced by the gypsum crystals at microscopic level, as observed in the physicochemical analyses. Therefore, although there is a reduction in strength, it remains quite elevated as a much more homogeneous material is obtained, reducing the possible failure at the bond between the matrix and the added secondary raw material [61]. On the other hand, the incorporation of MW fibres as reinforcement increases the flexural strength of all composites by 23.0–17.5 %, although this improvement is not so evident in terms of compressive strength. Similar results have been obtained in the case of gypsum and cement mortars where the mineral fibres also came from demolition and building construction waste [45,64].

It is noteworthy that in other research where crushed thermal insulation waste has been used to reduce the density and thermal conductivity of gypsum material, the mechanical performance of the resulting material has been diminished, even failing to meet minimum standards. In the consulted literature, thermal conductivities ranged between 0.15 and 0.28 W/m·K, with flexural strengths not exceeding 1.90 MPa and compressive strengths below 3.60 MPa [29–31,33]. In this study, for a decrease in density and thermal conductivity similar to that obtained by other researchers in previous studies, the strengths obtained for composites with GWPS and MW reinforcement fibres were significantly higher.

Fig. 7 shows images of the gypsum matrices produced after the



	P0.7 (Ref.)	P0.7-125	P0.7-250	P0.7-F	P0.7-125F	P0.7-.250F
■ Flexural	4.21	3.25	2.87	5.18	3.82	3.41
▨ Compression	11.01	7.98	6.27	9.87	7.64	6.70
● Hardness	79.45	70.4	61.7	81.6	73.3	65.5

Fig. 6. Surface hardness, flexural and compressive strength of the different gypsum composites produced.

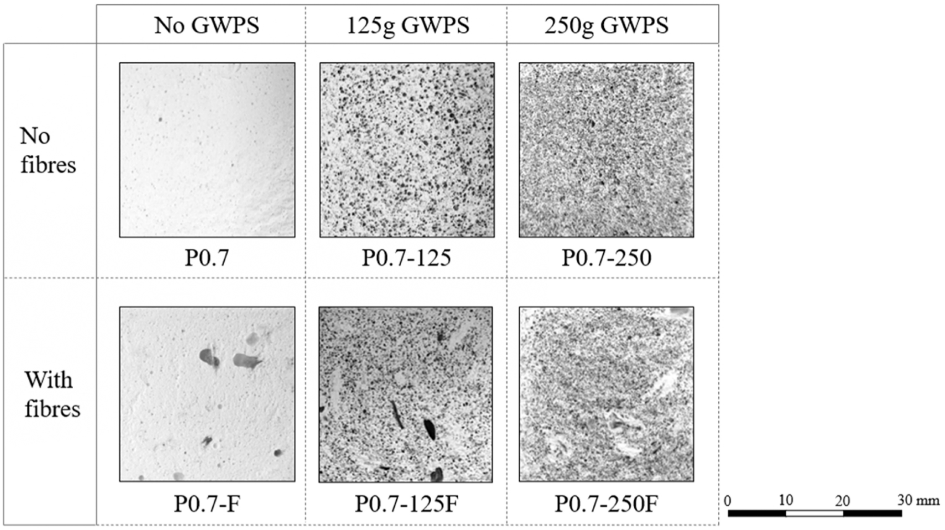


Fig. 7. Images of the matrices of the different gypsum composites produced.

flexural strength test, where the good distribution of the GWPS in the gypsum material can be observed. However, with the addition of MW, some fibres accumulations are noticeable, creating larger pores.

Table 8 below shows the bulk density of the compounds developed.

As can be observed in Table 8, the substitution of gypsum material by secondary raw materials leads to a reduction in the bulk density of all the composites produced. Thus, as the amount of recycled material increases in the gypsum composites, their bulk density decreases progressively. It is worth noting that the incorporation of GWPS obtained a maximum reduction of 19.5 % in the P0.7–250 composite, whereas the addition of recycled MW fibres increased this reduction to 20.3 % in relation to the reference.

Table 8
Bulk density results of the compounds proposed in this research.

	P0.7 (Ref.)	P0.7-125	P0.7-250	P0.7-F	P0.7-125 F	P0.7-250 F
Bulk density (kg/m^3)	1107.42	1031.45	891.60	1065.43	979.30	883.20
Δdensity (%)		6.86	19.49	3.79	11.57	20.25

The reduction in density and thermal conductivity with the addition of granulated or crushed EPS particles has been observed in previous studies [29], mainly due to the highly porous structure of EPS. In this research, the EPS structure is broken during the dissolution process, increasing the homogeneity of the mixture and ensuring better bonding between the recycled material and the matrix. Furthermore, the values of these properties remain similar to those observed in other studies incorporating shredded EPS [61].

3.1.3. Water absorption capacity and open porosity characterisation

Fig. 8 shows the results obtained in the total water absorption test and the open porosity of the composites.

In Fig. 8, it can be observed how the total water absorption follows a clear trend, decreasing as the partial replacement of the original gypsum composite with GWPS increases. Compared to conventional gypsum, P0.7–125 and P0.7–250 composites reduced their absorption by 5.2 %

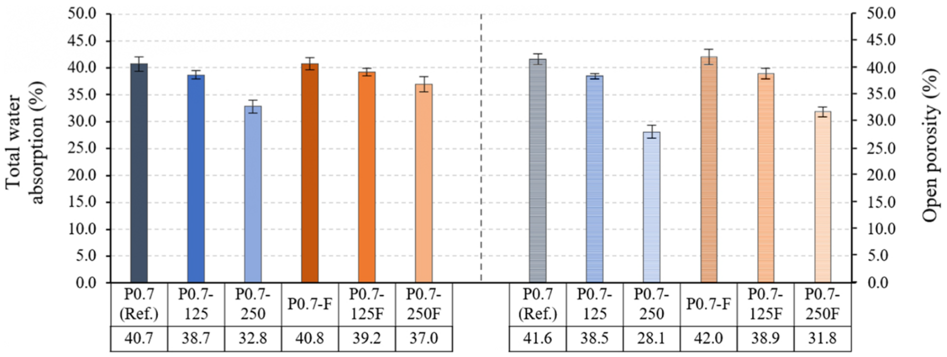


Fig. 8. Results of the total water absorption and open porosity tests of the composites.

and 19.6 % respectively. The hydrophobic nature of the solidified polystyrene within the gypsum matrix directly influences the impermeability of the composites, reducing water absorption significantly [61]. It is worth mentioning that, in the case of incorporating EPS in solid or granulated form, there are studies showing an increase in absorption of up to 57 %, demonstrating how the use of GWPS is an improved alternative to the addition of shredded EPS waste [29]. This aspect is particularly relevant in materials with low thermal conductivity and density, as they can rapidly lose their insulating properties in the presence of moisture and increase in weight by easily absorbing water due to their internal porosity. Additionally, there is a high probability of mould and bacteria growth due to moisture retention inside the material [65,66].

On the other hand, in cases where recycled MW fibres were incorporated, absorption increased slightly compared to the counterpart composites without fibres. This increase was more notable in P0.7–250 F composite, which increased its absorption by 12.8 %; however, its total absorption was the second lowest after that obtained by P0.7–250 composite. Other studies have pointed out how the addition of fibres can increase the hygroscopicity of cement and gypsum composites due to the increased small-diameter pores that they tend to generate within these materials [67].

Similarly, the open porosity of the composites also decreases as the proportion of GWPS in the samples increases, reaching up to 33.1 % in P0.7–250 composite compared to the reference. This effect indicates a higher amount of inaccessible pores in the composites with GWPS, which would be blocking and closing the porous structure of the gypsum material. These results highlight the ability of GWPS to reduce the density of gypsum composites without increasing water absorption derived from the increased porosity, which results in more durable materials by presenting a lower number of open pores to the external environment [68]. Again, the MW fibres generated an increase in the open porosity of the composites, being most pronounced in P0.7–250 F composite (+13.2 %). This suggests that the fibres could be facilitating the connection between pores that would otherwise have remained isolated [69].

The results obtained in the capillary water absorption test for all the composites produced are shown in Fig. 9.

As can be seen in Fig. 9, all the composites designed in this research absorbed a lower amount of water by capillary action with respect to the gypsum without additions, highlighting again the impermeable characteristics derived from the incorporation of GWPS in the gypsum composite materials. This reduction occurred directly proportional to the amount of added recycled material, with the greatest reduction being obtained in P0.7–250 composite, absorbing 40 % less than the reference at the end of the test. Likewise, the addition of MW fibres slightly increased the capillarity water absorption capacity, between 6 % and 14.2 % compared to their counterparts without fibres, indicating an increase in open and connected capillaries of sufficient thickness to favour absorption through them [70]. Romaniega described this effect of recycled mineral wool fibres from construction and demolition waste in her doctoral thesis, where the absorption increased as the amount of fibre added increased [71].

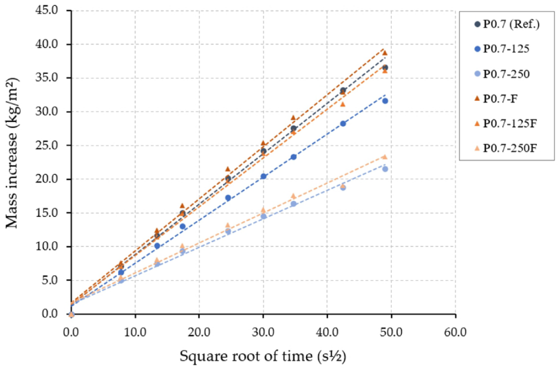


Fig. 9. Results of the capillary water absorption test using the variation of mass per unit area as a function of time.

3.1.4. Microstructure characterisation

Fig. 10 shows scanning electron microscopy (SEM) images of samples P0.7–250 and P0.7–250-F, being the most representative of all the gypsum composites produced.

