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Upcycling expanded polyethylene waste for novel composite materials: Physico-mechanical, hygrothermal and life cycle assessment

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ABSTRACT

Recycling plastic waste is a major challenge today, but it also offers an opportunity to create sustainable building products and promote a circular economy in construction. The aim of this article is to evaluate a new lightweight plaster composite incorporating expanded polyethylene (EPE) packaging waste for lightweight steel frame (LSF) partition walls. Mechanical and hygrothermal characterization and environmental life cycle assessment are carried out on these composites with a replacement of up to 30% of the original raw material by volume. The results show that the alternative plaster has 21.7% grater flexural strength in plates than required by standards. In addition, the reduced water vapour permeability of these materials makes them more resistant to damage in high humidity environments. On the other hand, the lightened composites have 43.9% lower thermal conductivity than the reference material, increasing the thermal resistance of LSF partition walls by 20.3%. Finally, cradle-to-gate global warming potential is reduced by up to 30% compared with the 100% virgin EPE. These results are encouraging and present a significant opportunity to advance the development of sustainable novel prefabricated modular building products.

1. Introduction

Changes in consumer habits have resulted in plastics replacing other raw materials in various applications and products [1]. However, their non-biodegradability has several environmental consequences [2]. Globally, approximately 330 million tonnes of plastic are produced each year, with only 9% being recycled [3]. Most plastic waste accumulates in landfills or is illegally dumped, affecting terrestrial and marine ecosystems [4]. This alarming situation highlights the need for new circular economy models that enable responsible economic growth [5]. The European Commission aims for a 55% recycling rate for plastic packaging waste by 2030 [6]. Additionally, the Extended Product Responsibility (EPR) legislation has encouraged companies to redesign products and select materials that promote circular economy [7].

One of the most widely produced plastics in the EU is low-density polyethylene (LD-PE), accounting for 13.4% of total European production, second only to polypropylene (PP) with 15.4%. LD-PE is used to produce expanded polyethylene (EPE), a material extensively used in packaging due to its lightness, flexibility and insulation properties. In Europe, 57.3% of post-consumer plastic waste comes from packaging-related applications. Notably, 17.3% of this waste still ends up in landfills, while 44.9% is incinerated for energy recovery [8].

Therefore, this article proposes a novel approach to redesigning conventional plaster partition panels incorporating recycling expanded polyethylene (EPE) waste. More specifically, it focuses on the need to give a second life to the so-called "single-use plastics". Approximately 36% of total plastic production is used for packaging and service articles, of which 85% becomes potential waste if poorly managed [9]. This situation becomes even more worrying when considering that the average use time of these plastics rarely exceeds 15–20 minutes, while their decomposition period in the environment exceeds 150 years [10, 11].

The construction sector is a key player in the recovery and reuse of plastic waste due to its high demand for raw materials and its crucial contribution to the economic growth of nations [12]. Recycling this plastic waste to develop new sustainable building materials contributes to mitigating environmental impacts and reducing the consumption of natural resources [13]. However, despite the significant potential of

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plastic waste as secondary raw materials, their current application is very limited [1]. This limitation is due to problems related to the quality, composition, and availability of recycled plastics, lack of adhesion between the binder and the addition, the required morphology of the waste, or the need to comply with specific physical-mechanical requirements [14].

Plastic wastes have been tested in developing gypsum-based modular components without high structural requirements [15]. These components are a potential solution for use in buildings interiors due to their versatile applications, good hygrothermal properties and fireproof resistance [16,17]. From an environmental perspective, their relevance is enhanced by the lower production temperature compared to other binders, as well as the fact that their main raw material ($CaSO_4–2H_2O$) is a by-product of many industrial processes [18]. Additionally, its potential for recycling has favoured its growing application in the construction industry [19]. In this context, several studies have tried to enhance the sustainability and technical performance of this material by incorporating single-use plastics into its matrix.

Other researchers have redesigned traditional gypsum composites by incorporating expanded polystyrene (EPS) and extruded polystyrene (XPS) residues, resulting in reduced density and significantly improved thermal performance, highlighting their potential for prefabricated products [20,21]. Recent research has further incorporated dissolved EPS waste during plasterboard fabrication [22], enhancing the durability of gypsum-based materials against water and improving their suitability for damp rooms. This expanded plastic waste is more economical and environmentally friendly than traditional raw materials like perlite and vermiculite, with no significant differences in the final properties of the hardened gypsum composite [23]. Moreover, the decrease in mechanical properties and ductility caused by adding expanded waste can be significantly mitigated by incorporating recycled reinforcing fibres [24,25].

In the last decade, manufacturers have increasingly applied polyethylene foam (EPE) in construction due to its thermal properties, low density, low water vapour permeability, and acceptable mechanical properties [26]. Studies have focused on hygrothermal performance of building solutions with EPE integration [27,28]. Different tests have shown promising results for the integration of foamed polymers into gypsum-based composites [26,29]. These studies agree that using these materials boosts building energy efficiency, improves water properties, reduces injury risk during installation, and increases productivity [30].

Additionally, the deterioration of ecosystems and urban environments has led to the evaluation of the physical and mechanical properties, as well as the environmental impacts, of these novel products [31]. Life Cycle Assessment (LCA) has been applied to evaluate the environmental impact of gypsum composites used in prefabrication with recycled materials [32–34]. Romero-Gómez *et al.* found that gypsum blocks incorporating 7.5% polypropylene and 2.5% waste fibres reduce energy consumption and global warming potential compared to a reference gypsum [35]. Rodrigo-Bravo *et al.* concluded that incorporating 4.9% recycled polyurethane foam in gypsum ceiling tiles reduced energy consumption, CO_2 emissions, and water use [36]. Quintana *et al.* compared traditional gypsum board to bio-based epoxy composite board made from natural fibres, showing a 50% reduction in CO_2 emissions [37].

Although previous studies have developed gypsum composites using plastic waste and circular economy principles, none have explored recycled EPE as partial replacement for the gypsum material. An alternative method is presented for recovering EPE waste from post-consumer packaging by incorporating it into prefabricated plaster. The main goal is to perform a complete characterization of different plaster composites integrating several percentages of EPE in their matrix, analysing their mechanical, hygrothermal, and environmental impacts. Unlike other research, this study goes a step further by analysing the potential application of these EPE wastes in the production of prefabricated panels, where the objective is to achieve the mechanical requirements of the current standards and, after a detailed study of the physical properties, to evaluate the thermal behaviour resulting from the implementation of these plaster composites in a lightweight steel frame (LSF) partition wall. Finally, a comparative LCA is implemented for a plaster plate incorporating 30% of EPE waste and a reference plaster composite (without recycled content), both produced at laboratory scale, to enhance the environmental benefits of using waste-based plastic composites.

2. Materials and methods

2.1. Materials and sample preparation

The following raw materials were used to elaborate the composite materials developed in this study:

- *Binder*: building gypsum type A according to UNE-EN 13279-1 (2009). Known as plaster, it is characterized by its fineness of grind and whiteness. The manufacturer Placo Saint-Gobain Ibérica S. A. (Madrid, Spain) provided the following properties: water vapor diffusion factor ($\mu = 6$), pH > 6, grain size 0–0.2 mm, reaction to fire A1 and purity index above 92% [38].
- *Tap water*: drinking water from Canal de Isabel II (*Comunidad de Madrid*, Spain), complying with Council Directive 98/83/EC [39]. It has an average hardness of 58.5 mg/l $CaCO_3$, pH of 8.15, total chlorine content of 1.29 mg/l and electrical conductivity 188.04 μS/cm at 20°C [40].
- *Expanded Polyethylene (EPE)*: this secondary raw material has been recovered from packaging waste. EPE is a moulded, flexible, non-cross-linked, closed-cell foam [41] with low thermal conductivity (48 mW/m·K), and bulk density of 0.5 kg/m^2, making it an effective thermal and acoustic insulator. The waste was manually shredded to a size between 1.0 and 3.0 mm. The maximum size of 3.0 mm was selected according to the limitations established in other research found in the literature [42], on the other hand, the minimum size of 1.0 mm was established due to the limitation in the process to obtain the EPE waste shredded manually.

To develop the composites, the recommendations of UNE-EN 13279-2:2014 standard [43] were followed. First, crushed EPE waste is mixed with dry plaster powder to prevent agglomeration. This dry mixture is then sprinkled over mixing water for 30 seconds. After 60 seconds resting, kneading process begins, consisting of 30 seconds of mixing, 30 seconds of rest, and 30 seconds of mixing. The quantity of mixing water was determined according to UNE-EN 13279-2:2014 standard [43], resulting in a water/binder ratio of 0.65 for all samples, which corresponds to a plastic and workable consistency by obtaining a plaster paste diameter of 165 ± 10 mm in the flow table method. The proportions of each material used in this research are shown in Table 1.

