buildings

MDPI

Article

Study of Different Recycling Approaches for Gypsum-Based Composites with Recycled Rubber Aggregates

Daniel Ferrández [1,†], Alicia Zaragoza-Benzal [1,†], Evangelina Atanes-Sánchez [2], Beatriz Merillas [3], Ricardo Mateus [4] and Paulo Santos [5,*]

[1] Departamento de Tecnología de la Edificación, Universidad Politécnica de Madrid, Avda Juan de Herrera, 6, 28040 Madrid, Spain; daniel.fvega@upm.es (D.F.); alicia.zaragoza@upm.es (A.Z.-B.)
[2] Departamento de Ingeniería Mecánica, Química y Diseño Industrial, Universidad Politécnica de Madrid, 28012 Madrid, Spain; evangelina.atanes@upm.es
[3] Cellular Materials Laboratory (CellMat), Department of Condensed Material Physics, Facultad de Ciencias, University of Valladolid, 47011 Valladolid, Spain; beatriz.merillas@uva.es
[4] Department of Civil Engineering, Institute for Sustainability and Innovation in Structural Engineering (ISISE), University of Minho, 4800-058 Guimarães, Portugal; ricardomateus@civil.uminho.pt
[5] University of Coimbra, Department of Civil Engineering, ISISE, ARISE, 3030-788 Coimbra, Portugal
* Correspondence: pfsantos@dec.uc.pt
† These authors contributed equally to this work.

Abstract: The worldwide demand for gypsum resources is continuously growing due to its versatility in the building industry. In this context, incorporating recycled aggregates is gaining attention for enhancing the physico-mechanical properties of gypsum-based composites. Recycled rubber aggregates have stood out in recent decades as a common option in the development of prefabricated panels and sheets. This study presents a design of gypsum-based composites in which 20 to 40% of the volume of the binding material has been replaced with recycled rubber in two different formats: granulates (1.0–2.5 mm) and powder (<0.8 mm). Three series of composites have been developed to explore their recyclability: Series 1, recycled rubber aggregates and commercial gypsum; Series 2, recycled rubber aggregates (by trituration of samples from Series 1) and commercial gypsum; and Series 3, 100% recycled gypsum and rubber aggregates. All the composites surpass the minimum values of flexural and compressive strength (1 and 2 MPa, respectively) indicated by the normative result. Furthermore, the physicochemical characterisation showed the effectiveness of the recycling process of the triturated dihydrate for obtaining the hemihydrate. A study of the environmental impact revealed a 60% reduction in CO_2 emissions, the equivalent of producing 1 m^2 of prefabricated board using traditional gypsum. Therefore, this research outlines the potential of gypsum recycling with recycled rubber aggregates, thus promoting the circularity of construction products and decreasing the building's environmental footprint. This represents a novelty compared to current studies, which are more oriented towards recycling and recovery of waste from conventional plasterboards.

Keywords: gypsum-based composites; recycled rubber; end-of-life tyres; circular economy; life cycle assessment; mechanical properties

check for updates

Academic Editor: Ahmed Senouci

Received: 17 January 2025
Revised: 8 February 2025
Accepted: 11 February 2025
Published: 13 February 2025

Citation: Ferrández, D.; Zaragoza-Benzal, A.; Atanes-Sánchez, E.; Merillas, B.; Mateus, R.; Santos, P. Study of Different Recycling Approaches for Gypsum-Based Composites with Recycled Rubber Aggregates. *Buildings* **2025**, *15*, 577. https://doi.org/10.3390/buildings15040577

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

According to recent research, the total consumption of rubber worldwide shows an annual growth of 2.8% [1]. This rubber is mainly used to fabricate tyres of different sizes and different purposes. Thus, it is estimated that in 2030, the fabrication of these products will increase to 1500 million annually [2]. This growth in demand provokes a progressive

increase in the number of end-of-life tyres (ELTs), generating a high environmental impact with regard to land and maritime pollution throughout the planet [3]. In fact, ELTs represent almost 2% of the total residues generated worldwide [4], and it is expected that the number of ELTs will reach 1.2 billion units by 2030 [5]. Moreover, it is estimated that 75% of ELT residues are deposited at landfills with no treatment for their revalorization, which worsens the situation, turning these accumulation points into potential hazards which may result in fires, mosquito proliferation, and the release of chemical substances [6–8].

Rubber is the main constituent of ELT and has a degradation time between 800 and 2000 years [9]. In view of this situation, it is necessary to seek alternatives to promote efficient management of these solid wastes, integrating solutions designed under the circular economy criteria.

This manuscript addresses the application of these secondary raw materials in the development of gypsum-based composites and explores the possibilities for recycling these building materials. This represents a novel approach to research on gypsum materials produced under circular economy criteria and is especially suitable for executing prefabricated products. To date, there have been several studies addressing the incorporation of ELT by-products in the processing of gypsum materials.

Below, we have listed the investigations directly related to this work, which were identified through a search in Web of Science according to the following criteria: ALL = ((‘Tyre*’ OR ‘Tire*’ OR ‘Rubber’) AND (‘Gypsum*’ OR ‘Plaster*’) NOT (‘Cement’ OR ‘Concrete’ OR ‘Lime’)). Papers which were not written in Spanish or English, research carried out before 2020, and manuscripts for which the full text was not available were excluded from the analysis.

- Pinto et al. conducted a study involving different amounts of recycled rubber (5, 10, and 15 wt%) with particle sizes smaller than 0.60 mm and 1.20 mm [10]. Remarkable results were obtained in terms of decreased water absorption, with greater lightness being observed in the composites made with the smaller-size rubber because of the greater porosity of these mixtures, which was analysed by scanning electron microscopy (SEM) techniques. This study highlights that the main application of these composites could relate to the hygrothermal regulation of built spaces.
- Lozano-Diez et al. tried to improve the mechanical behaviour of gypsum composites with rubber aggregates by incorporating synthetic reinforcing fibres [11]. Thus, they for a water/gypsum ratio of 0.6 by mass and additions of 1.5% by mass of carbon fibre of 12 mm in length, they obtained gypsum composites with sufficient mechanical resistance to bending and compression stresses to develop prefabricated constructions of large dimensions in plate or panel format.
- Ferrández et al. developed composites in which gypsum material was partially replaced with recycled rubber aggregates (up to 30% by volume) [12]. A decrease in mechanical properties was observed, although in all cases, the threshold of 1 MPa in bending and 2 MPa in compression was exceeded. The main improvement obtained using these composites was a decrease in thermal conductivity of about 35% compared to traditional gypsum materials.
- Meddah et al., in alignment with the previous work, developed gypsum composites with high thermal performance for application in Mediterranean climates [13]. In contrast to other studies, these authors used dune sand as an additional aggregate to improve compressive strength, thus creating gypsum mortars more suitable for coating or for forming prefabricated blocks.
- Castellón et al. studied the fire performance of a gypsum coating made using tyre rubber waste [14]. The incorporation of these residues in percentages of 14.50% and 46.60% by volume significantly reduced the mechanical resistance, while the fire tests

caused notable damage to the samples containing rubber, reducing the effectiveness of the gypsum coatings as a protective element in case of fire.

- Zaragoza-Benzal et al. developed a new gypsum composite that included recycled rubber waste with a diameter of less than 0.80 mm in combination with dissolved expanded polystyrene [15]. These composites showed excellent thermal insulation properties, up to 26.5% lower than those of conventional gypsum material, as well as excellent moisture resistance, which, together with their acceptable mechanical properties, made them widely applicable for use in damp rooms within dwellings.

In general terms, it can be said that these gypsum-based materials have great acceptability in the construction sector as a consequence of their good hygrothermal regulation capacity [16], the versatility of their applications in the design of modular building systems [17], gypsum's non-combustible nature and good acoustic absorption [18], as well as its low manufacturing cost, as it is sometimes obtained as a by-product in different industrial processes [19]. In this sense, and with the growing industrialisation of the building sector, the redesign of traditional prefabricated plates and panels is one of the main topics of research at present [20]. Likewise, gypsum-based materials do not have a structural function within buildings, which allows them to act as a conglomerate to incorporate different aggregates and recycled fibres in their matrix [21].

Thus, the annual production of natural gypsum is increasing every year and currently reaches figures close to 150 million tons (of which 11 million tons are produced in Spain alone, making this country the largest producer in the European Union) [22]. For this reason, it is not surprising that efforts have been made to study the potential recyclability of these gypsum compounds, as supported by the reactions (1) [23]:

$$CaSO_4 \cdot 2H_2O \xrightarrow{105\ ^\circ C\ to\ 200\ ^\circ C} CaSO_4 \cdot \frac{1}{2}H_2O + \frac{3}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O + \Delta Heat \quad (1)$$

In this sense, some studies, such as those of Erbs et al., recycled plasterboard to recover the gypsum material and produce new 100% recycled prefabricated products [24]. The results showed that for a recycled particle size of less than 290 µm and using temperatures of 180 °C for 24 h, a gypsum powder binder suitable for producing new prefabricates was obtained, and subsequent mechanical characterisation demonstrated its compliance with the Brazilian technical standards [25]. In the same way, Puerto et al. analysed the application of recycled gypsum material from prefabricated plates as a substitute for the execution of plastering; they proved its technical and economic viability, demonstrating that it is possible to develop a business model based on this type of by-product [26]. However, there is no consensus in the literature regarding the optimum heating time and temperature for recycling gypsum material. In this vein, we can highlight the work performed by Li et al., who found that the best results for the recycled composites were obtained at temperatures close to 165 °C, combining good mechanical behaviour with accessible costs [27]. It is also worth mentioning the study carried out by Weimann et al., in which an evaluation of the environmental impacts derived from the industrial-scale processing of these gypsum wastes was carried out, proving through the life cycle analysis methodology that it is an environmentally beneficial activity from the point of view of reducing the consumption of resources and the depletion of natural deposits [28]. However, these recycled gypsum composites have also found other fields of application; they may be used as earth-plastering mortars, in which they provide greater durability [29]; they can also be used to modify setting times and rheological properties in sustainable cementitious composites [30].