In Fig. 10 (a), corresponding to sample P0.7-F, the characteristic acicular structures of gypsum mineral can be observed in a light grey colour, and how the MW fibres exhibit a good bond with the matrix, with no cracks or gaps at the interface between materials. Furthermore, it can be seen how the fibres intertwine within the gypsum matrix, interconnecting the material as a whole, which aligns with the improved flexural strength experienced by these composites in mechanical tests.

On the other hand, in Fig. 10 (b), corresponding to sample P0.7–250, the solidified GWPS is clearly distinguished in a darker grey colour as it is an organic material and, therefore, contains a higher proportion of carbon. The P0.7–250 and P0.7–250 F composites present a less compact matrix, with the presence of pores that explain the low density of the composites. Moreover, in Fig. 10 (b) it can be appreciated how GWPS is introduced into the pores, coating and filling them, reflecting the exceptional integration of this secondary raw material in the composite, as well as the hydrophobicity of the resulting gypsum material.

In some areas the recycled waste forms agglomerations as shown in Fig. 10 (c). This circumstance would negatively affect the mechanical

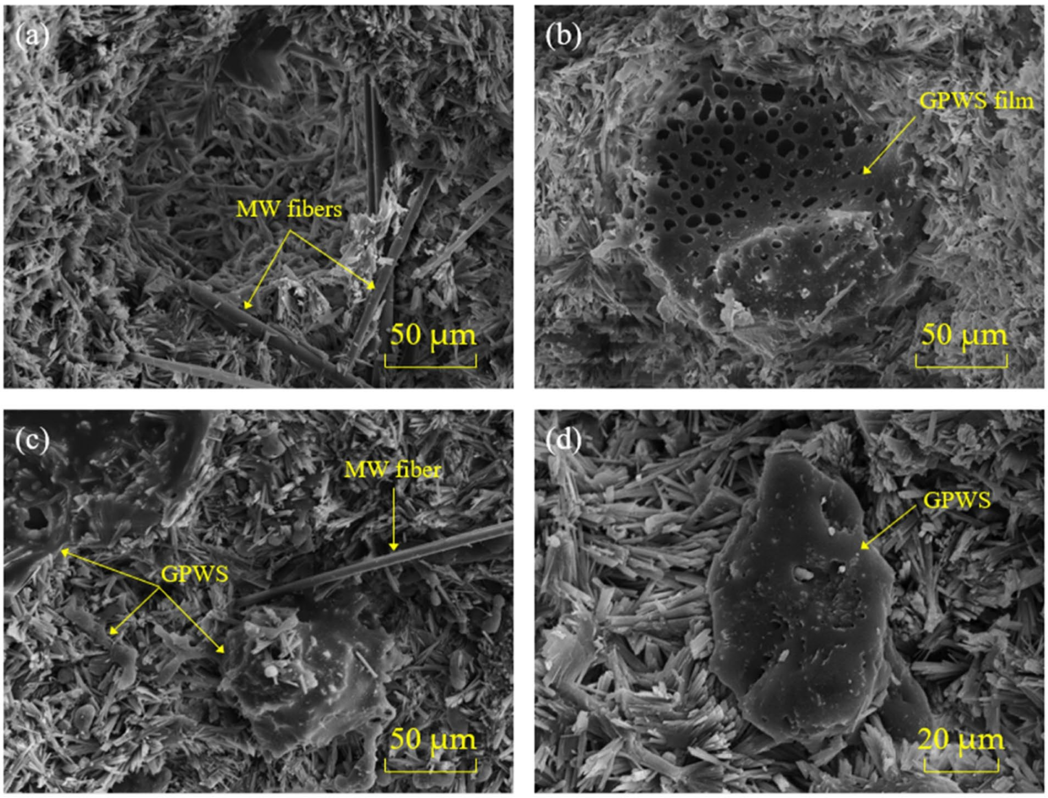


Fig. 10. Scanning electron microscopy (SEM) images: (a) P0.7-F, x1000 magnifications (b) P0.7–250, x1000 magnifications; (c) P0.7–250 F, x1000 magnifications; (d) P0.7–250, x2000 magnifications.

strength of the composites. However, by incorporating GWPS instead of the granulated EPS residue, the creation of preferential breakage points is avoided [63], although with the incorporation of the dissolution, crystal growth may be affected in a certain degree, as shown in Fig. 10 (d). The GPWS can acquire different morphologies when solidifying inside the gypsum matrix depending on the relative orientation of the gypsum crystallites in the composite as the hemihydrate hydration, evaporation of remaining water and evaporation of the GPWS solvent occurs [61]. If the ends of the crystals exceed the surface level of the GPWS solution, the solidified polystyrene is distributed around the dihydrate crystals (Fig. 10 (c)) as the solvent evaporation proceeds. However, when the gypsum crystals do not protrude from the surface level of the GPWS solution, sheets of hardened polystyrene covering the gypsum crystallites could be created during solvent evaporation (Fig. 10 (d)). In this case, the polystyrene solidifies on the surface of the gypsum crystals.

3.2. Thermal performance of composites

The results obtained for the guarded hot plate method, heat flow

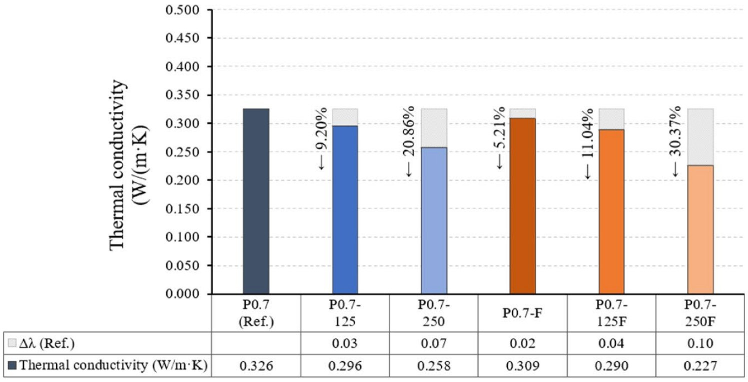


Fig. 11. Thermal conductivity of the processed gypsum composites.

meter (HFM) method and finite element numerical simulations of the gypsum materials analysed in this research are presented next.

3.2.1. *Thermal conductivity characterisation*

Fig. 11 shows the thermal conductivity of each composite produced, relating them to the values of the reference gypsum.

As can be observed in Fig. 11, there is a significant reduction in thermal conductivity with the addition of the secondary raw materials incorporated in the developed composites, in line with the observed decrease in density. Specifically, the thermal conductivity of the gypsum materials containing GWPS decreased to 0.258 W/m·K, 20.9 % less than the reference (P0.7). Additionally, it has been observed that the combination of GWPS and MW fibres results in a lower thermal conductivity of the gypsum composite materials, reaching a reduction of up to 30.4 % (0.227 W/m·K) compared to traditional gypsum. These results are in line with other studies, where MW fibres have been used to reduce the thermal conductivity of binder materials [72].

Partial replacement of the gypsum material by GWPS results in a less dense material due to the lower specific weight of GWPS and its function as an air-inclusive agent, leading to a reduction of the thermal conductivity of the compounds [73]. In addition, the graphite particles embedded in GWPS contribute to reducing the materials' thermal conductivity by reflecting and absorbing a considerable amount of infrared thermal radiation due to their laminar structure [74,75].

3.2.2. *Heat flow meter (HFM) characterisation*

Fig. 12 presents the results obtained for the thermal resistance of the different configurations of LSF walls tested (without and with TBS), where the final internal layer of plaster has been replaced by plates made with the new compounds developed in this research.

As the results in Fig. 12 show, the reduction in thermal conductivity of the gypsum material used as finishing in the tested wall configuration significantly influenced the total thermal resistance of the assembly despite its reduced thickness.

The use of GWPS as partial replacement for gypsum in the production of the prefabricated plates resulted in a thermal resistance of up to 1.453 m^2·K/W in the P0.7–250 composite, 4.0 % increase compared to using gypsum without additions. On the other hand, the use of MW fibres slightly increased this resistance in the P0.7-F composite. However, the greatest impact was observed in combination with the addition of GWPS in the P 0.7–250 F composite, obtaining an increase in the total thermal resistance of the wall of 7.7 % (1.505 m^2·K/W). These results are especially relevant considering the reduced thickness of the gypsum plates used (25 mm).

As might be expected, the use of recycled rubber-based TBS resulted in less energy transfer between the two sides of the wall, due to the lower thermal conductivity of rubber (0.12 W/m·K) compared to steel (50.00 W/m·K). Although all the thermal resistances obtained increased with this configuration, it is worth noting that the use of the gypsum plates with the incorporation of GWPS especially enhanced this resistance, increasing it by up to 9.5 % with the P0.7–250 compound. It can also be seen how in this case, the recycled MW fibres produce a slight increase in the thermal resistance of the precast elements, reaching 1.731 m^2·K/W with the P0.7–250 F compound.

The maximum increase in thermal resistance obtained with respect to the traditional gypsum material (P0.7) without TBS was similar (around 24 % in the P0.7–250 F sample with TBS) to that achieved in other studies where rubber TBS was incorporated on the cold side and on the hot side of the steel stud [19]. This implies that the newly developed lightweight composites can achieve similar comfort and energy saving conditions as systems with double TBS, which maximises the usable floor area of the buildings and reduces material consumption.