As shown in Table 1, a progressive substitution of the original raw materials (plaster and water) with EPE waste was implemented, achieving a 30% volume replacement. This approach addresses the potential application of these secondary raw materials to reduce natural resources consumption in the construction sector, aligning with the objectives of the European Green Deal for transitioning to a clean and circular economy [44].

In all cases, the composites were left in laboratory ambient for six days (23 ± 1°C and relative humidity 55 ± 5 %). Then, before testing, the samples were placed in a drying oven (40 ± 2°C) for 24 h until a constant mass was achieved.

2.2. Experimental programme

The experimental programme (Fig. 1), began with the design and manufacture of the composites, followed by their physical-mechanical characterisation. This characterisation included mechanical resistance

Table 1
Dosages of the composites used in this investigation.

Type	Mass ratio (g)			Volume ratio (%)			Setting time (min)
	Plaster	Water	EPE waste	Plaster	Water	EPE waste	
P0.65	1000.00	650.00	—	60.6	39.4	—	14
P0.65–7.5%	925.00	601.30	0.75	56.1	36.4	7.5	12
P0.65–15.0%	850.00	552.50	1.50	51.6	33.4	15.0	12
P0.65–22.5%	775.00	503.90	2.25	47.1	30.4	22.5	11
P0.65–30.0%	700.00	455.20	3.00	42.6	27.4	30.0	10

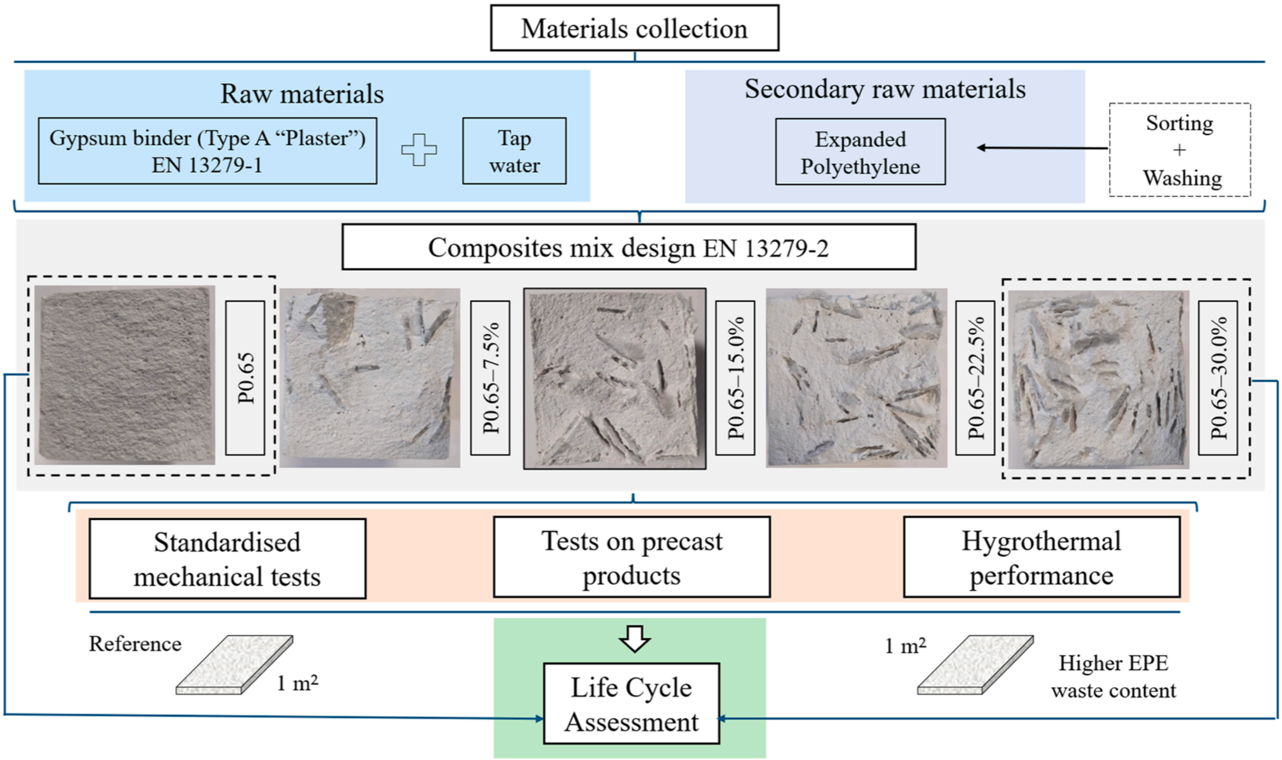


Fig. 1. Methodology followed for the research development.

tests, analysis of hygrothermal properties and a viability study for prefabricated plates. Subsequently, a LCA was conducted on the reference sample and the composite with the highest EPE waste content. This approach evaluates the feasibility of using these composites in prefabricated construction systems and addresses plastic waste management for construction applications.

2.2.1. *Mechanical characterisation*

- *Surface hardness,* determined with a Shore C hardness tester following UNE 102042 [45] on standardised RILEM samples (4 × 4 × 16 cm^3). Measurements are taken on two plane-parallel faces that were in contact with the mould, with five measurements per face across three samples of each dosage (Fig. 2(a)).

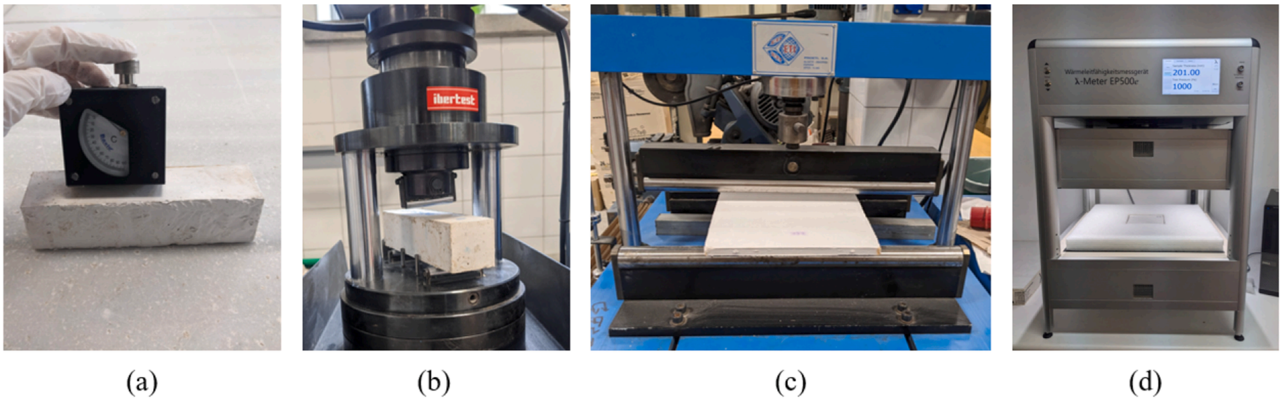


Fig. 2. Pictures of some of the tests carried out in this research: (a) surface hardness, (b) flexural strength, (c) flexural strength in plates, (d) thermal conductivity.

- *Mechanical strength,* evaluated for flexural and compressive strength according to UNE-EN 13279-2 [43] using six samples (4 × 4 × 16 cm^3) for each dosage. A hydraulic press model AUTOTEST 200-10SW was used to apply a progressively constant load until samples failure, at speeds of 10 N/s for bending and 20 N/s for compression (Fig. 2(b)).
- *Maximum breaking load in plates*, determined on plates measuring 40 × 30 × 1.5 cm^3, with six samples tested per plaster type. Following the UNE-EN 12859 standard [46], the minimum breaking load for prefabricated plates is established at 0.18 kN. It is performed with the help of a PÁCAM MPX-22 equipment, applying a progressive load until breakage (Fig. 2(c)).
- *Impact hardness,* in accordance with UNE-EN 12859 standard [46] by measuring the average diameter of the footprint produced by a 5 cm diameter steel sphere dropped from 50 cm onto the plaster plate. Five measurements are taken across three plates for each dosage.
- *Scanning electron microscopy (SEM),* conducted on the sample with the highest EPE waste content to analyse its integration in the matrix. TESCAN VEGA Generation 4 scanning electron microscope with an energy dispersive detector model was used. The EDX Oxford ISIS-Link software facilitated the acquisition, processing, and evaluation of the analyses of samples. Fragments were obtained from within sample, without altering the surface texture, and were coated with a thin gold layer using a Cressington 108 metalliser.

