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Case study

# New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry

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ABSTRACT

The overexploitation of natural resources and the shortage of labour in the building sector is encouraging the development of prefabrication applied to building. This is leading the agents involved in construction to increasingly opt for the application of prefabricated systems that optimise resources while shortening construction execution times. Thus, the main objective of this research is the development of a new lightweight construction material composed of plaster, in which the conglomerate has been partially replaced by dissolved expanded polystyrene (EPS) waste and the addition of textile fibres from end-of-life tyres (ELT). The results obtained after the physicochemical and mechanical characterisation of the new plaster composite show how a 31.3% lighter material is obtained, with a 66.7% lower thermal conductivity and a 33.3% higher flexural strength in plates compared to traditional gypsum material. This improvement in the technical performance of the composites produced, combined with the reduction in the consumption of natural resources and the large amount of waste recovered and reintroduced into the production process, confirm the suitability of the new construction material developed for use in the production of more sustainable prefabricated plates and panels.

## 1. Introduction

Building industry is one of the sectors that generates the greatest environmental impact, being responsible for between 40% and 50% of greenhouse gases worldwide [1]. These figures, together with the large amount of raw materials, water and energy demanded by the construction industry [2], have led the EU to establish urgent measures against climate change that place the construction sector as one of the main focal points for action [3,4]. A valuable ally in moving towards sustainability in building is the introduction of prefabricated systems in the construction process [5]. Prefabrication has amply demonstrated its potential to reduce embodied energy (EE) by optimising the use of raw materials and reducing waste production [6,7]. In addition, the speed in the execution of prefabricated systems, the reduction of indirect costs and the improvement of productivity, ensure prefabrication as an essential element in the construction industry of the future [8,9].

In this quest for sustainability and improved production performance, many materials have undergone an evolution that has

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increased their application possibilities [10,11]. This is the case of gypsum composites, well known since ancient times and widely used throughout the history of construction [12], which have experienced a strong development in their application for the elaboration of prefabricated elements. Prefabrication in the gypsum industry has made it possible to improve both the process of execution and installation of these materials, as well as the technical performance of the final product [13].

Currently, prefabricated plates and panels of gypsum or plaster are widely used in the execution of partitions and interior finishes [14], due to their rapid assembly, their good thermal and acoustic performance, as well as their high resistance to fire [14,15]. Only in Europe more than 1.6 billion m2 of interior surfaces are covered with prefabricated plasterboards every year, and it is expected that by 2050 the demand for gypsum and plaster in the EU will increase up to four times more [16]. This high material requirement not only leads to the potential depletion of natural resources, but also to a high energy demand [17]. This is compounded by the serious environmental problem of constant waste generation, with the construction sector being responsible for approximately 36% of the total solid waste produced in the EU [18].

On the other hand, compliance with the requirements of European regulations and the Energy Performance of Buildings Directive (2010/31/EU) [19], entails the renovation of the envelope of thousands of dwellings every year [20]. One of the most widely used systems for this purpose is the well-known External Thermal Insulation Composite Systems (ETICS) [21], in which expanded polystyrene (EPS) is used as thermal insulation in 85% of cases, generating a high volume of this plastic waste [22]. Given that, EPS is not only used in construction, but also as packaging and as a lightener in different materials [23], the generation of EPS waste has experienced a progressive annual growth. For instance, in 2018, Spain recycled 7440 tonnes of EPS, yet this only accounted for 22.5% of all of the waste produced by this material [22].

In order to avoid its progressive accumulation in landfills, several researches have been carried out to study possible recovery routes for EPS waste. More specifically, in the case of plaster materials, the introduction of shredded EPS waste improves their thermal [24] and acoustic properties [25], thanks to the increase in the amount of occluded air and the decrease in density of the hardened material [26]. In the literature review conducted, the lowest densities of EPS lightened plasters range between 950 and 660 kg/m$^3$ [26,27]. These densities coincide with the lowest thermal conductivities of 0.19 W/mK and 0.16 W/mK respectively. However, there is a large decrease in the mechanical strength of the composites, which does not exceed 2 MPa under bending stresses and around 3 MPa under compression [26,27]. In other studies incorporating EPS and recycled sands [21,28], although the mechanical strengths increase by around 1 MPa in bending and 2 MPa in compression compared to the studies mentioned above, the densities and thermal conductivity are also higher.

Another waste that generates serious environmental problems is End of Life Tyres (ELTs). In the EU, during 2019, around 3 Mt of ELT were generated [29] and it is estimated that by 2030 this amount will increase considerably [30]. ELTs are generally taken to landfills or dumped illegally, where they occupy a large volume for long periods of time as they are not biodegradable [31]; in addition, they promote the generation of pests due to the accumulation of rainwater inside them [32] and can constitute fire sources that are difficult to extinguish [33].

Concern about the consequences of the accumulation of ELTs has led the European Parliament and Council (2000) to establish specific directives for the treatment of these residues [34]. Today in Europe, 95% of ELTs are considered to be recovered, either by recycling (52%) or by energy recovery (40%) [29]. However, during the incineration of ELTs for energy recovery, environmentally harmful emissions are generated and only around 25% of the energy required for its production is recovered [32,35]. Therefore, the most sustainable option for this type of waste is to recycle it and reincorporate it into the manufacturing process of new materials using circular economy criteria.

During the recycling of ELTs, the main materials obtained are rubber (47%), steel (12%) and textile fibres (10%) [34]. Rubber obtained from the recycling of ELTs has been extensively studied in various research studies on asphalts [36], and as aggregates to replace natural sand in concrete, studying their hygrothermal and mechanical behaviour [37]. Steel waste, being easily recoverable, is mainly used in the production of new metal products [38,39]. Textile fibres, which still have no clear use after they have been obtained, are considered special waste according to the European Waste Code 19.12.08, and must be burned or stored [30,34]. Bearing in mind that around 320,000 tonnes of ELT textile fibre waste is generated in the EU every year [40], it is essential to study the possibilities of reincorporating this waste into the production process in order to reach different international agreements that promote the achievement of the Sustainable Development Goals [41].

Some of the research carried out on textile fibres from ELTs has studied their application as reinforcement in different materials such as bituminous binders [34,42]; polypropylene plastic composites [43] or geopolymers [44] to reduce shrinkage during setting and improve their tensile strength. On the other hand, the application of these wastes in rammed and sandy soils [45] increases their strength and ductility [38,46]. The effect of incorporating these ELT fibres in concrete has also been studied to reduce damage after being subjected to high temperatures thanks to the decomposition of the fibres [47] and in mortars, improving the mechanical properties with fibres previously cleaned of rubber residues [34]. Since the main characteristic of these fibres is their low thermal conductivity, between 0.0548 and 0.0632 W/mK [34], their use in the production of aerogels with high thermal and acoustic performance is quite widespread [30,48]. However, no research has been found concerning the introduction of ELT textile fibres in the production of plaster composites.

The aim of this study is the development and characterisation of a new plaster-based composite that incorporates EPS waste and ELT textile fibres in its composition. Unlike other studies, this research explores the possibility of dissolving the EPS waste prior to its incorporation into the plaster mixing process, using the textile fibre as an addition to reduce the thermal conductivity of the hardened material. The aim is to obtain a new construction material with a great potential for the production of prefabricated plates and panels, with high thermal resistance and good mechanical strength, incorporating circular economy approaches in the manufacturing process.

## 2. Materials and methods

### 2.1. Materials

The following materials were used to produce the composites developed in this work: plaster, expanded polystyrene (EPS) waste, universal solvent, ELT textile fibres and water, which are shown in Fig. 1.