As the literature review has shown, the potential recyclability of gypsum composites incorporating recycled rubber aggregates has not been explored to date. Therefore, our research contributes to identifying the possibilities of recycling and revaluing gypsum

composites produced under circular economy criteria. In particular, our investigation analysed the possibilities of recycling and recovering the composites with the addition of recycled rubber aggregates as a partial substitution for the original raw material. Thus, the results derived from this research can be extrapolated to other research projects in which gypsum-based composites have been developed with the incorporation of recycled aggregates of different types. This represents a boost towards advancing a more sustainable construction industry, as many companies are currently reluctant to use these types of secondary raw materials due to the challenges associated with using them in panel and plate production. This is, therefore, innovative research that addresses the mechanical and physicochemical characterisation of these materials and their environmental impact through life cycle analysis (LCA). This provides an objective and global vision to advance towards greater circularity of construction products in line with the objectives included in the European Green Deal [31].

2. Materials and Methods

In this section, the materials employed for the development of the gypsum-based composites of this research, as well as the mix ratios and the description of the experimental programme carried out, are given.

2.1. Materials

The raw materials used in this research were (1) commercial gypsum E35, (2) recycled rubber aggregates from ELT, and (3) tap water.

(1) Gypsum E-35 (Figure 1a): manufactured by Placo (Madrid, Spain), this material is obtained from the calcination of natural gypsum mineral ($CaSO_4 \cdot 2H_2O$). It is a binder material with high purity, whiteness and fineness of grind, so it is widely used in the production of mouldings, plates and prefabricated panels [32]. The main characteristics of this raw material are listed in Table 1.



Figure 1. Raw materials used for this research: (**a**) E35 powdered gypsum; (**b**) ELT recycled rubber (granulate); and (**c**) ELT recycled rubber (powder).

Table 1. Properties of gypsum E35 employed as binding material [33].

Purity (%)	>92	**Water vapour diffusion (μ)**	6
Granulometry (mm)	0–0.2	**Flexural strength (MPa)**	>3
pH	6	**Fire reaction**	Euroclass A1 (Regulation (UE) n° 305/2011 [34])
λ (W/m·K)	0.30	**Classification**	Tipo A (According to UNE-EN 13279-1:2009 [35])

(2) Recycled rubber aggregates (Figure 1b,c): These aggregates are obtained from end-of-life tyres, and in this study, were recovered and revalorised by the company SIGNUS Ecovalor, S.L. (Madrid, Spain). These aggregates were supplied in two different granulometries, one with a particle size between 1.0 and 2.5 mm, called 'granulate', and the other with a particle size of less than 0.8 mm, called 'powder'. These sizes, granular and powder,

are the ones commonly marketed for building applications [36], with the aggregate size varying according to the final application of these by-products. The main physical and chemical characteristics are listed in Table 2 [15–37].

Table 2. Physical and chemical properties of ELT recycled rubber aggregates.

Physical Properties		Chemical Properties [38]	
Density (kg/m^3)	1250	Ketone extract (%)	10–20
Grain morphology	Angular	Polymers (%)	40–55
Humidity	<0.75% by mass	Natural rubber (%)	21–42
Textile content (%)	<0.50% by mass	Carbon black (%)	30–38
Steel content (%)	<0.25% by mass	Ashes (%)	3–7

(3) Water: The water used in this study was obtained from the Canal de Isabel II (Madrid, Spain). This is tap water that is suitable for human consumption and can be successfully used for this type of research [39]. Its main characteristics are as follows [40]: pH = 8.04, 36.09 mg/L $CaCO_3$ and combined chlorine 1.33 mg/L.

2.2. Gypsum-Based Composites Preparation

For the development of this research, three series of three standardised RILEM samples (dimensions 4 × 4 × 16 cm^3) were developed, following the working scheme represented in Figure 2.

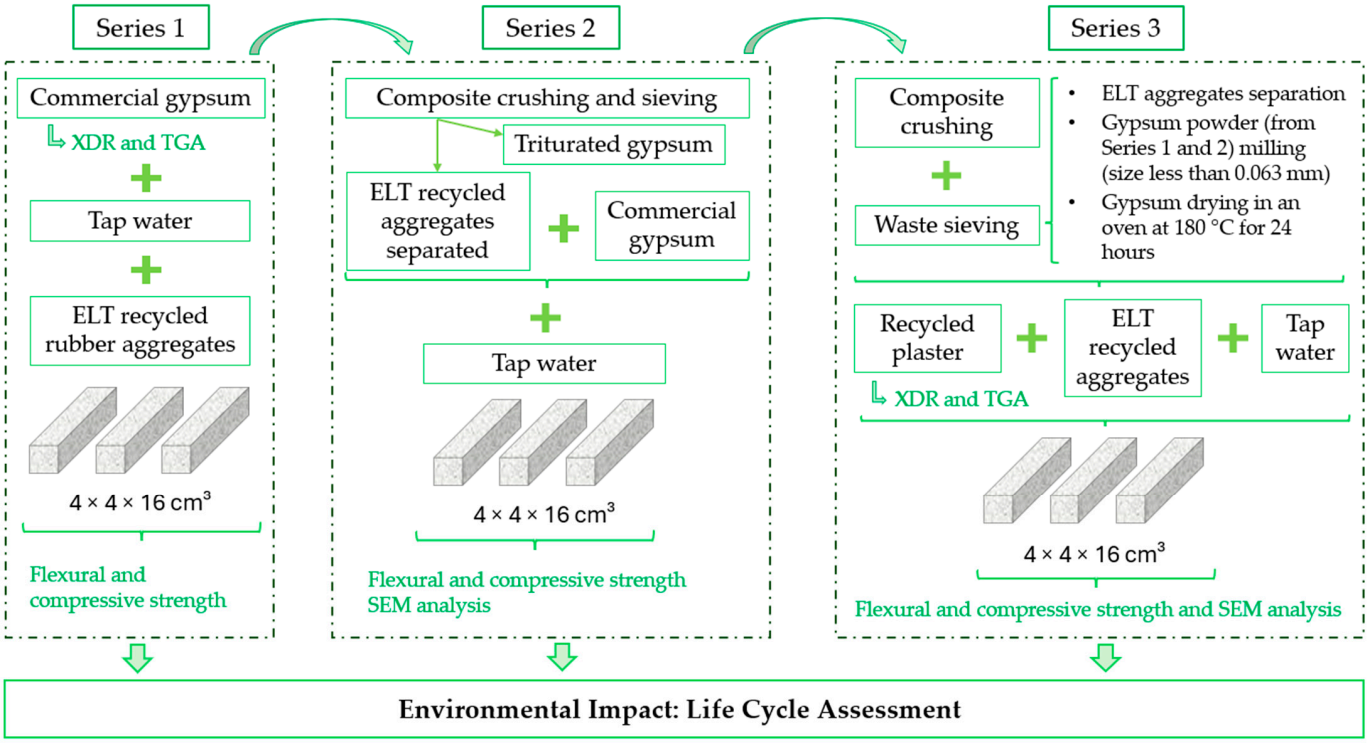


Figure 2. Scheme of the developed work programme and differently produced series.

As shown in Figure 2, to analyse the recyclability of gypsum composites with ELT aggregates, each series included a further stage in the recycling process of these products. Thus, in Series 1, gypsum composites were produced by partially substituting the original raw material with recycled rubber aggregates. Subsequently, and once their mechanical properties had been analysed, the samples were crushed and sieved, separating the recycled rubber from the gypsum material. The separated rubber from each sample was used for the counterpart specimen of Series 2, and a commercial plaster was used as a binder. It

is important to mention that the rubber used in Series 2 contains gypsum dihydrate as an impurity created during the crushing process. With these recovered compounds, new samples were processed, and their mechanical properties were analysed. Finally, in Series 3, composites were produced using the recycled gypsum powder material as a binder. This recycled gypsum was obtained from the crushing and screening of the composites produced in the previous series 1 and 2, with a final step of drying (180 °C, 24 h) to obtain hemihydrate. These Series 3 materials made with recycled gypsum and ELT rubber aggregates (powder and granules) were mechanically tested with regard to bending and compression to determine their mechanical properties. During the process, physicochemical characterisation tests (X-ray diffraction and thermogravimetric analysis) were conducted to determine the effectiveness of the recycling process, as well as microscopy studies on samples from Series 2 and 3. Finally, a study of the environmental impact of each gypsum composite presented was carried out using a life cycle analysis.

All the composites designed in this research were created according to the recommendations and methods stated in the UNE-EN 13279-2:2014 standard [41]. This involved a manual mixing process consisting of (60 s) dry mixing of powdered gypsum and rubber aggregates; (30 s) sprinkling of the powdered mixture over the mixing water; (60 s) resting of the mixture; (30 s) kneading; (30 s) resting of the mixture; and (30 s) kneading.

The proportions of each raw material used in the production of each composite designed for this research are shown in Table 3.

Table 3. Mix ratios employed for the preparation of the gypsum-based composites.

Designation			Gypsum (g)	Water (g)	ELT Rubber Aggregates	
Series 1	**Series 2**	**Series 3**			**Granulate (g)**	**Powder (g)**
REF	—	—	1000	800	—	—
S1-20%G	S2-20%G	S3-20%G	800	640	40	—
S1-40%G	S2-40%G	S3-40%G	600	480	80	—
S1-20%P	S2-20%P	S3-20%P	800	640	—	75
S1-40%P	S2-40%P	S3-40%P	600	480	—	150

In all the composites produced in Table 3, a water/gypsum ratio of 0.8 by mass was chosen. While this ratio for the compounds in Series 1 provided a fluid consistency in accordance with UNE-EN 1379-2:2014 [41], it allowed a plastic consistency to be obtained in the compounds produced in Series 2 and 3. This is due to two reasons: (i) the rubber aggregates used in Series 2 and recovered from Series 1 composites, after crushing and sieving, presented $CaSO_4 \cdot 2H_2O$ impurities that acted as accelerators in the setting process [42]; and (ii) the Series 3 composites were made with recycled plaster powder, which may also have contained dihydrate impurities that could have decreased the workability time of the mixture in the liquid state [43].

All the samples, independently of the series, were cured in the same conditions. For seven days, they were kept in the laboratory at a controlled temperature and relative humidity of 23 ± 2 °C and 50 ± 5%, respectively. Then, before testing commenced, they were placed in an oven for 24 h at a temperature of 40 ± 2 °C and relative humidity of 50 ± 5%.