2.2.2. Hygrothermal properties

- *Water absorption by capillary action,* applying the UNE-EN 1925 standard [47] by immersing 4 × 4 × 16 cm^3 samples vertically in water to a depth of one centimetre. The samples are placed on a grid to favour capillarity absorption through its square face (4 × 4 cm^2). Initial dried samples are recorded, along with weights after immersion for 1, 3, 5, 10, 15, 20 and 40 minutes, allowing calculation of water absorbed per unit of surface area over time.
- *Permeability to water vapour,* determined using the vase method [48]. Circular test samples (1.5 cm thick) are placed in airtight containers with a water-saturated potassium nitrate (KNO_3) solution. The assembly is sealed with silicone to ensure vapour migration across the sample, maintaining a distance of 1.5 ± 0.5 cm between the sample and the solution. The weight of the assembly is recorded weekly for eight weeks to measure water vapour permeability under controlled humidity and temperature conditions.
- *Thermal conductivity,* evaluated using the guarded hot plate method [49]. Samples (15 × 15 × 2 cm^3) are tested with a λ-Meter EP500e equipment at temperatures of 10°C, 25°C, and 40°C, measuring under steady conditions for 90 min at each temperature. Results are expressed as a thermal conductivity value obtained at 10°C based on a regression line of the three measurements (Fig. 2(d)).
- *Bulk density,* determined as the mass-to-volume ratio [45]. The mean value was determined from three prismatic samples (4 × 4 × 16 cm^3). Mass is measured with an electronic balance (accuracy 0.01 g), and volume was obtained using a calliper (accuracy 0.01 mm).

2.2.3. Numerical simulations

To evaluate the benefits of the new developed gypsum composites plasterboards when assembled to the lightweight steel framed (LSF) partition walls, some simulations using THERM finite element software were conducted and their thermal performances were compared. Making use of these two-dimensional THERM models, the thermal resistances (or *R*-values) were computed and the thermal performance improvements quantified.

The partition LSF wall is modelled with the new composite panels, having the lowest thermal conductivity (expected to be the P0.65-30%), as the finishing layer and compared to the reference plaster panels (P0.65). The steel studs are non-load-bearing ones, having a C-shape profile with the following cross-section dimensions C90 × 37 × 15 × 0.6 mm. Moreover, it was assumed that these steel studs are spaced 400 mm apart. Therefore, the length of the LSF model is the same (400 mm), being the steel profile at the middle length (or centre) of the model. As usual, the air cavity of this LSF partition is full filled with mineral wool insulation, improving both thermal and acoustic performance [50].

Regarding the boundary conditions, it was assumed an environmental air temperature of 25°C in one side of the partition wall and 15°C on the other side. Moreover, the surface thermal resistances were set at 0.13 m^2•K/W on both sides of the wall, as recommended by the Spanish CTE DB-HE standard [51] for envelopes in contact with indoor environment.

Regarding the implemented model's accuracy, notice that the authors have a large experience in modelling the thermal behaviour of LSF walls, as can be checked in previous scientific publications in international journals [50,52–55]. The maximum error in the THERM algorithm was set to 2%. Additionally, several verifications were performed to ensure the reliability of the computed values. First, notice that the THERM finite element method (FEM) algorithm is in compliance with the ISO 10211 standard [56], being classified as a steady-state high precision software. In this context, to ensure not only the accuracy of this FEM algorithm, but also the author's ability to correctly model using this software, the two test-cases displayed in Annex C of ISO 10211 standard [56] were modelled. These Annex C reference values were compared to the ones obtained by the authors and an excellent agreement between both were found [53].

Additionally, the 2D FEM models' reliability was checked by comparing the numerical results computed for a simplified model of the same LSF partition wall containing only homogeneous layers (i.e., without the steel frame). In these walls, having homogeneous layers, there are analytical solutions in standard ISO 6946 [57], which are easy to calculate based on the material thermal conductivities and thickness of each layer. Table 2 displays the thermal transmittances (*U*-values) calculated making use of analytical formulas [57] and computed by THERM simplified models (neglecting the steel frame). Once again, these results certify the high accuracy of the THERM software algorithm, as well as the authors' skills to correctly use it.

Notice that the THERM models are two-dimensional, instead of three-dimensional as real LSF walls and, therefore, the influence of some steel frame components, such as the bottom and upper tracks, are neglected. Moreover, the gypsum plasterboard fixing screws, which could originate some punctual thermal bridges (steel screws), are also neglected. Additionally, real building components (e.g., walls) are subjected to transient thermal conditions, while our THERM models performed a simplified steady-state thermal analysis.

2.2.4. Life cycle assessment

The environmental impacts of a plaster partition panel are assessed following the Life Cycle Assessment (LCA) methodology [58,59]. LCA is organized into four interrelated phases: goal and scope definition, in which functional unit and system boundaries are defined; life cycle inventory (LCI), which involves data collection and calculation procedures to quantify relevant inputs and outputs of material and energy in the product system; life cycle impact assessment (LCIA), which evaluates the potential environmental impacts using the results of the LCI analysis; and interpretation, in which the results of the impact assessment are interpreted, and opportunities for improvement are identified.

A cradle-to-gate LCA was developed for a lab-scale plaster partition

Table 2
Thermal transmittances computed for simplified wall models assuming homogeneous layers.

Wall Configuration (Without Steel Frame)	*U*-Value ($W/m^2.K$)	
	Analytical	THERM
P0.65 sheathing plates	0.3340	0.3340
P0.65-30% sheathing plates	0.3204	0.3204

panel incorporating 30% by volume of EPE waste, and a sample as reference was produced with 100% plaster. Since the product is still in the early stage of development (lab-scale), the potential end-of-life environmental impacts are very difficult to predict, so this stage was not included, due to the unavailability of specific data, such as the recycling processes. The functional unit (FU) is defined as 1 m^2 of plaster panel to be used on a partition wall. The selected functional unit allows for comparison with other studies and materials intended for the same function, regardless of differences in product dimensions. Fig. 3 presents the system boundaries of the reference P0.65 and P0.65–30% samples. It includes raw materials (production/transformation and transportation), and energy used to produce the plaster partition panel. The raw materials used are water, plaster (P0.65), and recycled EPE (P0.65–30%). The cut-off system model is considered, which means that the recycled material only accounts for the impacts of the recycling process and does not consider the impacts from its previous life (virgin EPE production). The EPE recycling process was modelled based on the study from Martín-Lara *et al.*, in which the authors conducted an LCA of mechanical recycling of post-consumer EPE flexible films in Granada (Spain) [60]. The EPE recycling comprises sorting and washing processes. The sorting process includes the bale opening followed by a drying process. Then, the material is pre-crushed, and optical separators eliminate the impurities, such as paper, textiles, and other plastics. The wash process starts with the plastic undergoing a wet grinder, where its size is reduced, washed by decantation basins and centrifugal washers, and dried by air heated through electrical resistance and mechanical drying. Additionally, the transportation from the recycling facility to the plaster partition panel production site is accounted for, with an assumed distance of 50 km. The production of plaster partition panel was based on a study from Romero-Gómez *et al.*, which involves mixing the dry raw material and gradually adding water (0.65 water/plaster ratio) until it reaches a homogeneous state [35]. The mixture is then placed in the mould, removed after 24 hours, and placed in a dry chamber. It is assumed that the plaster is made on-site at the plasterboards manufacturing facility, eliminating the need for transportation. Production consists of dehydrating the plaster in rotary kilns, followed by adding additives.

Table 3 depicts the mass inventory data to fulfil the FU for the plaster partition panel samples. The inventory of electricity used is scaled-up data from industry data based on literature. Tables 4 and 5 present the energy consumption per FU required to produce recycled EPE and the energy required to produce P0.65 and P0.65–30% plaster partition panels, respectively. The data on the recycling process of EPE was extracted from previous research [60]. The Spanish electricity mix from the Ecoinvent v3.9 database [61] is adopted as the plaster partition panel samples are produced in Spain. The LCIA of the plaster used in the samples was collected from the Environment Product Declaration (EPD) [62]. Waste management and the production of packaging are also considered. The water data was collected from the Ecoinvent v3.9

Table 3
Life cycle inventory of mass required for FU of P0.65 and P0.65-30%.