#### 2.1.1. Binder

The binder material used was plaster E-35 of type A according to the European designation specified in the UNE-EN 13279–1:2009 standard [49]. This is a high-quality and pure gypsum commonly used in construction [50], which is characterised by its fine granulometry and fast setting, which was supplied by the commercial firm Placo Saint-Gobain, from the Gelsa plant (Zaragoza, Spain). Its main technical characteristics are: thermal conductivity of 0.30 W/mK; pH greater than 6; particle size between 0 and 0.2 mm; purity greater than 92%; flexural strength at 3.5 N/mm2 in hardened state and water vapour diffusion resistance factor (μ) of 6 [51].

#### 2.1.2. Expanded polystyrene (EPS) waste

Expanded polystyrene is a polymer resulting from the expansion and bonding of expandable polystyrene beads, which is obtained from the polymerisation of the monomer styrene with an expanding agent (pentane). This material has a closed, air-filled cell structure, which gives it a low density and high thermal resistance. In construction, this material is often used as thermal insulation in building envelopes. The EPS used in this research comes from waste generated during the rehabilitation of facades where External Thermal Insulation Composite Systems (ETICS) has been used. EPS has the following physical properties: thermal conductivity coefficient of 0.031 W/mK, a density between 28 and 30 kg/m3 and a water vapour diffusion resistance factor (μ) between 20 and 100 [52]. The EPS waste was manually shredded so that no piece was larger than 5 cm to facilitate further handling.

#### 2.1.3. ELT textile fibre

Textile fibres are used to produce tyre reinforcement cords and can be composed of rayon, nylon and polyester [53]. Up to 10% of these textile fibres can be obtained from the recycling of end-of-life tyres. The textile fibres used come from the company Genan (Viborg, Denmark), which recycles all types of ELTs. These fibres have an approximate diameter between 18 and 28 μm and a thermal conductivity between 0.0548 and 0.0632 W/mK [34]. Due to the process of obtaining the fibres, they may contain small amounts of rubber, between 5% and 20% [54]. Fig. 2 shows a scanning electron microscopy image of the ELT textile fibres used in this research, where some rubber residues can be seen adhered to the fibres after the material recovery process.

On the other hand, Fig. 3 shows the thermogravimetric analysis of the textile fibres used (equipment and experimental conditions described in section 2.4), where the oxidative thermal decomposition of the fibres can be appreciated, with several successive events of mass loss, of exothermic character, due to the combustion of the fibres between 200 °C and 600 °C. In this temperature range, up to 94.88% of the total mass is lost.

#### 2.1.4. Universal solvent

Universal solvent is a mixture of different chemical agents derived from volatile hydrocarbons, which together have a strong dissolving power on organic substances. It is commonly used to dilute and fluidise paints, oils and greases. In this research, the universal solvent of the trade name Nazza was used, the chemical composition of which is as follows: toluene, xylene, n-butyl acetate, ethyl acetate, ethylbenzene, acetone, propan-2-one and propanone. According to the information provided by the manufacturer, this solvent has a vapour pressure at 20 °C of 85.5 mmHg and its density at 20 °C (ASTM D 1298/4052) is 812 ± 20 kg/m3 [55].

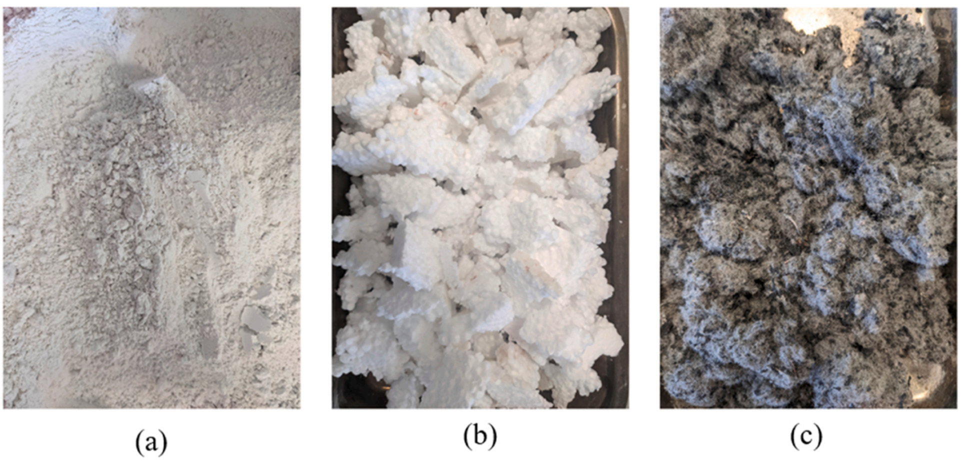


**Fig. 1.** Solid materials used: (a) E-35 plaster; (b) EPS waste; (c) ELT textile fibres.

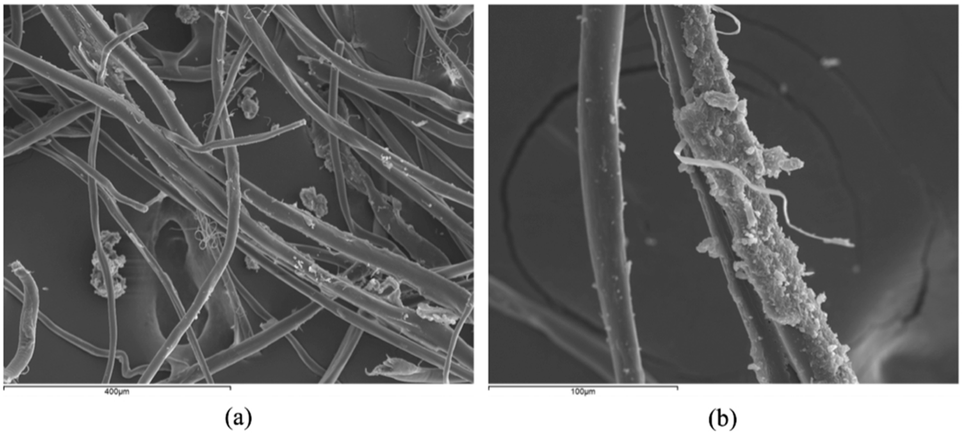


**Fig. 2.** Scanning electron microscopy of ELT fibres: (a) Magnification 150x; (b) Magnification x500.

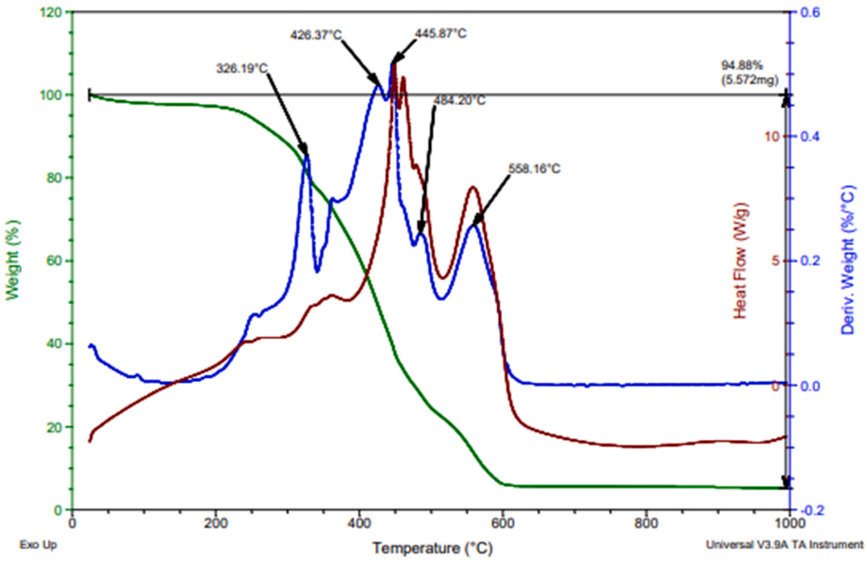


**Fig. 3.** Thermogravimetric analysis of ELT fibres.

### *2.1.5. Water*

To avoid contamination of the mixes with salts or impurities, drinking water from the Canal de Isabel II in Madrid was used, which has already been used successfully in the production of plaster in other studies [56]. This water has a medium hardness (25 mg