3.2.3. *Numerical finite element simulation for LSF wall characterisation*

The thermal resistance results for the different LSF wall configurations obtained from the HFM method, as well as those obtained by simulation using THERM software, are shown in Table 9. It can be observed that the measured thermal resistances, obtained through the HFM method, are higher in all studied cases, when compared to the simulation predicted values. This could be due to the fact that, in the real conditions, materials are not in perfect direct contact with each other, leaving some enclosed air gaps that may influence the values obtained to some extent. This does not occur in simulations, where a total perfect contact between material surfaces is assumed. However, in most cases the error falls between 0 % and 1 %, with a maximum difference of 4 %, validating the results in both tests.

The simulations conducted using THERM software are graphically displayed in Fig. 13. The configurations corresponding to the P0.7 and P0.7–250 F composites, with and without ELT rubber TBS, are displayed, as they exhibit the greatest difference between them. Additionally, three representative local temperatures have been indicated across the influence area of the steel stud inside the wall: on the hot side, on the cold side, and in the central zone of the wall.

As can be seen in Fig. 13, there is a large temperature difference of up to 7.2 °C between cold and hot sides for the reference wall with the P0.7 (Ref.) plate, indicating a considerable energy loss across the wall, due to a significant thermal bridge originated by the steel studs. When the ELT rubber band is used as TBS, it acts as insulation on the cold side, reducing the risk of interstitial condensation due to the higher temperature along the steel frame [76]. Thus, it prevents heat loss through the enclosure by increasing the temperature on the warm side by up to 1.7°C and reducing the thermal gradient between both sides of the wall by 0.8°C compared to the reference LSF wall (without TBS).

When the P0.7–250 F gypsum composite is used as the finish on the warm side of the wall, the temperatures inside the wall are reduced on average by 1.27 °C, as a result of the lower thermal conductivity of the

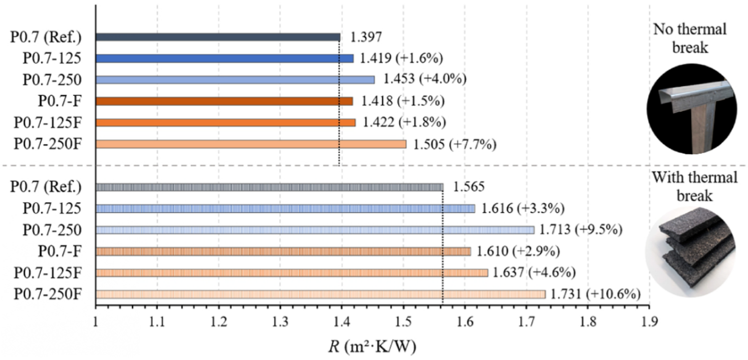


Fig. 12. Measured thermal resistances for LSF wall with the plaster elaborated without and with TBS.

Table 9
Thermal resistances measured with HFM method and predicted by simulations with THERM.

Without thermal break strips				With thermal break strips			
Sample	**Measured *R*** (m^2·K/W)	**Predicted *R*** (m^2·K/W)	**Δ*R*** (%)	**Sample**	**Measured *R*** (m^2·K/W)	**Predicted *R*** (m^2·K/W)	**Δ*R*** (%)
P0.7 (Ref.)	1.397	1.383	+1.0	**P0.7 (Ref.)**	1.565	1.554	+1.0
P0.7–125	1.419	1.410	+1.0	**P0.7–125**	1.616	1.616	0.0
P0.7–250	1.453	1.435	+1.0	**P0.7–250**	1.713	1.651	+4.0
P0.7-F	1.418	1.396	+2.0	**P0.7-F**	1.610	1.602	0.0
P0.7–125 F	1.422	1.409	+1.0	**P0.7–125 F**	1.637	1.623	+1.0
P0.7–250 F	1.505	1.456	+3.0	**P0.7–250 F**	1.731	1.660	+4.0

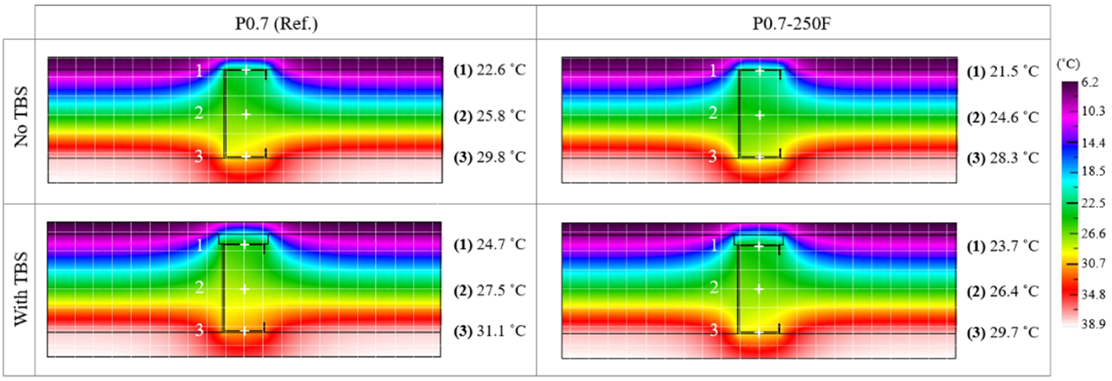


Fig. 13. Temperature distribution predicted by THERM models for LFS walls (with and without TBS) having gypsum composites P0.7 (Ref.) and P0.7–250 F.

newly designed composite. The greatest difference is observed in the area of the profile closest to the hot chamber, with a temperature 1.5 °C lower compared to the reference. Therefore, in this case, the energy required to maintain optimal conditions indoors is reduced, as less heat is lost from the walls.. By using ELT rubber TBS, the insulation of the cold side becomes more evident, increasing the temperature at this point by 2.2 °C, although its effect is less significant than for the reference P0.7 composite with TBS, as a consequence of the lower heat transmission through the wall. These results suggest that less energy would be required during the interior climate control process of a typical home, which accounts for about 63.6 % of the total energy consumed in the EU households [1], with façades being one of the main energy loss elements in buildings (about 20 % [77]).

4. Conclusions

This research has presented a new gypsum composite that contributes to energy savings in buildings by recycling thermal insulation waste from the energy renovation of facades. After the experimental campaign carried out, the following conclusions can be drawn:

- The new composites achieved raw material savings of between 7.4 % and 14.7 % compared to traditional gypsum composites, contributing to the responsible use of natural resources.
- The incorporation of GWPS and MW fibres reduced composites density by up to 20.3 %. Additionally, the graphite particles absorb and reflect thermal radiation, reducing the thermal conductivity of the material by up to 30.4 %.
- The reduction in thermal conductivity increased the thermal resistance of the tested LSF walls, achieving a 7.7 % decrease by replacing the last 25 mm interior finish layer of gypsum board with the developed composites.
- The use of recycled rubber as TBS minimised heat losses in the steel studs, increasing the thermal resistance by up to 10.6 % in configurations with the new gypsum composites, especially with P0.7–250 F sample.
- Finite element simulations showed how ELT rubber TBS acts as insulation on the cold side of the stud, while plaster with GWPS and MW increases insulation on the warm side, reducing condensation, energy loss and thermal dissipation through thermal bridges.
- GWPS modified the shape of gypsum crystalline structures in the composites, decreasing their size and reducing surface hardness (-22.3 %), as well as flexural and compressive strengths by up to 31.7 % and 43.1 % respectively for P0.7–250 sample. Despite this, the mechanical properties exceeded current standards, and the incorporation of recycled MW fibres significantly improved these properties due to good internal cohesion of the matrix.
- GWPS was integrated into the matrix of composites, waterproofing the material and reducing water absorption, capillary absorption and open porosity by up to 19.6 %, 40.0 % and 33.1 %, respectively. The addition of fibres slightly increased water absorption by increasing the porosity and the internal connection of the porous network.

Finally, it should be noted that in this research, the influence of humidity variation on obtaining the results of thermal properties has not been considered, nor its repercussion on the thermal resistance of the LSF wall compared to traditional gypsum composites. Additionally, future research lines include thermal analysis of the new material as part of other industrialised construction systems, as well as life cycle analysis of such composites alongside studying of their economic viability.

CRediT authorship contribution statement

Alicia Zaragoza-Benzal: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Daniel Ferrández:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Paulo Santos:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Conceptualization. **Evangelina Atanes-Sánchez:** Writing – review & editing, Visualization, Validation, Software, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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4. Discusión

En este apartado se lleva a cabo una discusión de los resultados obtenidos en este trabajo de investigación y de las soluciones alcanzadas en cada una de las publicaciones presentadas en el capítulo de Resultados. Adicionalmente, se presentan los aspectos más relevantes de las publicaciones que conforman la Tesis Doctoral y su vinculación con la sociedad, abordando una triple perspectiva: funcional, socioeconómica y medioambiental.

4.1. Residuos de EPS en disolución en sustitución parcial del conglomerante en compuestos de yeso

Zaragoza-Benzal, A., Ferrández, D., Atanes-Sánchez, E., Saiz, P. (2022). Dissolved recycled expanded polystyrene as partial replacement in plaster composites. *Journal of Building Engineering*, 65 (105697). https://doi.org/10.1016/j.jobe.2022.105697.

En este artículo se realiza el estudio y desarrollo de un nuevo material a base de yeso con la sustitución parcial del material conglomerante por una disolución de EPS reciclado. En la campaña experimental se han empleado diferentes dosificaciones donde se ha ido sustituyendo progresivamente el material de yeso por la disolución de EPS, para posteriormente realizar una caracterización química, física y mecánica de los compuestos.

Los resultados se genera un compuesto de yeso más cohesionado, favoreciendo la integración total de los residuos en la matriz del material. El nuevo compuesto presenta una baja densidad, elevada resistencia térmica y un excelente comportamiento a flexión en placas en comparación con los yesos tradicionales. Estas propiedades posicionan el material desarrollado como una alternativa viable en la elaboración de placas y paneles prefabricados más sostenibles mediante la aplicación de criterios de economía circular.