Samples	Plaster (kg)	Water (kg)	EPE waste (kg)
P0.65 [Ref.]	19.2000	12.4800	—
P0.65–30%	13.4400	8.7400	0.0578

Table 4
Energy consumption per FU required to produce recycled EPE.

Product	Process	Electricity (kWh)	Reference
Recycled EPE	Bale opening	0.0010	[60]
	Drying	0.0009	
	Pre-crushing	0.0070	
	Optical separation	0.0062	
	Compaction	0.0019	
	Washing	0.0102	
	Drying	0.0105	
	Gridding	0.0036	

Table 5
Energy consumption per FU required to produce P0.65 and P0.65-30% plaster partition panels.

Product	Process	Electricity (kWh)	Reference
P0.65 [Ref.]	Mixer	0.0253	[35]
	Former equipment	0.0881	
	Curing	0.0348	
P0.65–30%	Mixer	0.0940	
	Former equipment	0.3267	
	Curing	0.1293	

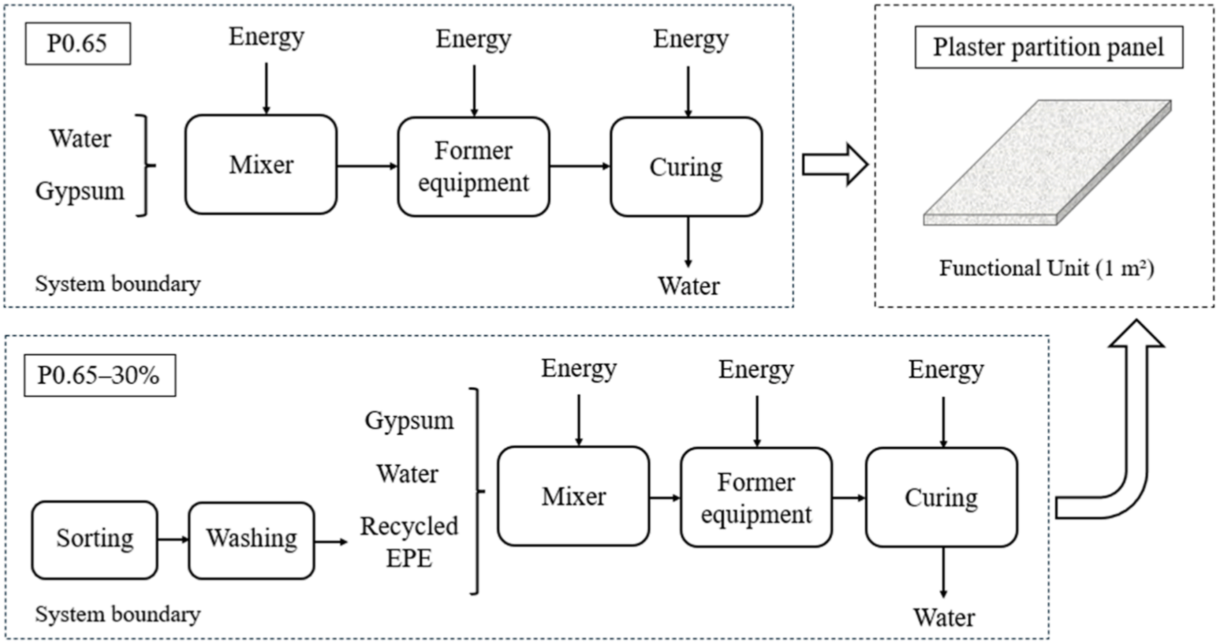


Fig. 3. System boundary of the production P0.65 and P0.65–30.0% samples.

database.

The LCIA impact categories selected are climate change (CC), ozone depletion (OD), resource use, fossil (Ruf), resource use, minerals and metals (Rum), and water use (WU). These categories were selected according to the EPD of gypsum production [62], and the categories recommended by the Product Environmental Footprint (PEF) [63]. Except for water use, the selected categories present the most robust methods according to the PEF classification [64]. Water use was selected due to the high quantity used to produce the novel composite. Nonetheless, these categories have been widely used to evaluate composite materials, particularly in the construction sector. The Environmental Footprint (EF) 3.1 method assessed the environmental impacts. The analysis is performed via SimaPro v.9.5 using Ecoinvent v3.9 cut-off database data.

3. Results and discussion

3.1. Mechanical characterisation

Fig. 4 shows the results obtained for the mechanical tests conducted on standardised samples of 4 × 4 × 16 cm^3.

Partially replacing the original plaster material with EPE waste results in a decrease in the surface hardness of the composites. Thus, as shown in Fig. 4, there is a decrease of 8.6% in the Shore C hardness for the P0.65-30% sample concerning the reference (P0.65). This decrease in surface hardness has been observed in previous research where plastic additions were used, such as the addition of shredded cable waste [65] or expanded polystyrene [20]. Furthermore, as reported in previous studies, this reduction in surface hardness is linked to a lower compressive strength [66].

Regarding the flexural and compressive strength of the newly designed composites, Fig. 4 shows that the minimum values established by the current standards were exceeded in all cases. As with the surface hardness, when replacing the original plaster material with EPE waste, there is a decrease in the flexural and compressive strength of the composites. This effect is due to the lower density and mechanical strength of the EPE waste compared to the original gypsum material, so that when incorporated as an addition to the composites, a more heterogeneous matrix is generated which may have preferential breaking points. Thus, in the most unfavourable case (P0.65-30%), the reduction concerning the material without additions was 37.5% for the flexural strength and 45.0% for the compressive strength. A similar effect has been observed in previous research, as presented in Table 6, where a comparative review has been conducted.

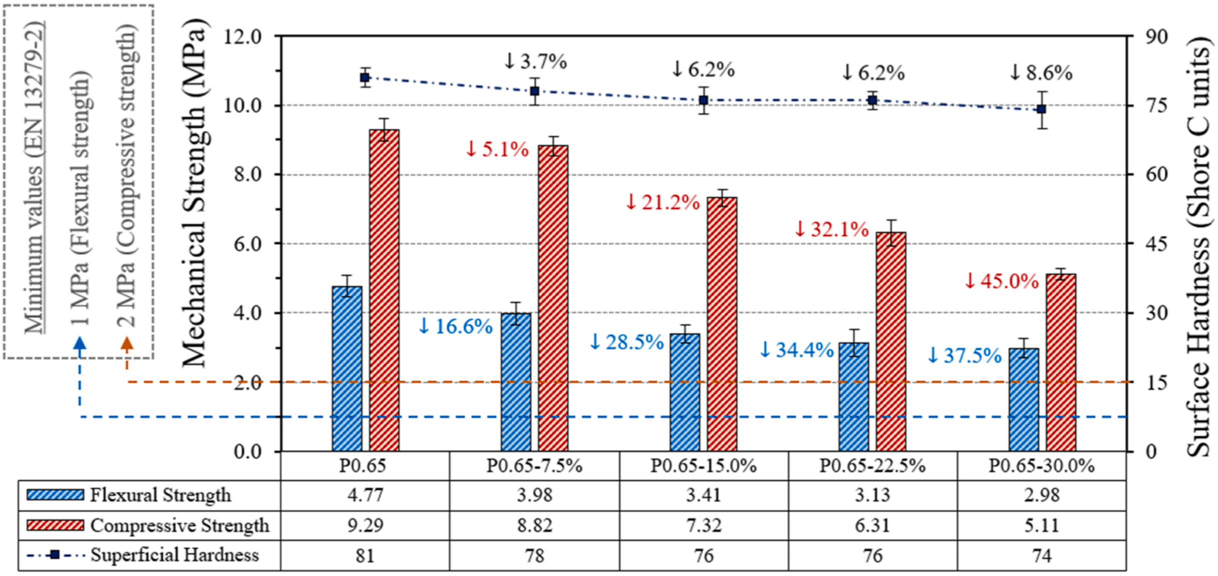
Table 6
Flexural and compressive strength for related studies with gypsum-based materials and plastic wastes.

Reference	Waste*	Addition	Flexural Strength (MPa)	Compressive Strength (MPa)
This study (P0.65-30%)	EPE	30% vol.	2.98	5.11
[21]	XPS	4% wt.	1.68	2.07
[67]	PP	10% vol.	2.40	7.30
[68]	CA	3.5% wt.	2.40	7.06
[65]	Cable pellet	70% vol.	2.30	5.20
[69]	Polycarbonate	40% wt.	2.61	7.63
[66]	ELT rubber	30% vol.	2.25	4.35
[70]	HDPE	10% vol.	3.34	7.88
[20]	EPS	3% wt.	1.62	3.06
[16]	EPS dissolution	26.5% wt.	3.79	6.26

[*] **Note**: XPS (expanded polystyrene), PP (polypropylene), CA (cellulose acetate), ELT (end-of-life tyre), HDPE (high-density polyethylene), EPS (expanded polystyrene).