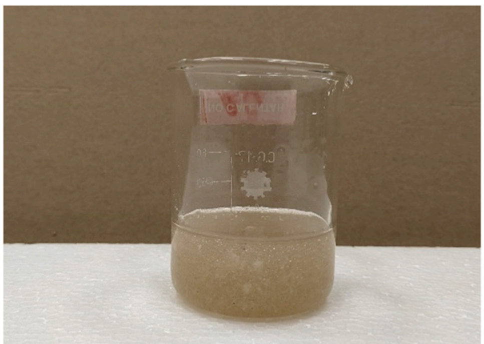

**Fig. 4.** EPS dissolution.

$CaCO_3$/L); a pH of between 7 and 8.5, and a chloride content between 1 and 1.5 mg/L. In addition, it contains other elements such as nitrates (0.6 mg/L), nitrites (<0.05 mg/L), sulphates (5.3 mg/L), calcium (17.8 mg/L), iron (0.01 mg/L) and copper (<0.05 mg/L) [56].

### 2.2. Preparation of test samples

#### 2.2.1. Sample production process

As a novelty in this research, EPS waste in solution is used to improve its integration in the mixing process of the gypsum composite materials finally produced. EPS was dissolved using universal solvent. EPS thermal insulation is a petroleum derivative, and therefore, it has an organic and low polar nature that the universal solvent can easily decompose. Thus, with an EPS/solvent ratio of 1:2 by mass, a uniform, viscous, grey-coloured paste was obtained (Fig. 4), with a density of 660 kg/m$^3$. This paste has a certain amount of air trapped inside in the form of bubbles from the air occluded in the EPS. The dissolution of the EPS, prior to the mixing of the plaster, allows a greater cohesion between the polystyrene and the rest of the components of the mixture. To prepare each of the solutions used in this research, the solvent was first poured into a container, and then the EPS residues were gradually introduced.

Next, the water and plaster were mixed and their consistency was obtained using the shaking table method indicated in the UNE-EN 13279–2: 2014 standard [57], until the diameter of the paste was 165 ± 5 mm. The resulting water/plaster ratio was 0.7 by mass, which was kept constant for all the mixes performed. Once this ratio was obtained for the reference plaster, the quantity of the water-plaster mixture was progressively replaced by the EPS solution prepared previously and by the ELT textile fibres. The amount of recycled fibres added was maintained for all the dosages.

In the preparation of the mixes, the methods and techniques specified in UNE-EN 13279–2: 2014 [57] were followed, according to which, firstly, the plaster powder is sprinkled evenly for 30 s on the water, in which the ELT textile fibres have been previously dispersed in the mixes containing them. The mixture is then left to stand for 60 s, after which it is mixed manually for 30 s with continuous circular movements. The mixture is then left to settle again for 30 s, at which point the EPS solution previously prepared is added. Finally, it is mixed again for another 30 s until a homogeneous paste is obtained. After the mixture has hardened, the specimens are demoulded and stored in a laboratory environment at a temperature of 23 ± 2 °C and 50 ± 5% relative humidity for seven days.

The different mixes have been named as follows: E0.7 refers to the water/plaster ratio used, the next number refers to the amount of EPS solution by mass introduced into the mixture in partial replacement of the water and plaster mixture, and finally the letter N refers to the ELT textile fibres. Table 1 shows all the dosages carried out in this research.

Regarding setting times of the different dosages produced, which were obtained by applying the Vicat Cone test described in the UNE-EN 13279–2: 2014 standard [57]. This test consists of measuring the depth of penetration of the Vicat needle into the plaster paste as it hardens in order to establish the start of setting.

As shown in Table 1, the addition of ELT textile fibres increased the setting time up to 6 min with respect to the reference plaster (E0.7). Also, the addition of the EPS dissolution further delayed the hardening of the mixtures, increasing the setting time as the amount of polystyrene increased and the amount of plaster decreased. The longest setting time was observed for the E0.7–450-N composite, reaching up to 45 min before it began to harden. It has been observed that the exothermic process linked to the setting of the plaster favours the evaporation of the solvent contained in the mixtures. Considering this, the progressive decrease in the amount of binder in the composites and the increase in the proportion of EPS solution leads to a reduction in the heat associated with the setting of the plaster and favours an increase in the setting time of the composites produced.

### 2.3. Experimental programme

In the experimental programme, physicochemical, physical and mechanical tests were carried out to achieve the most complete characterisation possible of the new material developed. Prior to the physical and mechanical tests, the specimens were placed in an oven at 60 ± 2 °C and 50 ± 5% relative humidity for 24 h.

As far as the physicochemical characterisation is concerned, thermogravimetric analysis (TGA) of each of the dosages was carried out to observe the thermal events and the loss of mass associated with a progressive increase in temperature in a controlled atmosphere. The test was started at room temperature, increasing the temperature at a rate of 10 °C/minute, until reaching 1000 °C in an atmosphere of previously filtered air with a flow rate of 100 ml/min. For sample preparation, the hardened plaster composites were ground with an agate mortar and sieved with a 0.3 mm mesh size until a sample quantity of 40–50 mg was obtained. The equipment used in this test was a TA Instruments SDT Q600 thermobalance.

As for the physical characterisation, the bulk density was calculated and Shore C surface hardness tests were carried out,

**Table 1**
Dosages used.

| Sample | Plaster (g) | Water (g) | EPS solution (g) | ELT fibres (g) | Plaster and water reduction (%) | Setting time (min) |
|---|---|---|---|---|---|---|
| **E0.7 (Ref.)** | 700 | 1000 | _ | _ | 0 | 11 |
| **E0.7-N** | 988 | 692 | _ | 20 | 1.2 | 17 |
| **E0.7–150-N** | 900 | 630 | 150 | 20 | 10 | 24 |
| **E0.7–300-N** | 812 | 568 | 300 | 20 | 18.8 | 29 |
| **E0.7–450-N** | 724 | 506 | 450 | 20 | 27.6 | 45 |

determination of the dynamic Young's Modulus by ultrasound (MOEus) and calculation of the coefficient of thermal conductivity. The bulk density of the composites in hardened state was obtained using an electronic balance and 40 × 40×160 mm specimens for each of the proposed dosages. The surface hardness test was carried out using a Shore C durometer on prismatic specimens of 40 × 40×160 mm, as established in the UNE-EN 13279–2:2014 standard [57]. For the dynamic Young's Modulus test by ultrasound, an Ibertest Ultrasonic tester E46 was used, according to UNE-EN ISO 12680–1 [58] on 40 × 40×160 mm specimens, taking the measurements in the longitudinal direction of the specimen.