In Figure 3, an image of the matrices of the composites produced for Series 1 and 3 can be seen, where a total integration of the rubber residue in the plaster matrix can be appreciated, independently of the particle size added.

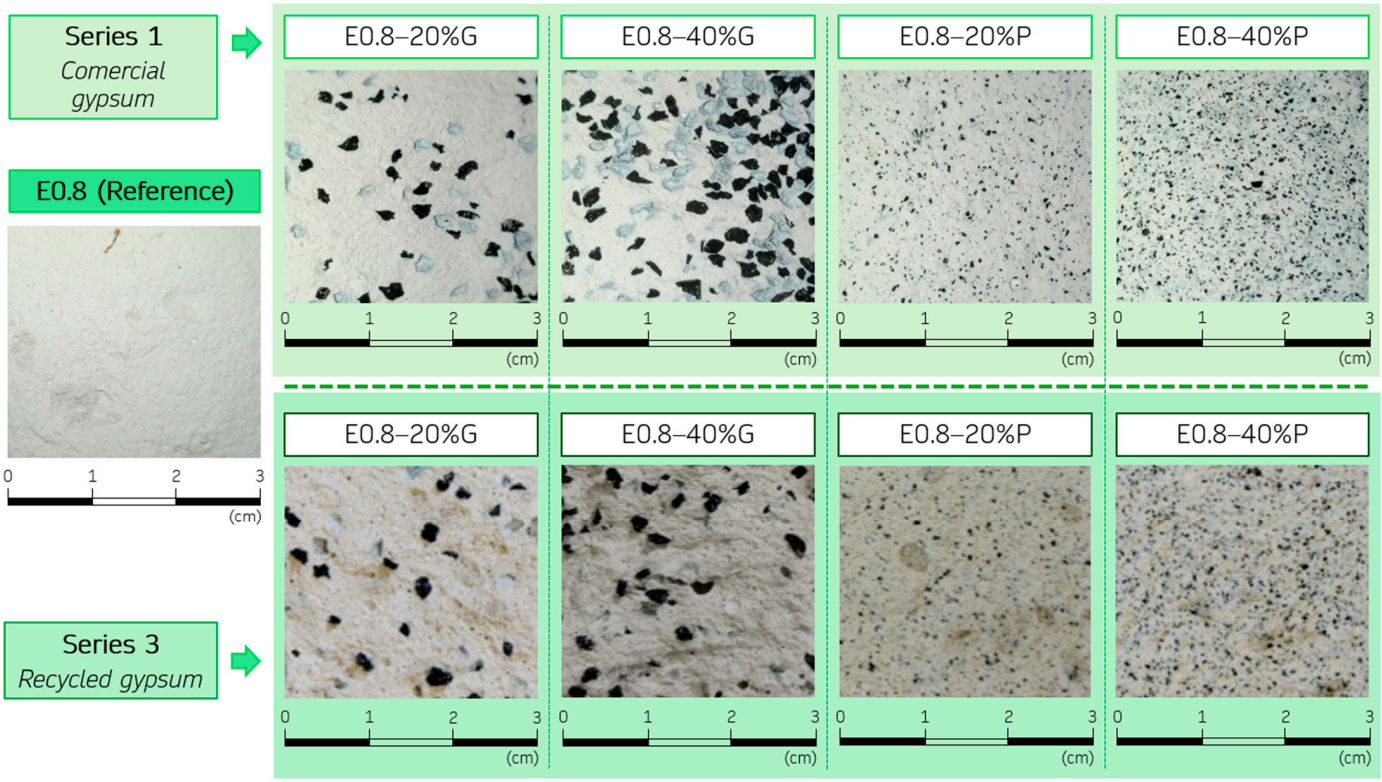


Figure 3. Images of the composite matrices produced in Series 1 and 3.

2.3. Test Procedures

For the experimental development of this research, physicochemical characterisation techniques were used to determine the properties of the gypsum materials produced, and mechanical characterisation tests were performed on the gypsum composites obtained in each of the series.

2.3.1. Physicochemical Characterisation

For this physicochemical characterisation of the raw materials, X-ray diffraction and thermogravimetric analysis tests were performed.

X-ray diffraction (XDR): Siemens Krystalloflex D5000 equipment was used, with a graphite monochromator with Cu Kα (1, 2). Diffractograms were obtained in a range of $5° \leq 2\theta \leq 60°$ every 0.04°, 4 s/step. The diffractograms were interpreted with the JCPDS database of the International Centre for Diffraction File.

Thermogravimetric analysis (TGA): A TA Instruments SDT Q600 analyser was used. The analysis was performed from room temperature up to 1000 °C at 10 °C/min under air atmosphere (100 mL/min). A total sample mass of 45 $\pm$ 5 mg was analysed in each test.

2.3.2. Mechanical Characterisation

The mechanical characterisation was carried out in accordance with the normative UNE-EN 13279-2:2014 [41] to determine the flexural and compressive strengths of the different composites produced. Subsequently, to obtain more information on this recycling process of gypsum-based materials and recycled rubber aggregates, SEM analysis was conducted on the Series 2 and 3 samples.

Flexural strength: The flexural strength was determined with an IBERTEST hydraulic press model AUTOTEST 200-10SW. This is a three-point bending test, wherein a progressive load of 10 N/s is applied until the sample breaks. Three standardised RILEM samples of $4 \times 4 \times 16$ cm^3 were used for each dosage and series analysed in this research.

Compressive strength: The compressive strength was determined using the same press employed in the flexural tests. For this assessment, the two semi-samples obtained after the flexural strength test were used. Each sample was tested by applying a load speed of 20 N/s applied on a 4 × 4 cm^2 surface until breakage occurred.

Scanning electron microscopy (SEM): To enrich the discussion of the results, images were extracted by SEM analysis. For this purpose, one sample from Series 2 and one from Series 3 were analysed, as they were produced after a previous recycling process involving the Series 1 samples. A TESCAN VEGA Generation 4 (Brno, Czech Republic) energy-dispersive detector microscope (SEM-EDX) was used, and the software used for the acquisition, processing, and evaluation of the analyses was EDX Oxford ISIS-Link. In addition, the samples were previously coated with a conductive gold film deposited with a Cressington 108 metalliser.

2.4. Environmental Performance Assessment

One of the main objectives of this work was to evaluate the environmental performance of the different gypsum composites, thus analysing the environmental impacts derived from the manufacture of these composites in each of the three series elaborated. For this purpose, the life cycle analysis (LCA) methodology, which is widely used in research works, was followed [44] and split into the following steps: objective and scope definition; inventory analysis; and impact assessment [45]. Each of these sections is described below according to the methodology used.

2.4.1. Declared Unit and System Boundaries

The declared unit taken as a reference for the development of the LCA was 1 m^2 of 12.5 mm thick commercial plasterboard, to be used in the finishing layer of lightweight partition walls. This stated unit serves as a reference for comparing the impacts of the different composites of each series analysed in this research. The boundary conditions for this analysis include the environmental impact derived from the extraction of raw materials to the manufacturing and packaging of these prefabricated panels (cradle-to-gate), as shown in the diagram in Figure 4.

In this way, as shown in Figure 4, this analysis covers the environmental impacts that occur until the final product is ready to be used in construction. As Teixeira et al. points out, this type of cradle-to-gate analysis is most commonly performed when designing new construction products made in accordance with circular economy criteria [46].

2.4.2. Inventory Analysis

The inventory analysis allows us to quantify the inputs (energy and raw materials) and outputs (emissions and waste) of the production process for the gypsum materials designed for this research. For this purpose, the Environmental Product Declarations (EPDs) of the raw materials used were considered, as well as the different types of energy and fuels used during the manufacturing process of 1 m^2 of prefabricated panel, as reported in the literature [47,48]. In addition, it has been considered that the industry producing gypsum as a raw material is also involved in the production of the prefabricated panels, as well as in the recycling of the gypsum-based materials for their reincorporation into the production process within the same plant. These considerations have been considered in stage A2 with regard to transport. In turn, the water used in the mixing process was tap water directly supplied to the manufacturing plant and the recycled rubber was from Valoriza Eco-Rubber, which is located at 70.3 km from the manufacturing industry. It should be noted that for the development of this work, it has been considered that the production plant is located in the Community of Madrid (Spain).

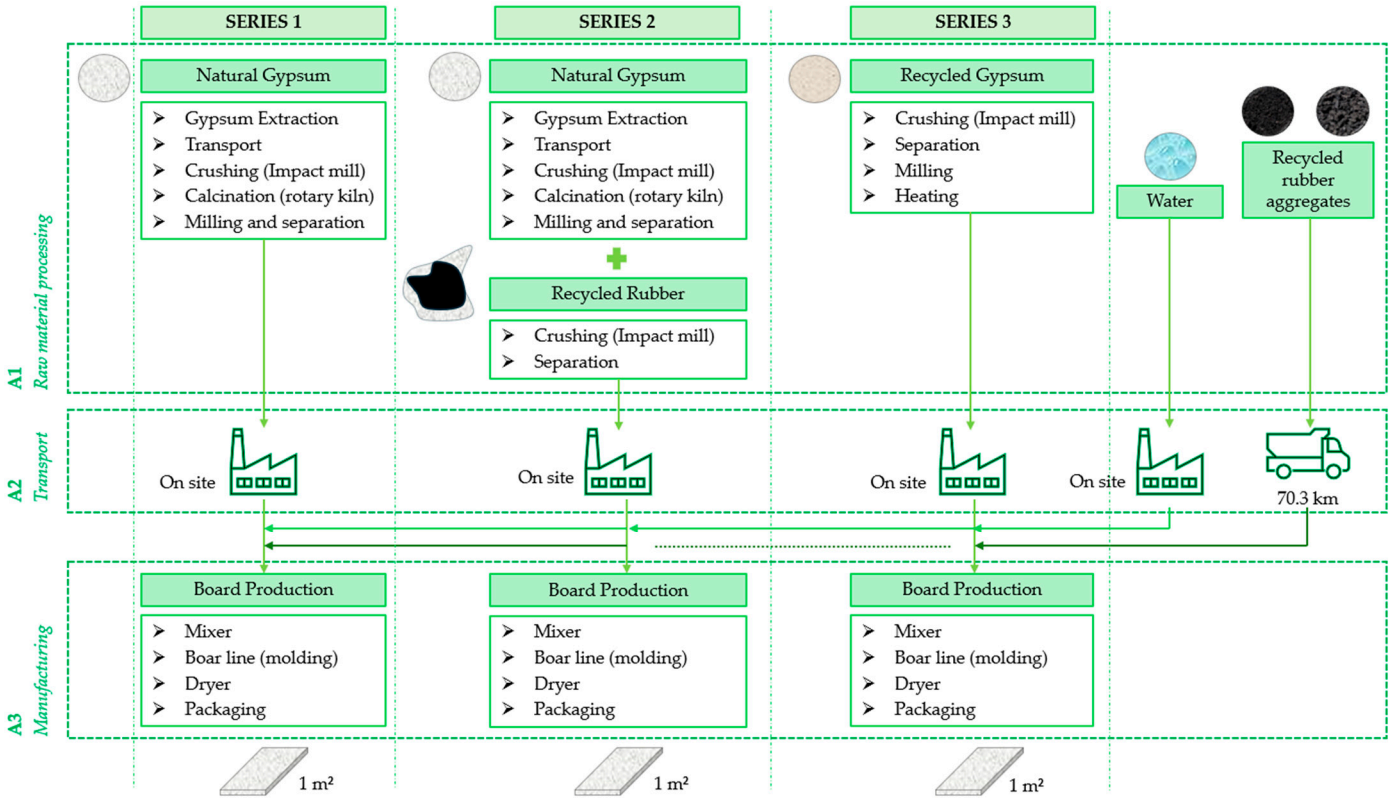


Figure 4. System boundary employed in the LCA of the studied gypsum composites.