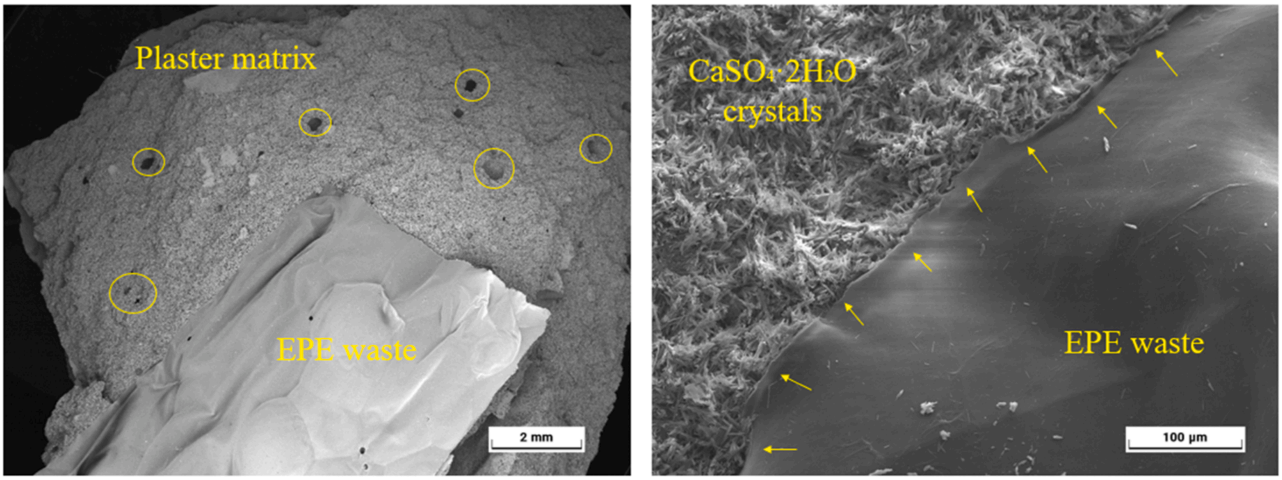
Table 6 shows that the values obtained in this research align with those obtained in previous research. From the perspective of the functionality required for these construction products, analysing the mechanical properties is fundamental to promoting their application in the building sector. Fig. 5 shows a scanning electron microscopy analysis of the P0.65-30% sample to visualise the effect of integrating EPE waste into plaster composites. This dosage was selected because it was considered the most unfavourable in terms of mechanical resistance and the most beneficial in terms of thermal and environmental performance.

As presented in Fig. 5(a), the EPE waste integrates well into the plaster matrix. Some pores generated during the setting process can be observed. Pedreño Rojas *et al.* (2019) observed similar behaviour when incorporating polycarbonate waste, with the pore size increasing as larger particles were added [71]. Fig. 5(b) shows the good adhesion between the recycled material and the matrix. The formation of the typical dihydrate crystals ($CaSO_4$–$2H_2O$) generated after the hydration of the plaster can be seen, which present a characteristic acicular morphology [72]. The formation of these crystals at the plaster-EPE interface is also visible, which makes it difficult to pull out the residue after flexural breakage [67,73].



	P0.65	P0.65-7.5%	P0.65-15.0%	P0.65-22.5%	P0.65-30.0%
▨ Flexural Strength	4.77	3.98	3.41	3.13	2.98
▨ Compressive Strength	9.29	8.82	7.32	6.31	5.11
-·■·- Superficial Hardness	81	78	76	76	74

Fig. 4. Results for mechanical tests, including minimum values from EN 13279-2.



(a) (b)

Fig. 5. SEM analysis of the sample P0.65-30%.

Finally, as highlighted in the literature [74,75], it is convenient to conduct mechanical tests on larger samples to better analyse their behaviour in commercially sized elements. Thus, Fig. 6 presents the results of tests performed on plaster partition panels made at laboratory scale and with dimensions of 40 × 30 × 1.5 cm^3.

Aligned with the results obtained in Fig. 4, Fig. 6 shows how the progressive incorporation of EPE waste produces a significant decrease in the flexural strength. Thus, the maximum ultimate load that P0.65-30% samples were able to withstand was 0.23 kN, 47.7% lower than that obtained by the reference sample (P0.65). However, as in the standard EN 13279-2 test, all the tested plates exceeded the minimum breaking load established by the standard by 0.18 kN. This reflects the viability of these composites for use in manufacturing prefabricated boards and panels. These mechanical test results align with those obtained in other studies where LDPE waste from single-use bags [29] or discarded CDs and DVDs [76] was added.

On the other hand, Fig. 6 also includes the results obtained for the impact resistance test. It can be seen that by replacing the original plaster raw material with EPE waste, the plaster composites can better absorb the impact after the test. Thus, the diameter produced by the steel sphere on the plates increased by 16.8% for the P0.65-30% composite for the P0.65% reference. Furthermore, it was observed that the plates with an addition of 15% EPE waste did not break during the test, maintaining their integrity. A similar result was observed in a previous investigation when incorporating recycled rubber waste aggregates from discarded tyres [66].

3.2. Hygrothermal properties

Water absorption by capillary action was determined to evaluate the hygrothermal properties of composites. These results are shown in Fig. 7.

As shown in Fig. 7, the capillary water absorption of these composite materials reduces as the replacement of the original plaster material with EPE waste increases. Thus, at the end of the test, the P0.65-30% sample absorbed 33.8% less water than the P0.65% reference sample. Therefore, there is a tendency for water absorption to decrease as the recycled content of the samples increases. This effect attributed to the impermeable nature of this plastic waste has already been observed in other investigations on gypsum materials with the addition of recycled rubber aggregates [77] or HDPE recycled aggregates [70]. Thus, this research reinforces the idea reflected in the study of Vidales *et al.* (2020) on the possibility of using recycled plastics to improve the water resistance of gypsum composites [30].

Gypsum composites are characterised by their good hygrothermal regulation capacity [72]. However, in certain geographical regions, it is desirable to reduce the water vapour permeability to avoid condensation and mould on the plasterboards surface [78]. Fig. 8 shows the effect of

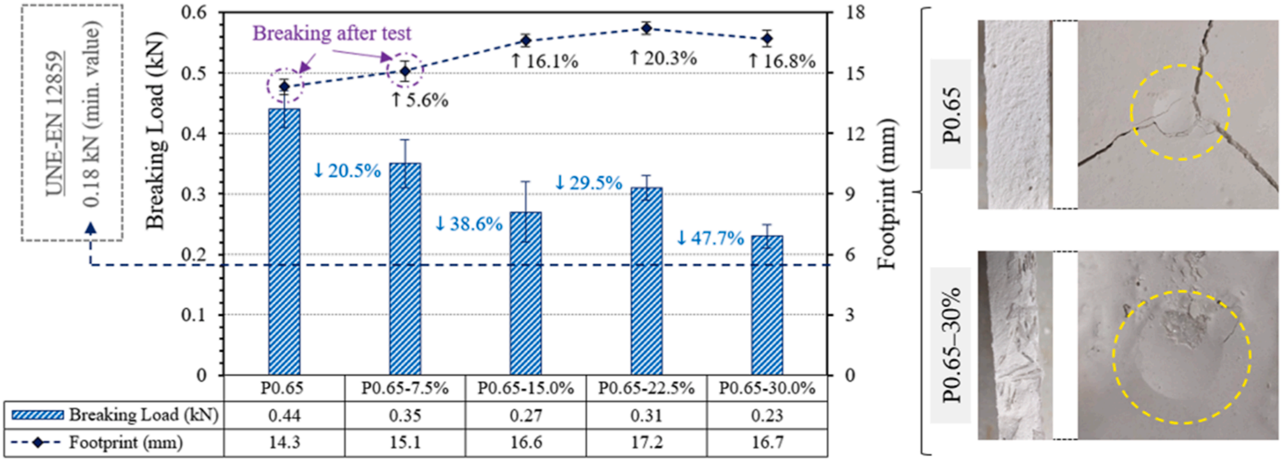


Fig. 6. Results for maximum ultimate load and impact strength of precast plates.