The thermal conductivity coefficient of the plaster composites was obtained using the "Thermal box" test. This test consists of a box lined all around its perimeter with expanded polystyrene plates that insulate it from the outside. The 300 × 300×30 mm test specimens are placed on the inside of the box, juxtaposed to the thermal insulation. A heat source is placed inside the box, which produces a temperature variation between the inside and the outside along the thickness of the box. Once the heat flow is stationary, a series of thermocouples record the temperature at different points of the enclosure every 30 s for 15 min, allowing the thermal conductivity factor of the materials to be calculated.

Finally, for the mechanical characterisation of the composites, flexural strength, compressive strength and plate flexural strength tests were performed. The flexural and compressive strength tests were performed according to the specifications of the UNE-EN 13279–2:2014 standard [57], using an AUTOTEST 200–10SW equipment from IBERTEST and using standardised RILEM specimens measuring 40 × 40×160 mm. The mechanical flexural strength test on plates was performed according to UNE-EN 520:2005 [59], using 400 × 300×20 mm specimens. The test equipment used was a PÁCAM MPX-22, which allows a central load to be applied to the plate supported horizontally on two points until the plate breaks.

In addition to the mechanical tests, scanning electron microscopy (SEM) was carried out to determine the microscopic internal structure of the plaster composites produced. A Jeol JSM-820 microscope operating at 20 kV, equipped with Oxford EDX analysis, was used for this purpose. To ensure the proper functioning of the equipment's sensors, the samples were coated with a thin layer of gold, using a Cressington 108 metalliser. The samples were obtained in such a way that their surface texture remained unaltered prior to the test.

## 3. Results and discussion

The results derived from the experimental plan carried out, as well as the discussion of these results, are presented below.

### 3.1. *Thermogravimetric analysis (TGA)*

Figs. 5–7 show the thermograms of the compounds E0.7 (Ref.), E0.7-N and E0.7–450-N respectively, as it is in these samples where the main differences between the elaborated compounds can be seen more clearly. In these thermograms, the percentage mass loss experienced by the samples as the temperature increases is represented by a green line, the first derivative of mass with respect to temperature is indicated by a blue line and the heat flux produced during the whole process is shown by a brown line (the peaks being exothermic events upwards and endothermic events downwards). In addition, Table 2 shows the numerical results of the