For the specific case of water, generic data from the life cycle inventory database Ecoinvent report V3.9 were used. Likewise, the latest Spanish energy mix data available in Ecoinvent was considered to estimate the environmental impacts related to the energy vectors consumed in the manufacturing plant. The inventory related to the transportation was also based on the figures provided by Ecoinvent, considering the characteristics of average transportation fleet in the Spanish context. Table 4 shows the quantities and distances to be considered for the execution of 1 m^2 of prefabricated panel depending on the gypsum compound analysed among those included in this research.

Table 4. Materials and transport input inventory for 1 m^2 (thickness 12.5 mm) of plasterboard for each composite.

Designation			Gypsum (t)	Water (t)	ELT Rubber Aggregates		
Series 1	Series 2	Series 3			Granulate (t)	Powder (t)	Transport (km)
REF	—	—	0.01627604	0.01302083	—	—	—
S1-20%G	S2-20%G	S3-20%G	0.01302083	0.01041667	0.000651042	—	70.3
S1-40%G	S2-40%G	S3-40%G	0.00976563	0.00781250	0.001302083	—	70.3
S1-20%P	S2-20%P	S3-20%P	0.01302083	0.01041667	—	0.00122070	70.3
S1-40%P	S2-40%P	S3-40%P	0.00976563	0.00781250	—	0.00244141	70.3

The values in Table 4 are in accordance with those used in the design of the mix ratios (Table 3). Figure 5 shows the inventory of processes and energy consumption taken into consideration in the production of a functional unit of each compound.

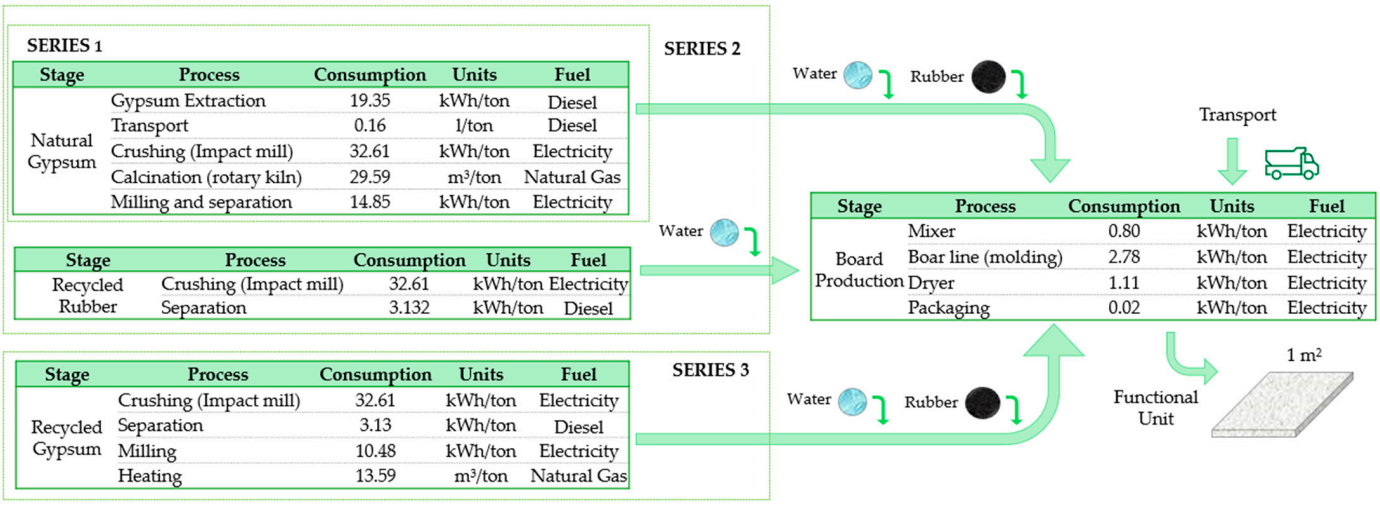


Figure 5. Inventory of processes and energy considered in the production of 1 m^2 of the prefabricated panel [47,48].

2.4.3. Impact Assessment

The assessment of environmental impacts, excluding those related to energy use, water consumption, and transportation, was primarily based on the Environmental Product Declarations (EPDs) of the materials utilised in the manufacturing process. By analysing the quantities of each material input per declared unit, it was possible to estimate the contribution of each material to the overall environmental impact of each sample.

For the remaining inputs, the related environmental impacts were estimated using generic values from the Ecoinvent report V3.9. This estimation process was facilitated by the use of SimaPro 9.4 software and using the EN 15804+A2 life cycle assessment method. This approach ensures a comprehensive evaluation of the main environmental impacts associated with the materials and other inputs involved in production.

Table 5 presents the environmental impact categories that have been taken into consideration to quantify the environmental impacts.

Table 5. Indicators and units employed.

Environmental Indicators	Units
Global Warming Potential (GWP)	(kg CO_2 eq)
Ozone Layer Depletion (ODP)	(kg CFC-11 eq)
Acidification Potential (AP)	(kg SO_2 eq)
Eutrophication Potential (EP)	(kg PO_4 eq)
Formation Potential of Tropospheric Ozone (POCP)	(kg C_2H_4 eq)
Abiotic Depletion Potential of Fossil Resources (ADP_FF)	(MJ eq)

3. Results and Discussion

This section presents the results obtained in this research, presenting each subsection according to the experimental programme.

3.1. Physicochemical Characterisation

The purpose of this section is to show the effectiveness of the gypsum material recycling process. In this way, Figure 6 gathers the diffractograms corresponding to the two raw materials used as binders in this research: commercial gypsum and recycled gypsum.

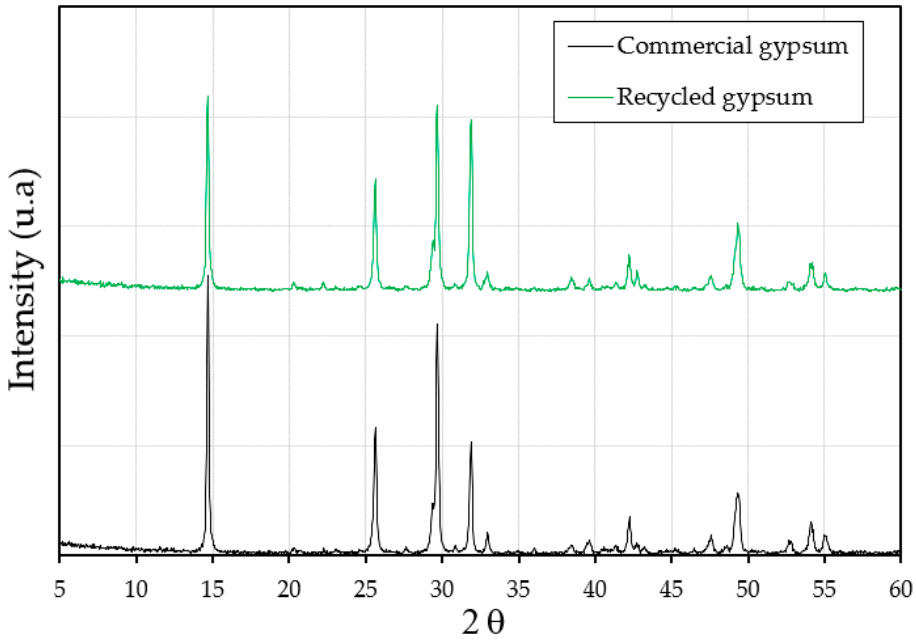


Figure 6. Diffractogram of the raw materials used to produce the composites: commercial gypsum and recycled gypsum.

As shown in Figure 6, both raw materials show the same diffraction pattern, with more intense peaks appearing at angles of 2θ = 14.750°, 25.660°, 29.700°, 31.856° and 49.300°, corresponding to hemihydrate gypsum ($CaSO_4 \cdot 1/2H_2O$) [49]. Nevertheless, there is indeed a slight decrease in the crystalline intensity in the recycled plaster sample as a consequence of its recovery process. On the other hand, as a complementary analysis, Table 6 shows the results obtained for TGA, and Figures 7 and 8 depict the thermograms obtained for both samples.

Table 6. Summary of thermal events of the samples obtained from the thermogravimetric analysis (TGA).

Sample	Total Mass Loss (%)	Interval (°C)	Maximum Temperature (°C)	Partial Mass Loss (%)	Associated Thermal Effects	Comments (*)
Commercial gypsum	11.100	<200	129.18	6.590	Endothermic	HH to anhydrite
		200–550	365.19	-	Exothermic	Phase transition of anhydrite
		550–800	702.05	4.116	Endothermic	$CaCO_3$ to CaO
Recycled gypsum	9.651	<200	125.14	6.177	Endothermic	HH to anhydrite
		200–550	365.86	-	Exothermic	Phase transition of anhydrite
		550–800	681.88	2.832	Endothermic	$CaCO_3$ to CaO

(*) HH = Hemihydrate gypsum.