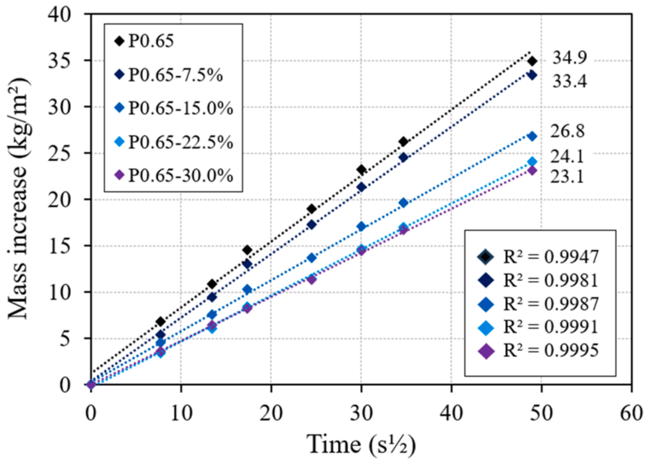


Fig. 7. Capillary water absorption of plaster composites.

the partial replacement of the original plaster raw material by EPE waste on the water vapour permeability of the composites.

As seen in Fig. 8, adding EPE waste leads to a decrease in the water vapour permeability of the plaster composites. The test was carried out for eight weeks under controlled conditions of relative humidity (58.7 ± 2.7 %) and temperature (21.5 ± 3.3°C), all samples subjected to the same environmental conditions. Thus, a decrease of up to 19.7 % in water vapour diffusion was observed for the P0.65-30% sample compared to the reference plaster. This effect reinforces the idea presented by Zaragoza-Benzal *et al.* in their research, where the possibility of developing prefabricated elements for wet rooms by partially replacing the original plaster material with plastic waste was addressed [22]. Thus, incorporating EPE waste would broaden the application field of conventional gypsum materials, allowing their use in the fabrication of partition panels for high-humidity spaces, without the need for special surface treatments and, thereby, reducing execution time and costs. Thermal behaviour of the new plaster composites was also analysed. Fig. 9 shows the results for thermal conductivity and bulk density of each dosage used in this research.

As seen in Fig. 9, there is a progressive decrease in the bulk density of the plaster composites as the EPE waste content increases. Thus, the P0.65-30% sample has a density of 986.3 kg/m^3, representing an 18.7% decrease compared to the original material without additions, P0.65. Therefore, as stated in the UNE-EN 14246:2007 standard, these newly developed composites can be used to manufacture lightweight partitions. A similar effect was obtained by Álvarez *et al.* by adding lightweight fillers to develop new composites for building applications [79]. In the same way, and in agreement with the results obtained by San Antonio *et al.*, this decrease in bulk density led to a reduction in the thermal conductivity of the developed composites [21]. In this sense, the thermal conductivity of the P0.65-30% composite was 172.5 mW/m·K, which represents a decrease of 43.9% compared to the traditional material. These results align with those obtained by other researchers, as shown in Table 7.

3.3. Numerical simulations

Some numerical simulations were carried out to determine the influence of the new plaster composites on the thermal performance of a building partition using THERM software. Light Steel Frame (LSF) wall partition (Fig. 10) was modelled in the software. Fig. 10 also shows the thicknesses and thermal conductivity of the wall materials.

As shown in Fig. 10, the thermal resistance of a partition wall made with P0.65-30% increases by 20.3% compared to the reference material without EPE waste. The results obtained after this simulation position the new composites developed in this research as a viable solution to improve the thermal performance of building systems. The fact that buildings account for approximately 32% of the world's total energy consumption highlights the need to develop enclosures with greater thermal resistance [80]. For this reason, although the development of these new sustainable materials with lower thermal conductivity can currently be considered a potential source of competitive advantage, they are increasingly becoming necessary to move towards net-zero energy buildings [81].

3.4. Life cycle impact assessment

Fig. 11 presents the comparative LCIA results for climate change, ozone depletion, resource use -fossil, resource use - mineral and metal, and water use for the partition panel made with 100% plaster and the alternative by replacing 30% plaster with recycled EPE.

Comparing the results shown in Fig. 11, partially substituting plaster reduces environmental impacts by approximately 30% for all impact

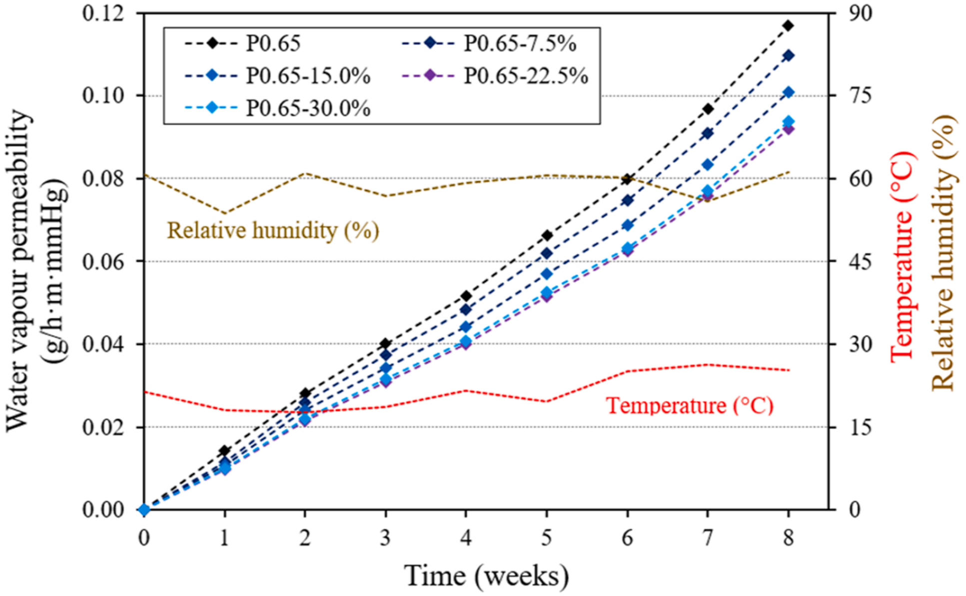


Fig. 8. Water vapour permeability obtained for the plaster composites.

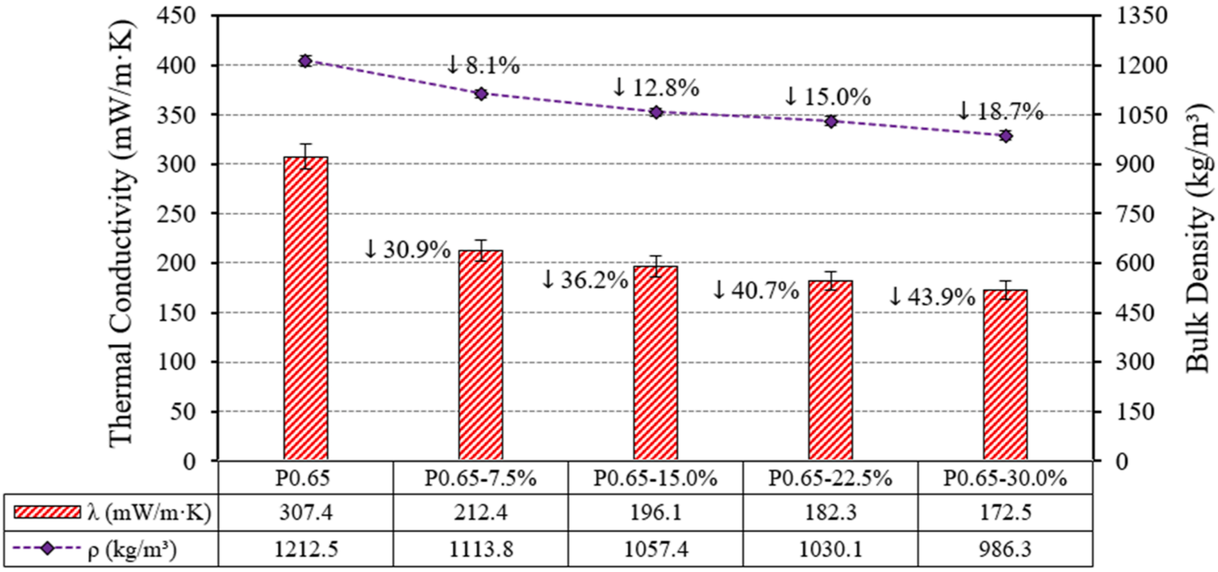


Fig. 9. Thermal conductivity and bulk density of the plaster composites.