La publicación de este artículo en *Journal of Building Engineering* evidencia su gran relevancia gracias a varios indicadores internacionales con los que cuenta la revista. En *Web of Science*, la revista está incluida dentro del Journal Citation Report (JCR) con un factor de impacto de 6.4 en el año 2022. Dentro de esta clasificación está situada en la posición 8/92 (Q1, primer decil) del área

Construction and Building Technology y en la posición 9/182 (Q1, primer decil) en el área *Civil Engineering*.

Esta revista posee a su vez un *Journal Citation Indicator* (JCI) de 1.34 (datos de 2022). Además, en el año de publicación *Journal of Building Engineering* estaba indexada en la base de datos de Scopus, con un indicador de impacto Scimago Journal Rank (SJR) de 1.232 y un H-index de 92. Esta valoración la posiciona entre las revistas indexadas de primer cuartil en la base de datos de *Scopus* en cinco áreas: *Arquitecture*, posición 2/177; *Building and Construction*, posición 20/210; *Civil and Structural Engineering*, posición 42/367; *Mechanics of Materials*, posición 44/399; y, Safety, Risk, Reliability and Quality, posición 18/206.

4.2. Refuerzo y mejora de las propiedades de los compuestos mediante la incorporación de fibras textiles de NFU

Zaragoza-Benzal, A., Ferrández, D., Atanes-Sánchez, E., Fernández, C. (2023). New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry. *Case Studies in Construction Materials*, 18 (e02178). https://doi.org/10.1016/j.cscm.2023.e02178.

En este artículo se explora la incorporación de fibras textiles procedentes de NFU para su adición en los compuestos con sustitución de la amasada de yeso y agua por residuos de EPS en disolución. Con ello, se espera conseguir un nuevo material de construcción aligerado y mejores prestaciones térmicas que fomenten la eficiencia energética en los edificios.

Los resultados obtenidos tras la caracterización fisicoquímica y mecánica del nuevo compuesto muestran cómo se consigue un material más ligero, con una reducida conductividad térmica y una mayor resistencia a flexión en placas en comparación con el material de yeso tradicional. Con ello se ha conseguido una mejora en las prestaciones técnicas de los compuestos elaborados, la reducción del consumo de recursos naturales y un aumento en el volumen de residuos recuperados y reintroducidos en el proceso productivo.

Este artículo fue publicado en *Case Studies in Construction Materials,* una revista con alto reconocimiento internacional con diferentes índices de calidad en su aval. Incluida en *Journal Citation Reports* (JCR) de la *Web of Science* con un factor de impacto de 6.5 en el año 2023, lo que la situaba en la posición 11/92 (Q1) en el área *Construction & Building Technology*, 12/182 (primer decil) en el área *Civil*

Engineering, y 96/439 (Q1) en el área *Materials Science, Multidisciplinary*. En ese mismo año, su *Journal Citation Indicator* (JCI) fue de 1.34. Además, esta revista se encuentra indexada en la base de datos internacional *Scopus* donde en 2023, de acuerdo con su indicador de impacto *Scimago Journal Rank* (SJR), tuvo una valoración de 1.464, siendo revista de primer cuartil (Q1) en el área Materials Science (miscellaneous), posición 89/637 (H-index, 62).

4.3. Estudio de la durabilidad y evaluación logística de los compuestos con residuos de EPS en disolución

Zaragoza-Benzal, A., Ferrández, D., Díaz Velilla, J. P., Zúñiga-Vicente, J. A. (2023). Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria. *Case Studies in Construction Materials*,19 (e02380). https://doi.org/10.1016/j.cscm.2023.e02380.

La concepción de nuevos materiales bajo criterios de economía circular es un factor clave para el desarrollo sostenible del sector de la edificación y la mejora de rendimiento empresarial de las empresas constructoras. En este artículo se presenta un nuevo material compuesto de yeso en el que se reemplaza parcialmente la materia prima original por residuos de EPS en disolución y fibras textiles de NFU, el cual ha sido ensayado para determinar su comportamiento tras ensayos de envejecimiento acelerado y determinar la durabilidad de los compuestos. Los resultados muestran como resistencias obtenidas tras la exposición del material a ciclos de humedad-sequedad, son muy superiores a los valores requeridos por la normativa actual.

De esta manera, se ha desarrollado un compuesto de yeso aligerado en el que el material reciclado está completamente integrado en la matriz, obteniendo un producto técnicamente viable para la elaboración de prefabricados para cuartos húmedos. Finalmente, se ha llevado a cabo una simulación mediante la herramienta *FlexSim*, que ha permitido corroborar la mejora en el proceso de distribución de un prototipo de placa prefabricada de falso techo elaborada con este nuevo producto, así como, la disminución en costes derivados de un transporte más eficiente y con menor impacto medioambiental.

Este artículo fue publicado en *Case Studies in Construction Materials,* una revista con alto reconocimiento internacional. Entre sus índices de calidad destacan un factor de impacto de 6.5 en el año 2023 en el *Journal Citation Reports* (JCR) de la *Web of Science,* situándose en la posición 11/92 (Q1) en el área *Construction &*

Building Technology, 12/182 (primer decil) en el área *Civil Engineering*, y 96/439 (Q1) en el área *Materials Science, Multidisciplinary*. Su *Journal Citation Indicator* (JCI) en ese año se sitúa en 1.34. Además, en 2023, esta revista se encuentraba indexada en *Scopus*, con un indicador de impacto *Scimago Journal Rank* (SJR) de 1.464, siendo revista de primer cuartil (Q1) en el área Materials Science (miscellaneous), posición 89/637 (H-index, 62).

4.4. Estudio del comportamiento frente a la acción del agua de en los compuestos con residuos de EPS en disolución

Zaragoza-Benzal, A., Ferrández, D., Atanes-Sánchez, E., Saiz, P. (2023). Study of the hygroscopic properties of environmentally friendly lightened composites through waste recovery. *Construction and Building Materials,* 404 (133219). https://doi.org/10.1016/j.conbuildmat.2023.133219.

En esta investigación se han desarrollado nuevos compuestos de yeso aligerado resistentes al agua mediante la incorporación de una disolución de residuos de EPS y fibras textiles procedentes de NFU. Se han planteado dosificaciones en las cuales se ha ido reemplazado el material de conglomerante por los residuos en masa, consiguiéndose reducciones de en torno al 28% de las materias primas originales. Con el objetivo de abarcar un completo estudio del efecto del agua en los compuestos desarrollados, se han realizado ensayos de porosimetría de mercurio, absorción de agua por capilaridad, absorción total de agua, permeabilidad al vapor de agua, penetración superficial, ciclos de agua-estufa, así como el análisis de imágenes obtenidas mediante microscopia electrónica de barrido (SEM).

Los resultados obtenidos indican como los compuestos de yeso elaborados muestran una muy baja absorción, reduciéndose también su permeabilidad al vapor y manifestando una excelente durabilidad tras someter los compuestos a ciclos de envejecimiento acelerado. Así mismo, se ha observado como la incorporación de EPS disuelto en el material de yeso genera una alta porosidad, relacionada el bajo peso específico de los compuestos. Por este motivo, la investigación realizada muestra el gran potencial de los compuestos desarrollados para la elaboración de elementos prefabricados, especialmente indicados para su utilización en espacios donde se requiera una elevada resistencia a la acción del agua.

La publicación de este artículo en *Construction and Building Materials* muestra la relevancia del mismo, ya que esta revista es una de las mejor valoradas en el ámbito de la construcción. En *Web of Science* presenta un factor de impacto de 7.4 en el *Journal Citation Reports* (JCR), (datos de 2023). Para ese año, la revista se encuentra en primer cuartil en tres categorías: *Construction and Building Technology* (posición 6/92, primer decil); *Civil Engineering* (posición 6/182, primer decil) y *Materials Science, Multidisciplinary* (posición 82/432). Su Journal Citation Indicator (JCI) en 2023 fue de 1.24. Además, en Scopus cuenta con un índice SJR de 1.999 dentro del Scimago Journal Rank de Scopus (H-index 259). Estos datos la situaron en primer cuartil en ese año en tres áreas dentro de esta base de datos: *Building and Construction* (posición 7/210), *Civil and Structural Engineering* (posición 13/367); y *Materials Sciences, Miscellaneous* (posición 62/637).

4.5. Análisis del comportamiento frente al fuego de los compuestos con residuos de EPS en disolución incluyendo fibras de refuerzo de basalto y de vidrio

Zaragoza-Benzal, A., Ferrández, D., Prieto, M. I., Atanes-Sánchez, E. (2024). Fire-resistant performance of new sustainable waste-lightened composites with glass and basalt fibres reinforcement. *Construction and Building Materials,* 411 (134620). https://doi.org/10.1016/j.conbuildmat.2023.134620.

En este trabajo se han desarrollado diferentes compuestos de yeso aligerados, reemplazando parcialmente las materias primas originales por residuos de EPS en disolución hasta un 23.5%, y reforzándolos con fibras de vidrio y basalto. Tras exposición de los compuestos a un fuego real directo, se ha realizado una caracterización mecánica y una caracterización fisicoquímica, incluyendo el cálculo de las emisiones de CO y CO_2 vinculadas a la combustión de los compuestos, así como la obtención de imágenes MEB.

Los resultados muestran como la reducción de la alta porosidad de los compuestos disminuyó la temperatura alcanzada durante la exposición a las llamas, evitando la fisuración del material. Además, tras el fuego, los compuestos obtuvieron mayores resistencias mecánicas residuales en comparación con el yeso sin adiciones. La adición de fibras de vidrio demostró conferir un mejor comportamiento a flexión a los compuestos con adición del residuo, mientras que a compresión las fibras de basalto fueron más eficientes. La estimación de las emisiones tóxicas producidas durante la combustión de los compuestos diseñados no superó los valores inmediatamente peligrosos para la vida o la salud (IDLH).