As can be observed, the mass loss and main thermal events of the commercial gypsum and recycled gypsum are presented in Table 6. These data are derived from the thermograms shown in Figures 7 and 8. In both compounds, there is an initial loss of mass corresponding to the dehydration of the gypsum hemihydrate ($CaSO_4 \cdot 1/2H_2O$) to soluble anhydrite III ($CaSO_4$) [50]. This initial mass variation occurs at a temperature below 200 °C, with a maximum mass loss rate of around 125–130 °C, and similar mass losses of around 10%. Next, in both samples, the exothermic transition from anhydrite III to insoluble anhydrite II can be seen at around 360 °C, with no associated mass loss, indicating that both gypsum samples contain hemihydrate-β. Finally, for both raw materials, a loss of mass between 550 and 800 °C—less than 5% in both compounds—is observed, corresponding

to the decomposition of calcium carbonate ($CaCO_3$) present in the gypsum to give rise to calcium oxide (CaO) [51,52].

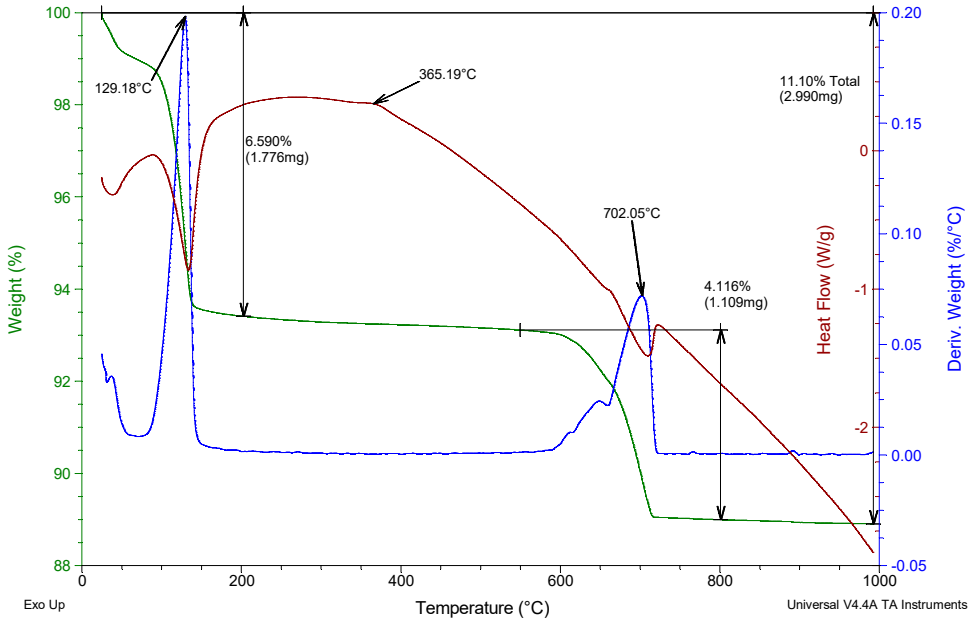


Figure 7. Thermogram performed on commercial gypsum powder.

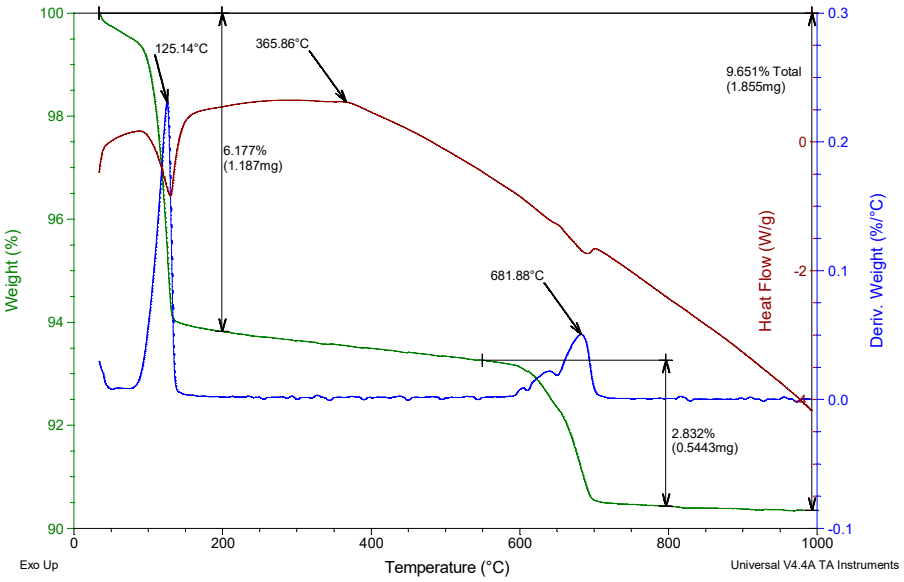


Figure 8. Thermogram performed on recycled gypsum powder.

3.2. Mechanical Characterisation

Firstly, the results of the flexural strength (Figure 9) and compressive strength (Figure 10) tests, obtained on standardised RILEM prismatic specimens of 4 × 4 × 16 cm^3 for each dosage and series produced, are presented. To facilitate the interpretation of the results, the minimum strength value recommended by the UNE-EN 13279-2:2014 standard [41] has been included in the graphs for each test, as well as the percentage decrease in all the samples with respect to the reference (black) and the variation between samples with the same composition and different series (green).

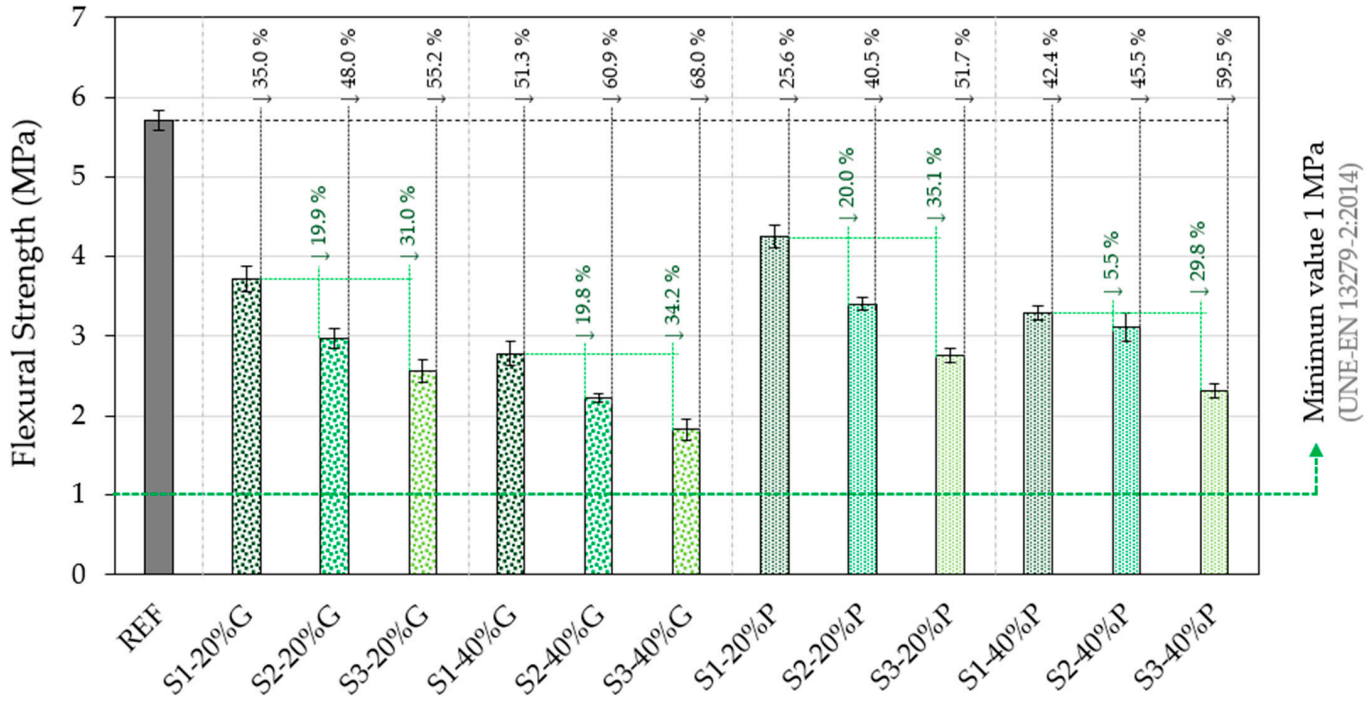


Figure 9. Flexural strength test results for gypsum composites.

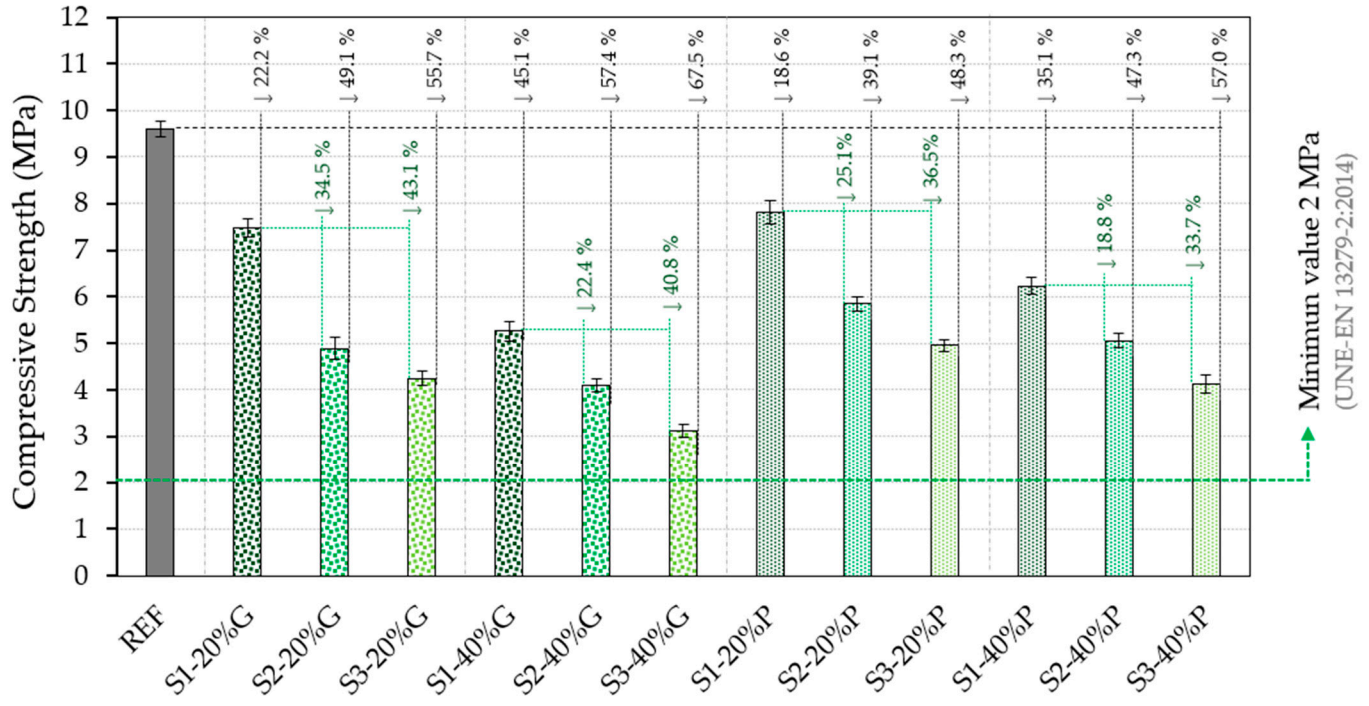


Figure 10. Compressive strength results for gypsum composites.