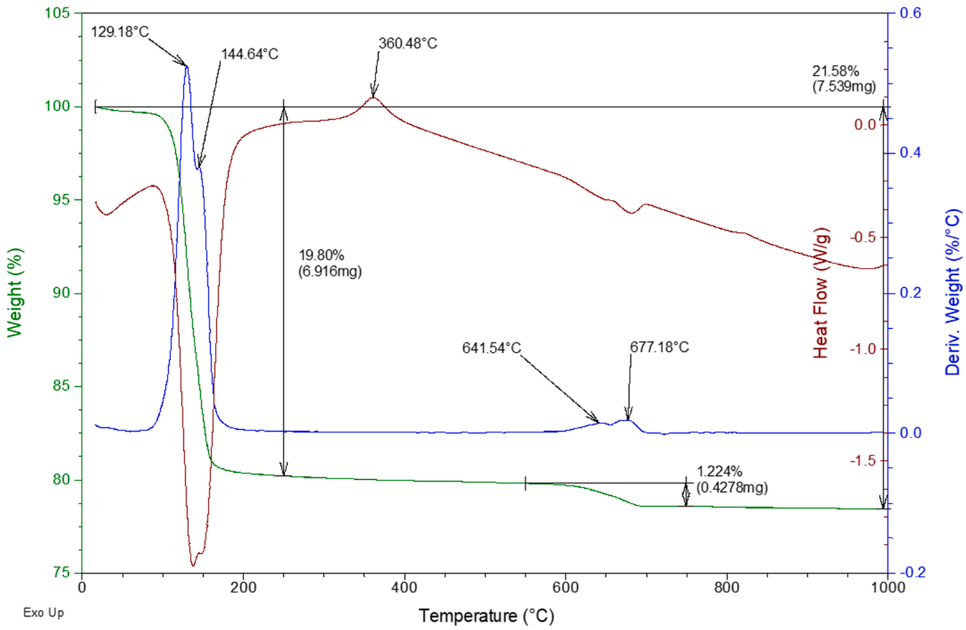


**Fig. 5.** Thermogram of reference sample E0.7.

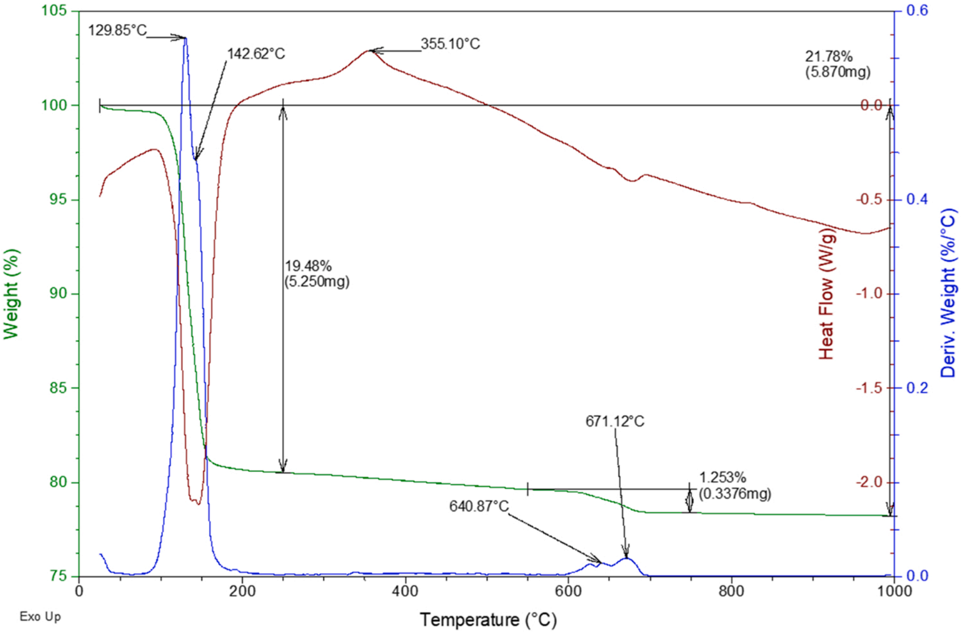


**Fig. 6.** Thermogram of sample E0.7-N.

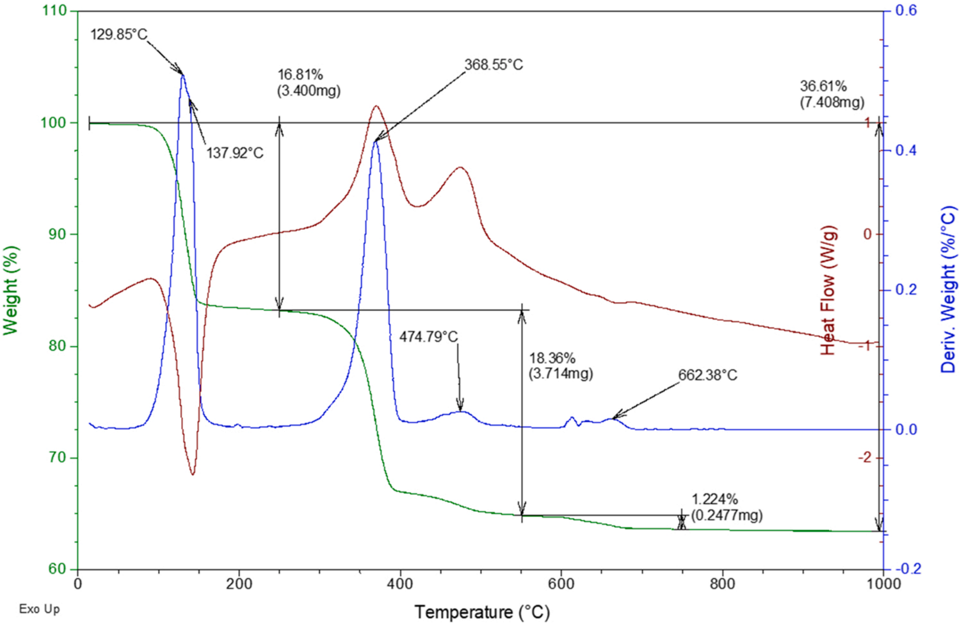


**Fig. 7.** Thermogram of sample E0.7–450-N.

thermogravimetric analyses of all the dosages considered with the following information: total mass loss of the samples, partial mass loss by temperature bands, maximum temperature value of the mass derivative with respect to temperature (blue line) of each thermal event, and the endothermic or exothermic character of the same; the last column shows the reaction to which each of the events observed is attributed.

As shown in Table 2, the addition of ELT textile fibres and EPS dissolution increases the total mass loss experienced by the samples, being this loss directly proportional to the amount of addition introduced in the composites. Sample E0.7–450-N experienced the greatest variation in total mass after the test, losing 15% more mass than sample E0.7 (Ref.). The reference plaster E0.7 experiences the highest mass loss (19.80%) in the temperature range between 0 °C and 250 °C in an endothermic process with two consecutive thermal events, which present two peaks in the derivative of mass loss with temperature at temperatures very close to each other. The first peak

**Table 2**
Results of the thermogravimetric analysis of the plaster composites.

| Sample | Total mass loss (%) | Interval (°C) | Máx. temperature (°C) | Partial mass loss (%) | Associated heating effects | Coments |
|---|---|---|---|---|---|---|
| **E0.7** | 21.58 | 0–250 | 129.18 | 19.80 | Endothermal | DH to HH |
| | | | 144.64 | | Endothermal | HH to anhydrite |
| | | 250–550 | 360.48 | - | Exothermal | Anhydrite phase transition |
| | | 550–700 | 641.54; 677.18 | 1.22 | Endothermal | $CaCO_3$ to CaO |
| **E0.7-N** | 21.78 | 0–250 | 129.85 | 19.48 | Endothermal | DH to HH |
| | | | 142.62 | | Endothermal | HH to anhydrite |
| | | 250–550 | 355.10 | - | Exothermal | Anhydrite phase transition |
| | | 550–700 | 640.87; 671.12 | 1.25 | Endothermal | $CaCO_3$ to CaO |
| **E0.7–150-N** | 28.51 | 0–250 | 127.83 | 18.38 | Endothermal | DH to HH |
| | | | 137.92 | | Endothermal | HH to anhydrite |
| | | 250–550 | 386.03; 474.11 | 8.40 | Exothermal | EPS combustion |
| | | 550–700 | 659.02 | 1.46 | Endothermal | $CaCO_3$ to CaO |
| **E0.7–300-N** | 33.46 | 0–250 °C | 131.19 | 17.55 | Endothermal | DH to HH |
| | | | 142.62 | | Endothermal | HH to anhydrite |
| | | 250–550 °C | 379.98; 474.79 | 14.63 | Exothermal | EPS combustion |
| | | 550–700 °C | 667.09 | 1.15 | Endothermal | $CaCO_3$ to CaO |
| **E0.7–450-N** | 36.61 | 0–250 °C | 129.85 | 16.81 | Endothermal | DH to HH |
| | | | 137.92 | | Endothermal | HH to anhydrite |
| | | 250–550 °C | 368.55; 474.79 | 18.36 | Exothermal | EPS combustion |
| | | 550–700 °C | 662.38 | 1.22 | Endothermal | $CaCO_3$ to CaO |

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

at 129.18 °C is due to the dehydration of calcium sulphate dihydrate (DH) $CaSO_4$-2 $H_2O$ to form hemihydrate (HH) $CaSO_4$-0.5 $H_2O$. The second peak at 144.64 °C corresponds to the dehydration of the hemihydrate to anhydrite $CaSO_4$. These events occur in all samples, with quite similar temperature maximum values, however, the amount of mass lost in this temperature range decreases as the proportion of additions (EPS dissolution and ELT textile fibre) increases and the amount of plaster in the samples decreases. The lowest mass loss in the range from 0 °C to 250 °C is observed in the sample E0.7–450-N (16.81%), being approximately 3% lower than the variation obtained in the reference plaster for the same temperature range.

Then, in the temperature range from 250 °C to 550 °C, in the reference plaster (E0.7) an exothermic event occurs where the temperature of the maximum of the mass derivative occurs at 360.48 °C, corresponding to the phase change from soluble anhydrite to insoluble anhydrite, and where no associated mass loss is observed [60,61]. This process is also clearly observed in sample E0.7-N, with a maximum at a temperature of 355.10 °C, while, in the same range, the compounds incorporating the textile fibres and the EPS dissolution do experience a mass loss that increases as the amount of polystyrene in the samples increases. In this case, two consecutive mass losses are observed, with maxima in the derivative of mass with temperature, the first around 370–380 °C and the next around 474 °C, which would correspond to the combustion of the polystyrene present in the samples, since the degradation of polystyrene occurs around 360 °C [22]. In this range, sample E0.7–450-N experiences the highest mass loss (18.36%). Finally, in the temperature range between 550 °C and 700 °C, an endothermic event occurs in all samples, with a mass loss between 1.15% and 1.46%, corresponding to the formation of calcium oxide (CaO) from the calcium carbonate ($CaCO_3$) of the plaster present in all composites.

It should be noted that the minimal differences observed in this test between the reference sample (E0.7) and the E0.7-N compound may be due to the process carried out during the preparation and prior manual sieving necessary to perform the thermogravimetric analysis, as this procedure makes it difficult to preserve the ELT textile fibres in the samples to be tested.

### 3.2. *Bulk density*

Currently, manufacturers of prefabricated elements with plaster material are aiming to reduce the density of their products, since the weight of these composites will be decisive in the transport stages and placement on the construction site [62]. As shown in Table 3, both ELT textile fibres and EPS dissolution reduced the density of the composites in relation to traditional plaster, with the reduction being greater as the amount of EPS dissolution in the mixtures increased. The introduction of textile fibres in the plaster reduced the density by 5.1%, while the lowest density was obtained in the E0.7–450-N composite, being 31.3% lower than in the reference plaster.

The reduction of the bulk density of plasters with the addition of EPS waste has already been observed in other investigations where the waste was added in a solid state [21,25,27], however, in those studies, the densities achieved were higher than those obtained in

**Table 3**
Results obtained in bulk density test and expanded combined uncertainty.

| | E0.7 (Ref.) | E0.7-N | E0.7-150-N | E0.7-300-N | E0.7-450-N |
|---|---|---|---|---|---|
| Bulk density (kg/m$^3$) | 1105.25 ± 2.46 | 1049.49 ± 7.55 | 915.21 ± 5.82 | 833.37 ± 7.52 | 759.75 ± 3.66 |

the present study. In addition, by incorporating shredded EPS, the amount of recovered residue was much lower.