Este estudio contribuye a un mayor conocimiento del comportamiento de estos compuestos con incorporación de residuos plásticos en caso de incendio.

Este artículo fue publicado en *Construction and Building Materials*. Entre sus índices de calidad se encuentran un factor de impacto de 7.4 en el *Journal Citation Reports* (JCR) en *Web of Science* (datos de 2023). Para ese año, la revista se encuentra en primer cuartil en tres categorías: *Construction and Building Technology* (posición 6/92, primer decil); *Civil Engineering* (posición 6/182, primer decil) y *Materials Science, Multidisciplinary* (posición 82/432). Su Journal Citation Indicator (JCI) en 2023 fue de 1.24. Además, en Scopus cuenta con un índice SJR de 1.999 dentro del Scimago Journal Rank de Scopus (H-index 259). Estos datos la situaron en primer cuartil en ese año en tres áreas dentro de esta base de datos: *Building and Construction* (posición 7/210), *Civil and Structural Engineering* (posición 13/367); y *Materials Sciences, Miscellaneous* (posición 62/637).

4.6. Incorporación de caucho procedente de NFU en la mejora de las propiedades de los nuevos compuestos con residuos de EPS en disolución

Zaragoza-Benzal, A., Ferrández, D., Santos, P., Atanes-Sánchez, E. (2024). Development and characterization of new lightweight waste-based plaster composites for building applications. *Journal of Building Engineering*, 96 (110525). https://doi.org/10.1016/j.jobe.2024.110525.

En este artículo se presenta un nuevo material que incorpora residuos de EPS en disolución y adición de caucho reciclado como materias primas secundarias en sustitución parcial del material de yeso tradicional. De esta manera, se han alcanzado sustituciones parciales en masa de hasta el 12.5%, con respecto a los compuestos de referencia sin adiciones. Los resultados muestran cómo la incorporación de EPS en disolución permite una integración más homogénea del residuo en la matriz del compuesto de yeso. Si bien es cierto que la incorporación de ambos residuos ha reducido ligeramente las resistencias mecánicas a flexión y compresión se han obtenido resultados que superan con creces los valores mínimos exigidos en la normativa actual.

Por otro lado, en el estudio llevado a cabo con placas prefabricadas para falso techo, se ha observado como el efecto combinado de ambos residuos permite obtener unas resistencias a flexión simple superiores a los compuestos tradicionales, con una reducción de la densidad aparente y la conductividad térmica de hasta un 30.1% y un 26.5%, respectivamente. Así, se presenta una alternativa viable para el desarrollo de nuevos compuestos de yeso más sostenibles, ligeros y que permiten avanzar hacia una industrialización del sector de la construcción.

Esta publicación en *Journal of Building Engineering* se encuentra avalada por diferentes indicadores internacionales. Según los datos más recientes disponibles (2023), en *Web of Science*, la revista está incluida dentro del *Journal Citation Report* (JCR) con un factor de impacto de 6.7. En esta clasificación se sitúa en la posición 8/92 (Q1, primer decil) del área *Construction and Building Technology* y en la posición 9/182 (Q1, primer decil) en el área *Civil Engineering*. Esta revista posee a su vez un *Journal Citation Indicator* (JCI) de 1.39 (2023). Además, la revista se encuentra indexada en *Scopus*, con un indicador de impacto *Scimago Journal Rank* (SJR) de 1.397 y un H-index de 92. Esta valoración la posiciona entre las revistas indexadas de primer cuartil en la base de datos de *Scopus* en cinco áreas: *Arquitecture*, posición 1/179; *Building and Construction*, posición 15/210; *Civil and Structural Engineering*, posición 30/367; *Mechanics of Materials*, posición 34/397; y, *Safety, Risk, Reliability and Quality*, posición 11/204.

4.7. Evaluación del comportamiento térmico de los compuestos con residuos de EPS en disolución incluyendo fibras recicladas de lana mineral

Zaragoza-Benzal, A., Ferrández, D., Santos, P., Atanes-Sánchez, E. (2024). Upcycling EPS waste and mineral wool to produce new lightweight gypsum composites with improved thermal performance. *Construction and Building Materials,* 440 (138464). https://doi.org/10.1016/j.conbuildmat.2024.138464.

Esta investigación presenta un nuevo compuesto en el que se sustituyen las materias primas tradicionales por residuos de aislamientos térmicos procedentes de trabajos de rehabilitación energética, empleando un proceso innovador de recuperación. Se ha realizado un análisis del comportamiento térmico de estos nuevos compuestos, tanto del material en si, como de su rendimiento como parte de un sistema constructivo real, incluyendo el análisis por medio de elementos finitos del sistema constructivo. Adicionalmente, se ha realizado la caracterización fisicoquímica, física y mecánica, de los nuevos compuestos.

Los resultados muestran como el nuevo material presenta una densidad un 20.3% menor que el compuesto de yeso tradicional, lo que repercute en una reducción del 30.4% de su conductividad térmica. El empleo de estos nuevos compuestos en sistemas *lightweight steel frame* (LSF) permite reducir la resistencia térmica global del muro hasta un 10.61%. Por otro lado, sus resistencias mecánicas superan los valores normativos entre 4.18-1.87 MPa y 7.87-4.27 MPa para la resistencia a flexión y compresión respectivamente. Además, se ha observado la reducción de la absorción de agua total y por capilaridad en un 19.6% y 40% respectivamente, lo que favorece la durabilidad del material y el mantenimiento de sus excelentes propiedades térmicas a lo largo de su vida útil.

Los datos disponibles más recientes de esta publicación en *Construction and Building Materials* reflejan la relevancia del mismo en el ámbito de la construcción. En *Web of Science* presenta un factor de impacto de 7.4 en el *Journal Citation Reports* (JCR), (datos de 2023). En ese año, la revista se encuentra en primer cuartil en tres categorías: *Construction and Building Technology* (posición 6/92, primer decil); *Civil Engineering* (posición 6/182, primer decil) y *Materials Science, Multidisciplinary* (posición 82/432). Su Journal Citation Indicator (JCI) en 2023 fue de 1.24. Además, en Scopus cuenta con un índice SJR de 1.999 dentro del Scimago Journal Rank de Scopus (H-index 259). Estos datos la situaron en primer cuartil en ese año en tres áreas dentro de esta base de datos: *Building and Construction* (posición 7/210), *Civil and Structural Engineering* (posición 13/367); y *Materials Sciences, Miscellaneous* (posición 62/637).

4.8. Discusión de las contribuciones

4.8.1. Perspectiva funcional

Todos los materiales desarrollados para esta investigación toman como base el mismo principio: matriz base de yeso/escayola y adición de EPS en disolución. Esta fórmula destaca por su marcado carácter original (recogido en la patente española con n.º de referencia: ES 2 933 873 B2) y sus prestaciones técnicas mejoradas en comparación con los compuestos con base yeso tradicionales. Así, se pueden resaltar entre otras las siguientes:

i. La integración del material reciclado (EPS disuelto) en la matriz del compuesto base de yeso/escayola se realiza de forma homogénea sin debilitar estructura interna del composite. Esto supone un avance en el rediseño de los tradicionales productos de construcción, consiguiendo una mezcla cuyo aspecto visual es semejante al que se obtiene con el material tradicional.

ii. Esta integración en fase líquida de ambas materias primas permite obtener un material en estado endurecido con unas propiedades mecánicas superiores a las obtenidas en otras investigaciones. A modo de ejemplo, se destaca el estudio de Del Río *et al.*, donde se incorporaba el residuo de EPS triturado para conformar compuestos de yeso aligerados [119]. En esta investigación se adicionaban cantidades de hasta un 3% en peso de EPS triturado y se obtenían unas resistencias a flexión y compresión de los compuestos de yeso de 1.70 MPa y 3.05 MPa, respectivamente. En esta investigación, con el material base (yeso y EPS disuelto) presentado en el primer artículo del compendio [191], se incorporó hasta un 26.5% de material reciclado en peso, y las resistencias a flexión y compresión alcanzadas fueron de 3.79 MPa y 6.26 MPa, respectivamente. Así, no solo se consigue integrar una mayor cantidad de material reciclado, sino que también se mejoran las propiedades mecánicas al emplear la solución diseñada en esta investigación.

iii. Así mismo, esta formulación de material de yeso y disolución de EPS permite la integración de otras adiciones de forma homogénea en la matriz del composite endurecido. Se han testado entre otros, fibras sintéticas (ej.: vidrio, basalto, polipropileno, fibra textil de neumático, lana mineral) y agregados de caucho, perlita y vermiculita. Todas estas composiciones permiten obtener prefabricados con versatilidad de forma y dimensión.

iv. La incorporación del EPS en disolución reduce significativamente la conductividad térmica final de los compuestos de yeso o escayola endurecidos. Esto se ha podido observar en las diferentes publicaciones incluidas en el compendio y supone una contribución significativa para mejorar la eficiencia energética de las edificaciones.

v. Otro aspecto clave es la mejora obtenida en el comportamiento frente al agua de los compuestos de yeso. Tradicionalmente, estos materiales se desgastan fuertemente con la acción del agua (ej.: ciclos de humedad-sequedad o ciclos de agua-estufa), no obstante, con la solución presentada en esta investigación se resuelven en parte estos problemas. Así, los compuestos diseñados reducen la absorción de agua por capilaridad, la absorción total de agua, la porosidad abierta, la permeabilidad al vapor de agua, la penetración de agua bajo presión y soportan firmemente los ciclos de humedad sequedad. Con todo ello, se extiende el campo de aplicación de estos materiales de yeso desarrollados para la elaboración de placas y paneles para cuartos húmedos.

vi. Los ensayos de resistencia al fuego han puesto de manifiesto la resistencia de los composites elaborados en caso de incendio. De esta manera, aunque se reduce la resistencia mecánica tras verse sometidos a estas temperaturas extremas, los materiales mantenían su integridad física y la adición de EPS no reducía la naturaleza ignífuga del material de yeso original. Asimismo, se pudo comprobar que no se emitían gases nocivos durante la combustión en cantidades que pusieran en riesgo la salud humana.