The results of Figure 9 show how the flexural strength is affected by incorporating these recycled rubber aggregates; the strength achieved by the reference sample is not exceeded in any instance. At the same time, it is observed that for the same proportion of these ELT aggregates, the flexural strength decreases as the recycled plaster content increases. The Series 3 composites made with 100% recycled gypsum–plaster are the ones with the worst mechanical performance. Likewise, the samples in which the gypsum material has been partially replaced with powdered ELT residue (with a particle diameter of less than 0.8 mm) show higher flexural strength than the composites with the addition of

rubber granules (diameters between 2.0 and 4.0 mm). However, in all cases, the minimum flexural strength recommended to be used in the production of plates (1 MPa) was exceeded, as the composites made up of 40% rubber granules exhibited lower strengths (up to 68.0% less than the reference for gypsum composites type S3-40%G).

In any case, and with the values obtained in this test, it can be affirmed that regardless of the recycling process conducted to produce these composites, the gypsum-based materials analysed in this research met the flexural strength requirements expected for their application in construction.

On the other hand, Figure 10 shows the results of the compressive strength tests. As can be seen, the behaviours of the different gypsum composites are similar to those observed in the flexural strength tests, with the minimum strength recommended by the standard now being 2 MPa. As was the case for the flexural strength, the composites of Series 3 exhibited poorer mechanical behaviour, with an up to 67.5% reduction in strength for materials S3-40% compared to the reference materials. Likewise, the series with powdered rubber additives exhibited higher strength than their counterparts that contained recycled rubber granules. This lower strength is linked to a weaker crystalline structure after the incorporation of recycled gypsum and a higher amount of air occluded during mixing [43]. With the aim of expanding the discussion of the results, in Table 7, some recent values obtained for gypsum composites containing recycled rubber are shown. The values obtained for the series containing 40% recycled rubber that was developed in this research have been included in this table as a reference.

Table 7. Discussion of mechanical results: comparison with other research reviewed in the literature.

Reference	Rubber Aggregate Size (mm)	Addition	Other Additions	Flexural Strength (MPa)	Compression Strength (MPa)
[53]	0.60–2.50	5% wt.	—	2.56	3.97
[37]	0.00–0.60	34% wt.	—	0.78	0.55
[38]	2.50–4.00	50% wt.	—	1.50	1.56
[11]	0.06–0.80	5% wt.	Carbon fibre	5.92	7.77
[54]	2.50–10.00	20% vol.	—	3.55	5.68
[20]	0.00–0.60	1% wt.	—	4.96	7.36
[10]	0.60–1.20	15% wt.	—	0.89	4.98
[13]	0.00–1.00	50% vol.	Dune sand	1.30	2.10
Values obtained in this research:					
Series 1	1.0–2.5	40% vol.	—	2.78	5.27
	0.0–0.8	40% vol.	—	3.25	6.23
Series 2	1.0–2.5	40% vol.	—	2.23	4.09
	0.0–0.8	40% vol.	—	3.11	5.06
Series 3	1.0–2.5	40% vol.	—	1.83	3.12
	0.0–0.8	40% vol.	—	2.31	4.13

In order to complement the discussion of the results, images obtained in SEM analysis of the composites with the addition of 40% rubber powder elaborated in series 2 and 3 are shown below. These samples have been chosen because of the high content of incorporated ELT material. Likewise, series 2 and 3 obtained after the recycling process of the original gypsum material of Series 1, have been elaborated with original character in this work to explore the recyclability of these composites. For this reason, these images allow us to deepen the proposed solution for the recovery and revaluation of gypsum compounds with ELT aggregates and are important to know the integration of the rubber in the binding matrix. It should be noted that all the samples extracted for this analysis were obtained from the interior of the matrix of the plaster composites, without modifying the surface texture and ensuring the maximum representativeness of the composite. These micrographs are shown in Figure 11.

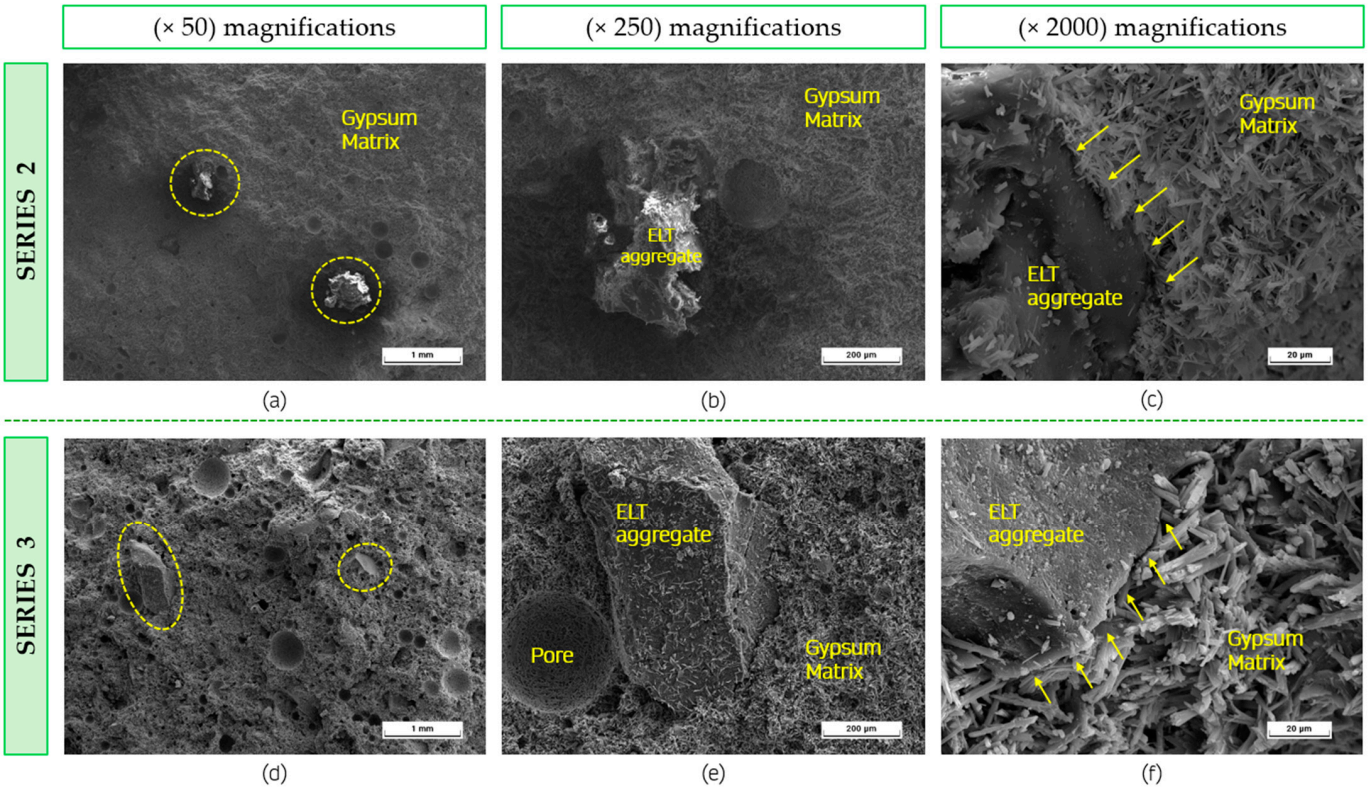


Figure 11. SEM images of the samples S2-40%P (**a**–**c**) and S3-40%P (**d**–**f**).

First, in the top row of Figure 11, the results obtained for sample S2-40%P are shown. Series 2 composites are peculiar in that the rubber is recovered after a process of crushing and sieving of the original sample, ensuring that gypsum dihydrate impurities are contained on its surface. As a consequence, these compounds experience faster setting, as the dihydrate acts as a crystallisation nucleus and reduces workability [29]. This can be seen in Figure 11a, which shows where pores have formed during the setting process. Although the dispersion of the rubber in the matrix appears homogeneous, the bonding between the new gypsum material used as a binder and the surface dihydrate adhered to the rubber can weaken the composite and reduce its mechanical strength [55]. In Figure 11b,c, it is shown that the integration of the rubber residue in the matrix is good and there are no voids between the added particle and the composite. This has a positive effect on the integration of these ELT wastes in the construction sector, which is one of the most viable alternatives currently available [56].

On the other hand, in the bottom row of Figure 11, the images obtained for the composite S3-40%P are displayed. These samples, which employed recycled rubber directly provided by the company SIGNUS Ecovalor S.L. (Madrid, Spain), were produced using 100% recycled gypsum obtained via the process described in the Methodology Section. It is shown in Figure 11d that the processed composite has a higher porosity, a phenomenon that has been observed previously by other researchers [57]. These composites are characterised by a weaker matrix that contributes to diminishing the mechanical resistance. However, in Figure 11e,f, a good integration of the residue in the matrix can be observed, alongside the formation of the characteristic crystals with acicular morphology associated with the dihydrate, which formed during the setting process of the plaster [58]. Thus, these images demonstrate the effectiveness of the recycling process employed in this research.