### 3.3. Surface hardness

As shown in Table 4, the introduction of ELT textile fibres in the plaster decreases the surface hardness by up to 17.1% compared to the reference. If the EPS dissolution is also incorporated, this decrease reaches up to 23.2% in the composites with the highest dissolution proportions (E0.7–300 N and E0.7–450-N).

Although lower hardnesses were obtained with both additions than with the reference plaster, the addition of dissolved EPS in the most unfavourable case (E0.7–450-N) reduced the hardness by just 7.4% compared to the composite containing only textile fibres (E0.7-N), which reduced the hardness of the reference plaster by 17.1%. This suggests that the reduction in hardness resulting from the addition of the EPS dissolution is less significant than that obtained with the addition of textile fibres.

### 3.4. Dynamic Young's modulus by ultrasound ($MOE_{us}$)

As with the surface hardness of the composites, the dynamic Young's modulus obtained using the ultrasound technique is also affected by the incorporation of textile fibres. As can be seen in Table 5, the progressive increase in the amount of polystyrene decreases the Young's modulus of the plaster composites proportionally, being the most unfavourable dosage E0.7–450-N.

The results obtained in this test confirm the greater heterogeneity present in the lightened composites compared to sample E0.7, as well as suggesting the presence of voids or pores that would hinder the propagation of ultrasound through the specimens.

### 3.5. Thermal conductivity

The building sector demands about 40% of the total energy consumed in the EU [63], and in particular, heating use represents 62.8% of the total energy used in dwellings [64]. These data make the reduction of energy consumption in buildings essential to achieve the EU's ambitious goal of emission neutrality by 2050 [65]. It is here where the use of building envelope materials with high thermal resistance to minimise the use of both heating and cooling in buildings comes into play.

Table 6 shows the results of the thermal conductivity test of the plaster composites developed.

According to the results in Table 6, it can be seen how the thermal conductivity is reduced with the incorporation of ELT textile fibres (E0.7-N) up to 14.3% with respect to the reference plaster. Likewise, the progressive incorporation of the dissolved EPS further reduces the thermal conductivity coefficient as the amount of this dissolution in the plaster composites increases. The lowest thermal conductivity was obtained in the E0.7–450-N composite, being 66.7% lower than traditional plaster (E0.7).

The positive relationship between densities and low thermal conductivities in lightened plasters has already been observed in other investigations [66]. Some additions studied in this regard have been cellular glass [67], EPS and ceramic waste [21], cable waste [68], polycarbonate [69], extruded polystyrene (XPS) [70], and the combination of shredded EPS and XPS waste [26]. Fig. 8 shows the thermal conductivity and density results of all these studies compared to the composites developed in the present research.

Fig. 8 shows how all the aforementioned additions reduce the specific weight of the reference plaster. However, for similar values in bulk density, the plaster composites with ELT textile fibres and EPS dissolution achieve significantly lower thermal conductivities, being this reduction practically linear as the amount of EPS dissolution in the mixtures increases.

### 3.6. Flexural strength

Fig. 9 shows the results of the flexural strength test, with error bars referred to the standard deviation, on standard RILEM specimens of 40 $\times$ 40$\times$160 mm.

Fig. 9 shows how the incorporation of ELT fibres and dissolved EPS decreases the flexural strength as the amount of polystyrene in the plaster composites increases. The results indicate that just with the addition of the textile fibres the flexural strength decreases very slightly, only 6.6% with respect to the reference plaster. This result shows that these fibres are not strong enough to improve the ductility of the composites as suggested by other studies where the incorporation of recycled fibres increases the deformation capacity of the plaster composites [71]. However, the ELT textile fibres did prevent brittle fracture of the specimens in two pieces after testing as shown in Fig. 10.

The greatest decrease in flexural strength is observed in the composite with the highest amount of dissolved EPS replacing the plaster mix (E0.7–450-N), with a flexural strength 27.1% lower than the reference. In other investigations, it has already been observed that the incorporation of residues in order to lighten and reduce the thermal transmittance of traditional plaster results in lower flexural strength, this is the case of the incorporation of XPS residues (2. 32 MPa) [70]; polycarbonate (3.32 MPa) [69]; plastic cable waste (2.63 MPa) [68]; the combination of shredded EPS and ceramic waste (2.9 MPa) [21] and the combination of shredded EPS and

**Table 4**
Results obtained in surface hardness test.

| | E0.7 (Ref.) | E0.7-N | E0.7-150-N | E0.7-300-N | E0.7-450-N |
|---|---|---|---|---|---|
| Surface Hardness (Shore C Units) | 82 | 68 | 66 | 63 | 63 |

**Table 5**
Results obtained in $MOE_{US}$ test and expanded combined uncertainty.

| | E0.7 (Ref.) | E0.7-N | E0.7-150-N | E0.7-300-N | E0.7-450-N |
|---|---|---|---|---|---|
| $MOE_{US}$ (MPa) | 5051.7 ± 45.0 | 4228.6 ± 74.1 | 3973.4 ± 42.8 | 2878.9 ± 89.4 | 2051.2 ± 75.5 |

**Table 6**
Result of thermal conductivity coefficient test and expanded combined uncertainty.

| | E0.7 (Ref.) | E0.7-N | E0.7-150-N | E0.7-300-N | E0.7-450-N |
|---|---|---|---|---|---|
| Thermal conductivity (W/mK) | 0.210 ± 0.007 | 0.180 ± 0.007 | 0.150 ± 0.009 | 0.110 ± 0.008 | 0.070 ± 0.003 |

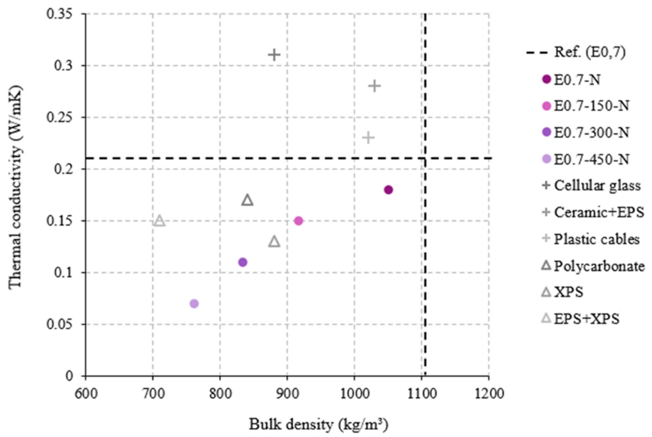


**Fig. 8.** Results of thermal conductivity in comparison with bulk density.

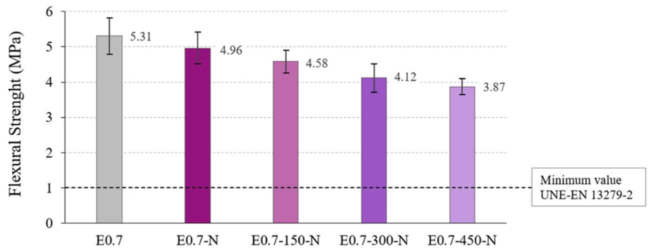


**Fig. 9.** Results of the flexural strength test on standard 40 × 40 × 160 mm sample.

XPS (1.9 MPa) [26]. This fact is usually due to the heterogeneity present in the composites, which would be producing preferential fracture points that have a negative impact on the flexural strength of the material [72]. Nevertheless, the material developed in this research shows a flexural strength higher than that of other plaster composites with waste incorporation, even in the most unfavourable case (E0.7–450-N), as well as far exceeding the minimum flexural strength of 1 MPa established by the UNE-EN 13279–2 standard [57].