Finalmente, cabe destacar los resultados obtenidos en los ensayos con placas y paneles. En esta investigación se han ensayado diferentes configuraciones de muestras de dimensión 400 × 300 × 15 mm^3, y en todas ellas se han obtenido resultados por encima de los recomendados en la normativa y en múltiples ocasiones superiores a los obtenidos para el material de referencia. Esto supone un gran avance frente a los resultados obtenidos en otras investigaciones recogidas en la literatura donde se adicionan residuos en el diseño de los compuestos con base yeso, ya que hasta la fecha no se ha encontrado ninguna referencia en la que se mejore la resistencia a flexión cuando se incorpora material reciclado en el diseño de placas y paneles prefabricados.

4.8.2. Perspectiva socioeconómica

Otro aspecto clave en el diseño de materiales bajo criterios de economía circular son los aspectos socioeconómicos. En este sentido, el desarrollo de investigaciones que se alineen con las directrices de Pacto Verde Europeo [70] y los Objetivos para el Desarrollo Sostenible y Agenda 2030 [45], es crucial para resaltar el potencial de las investigaciones en el área de construcción e ingeniería civil. Así, bajo este enfoque, se pueden resaltar las siguientes contribuciones alcanzadas en la presente Tesis Doctoral:

i. La disminución en la conductividad térmica obtenida para los compuestos de yeso diseñados contribuye a la mejora del confort térmico en el interior de las estancias habitables. De esta manera, los prefabricados elaborados mejorarían la resistencia térmica global de cerramientos y particiones, contribuyendo así a mejorar la calidad de vida de los individuos que habitan esos espacios. Esto se encuentra alineado con el creciente interés actual por rehabilitar energéticamente los edificios de viviendas y la generación de redes de edificios de consumo casi nulo.

ii. Esta disminución en la conductividad térmica se encuentra ligada a la reducción en la densidad de los compuestos de yeso con adición de EPS disuelto. Así, se consigue conformar prefabricados más ligeros que disminuyen el peso por metro cuadrado de los forjados. Sin embargo, esta disminución de la densidad puede ser entendida como una potencial fuente de ventaja competitiva en costes, al reducirse los tiempos de ejecución de los sistemas constructivos y mejorar la ergonomía del trabajador que coloca estos prefabricados *in situ*.

iii. Vinculado con lo anterior, desde el punto de vista de la distribución física, una disminución en el peso de las placas y paneles prefabricados supone un abaratamiento de los costes derivados del transporte.
iv. Por otro lado, al emplear materiales reciclados de aislamiento térmico (EPS) que ocupan grandes volúmenes en vertederos, se liberan espacios en las grandes ciudades y se reducen costes de fabricación al reducir la demanda de materias primas naturales.
v. Al tratase de un material conglomerante con tiempos de fraguado comprendidos entre los 15 y 30 minutos, se posibilita el desarrollo de gran cantidad de piezas modulares con aplicación en la construcción. Esta versatilidad en el diseño de formas y soluciones permite ampliar su campo de aplicación en la industria.
vi. Las mencionadas mejoras desde el punto de vista funcional también pueden ser entendidas como una ventaja competitiva en diferenciación de producto. Esto supone la creación de valor en cada en cada pieza diseñada con los materiales analizados y la aparición de nuevos segmentos estratégicos.
vii. Por último, como consecuencia de la alta durabilidad de estos composites, se reducen los costes de mantenimiento y lo consumidores pueden disponer de prefabricados con una mayor vida útil.

Así, las ventajas mencionadas en este apartado reflejan el valor que este material desarrollado aporta a la industria actual, cuyos focos se pueden resumir en: abaratamiento de costes de fabricación, menores tiempos de ejecución en sistemas de tabiquería y falso techo y mayor rendimiento y ergonomía por operario. Además, el carácter social de la investigación se centra fuertemente en la ampliación de la vida útil durante la fase de uso de estos productos, y la mejora del confort térmico y eficiencia energética de los sistemas constructivos actuales.

4.8.3. Perspectiva medioambiental

El último punto de esta discusión de los resultados se centra en la repercusión medioambiental del estudio. Desde el inicio, se ha constatado que se trata del desarrollo de un material elaborado con incorporación de materias primas secundarias, lo que refleja el interés que presenta el composite para reducir la generación de Residuos de Construcción y Demolición (RCD) generados en entornos urbanos. Así, desde este punto de mira se pueden destacar las siguientes implicaciones derivadas del estudio:

i. A través de la elaboración de estos nuevos compuestos de yeso se impulsa la recuperación, reciclaje y revalorización de los residuos de EPS generados como consecuencia de las obras de construcción. En este sentido, los composites elaborados son capaces de incorporar en su matriz un mayor volumen de material reciclado en comparación con otros estudios desarrollados con yesos y adiciones de aislamiento térmico. Esto es debido al procesado previo del EPS (disolución), que permite integrar un volumen mayor de este polímero.

ii. El material contribuye a resolver el problema de ocupación en los grandes vertederos urbanos, ya que, los residuos de EPS poseen un proceso lento de degradación y son muy voluminosos acaparando una gran cantidad de espacio en los puntos de vertido.
iii. Contribuye a reducir la extracción y demanda de materias primas conglomerantes de construcción, tales como el yeso o la escayola. Estas actividades de extracción dañan los ecosistemas y liberan grandes cantidades de CO_2 durante el proceso.
iv. Al tratarse de un material no estructural, los compuestos de yeso diseñados pueden incorporar en su composición otras materias primas recicladas compatibles, que de otra manera acabarían en vertederos o dañando los ecosistemas. Esto supone un punto clave para impulsar esta tecnología y anima impulsar la investigación en esta dirección.

Como se puede observar, estos beneficios medioambientales pueden ser aprovechados por las empresas constructoras para ofrecer un producto diferenciado y sostenible. Si bien es cierto que hay un punto que debe resaltarse y que no contribuye a mejorar la imagen de material medioambientalmente amigable. Este es el proceso de disolución del EPS, donde es necesario emplear agentes químicos para obtener la pasta o gel empleado en las diferentes investigaciones presentadas. Si bien es cierto que estos disolventes no siempre son respetuosos con el medio ambiente, existen soluciones menos nocivas y más fácilmente manipulables por el ser humano que permitirían obtener un producto final con un reducido impacto ambiental. Por ello, es necesario continuar desarrollando este tipo de trabajos académicos para avanzar hacia un uso responsable y sostenible de los recursos en la industria de la construcción.

5. Conclusiones y futuras líneas

En este apartado se recogen las conclusiones derivadas de la investigación llevada a cabo, así como las futuras líneas de estudio que surgen a partir de los hallazgos y limitaciones identificados.

5.1. Conclusiones

En esta investigación se ha comprobado la viabilidad técnica de la incorporación de residuos de EPS en disolución en compuestos de yeso. Así como, el comportamiento de estos composites al adicionar otras materias primas secundarias descartadas por la industria o materiales de refuerzo. Todas las materias primas secundarias han sido introducidas como sustitución parcial durante el proceso de fabricación de los materiales con base yeso, reduciendo así el consumo de recursos naturales comúnmente utilizados en la elaboración de placas y paneles prefabricados para el sector de la edificación.

De este modo, el proceso de elaboración de los materiales desarrollados en esta investigación apuesta por la incorporación de los criterios de economía circular y uso sostenible y responsable de los recursos naturales en la construcción, en línea con las indicaciones del Pacto Verde Europeo presentado por la Comisión Europea el 11 de diciembre de 2019 [70].

Tras la investigación realizada en esta Tesis Doctoral, se pueden extraer las siguientes conclusiones:

- **Reducción en el uso de recursos naturales:** Los resultados obtenidos en esta investigación respaldan la viabilidad técnica de la incorporación de residuos de EPS en disolución como sustituto parcial del conglomerante en compuestos de yeso para elaborar materiales con aplicación en el sector de la construcción. Mediante el proceso de reciclaje químico de este tipo de residuos se consigue la reducción significativa del uso de recursos naturales, de hasta un 27% en masa, junto a un alto índice de reutilización de residuos. Esta nueva forma de reutilizar los residuos de EPS constituye un avance hacia la producción de materiales alternativos más sostenibles y duraderos en el sector de la edificación.