3.3. Environmental Impact Analysis

In Table 8, the values obtained for the quantification of the different environmental impacts for each gypsum composite are presented.

Table 8. Environmental impact indicators determined for each gypsum composite analysed in this research.

Series	GWP (kg CO_2 eq)	ODP (kg CFC-11 eq)	AP (kg SO_2 eq)	POCP (kg C_2H_4 eq)	EP (kg PO_4 eq)	ADP_FF (MJ)
REF	5.28	1.50×10^{-7}	2.32×10^{-2}	1.14×10^{-3}	9.97×10^{-3}	5.42×10
S1-20%G	4.56	1.26×10^{-7}	1.94×10^{-2}	9.64×10^{-4}	8.19×10^{-3}	6.48×10
S1-40%G	3.85	1.02×10^{-7}	1.56×10^{-2}	7.89×10^{-4}	6.41×10^{-3}	7.55×10
S1-20%P	4.59	1.26×10^{-7}	1.95×10^{-2}	9.67×10^{-4}	8.20×10^{-3}	7.95×10
S1-40%P	3.89	1.03×10^{-7}	1.57×10^{-2}	7.96×10^{-4}	6.43×10^{-3}	1.05×10^{2}
S2-20%G	4.68	1.28×10^{-7}	2.00×10^{-2}	9.86×10^{-4}	8.32×10^{-3}	6.81×10
S2-40%G	3.97	1.04×10^{-7}	1.62×10^{-2}	8.11×10^{-4}	6.53×10^{-3}	7.87×10
S2-20%P	4.17	9.49×10^{-8}	1.80×10^{-2}	8.82×10^{-4}	7.87×10^{-3}	5.88×10
S2-40%P	3.93	8.55×10^{-8}	1.57×10^{-2}	7.89×10^{-4}	6.44×10^{-3}	9.50×10
S3-20%G	2.74	8.04×10^{-8}	1.45×10^{-2}	6.66×10^{-4}	6.97×10^{-3}	2.97×10
S3-40%G	2.08	6.08×10^{-8}	1.10×10^{-2}	5.04×10^{-4}	5.24×10^{-3}	4.31×10
S3-20%P	2.45	6.42×10^{-8}	1.35×10^{-2}	6.10×10^{-4}	6.73×10^{-3}	3.13×10
S3-40%P	2.13	6.15×10^{-8}	1.11×10^{-2}	5.10×10^{-4}	5.26×10^{-3}	7.24×10

For the CO_2 emissions (GWP), the reference composite made only with commercial gypsum had the greatest environmental impact. This was due to the emissions associated with the extraction and preparation process of the natural gypsum [47]. Thus, Series 1 compounds have lower atmospheric CO_2 emissions, as in these compounds, part of the original gypsum is replaced by recycled rubber aggregates. Series 2 exhibits a similar effect; however, it exhibits a slight increase in associated emissions compared to Series 1 due to the process of crushing and screening of the original gypsum aggregates. Finally, the most environmentally friendly composites were those produced for Series 3, which demonstrated the benefits of using recycled plaster in the manufacturing process of these composites [21]. A similar trend to the one described above can be observed in the other indicators: ODP, AP, POCP and EP, to ADP_FF. For this last indicator, which is associated with the consumption of non-renewable energy, an increase was observed in the composites incorporating ELT aggregates; this was associated with the process of obtaining them from discarded tyres. The process of crushing, milling and separation of rubber had a negative effect on the final energy balance of these composites with respect to the reference plaster, except in the Series 3 composites; for these, it was possible, in some cases, to reduce the demand for these non-renewable energy resources as a result of using recycled plaster to prepare the samples.

In Figure 12, the impact of each composite compared to the reference for each indicator analysed can be observed. Each diagram represents the variation in each impact category compared to the reference solution.

Nowadays, the industry offers different alternatives to reduce the effects that waste tyres have on the environment. The most common recovery methods are tyre retreading, rubber grinding, mechanical lapping, and rubber reclaiming [59]. Physically transforming rubber by shredding to obtain recycled aggregates offers a more sustainable alternative to burning tyres for energy generation, which produces many harmful gases [60]. However, current regulations have limited the applicability of these recycled rubber aggregates by classifying them as microplastics [61]; as such, their application in the construction

sector is postulated as one of the most viable alternatives. The results shown in Figure 12 demonstrate that the environmental impact derived from producing prefabricated gypsum panels can be considerably reduced by partially replacing the original gypsum material with ELT aggregates.

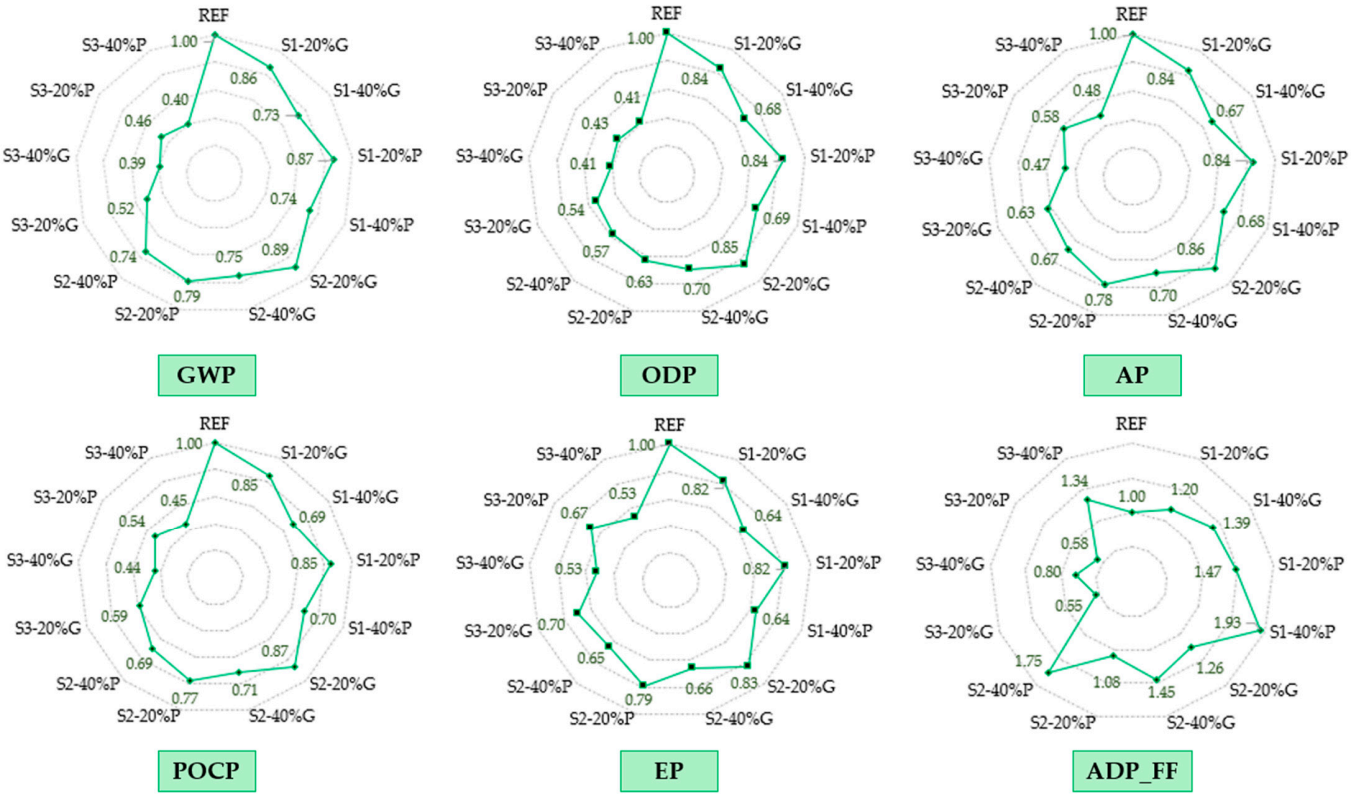


Figure 12. Comparative radial diagrams for each composite with respect to the reference for each of the analysed environmental indicators.

Furthermore, the construction and demolition sectors are responsible for about 35% of the total solid waste deposited in landfills and are some of the key areas in which efforts are needed to improve the sustainability and circularity of materials in the EU [62]. Gypsum is one of the most versatile building materials that can be easily recycled; yet enormous quantities of gypsum building waste, prefabricated plasterboard, and gypsum composite blocks continue to be deposited in landfills in Europe and around the world [63]. An approach focused on recovery of this raw material, as shown in this research, contributes to mitigating the depletion of natural resources, while, as can be seen in Figure 12, atmospheric CO_2 emissions can be reduced by up to 60% compared to traditional composites. However, there is still a long way to go in terms of sustainability in the construction industry. Although this work highlights the benefits of using these recycled raw materials to manufacture non-structural components in the field of construction, the quantification of the environmental impacts and the study of alternatives for the recovery, recycling and revaluation of construction waste remain challenging.