### *3.7. Compressive strength*

The results of the compressive strength test, with error bars taking into account the sample standard deviation, are shown in Fig. 11.

As with the flexural strength, the compressive strength of the composites is also generally affected with the incorporation of textile fibres, and even more so as the amount of EPS dissolution increases. The E0.7–450-N composite had the lowest compressive strength, with a 47.9% lower strength than the reference plaster. However, as was the case in the previous test, all the plaster composites greatly exceeded the minimum value of 2 MPa indicated in UNE-EN 13279–2 [57].

Again, this lower strength has already been observed in other investigations, such as the incorporation of XPS waste (3.15 MPa) [70]; plastic cable waste (5.12 MPa) [68]; the combination of shredded EPS and ceramic waste (4.56 MPa) [21] and the combination of shredded EPS and XPS waste (3.56 MPa) [26]. However, the results obtained in the compressive strength test of all plaster composites with the incorporation of ELT fibres and EPS dissolution are superior to those shown in these investigations. Although slightly

**Fig. 10.** Specimen E0.7–450-N after flexural strength test.

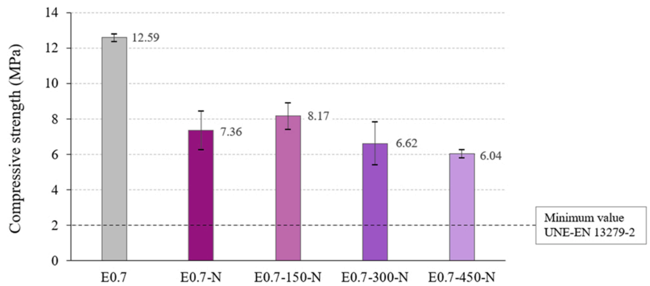


**Fig. 11.** Results of the compressive strength test on standard 40 × 40 × 160 mm sample.

higher compressive strengths were obtained with the addition of polycarbonate waste (7.98 MPa) [69], the plaster composites developed in this research achieve a thermal conductivity 58.8% lower than the addition of polycarbonate.

It is noteworthy that, with the lower proportion of EPS dissolution (E0.7–150-N) in partial replacement of the plaster mix, the compressive strength of the plaster containing only textile fibres was improved by 11%. This result highlights the potential of EPS dissolution in the reinforcement of plaster composites with the addition of recycled fibres where the compressive strength of the material is compromised, such as in the case of recycled fibres from thermal insulation [73].

### *3.8. Flexural strength of plates*

When it comes to developing a new material for the production of prefabricated plates and panels, it is essential to carry out tests with specimens that are as close as possible to the dimensions that these elements could have on site, in order to know their real behaviour. The results obtained in the flexural strength test on 400 × 300×20 mm plates are shown in Fig. 12.

As can be seen in Fig. 12, the progressive replacement of the plaster mix by the EPS dissolution increases the flexural strength of the elaborated plates. As in the compressive strength test, the isolated addition of ELT textile fibre (E0.7-N) decreases the strength by up to 10.3% compared to the reference (E0.7). However, with the lower proportion of EPS dissolution (E0.7–150-N), this loss of strength is corrected to the values of the plaster without additions. Furthermore, as the amount of EPS dissolution in the mixes increases, the flexural strength also increases considerably. The best result was obtained with the E0.7–450-N compound, which is 33.3% stronger than traditional plaster. In this case, all the plates made with the plaster composites also managed to exceed the minimum resistance (0.18 kN) established by the UNE-EN 12859 standard [74].

### *3.9. Scanning electron microscopy (SEM)*

Scanning electron microscopies have been performed on the composites E0.7, E0.7-N and E0.7–450-N, as they are the most significant of all the composites produced, in order to support the results of the mechanical tests obtained previously.

Fig. 13 (a) and (b) show the hardened plaster without any type of addition (E0.7). In them, although some pores are visible, in general a rather compact needle structure is observed, composed of calcium sulphate dihydrate, which is formed during the setting of the plaster. The E0.7-N composite is shown in Fig. 13 (c) and (d), where some textile fibres can be seen embedded in the plaster matrix. These fibres show a good bonding with the plaster crystals, with some of these crystals scattered on the surface of the fibres. Finally, in Fig. 13 (e) and (f), it can be seen how the E0.7–450-N composite presents a greater disintegrated aspect than the previous ones. This