- **Obtención de un compuesto aligerado cohesionado:** La incorporación de los residuos de EPS en disolución permite la integración del residuo a nivel microscópico en la matriz de yeso, generándose un material altamente cohesionado y homogéneo en comparación con los compuestos que integran el residuo en estado sólido.
- **Material con baja densidad y térmicamente eficiente:** Los nuevos compuestos diseñados en esta investigación presentan una microestructura altamente porosa, lo que resulta la reducción de la densidad de forma directamente proporcional a la cantidad de residuo adicionado. En esta investigación, las mayores disminuciones de la densidad y la conductividad térmica fueron de un 33% y 62% respectivamente con respecto a los compuestos de yeso tradicional. Adicionalmente, se ha podido comprobar como los sistemas constructivos que incorporan los compuestos desarrollados como capa da acabado interior, consiguen un aumento de la resistencia térmica del muro del 7.7%, alcanzando incluso un incremento del 10.6% al usarse en combinación con de bandas de rotura de puente térmico.
- **Compuesto con adecuadas resistencias mecánicas:** La incorporación de los residuos de EPS disueltos modificó la cantidad y la morfología de la microestructura del yeso, disminuyendo su tamaño cristalito conforme aumenta la cantidad de esta materia prima secundaria. Con las imágenes SEM se ha podido comprobar como el poliestireno disuelto reciclado, una vez solidificado, queda adherido en torno a los cristales de yeso, reduciendo sus interconexiones y disminuyendo así las resistencias mecánicas de los compuestos. Aun así, todas las propiedades mecánicas analizadas superaron ampliamente los valores indicados en la normativa vigente y superiores las obtenidas por otras investigaciones donde los residuos de EPS se introducen en estado sólido. Adicionalmente, cabe destacar que la resistencia a flexión en placas aumentó considerablemente (hasta un 64%) conforme se aumentaba la cantidad de EPS en disolución en las mezclas.
- **Sinergias con otras materias primas secundarias:** En esta investigación se ha podido comprobar la versatilidad del uso de los residuos de EPS en disolución como sustitución parcial del conglomerante al combinarse con otros materiales reciclados. Con la adición de fibras textiles de NFU, fibras recicladas de lana mineral y caucho de NFU, se han alcanzado ahorros de

28.5%, 14.7% y 12.5% respectivamente en materia prima natural en compuestos de yeso.

Esas adiciones han permitido reducir sensiblemente las densidades obtenidas únicamente con el EPS disuelto en los compuestos, obteniéndose disminuciones de hasta el 31.3%, 20.3% y 30.1% al incorporar fibras textiles de NFU, fibras recicladas de lana mineral y caucho de NFU respectivamente. Los materiales reciclados en formato fibra han favorecido el aumento de microporos en la matriz del material. Este aspecto unido a la baja conductividad de las fibras, generala reducción más significativa de la conductividad térmica de los compuestos, en un 66.7% y 30.37%, en el caso de las fibras textiles de NFU y las fibras recicladas de lana mineral respectivamente.

Cabe destacar como los residuos de EPS en disolución repercuten positivamente en los compuestos con adición de fibras recicladas al paliar la pérdida de resistencia mecánica y reducir la absorción de agua que suelen presentar los compuestos con adiciones de este tipo de fibras, alcanzando valores próximos a los obtenidos por los compuestos sin fibras.

- **Compuestos con gran durabilidad:** Los compuestos desarrollados en esta investigación cumplen con los requisitos de la normativa actual de referencia para su aplicación en edificación incluso tras haber sido sometidas a ciclos severos de envejecimiento acelerado. Si bien es cierto que los ciclos repetidos de humedad sequedad perjudican el comportamiento mecánico de los materiales elaborados, las prestaciones mecánicas obtenidas siguieron situándose por encima de las normativas, siendo superiores a las recogidas por otros investigadores que elaboran compuestos de yeso bajo criterios de economía circular.

- **Comportamiento frente al agua:** El EPS en disolución fue capaz de introducirse en el interior de los poros de los compuestos, lo que generó un efecto impermeabilizante. Tanto la absorción de agua por capilaridad como la absorción total de agua se redujeron hasta un 30% conforme se incrementa la cantidad de disolución en las muestras. La adición de las fibras aumentó ligeramente estos índices al aumentar la porosidad y la conexión interna de la red porosa. Los compuestos con una mayor proporción de EPS disuelto presentaron la permeabilidad al vapor de agua más baja de entre todas los yesos elaboradas, entre un 15.5% y 18.6% más bajo que el yeso sin adiciones. Además, los compuestos desarrollados mostraron una absorción superficial de agua muy inferior a la del compuesto sin adiciones, con una reducción del 97.8%.

- **Comportamiento frente al fuego:** Los compuestos que incorporaban residuos de EPS disuelto registraron las temperaturas más bajas durante el ensayo de fuego y no presentaron fisuras tras la exposición a las llamas, al contrario que los yesos de referencia. La incorporación de fibras de refuerzo de basalto y vidrio contribuyó a mitigar la pérdida de masa entre un 1.10% y 1.80% respectivamente. Al exponer los nuevos compuestos a elevadas temperaturas, las vías que se generan tras la degradación del EPS favorecen la liberación del vapor contenido en la matriz, aumentando la resistencia residual del material. A su vez, los compuestos reforzados con fibras de basalto presentaron un aumento de sus resistencias mecánicas en torno al 60% al incorporar los residuos de EPS disuelto. Durante la combustión de estos compuestos, las emisiones de CO y CO_2 estimadas no superaron en ningún caso las concentraciones máximas establecidas por el IDLH standard para ambos gases.
- **Alternativa viable en edificación:** El estudio del proceso de distribución de placas prefabricas elaboradas con el nuevo compuesto muestra el incremento de la productividad en el proceso de carga y descarga de almacenamiento conforme se reduce el peso de los prefabricados. Además, se disminuye la ratio de consumo unitaria “litros/placa” conforme se incrementa la cantidad de material reciclado adicionado, con el consiguiente ahorro económico en términos de transporte y disminución de las emisiones de CO_2 atmosférico, especialmente si se considera el efecto de posibles economías de escala. Estos resultados respaldan las excelentes posibilidades de aplicación de este novedoso producto para su empleo en la ejecución de placas y panales prefabricados para cuartos húmedos, apostando por un rápido y eficiente proceso de montaje/distribución y un uso más eficiente de los recursos existentes.

Tomando en consideración los resultados obtenidos para esta investigación, el nuevo compuesto de yeso desarrollado se presenta como una alternativa viable para la elaboración de placas y paneles prefabricados de yeso más sostenibles mediante la optimización y limitación del uso de recursos naturales y la reducción del consumo energético. El bajo peso específico de los compuestos, junto con sus altas prestaciones térmicas y su buen comportamiento mecánico origina un material muy interesante para su empleo en la construcción industrializada, suponiendo una fuente de ventaja competitiva para los fabricantes y empresas constructoras que apuesten por una mayor gestión de RCD, disminuyendo el consumo de materia prima necesario para elaborar materiales compuestos de yeso. Además, la reducción del uso de materia prima y la reutilización de residuos, necesarios para su elaboración, hacen de este material una opción más respetuosa con el medio ambiente, en línea con los criterios de economía circular.

5.2. Futuras líneas

La investigación iniciada en la presente Tesis Doctoral aun presenta múltiples líneas de trabajo abiertas que se pretenden continuar en los próximos años. Así, se pueden mencionar entre otras:

- Probar otras adiciones en formato agregado aligerado o fibra, con gran interés en las materias primas secundarias, para obtener soluciones diferentes e innovadoras que complementen a las ya analizadas.
- Analizar el efecto derivado de incorporar la disolución de EPS empleada en el desarrollo de los compuestos con base yeso en otros materiales conglomerantes de construcción.
- Tratar de reducir el impacto ambiental de los materiales desarrollados a través de la utilización de disolventes más ecológicos y menos nocivos para el medio ambiente.
- Estudiar en profundidad los costes de producción de una placa o panel prefabricado comercializable elaborado con los materiales de yeso objeto de esta investigación.
- Continuar con la línea de investigación vinculada al Análisis de Ciclo de Vida (ACV) de los nuevos materiales de construcción elaborados bajo criterios de economía circular.
- Mantener la colaboración internacional con las Universidades de Portugal donde se han realizado las diferentes estancias de investigación y desarrollar trabajos vinculados a la mejora de la eficiencia energética y sostenibilidad de los edificios. A la vez que, si es posible, se habrán nuevas líneas de colaboración con otras universidades y organismos públicos.

Además, aparte de las arriba mencionadas existen otros objetivos transversales vinculados a la investigación realizada que serán llevados a cabo en el futuro. Por un lado, se pretende explotar posibles vías de comercialización y aplicación real a la construcción de los nuevos materiales de yeso diseñados. Para ello, se han establecido vínculos de contacto con la empresa Saint-Gobain Placo Ibérica, S.A., y con organismos sin ánimo de lucro como COPADE y SIGNUS Ecovalor, S.L. para impulsar proyectos que integren estos materiales en sistemas constructivos.

Asimismo, durante los cursos 2025-2026 se encuentra activo el proyecto Waste2BuildIns con una financiación de 38.660,00 € para impulsar la investigación en materiales elaborados bajo criterios de economía circular, y cuyo objetivo principal es completar la caracterización de los materiales de yeso con disolución de residuos de EPS adicionada. No obstante, se seguirán explorando vías que impulsen el trabajo desarrollado y que hagan crecer la investigación realizada hasta la fecha, tanto en el ámbito nacional, como internacional.

6. Conclusions and future work

This section contains the conclusions derived from the study conducted, as well as the future work lines arising from this research's findings and limitations.

6.1. Conclusions

This research examines the technical feasibility of incorporating EPS waste in solution in gypsum composites. Likewise, the behaviour of these composites when adding other secondary raw materials discarded by the industry or reinforcement materials has been evaluated. All secondary raw materials have been introduced as partial substitution during the manufacturing process of gypsum-based materials, thus reducing the consumption of natural resources commonly used in the production of prefabricated boards and panels for the building sector.

Thus, the elaboration process of the developed materials in this research is committed to incorporating circular economy principles and promoting sustainable and responsible use of natural resources in construction, aligning with the guidelines of the European Green Deal presented by the European Commission on 11 December 2019 [70].