Table 7

Bulk density and thermal conductivity for related studies with gypsum-based materials and plastic wastes.

Reference	Waste	Addition	Bulk density (kg/m³)	Thermal Cond. (mW/m·K)
This study (P0.65-30%)	EPE	30% vol.	986	173
[21]	XPS	4% wt.	730	89
[68]	CA	3.5% wt.	1186	325
[65]	Cable pellet	70% vol.	1015	246
[69]	Polycarbonate	40% wt.	1190	177
[66]	ELT rubber	30% vol.	1060	168
[70]	HDPE	10% vol.	1040	190
[29]	LDPE	3% wt.	1035	270
[16]	EPS dissolution	26.5% wt.	746	80

*__Note__: XPS (extruded polystyrene), CA (cellulose acetate), ELT (end-of-life tyre), HDPE (high-density polyethylene), LDPE (low-density polyethylene), EPS (expanded polystyrene)

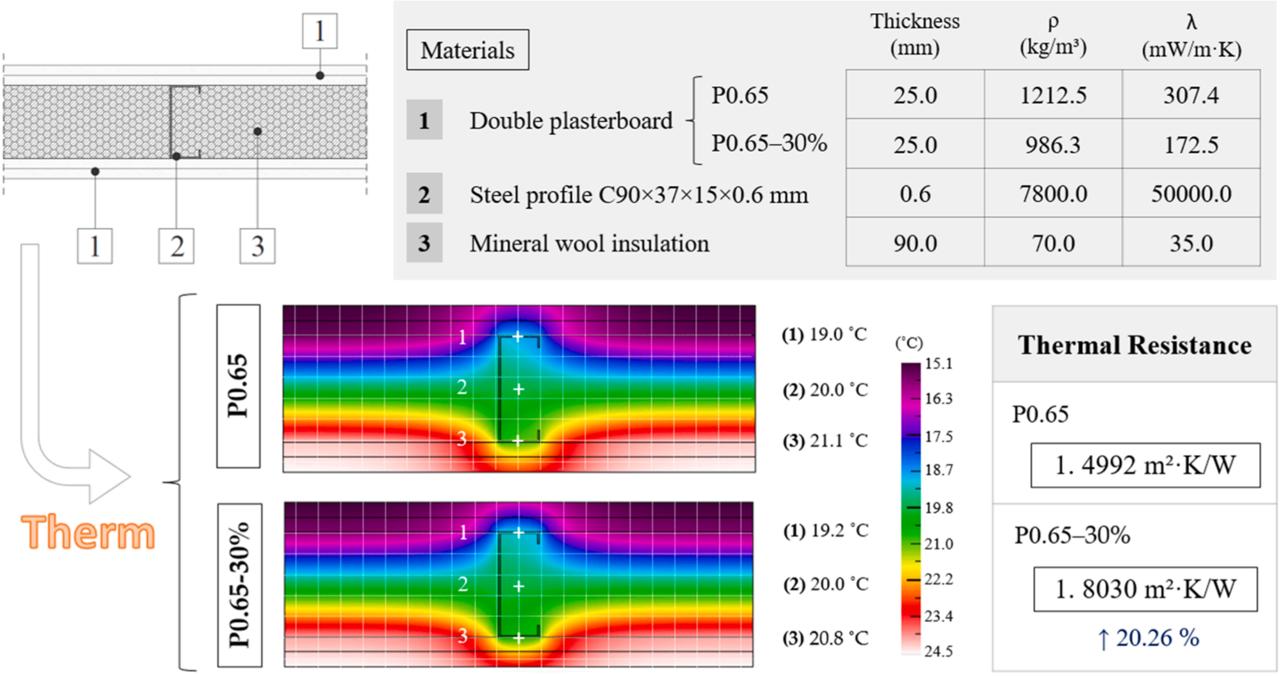
categories. The highest impact in climate change, resource use – fossil, resource use – mineral and metal, and ozone depletion is due to plaster production, representing more than 90% of the total impacts and almost 100% for OD. The highest contribution to water use is the water (90%) used in plaster partition panel manufacturing. The EPE recycling impact represents less than 1% for ozone depletion, 1% for climate change and resource use – fossil, and 2% for Rum and water use. The impacts of the energy used in the plaster partition panel production account for 2% of climate change and resource use – fossil impacts, 4% for water use in both samples and 5% (P0.65) and 4% (P0.65-30%) for resource use – mineral and metal. The transport impact represents less than 1% for all categories. Therefore, incorporating recycled EPE reduces the environmental impacts by decreasing the plaster manufacturing process burdens, due to less virgin raw material needed. Furthermore, the burdens of recycled EPE are low since it only accounts for the recycling process (sorting and washing) of the EPE waste to be used as secondary raw material.

To compare the benefits of replacing 30% plaster with recycled EPE, the results were compared with those from a similar study by [35]. They compared the environmental impacts of a conventional plaster partition panel (AGB-Reference) and an alternative incorporating polypropylene (AGB/G/PP/7.5%) and waste fibres (AGB/G/PA6/2.5%). To compare both studies, LCI data was adjusted for 1 m^3 of plaster partition panel (FU). The system boundaries included the raw materials and energy required to produce the plaster partition panels. It was assumed that the plaster and the panel are produced in the same plant, so no transportation is considered, and the recycled materials were collected from a 50 km distance. LCIA results were calculated for climate change. Fig. 12 shows that replacing 30% plaster with recycled expanded polyethylene reduces climate change impacts by 48% and 46% compared to the AGB (Reference) and AGB/G/PA6/2.5%, respectively. Compared with AGB/G/PP/7.5%, the reduction was 41% for the sample P0.65–30%. These results demonstrate the environmental benefits of incorporating recycled materials and the feasibility of EPE waste as an additive for manufacturing lightweight plaster partition panels.

4. Conclusions

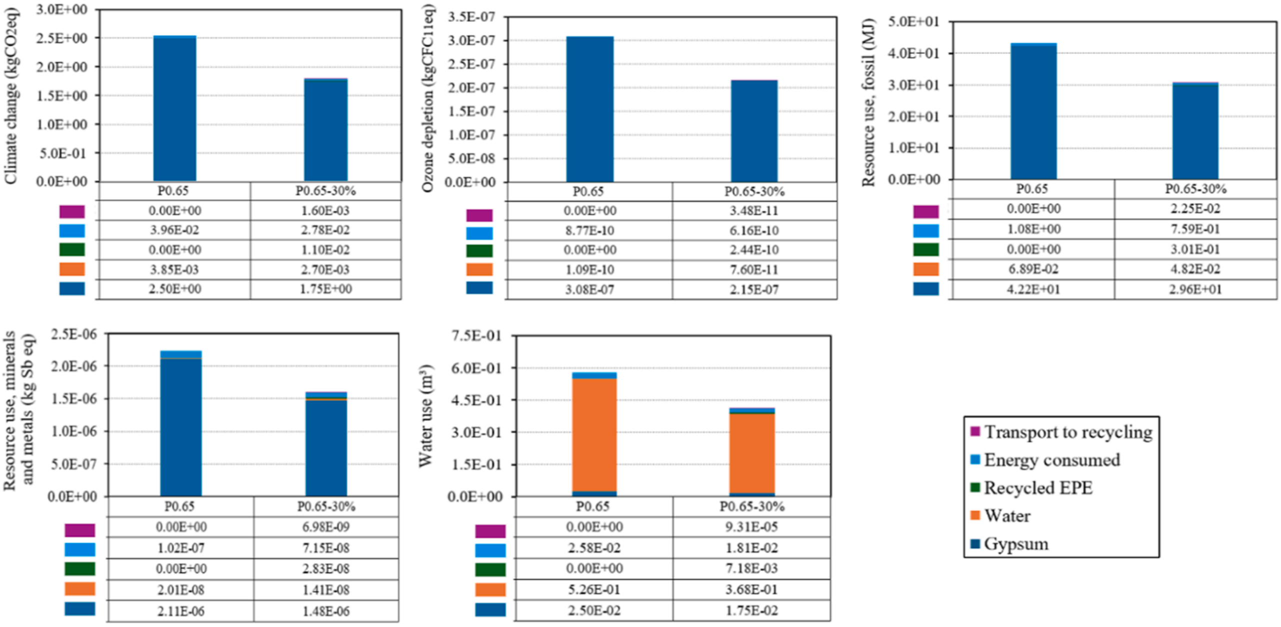
This article addresses the problem of managing single-use plastic waste, highlighting the potential of these secondary raw materials to develop sustainable construction products. It represents a breakthrough in developing new composite materials for lightweight plaster partition panels. The main findings are summarised as follows:

- The flexural and compressive strength of all tested composites exceeded the minimum values established by current standard [43]. However, P0.65-30% sample showed a decrease of 37.5% in flexural strength and 45.0% in compressive strength compared to the reference. Surface hardness was less affected, with a slight decrease of 8.6% with respect to the reference material.
- In 40 × 30 × 1.5 cm^3 precast plates, the composite with the highest EPE waste content withstood a maximum bending load of 0.23 kN, exceeding the minimum standards by 21.7%. Moreover, the progressive addition of EPE waste improved impact resistance, preventing plates breakage during testing. These results were further supported by SEM analysis, which demonstrated good waste integration in the matrix.
- The performance under water action significantly improved with the addition of EPE waste. Thus, capillary water absorption capacity decreased progressively, with P0.65-30% composite being 33.8% lower than the reference. Additionally, these composites are especially beneficial for damp rooms due to their higher resistance to water vapour permeability.
- The developed composites showed their feasibility of producing lightweight partitions with improved thermal behaviour. The P0.65-



Materials			Thickness (mm)	ρ (kg/m³)	λ (mW/m·K)
1	Double plasterboard	P0.65	25.0	1212.5	307.4
		P0.65–30%	25.0	986.3	172.5
2	Steel profile C90×37×15×0.6 mm		0.6	7800.0	50000.0
3	Mineral wool insulation		90.0	70.0	35.0

Fig. 10. THERM simulation for thermal performance of an LSF wall partition with P0.65 and P0.65-30%.



Climate change (kgCO2eq)

	P0.65	P0.65-30%
🟪	0.00E+00	1.60E-03
🟦	3.96E-02	2.78E-02
🟩	0.00E+00	1.10E-02
🟧	3.85E-03	2.70E-03
■	2.50E+00	1.75E+00

Ozone depletion (kgCFC11eq)

	P0.65	P0.65-30%
🟪	0.00E+00	3.48E-11
🟦	8.77E-10	6.16E-10
🟩	0.00E+00	2.44E-10
🟧	1.09E-10	7.60E-11
■	3.08E-07	2.15E-07

Resource use, fossil (MJ)

	P0.65	P0.65-30%
🟪	0.00E+00	2.25E-02
🟦	1.08E+00	7.59E-01
🟩	0.00E+00	3.01E-01
🟧	6.89E-02	4.82E-02
■	4.22E+01	2.96E+01

Resource use, minerals and metals (kg Sb eq)

	P0.65	P0.65-30%
🟪	0.00E+00	6.98E-09
🟦	1.02E-07	7.15E-08
🟩	0.00E+00	2.83E-08
🟧	2.01E-08	1.41E-08
■	2.11E-06	1.48E-06

Water use (m³)

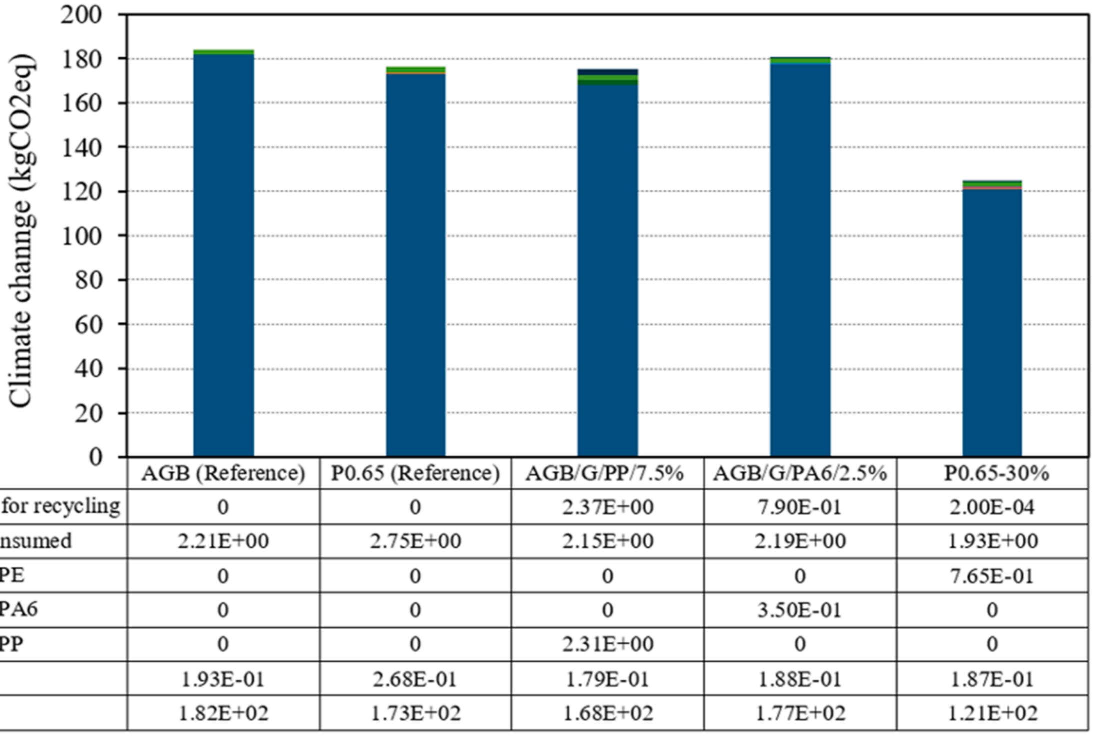
	P0.65	P0.65-30%
🟪	0.00E+00	9.31E-05
🟦	2.58E-02	1.81E-02
🟩	0.00E+00	7.18E-03
🟧	5.26E-01	3.68E-01
■	2.50E-02	1.75E-02

Fig. 11. LCIA results for the plaster partition panel production on a laboratory scale for P0.65 and P0.65-30%.

30% composite exhibited a density 18.7% lower than the reference and a 43.9% decrease in thermal conductivity. This improvement is evidenced by simulations using THERM software, which show that partitions made with P0.65-30% panels increase thermal resistance by 20.3%.

- The life cycle environmental impact assessment identified plaster production as the main contributor, accounting for 90 % of the impacts across all categories, except for water use, where water consumption during manufacturing is the hotspot. Partially substituting plaster with recycled EPE leads to significant environmental benefits, reducing the overall environmental impacts for all categories by 30% due to the avoided use of plaster. Additionally, the environmental impacts of the recycling process of EPE have a low contribution to the total burdens. The findings demonstrated that using recycled EPE represents a promising alternative for enhancing the sustainability of plasterboards, reducing significant environmental impacts, and promoting resource conservation, which aligns with circular economy and sustainable production practices.

The progressive substitution of original plaster material with expanded plastic waste promotes a more sustainable construction industry. These materials meet current regulatory standards, enhance hygrothermal performance and are environmentally friendly and lightweight. Future research should focus on characterising the performance



	AGB (Reference)	P0.65 (Reference)	AGB/G/PP/7.5%	AGB/G/PA6/2.5%	P0.65-30%
■ Transport for recycling	0	0	2.37E+00	7.90E-01	2.00E-04
■ Energy consumed	2.21E+00	2.75E+00	2.15E+00	2.19E+00	1.93E+00
■ Recycled PE	0	0	0	0	7.65E-01
■ Recycled PA6	0	0	0	3.50E-01	0
■ Recycled PP	0	0	2.31E+00	0	0
■ Water	1.93E-01	2.68E-01	1.79E-01	1.88E-01	1.87E-01
■ Gypsum	1.82E+02	1.73E+02	1.68E+02	1.77E+02	1.21E+02

Fig. 12. LCIA results for the plaster partition panel production, comparing P0.65 and P0.65–30% with the results from Romero-Gómez *et al.* (2023) [35], which assessed the gypsum precast (AGB Reference) and substituted gypsum by 7.5% of polypropylene (AGB/G/PP/7.5%) and 2.5% of waste fibre (AGB/G/PA6/2.5%).

of these new materials in terms of fire resistance, acoustic behaviour, as well as to evaluate the incorporation of other polymer waste types. Additionally, it is crucial to conduct a cost analysis to evaluate their economic viability for commercial exploitation. It is also essential to upscale the production of plaster partition panels by incorporating recycled EPE, assessing alternative scenarios, for instance, the end-of-life phase, conducting uncertainty analysis of parameters, and comparing the developing product with conventional materials in the market.

CRediT authorship contribution statement

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

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.

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Data availability

The authors do not have permission to share data.

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