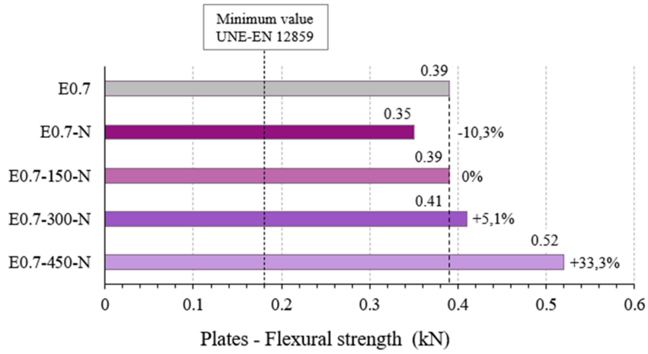


**Fig. 12.** Results of the flexural strength test on standard 400 × 300×20 mm sample.

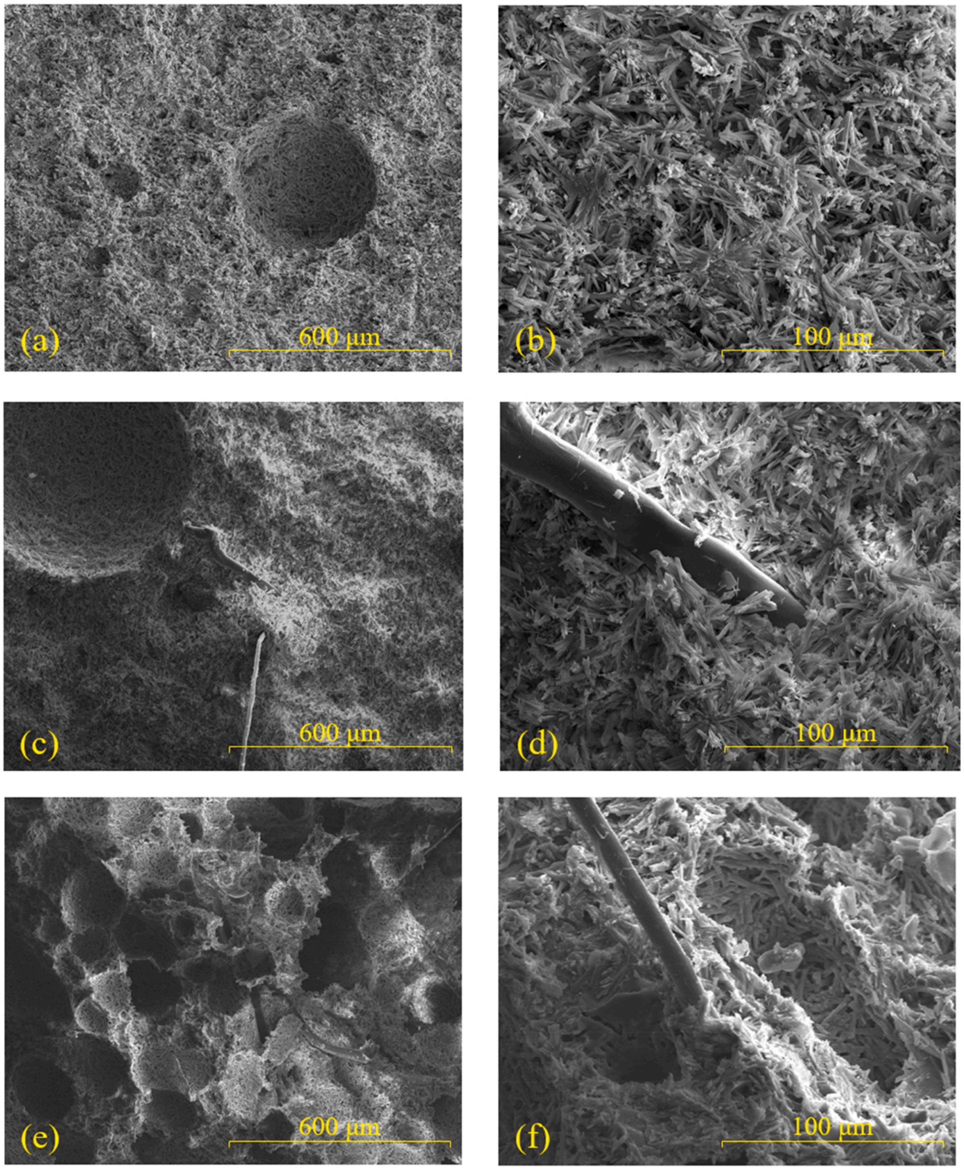


**Fig. 13.** Microscopy of composites: (a) E0.7, 100x; (b) E0.7, 500x; (c) E0.7-N, 100x; (d) E0.7-N, 500x; (e) E0.7–450-N, 100x; (f) E0.7–450-N, 500x.

composite is the one with the highest replacement of the plaster mix by the dissolution of EPS and ELT fibres, which results in a considerably more porous structure, with large voids and grooves present throughout the sample. This fact would explain the loss of compressive strength in the dosages with higher amounts of raw material replacement (E0.7–450-N). Likewise, the dissolved EPS appears hardened around the plaster crystals and coating the inside of some pores, which could stiffen the material to a certain extent. This high porosity is in concordance with the results obtained for the low bulk density and the reduced thermal conductivity of the processed composites.

### 3.10. Summary and discussion

The rapid development of modern industries has led to the release of a large number of pollutants in recent decades [75], some of which, such as the EPS insulation or end-of-life tyre waste discussed in this research, decompose to generate microplastics. These microplastics have become an emerging group of pollutants that have attracted the attention of policy makers and researchers all over the world [76]. In this sense, the treatment of slow and costly degradation waste and its physicochemical recovery and revalorisation is of great interest for the industry in general [77].

This work contributes to the development of new sustainable building materials produced under circular economy criteria. A plaster composite material specially designed to elaborate prefabricated elements has been presented, describing its production process and morphology, and showing its excellent mechanical performance and good thermal behaviour for use in building works. A discussion of the results has also been carried out, taking into consideration other previous studies, where it has been verified that to date there is no prefabricated plaster that resembles the material developed in this research. The preparation method described, incorporating the dissolved EPS in the plaster composites, its microscopic composition with an excellent integration of the recovered waste in the matrix, and its technical feasibility to produce false ceiling panels, demonstrate the suitability of this new material for use in the development of lightweight housing panels and plates. For all these reasons, it is understood that this research makes a relevant and novel contribution to the building sector, and that it can serve as a basis for future researchers interested in the development of new sustainable building materials.

## 4. Conclusions

In this research, the technical feasibility derived from the incorporation of ELT textile fibres and dissolved EPS waste in plaster composites has been tested. These recycled materials have been introduced into the manufacturing process as a partial replacement of the raw materials that form the traditional prefabricated plates and panels of plaster, that is, reducing the consumption of water and plaster used to produce the industrialised composites commonly employed in the building sector. In this way, it is committed to the development of prefabricated elements that, together with the reincorporation of waste in the production process of the material, promote the optimisation and limitation of the use of natural resources and the reduction of energy consumption. Likewise, the new material developed in this research has been registered as a Spanish patent with application number P202230251 [78]. The following conclusions can be drawn from the experimental programme carried out:

- The addition of ELT textile fibres and EPS dissolution as a partial replacement of raw materials in plaster composites reduces the consumption of plaster and water in these composites by up to 28.5%. This results in a material significantly more sustainable by reducing the use of natural resources and a high rate of waste recovery.
- The thermogravimetric analysis of the composites in an air atmosphere shows that they are able to retain up to 3% more mass in the 0–250 °C range compared to the reference plaster. However, in the 250–550 °C range the mass loss increases due to the combustion of the incorporated additions, this effect is more important as the amount of EPS dissolution in the composites increases.
- The incorporation of ELT textile fibres and the dissolution of EPS generate a highly porous material as shown in the SEM images. This effect reduces the density of the plaster composites developed up to 31.3% for the E0.7-450-N mix with respect to the reference plaster (E0.7). However, as in other investigations, this decrease in density is associated with a decrease in the surface hardness of the developed composites.
- The high thermal resistance of the ELT textile fibres, together with the large amount of occluded air that is capable to retain the EPS dissolved in the plaster matrix, manages to reduce the thermal conductivity coefficient of the composites by up to 66.7% compared to traditional plaster. This increase in thermal resistance is higher than the one obtained by other researchers who reincorporate construction and demolition waste in order to lighten the plaster composites.
- Regarding the flexural strength test, it has been observed that the incorporation of ELT textile fibres in the matrix of the plaster composites avoids brittle fracture after the test. However, the incorporation of ELT textile fibres and the progressive increase of EPS dissolution as a partial replacement of the raw materials (plaster and water), decrease the flexural strength of the lightened composites compared to the reference plaster E0.7. In spite of this, the material produced in the present study has a higher standardised flexural strength than that obtained by the studies consulted in the literature that incorporate residues to lighten the plaster composites, as well as exceeding the minimum strength of 1 MPa established by the UNE-EN 13279–2 standard in all the mixes produced [57].
- The composite with 150 g of dissolved EPS and textile fibres (E0.7-150-N) improved the compressive strength of the plaster containing only the fibres (E0.7-N), although in no case did it reach the strength values obtained by the reference plaster. This behaviour highlights the potential of the EPS dissolution for its application as reinforcement in plaster composites with recycled

fibres where the compressive strength is affected. In addition, all the composites produced in this research exceeded the minimum strength of 2 MPa as stated in the UNE-EN 13279–2 standard [57].
- The addition of 150 g of EPS dissolution to the plaster containing only textile fibres (E0.7-N) prevented the loss of flexural strength in plates caused by the incorporation of fibres until the values of the reference plaster were reached. Likewise, the progressive increase in the amount of EPS dissolution in the plaster composites improved the flexural strength in plates by up to 33.3% with respect to the reference plaster.

Taking into consideration the results obtained for this research, the new plaster composite developed is presented as a viable alternative for the production of more sustainable prefabricated plates and panels of plaster. The low specific weight of the composites, together with their high thermal performance and good mechanical behaviour, results in a very interesting material for use in industrialised construction. However, as a future line of research the hygric properties of the developed materials such as water vapour resistance factor and water absorption coefficient should be measured. These tests would allow to determine the hygric function of these composites which should be taken into consideration before the practical application of these materials in buildings.

In any case, the reduction in the use of raw materials and the reuse of waste, necessary for the production of the new plaster composite developed, make this construction material a more environmentally friendly option, in line with the circular economy criteria set out in the European Green Deal presented by the European Commission [65].

## 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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