Following the research conducted in this Doctoral Thesis, the following conclusions can be drawn:

- **Reduction in the use of natural resources:** The results obtained in this research support the technical feasibility of incorporating EPS waste in solution as a partial substitute for the binder in gypsum composites to produce construction materials. Through the chemical recycling process of this waste, a significant reduction in the use of natural resources of up to 27% by mass is achieved, together with a high rate of waste reuse. This new way of reusing EPS waste is a step towards the production of more sustainable and durable alternative materials in the building sector.
- **Obtaining a cohesive, lightweight composite:** Incorporation of the EPS waste in solution allows the integration of the waste at a microscopic level in the gypsum matrix, generating a highly cohesive and homogeneous material compared to composites that incorporate the waste in a solid state.

- **Low-density and thermally efficient material:** The new composites designed in this research present a highly porous microstructure, which results in density reduction directly proportional to the amount of residue added. In this research, the greatest decreases in density and thermal conductivity were 33% and 62% respectively compared to traditional gypsum composites. Additionally, it has been possible to verify how the construction systems that incorporate the developed composites as an interior finishing layer, achieve an increase in the thermal resistance of the wall of 7.7%, even reaching an increase of 10.6% when combined with thermal break strips.
- **Composite with suitable mechanical strengths:** Incorporation of the dissolved EPS residues modified the quantity and morphology of the gypsum microstructures, decreasing its crystallite size as the quantity of this secondary raw material increased. SEM images showed how the recycled polystyrene, once solidified, adheres to the gypsum crystals, reducing their interconnections and thus decreasing the mechanical strength of the composites. Even so, all the mechanical properties analysed far exceeded the values indicated in the current regulations and exceeded those obtained in other studies where EPS waste is introduced in a solid state. In addition, it should be noted that the flexural strength in plates increased considerably (up to 64%) as the amount of EPS in solution in the mixtures increased.
- **Synergies with other secondary raw materials:** In this research, the versatility of using EPS waste in solution as a partial replacement of the binder when combined with other recycled materials has been demonstrated. With the addition of NFU textile fibres, recycled mineral wool fibres and NFU rubber, savings of 28.5%, 14.7% and 12.5% respectively in natural raw materials have been achieved in gypsum composites.

  These additions have made it possible to significantly reduce the densities obtained only with dissolved EPS, obtaining reductions of up to 31.3%, 20.3% and 30.1% when incorporating NFU textile fibres, recycled mineral wool fibres and NFU rubber, respectively. The recycled materials in fibre format have favoured the increase of micropores in the material matrix. This aspect, together with the low conductivity of the fibres, led to the most significant reduction in the thermal conductivity of the composites, by 66.7% and 30.37%, in the case of NFU textile fibres and recycled mineral wool fibres respectively.

It is worth highlighting how dissolved EPS waste has a positive impact on composites with the addition of recycled fibres by mitigating the reduction in strength and decreasing the water absorption that composites with additions of this type of fibres tend to show, reaching values close to those obtained by composites without fibres.

- **Composites with great durability:** The composites developed in this research meet the requirements of the current reference standards for their application in buildings even after being subjected to severe accelerated ageing cycles. While it is true that repeated cycles of humidity and dryness damage the mechanical behaviour of the materials produced, the mechanical performance obtained was still above the standards, being superior to those reported by other researchers who produce plaster composites under circular economy criteria.
- **Behaviour when exposed to water:** EPS in solution can penetrate the composite pores, which produces a waterproofing effect on the composites. Both capillary water absorption and total water absorption decreased by up to 30% as the amount of solution in the samples increased. The addition of the fibres slightly increased these rates by increasing the porosity and the internal connection of the porous network. The composites with a higher proportion of dissolved EPS had the lowest water vapour permeability among all composites developed, between 15.5% and 18.6% lower than the gypsum without additions. Furthermore, the developed composites showed a much lower surface water absorption than the composite without additions, with a reduction of 97.8%.
- **Behaviour when exposed to fire:** Composites incorporating dissolved EPS waste recorded the lowest temperatures during the fire test and showed no cracking after flame exposure, in contrast to the reference gypsum. The incorporation of basalt and glass reinforcement fibres contributed to mitigate mass loss by 1.10% and 1.80% respectively. By exposing the new composites to elevated temperatures, the pathways generated after EPS degradation favour the release of the vapour contained in the matrix, increasing the residual strength of the material. In turn, the basalt fibre-reinforced composites showed an increase in mechanical strength of around 60% when incorporating the dissolved EPS residues. During the combustion of these composites, the estimated CO and CO_2 emissions never exceeded

the maximum concentrations established by the IDLH standard for both gases.

- **Feasible alternative in construction:** The distribution process study of precast elements made with the new composite shows the increase of productivity in the storage loading and unloading process as the weight of the precast elements is reduced. In addition, the unit consumption ratio 'litres/plate' decreases as the amount of recycled material added increases, with consequent economic savings in terms of transport and reduced atmospheric CO_2 emissions, especially when considering the effect of possible scale economies. These results support the excellent application possibilities of this novel product for use in the execution of prefabricated panels and panels for wet rooms, with a fast and efficient assembly/distribution process and more efficient use of existing resources.

Considering the results obtained for this research, the new gypsum composite developed is presented as a viable alternative to produce more sustainable prefabricated gypsum boards and panels by optimising and limiting the use of natural resources and reducing energy consumption. The low specific weight of the composites, together with their high thermal performance and good mechanical behaviour, creates a very interesting material for its use in industrialised construction, representing a source of competitive advantage for manufacturers and construction companies that are committed to better management of CDW, reducing the consumption of raw materials needed to produce plaster composite materials. In addition, the reduction in the use of raw materials and waste reuse, necessary for its production, make this material a more environmentally friendly option, in line with circular economy principles.

6.2. Future work

The research in this Doctoral Thesis opens several work lines to be pursued in the coming years, including the following:

- Test other additions in the form of lightweight aggregate or fibre, with a strong focus on secondary raw materials, to obtain different and innovative solutions to complement those already analysed.
- To analyse the effect of incorporating the EPS solution used in the development of gypsum-based composites into other construction binders.

- To reduce the environmental impact of the materials developed through the use of more environmentally friendly and less toxic solvents.
- To thoroughly examine the production costs of a marketable prefabricated plate or panel made with the gypsum materials that are the subject of this research.
- To continue with the research line linked to the Life Cycle Assessment (LCA) of new construction materials produced under circular economy criteria.
- Maintain international collaboration with the universities in Portugal where the different research stays have been carried out and develop work linked to energy efficiency and building sustainability improvement. At the same time, if possible, there will be new lines of collaboration with other universities and public organisations.

Additionally, beyond those already mentioned, there are other cross-cutting objectives linked to this research that will be pursued in the future. On the one hand, the goal is to explore potential commercialisation pathways and real applications for the new gypsum materials designed. To this end, connections have been established with Saint-Gobain Placo Ibérica, S.A., as well as with non-profit organisations such as COPADE and SIGNUS Ecovalor, S.L. to foster projects that incorporate these materials into construction systems.

Likewise, the Waste2BuildIns project is active during the 2025-2026 academic years with funding of €38,660.00 to promote research into materials produced under circular economy criteria, the main objective of which is to complete the characterisation of gypsum materials with added EPS waste solution. Nevertheless, new avenues will continue to be explored to promote the work developed and to expand the research carried out to date, both nationally and internationally.

7. Índices de calidad

7.1. Artículos en revistas internacionales

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7.4. Proyectos vinculados a la tesis

Aula Signus. Convenio Aula Universidad Empresa Signus en la E.T.S. de Edificación. 2023-2025. El Aula SIGNUS tiene como objetivo la colaboración entre SIGNUS ECOVALOR S.L. y la UPM en actividades de docencia y difusión en el área de la economía circular, vinculada a la recuperación, reciclaje y búsqueda de aplicaciones para los residuos de neumáticos fuera de su vida útil (en adelante NFU) en el sector de la edificación. Financiación: 20000,00 euros. I.P.: Daniel Ferrández Vega. Participación: Equipo de Investigación. Dedicación: Completa.

Waste2BuildIns: Transformación de residuos para desarrollar nuevos productos de construcción medioambientalmente sostenibles con propiedades mecánicas y térmicas mejoradas (M230020126A-DFV). Concedido en el marco de la Convocatoria correspondiente a la Línea A, Doctores Emergentes, de la Universidad Politécnica de Madrid, en el marco del Convenio Plurianual entre la Comunidad de Madrid y la Universidad Politécnica de Madrid para la concesión de una subvención directa para el fomento y promoción de la investigación y la transferencia de tecnología 2023-2026. Financiación: 38660,00 euros. I.P.: Daniel Ferrández Vega. Participación: Equipo de Investigación. Dedicación: Completa.

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Anexos

- Anexo 1: Ferrández Vega, D., Zaragoza Benzal, A., Morón Fernández, C. (2023). Material de construcción aislante aligerado, panel o placa prefabricado, proceso de elaboración de dicho material de construcción y de dicho panel o placa prefabricado (ES 2 933 873 B2). Oficina Española de Patentes y Marcas.
- Anexo 2: Zaragoza Benzal, A., Ferrández Vega, D., Morón Fernández, C. (2023). Diseño y método de elaboración de un nuevo material conglomerante y su aplicación en el desarrollo de bloques para construcción modular aligerada y sostenible (ES 2 935 175 B2). Oficina Española de Patentes y Marcas.
- Anexo 3: Zaragoza-Benzal, A., Ferrández, D., Barrios, A.M., Morón, C. (2024). Water Resistance Analysis of New Lightweight Gypsum-Based Composites Incorporating Municipal Solid Waste. *Journal of Composites Science*, 8, 393. https://doi.org/10.3390/jcs8100393.
- Anexo 4: Zaragoza-Benzal, A., Ferrández, D., Santos, P., Atanes-Sánchez, E. (2024). Lightweight gypsum composite material to improve energy efficiency: Assessment of physico-chemical, mechanical, thermal and fire performance properties. *Materiales de construcción.* (aceptado, en prensa).