4. Conclusions

In this work, we have studied the recyclability of plaster materials for use in prefabricated products which incorporate recycled rubber aggregates. This is an important step towards analysing the existing alternatives at the end of the lifetime of gypsum-based composites that incorporate solid waste in their matrix as a lightener or to improve their physical–mechanical properties. This is a new approach compared to existing studies,

which have focused on the recycling and recovery of waste from commercial plasterboards. In this sense, this work shows the potential of prefabricated gypsum materials produced under circular economy criteria, which can be used as environmentally friendly materials in the construction industry. The main conclusions that can be drawn from the results obtained are as follows:

- The recycling process of the gypsum material used (180 °C for 24 h) has proved to be effective for transforming the dihydrate into new hemihydrate to form the composites produced in Series 3. However, in the diffractogram of both raw materials, a lower crystalline intensity can be observed in the recycled composite compared to the commercial gypsum.
- All the composites produced, regardless of the recycled rubber content and the series analysed, exceeded the minimum flexural strength (1 MPa) recommended by the standard UNE-EN 13279-2. However, the resistance decreased progressively in the compounds of Series 2 and 3 with respect to Series 1, which was made with commercial gypsum. In fact, the composites of Series 3 showed flexural strengths which were, on average, 30% lower than their Series 1 counterparts. This means the composites which contained a greater proportion of recycled rubber aggregates (40% substitution by volume) had lower strength than the reference sample, which contained about 60%.
- Similar behaviour was observed for the same composites after the compression test; nevertheless, all of the composites exceeded the minimum value established in the standard guidelines, which was 2 MPa.
- Regarding SEM analysis of the compounds of Series 2 and 3 that underwent recycling as part of their manufacturing process, good integration of the residue in the matrix was observed with the formation of dihydrate crystals around the ELT aggregates. However, higher porosity was also observed in the samples, especially in the compounds of Series 3. This higher porosity could explain their lower mechanical strength.
- LCA has revealed the environmental benefit derived from these recycling processes. For all the environmental impact indicators, a decrease in emissions was achieved with respect to the reference plaster, reaching up to 60% in the case of S3-40%P in terms of CO_2 release. Only for the ADP_FF indicator was a worse environmental performance obtained for the composites made with recycled material, as these require a greater amount of non-renewable energy during their manufacturing process, which can be attributed to the process of obtaining the rubber aggregates. However, in any case, the results obtained are encouraging and demonstrate the need to focus on recycled raw materials when developing building materials.

In conclusion, it should be noted that there are still some pending issues that should be addressed in future works, such as the study of other alternative processes for the recycling of the plaster material, the study of the physical–mechanical behaviour of these gypsum-based composites on a real scale, or the extension of the life cycle analysis to include stages after the cradle-to-gate study. In this context, we propose that in future, this study should be expanded upon by increasing the number of stages included in the LCA and analysing the performance of these gypsum composites using a real precast scale. It would also be interesting to evaluate the maximum number of recyclability cycles to which these gypsum-based materials can be subjected, which would provide results with significant applicability within the construction industry.

In any case, developing building materials in accordance with circular economy criteria is a fundamental initiative which will promote the reuse of resources, reduce the volume of discarded materials, and mitigate the environmental impact of this industry, contributing to more sustainable and efficient urban development.

Author Contributions: Conceptualization, D.F. and A.Z.-B.; methodology, D.F., A.Z.-B. and E.A.-S.; software, A.Z.-B., D.F., R.M. and P.S.; formal analysis, D.F., A.Z.-B. and E.A.-S.; investigation, D.F., A.Z.-B., E.A.-S. and P.S.; resources, D.F. and P.S.; data curation, A.Z.-B.; writing—original draft preparation, D.F. and A.Z.-B.; writing—review and editing, A.Z.-B., E.A.-S., B.M., R.M. and P.S.; visualisation, B.M., R.M. and P.S.; supervision, E.A.-S., R.M. and P.S.; project administration, D.F. and P.S.; funding acquisition, D.F. and P.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research is included within the framework of the project: 'Waste2BuildIns: Transformación de residuos para desarrollar nuevos productos de construcción medioambientalmente sostenibles con propiedades mecánicas y térmicas mejoradas', grant number DOCTORES-EMERGENTES-24-DOCTORES-FL6X (OTT-UPM code: M230020126A-DFV), of the E.T.S. de Edificación de Madrid.

Data Availability Statement: All data have been included in the manuscript.

Acknowledgments: This research was supported by Oficina de Aprendizaje y Servicio de la Universidad Politécnica de Madrid through the Educational Innovation Project "Nuevas vías de reciclaje y valorización de los Neumáticos Fuera de Uso: Posibilidades de aplicación en el Sector de la Construcción", grant number APS24.5404 and the University-Company classroom SIGNUS Ecovalor, S.L (PAU2354090272). The authors would also like to acknowledge Cecilia Aguilar Simón for the work carried out as part of her research grant at the E.T.S. de Edificación. This work was also partly supported by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020 (doi.org/10.54499/UIDB/04029/2020), and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Abbas-Abadi, M.S.; Kusenberg, M.; Shirazi, H.M.; Goshayeshi, B.; Van Geem, K.M. Towards full recyclability of end-of-life tires: Challenges and opportunities. *J. Clean. Prod.* **2022**, *374*, 134036. [CrossRef]
2. Arulrajah, A.; Mohammadinia, A.; Maghool, F.; Horpibulsuk, S. Tire derived aggregates as a supplementary material with recycled demolition concrete for pavement applications. *J. Clean. Prod.* **2019**, *230*, 129–136. [CrossRef]
3. Tafreshi, S.N.M.; Amiri, A.; Dawson, A.R. Sustainable use of End-of-Life-Tires (ELTs) in a vibration isolation system. *Constr. Build. Mater.* **2023**, *405*, 133316. [CrossRef]
4. Dziejarski, B.; Hernández-Barreto, D.F.; Moreno-Piraján, J.C.; Giraldo, L.; Serafin, J.; Knutsson, P.; Andersson, K.; Krzyżyńska, R. Upgrading recovered carbon black (rCB) from industrial-scale end-of-life tires (ELTs) pyrolysis to activated carbons: Material characterization and CO_2 capture abilities. *Environ. Res.* **2024**, *247*, 118169. [CrossRef]
5. Zaragoza-Benzal, A.; Ferrández, D.; Barrios, A.M.; Morón, C. Water Resistance Analysis of New Lightweight Gypsum-Based Composites Incorporating Municipal Solid Waste. *J. Compos. Sci.* **2024**, *8*, 393. [CrossRef]
6. Zabaniotou, A.; Antoniou, N.; Bruton, G. Analysis of good practices, barriers and drivers for ELTs pyrolysis industrial application. *Waste Manag.* **2014**, *34*, 2335–2345. [CrossRef]
7. Al-Salem, S.M. Valorisation of End of Life Tyres (ELTs) in a Newly Developed Pyrolysis Fixed-Bed Batch Process. *Process Saf. Environ. Prot.* **2020**, *138*, 167–175. [CrossRef]
8. Lavagna, L.; Colucci, G.; Pavese, M. Effect of oxidation of end-of-life tire rubber as aggregate substitute in cement mortars. *Results Mater.* **2024**, *24*, 100642. [CrossRef]
9. Basik, A.A.; Sanglier, J.-J.; Yeo, C.T.; Sudesh, K. Microbial Degradation of Rubber: Actinobacteria. *Polymers* **2021**, *13*, 1989. [CrossRef]
10. Pinto, N.; Fioriti, C.; Akasaki, J.; Acunha, T.; Okimoto, F. Performance of plaster composites incorporating rubber tire particles. *Rev. Ing. Construcción* **2020**, *35*, 216–232. [CrossRef]
11. Lozano-Díez, R.V.; López-Zaldívar, Ó.; Herrero-del-Cura, S.; Mayor-Lobo, P.L.; Hernández-Olivares, F. Mechanical Behaviour of Plaster Composites Based on Rubber Particles from End-of-Life Tires Reinforced with Carbon Fibres. *Materials* **2021**, *14*, 3979. [CrossRef] [PubMed]
12. Ferrández, D.; Álvarez, M.; Zaragoza-Benzal, A.; Santos, P. Eco-Design and Characterization of Sustainable Lightweight Gypsum Composites for Panel Manufacturing including End-of-Life Tyre Wastes. *Materials* **2024**, *17*, 635. [CrossRef]

13. Meddah, A.; Laoubi, H.; Bederina, M. Effectiveness of using rubber waste as aggregates for improving thermal performance of plaster-based composites. *Innov. Infrastruct. Solut.* **2020**, *5*, 61. [CrossRef]
14. Castellón, F.; Ayala, M.; Lanzón, M. Influence of tire rubber waste on the fire behaviour of gypsum coatings of construction and structural elements. *Mater. Construcción* **2022**, *72*, e275. [CrossRef]
15. Zaragoza-Benzal, A.; Ferrández, D.; Santos, P.; Atanes-Sánchez, E. Development and characterization of new lightweight waste-based plaster composites for building applications. *J. Build. Eng.* **2024**, *96*, 110525. [CrossRef]
16. Charai, M.; Oualid Mghazli, M.; Channouf, S.; El hammouti, A.; Jagadesh, P.; Moga, L.; Mezrhab, A. Lightweight waste-based gypsum composites for building temperature and moisture control using coal fly ash and plant fibres. *Constr. Build. Mater.* **2023**, *393*, 132092. [CrossRef]
17. Rodrigo-Bravo, A.; Calderón, V.; Alameda, L.; Arroyo, R.; Gutiérrez-González, S. Eco-efficiency and economic assessment of gypsum-based precast with polymeric waste: A case study. *Case Stud. Constr. Mater.* **2024**, *20*, e03052. [CrossRef]
18. Aguilera-Benito, P.; Morales-Segura, M.; Caballol, D.; Porras-Amores, C. Thermal and acoustic properties of new plasterboard composites with additions of cigarette butt waste. *Constr. Build. Mater.* **2023**, *402*, 133050. [CrossRef]
19. Doleželová, M.; Krejsová, J.; Scheinherrová, L.; Keppert, M.; Vimmrová, A. Investigation of environmentally friendly gypsum based composites with improved water resistance. *J. Clean. Prod.* **2022**, *370*, 133278. [CrossRef]
20. Zaragoza-Benzal, A.; Ferrández, D.; Diaz-Velilla, J.P.; Zúñiga-Vicente, J.A. Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria. *Case Stud. Constr. Mater.* **2023**, *19*, e02380. [CrossRef]
21. Ferrández, D.; Zaragoza-Benzal, A.; Barrak, E.; Santos, P.; Rodrigues, C. Upcycling expanded polyethylene waste for novel composite materials: Physico-mechanical, hygrothermal and life cycle assessment. *Results Eng.* **2024**, *24*, 103535. [CrossRef]
22. Tèebwaoga Sina, A.; Ait Brahim, J.; Ben Ali, B.; Achiou, B.; Haneklaus, N.; Beniazza, R. Securing gypsum demand in cement industry by gypsum by-products: Current challenges and prospects. *Mater. Today Sustain.* **2024**, *28*, 101034. [CrossRef]
23. Pedreño-Rojas, M.A.; de Brito, J.; Flores-Colen, I.; Pereira, M.F.C.; Rubio de Hita, P. Influence of gypsum wastes on the workability of plasters: Heating process and microstructural analysis. *J. Build. Eng.* **2020**, *29*, 101143. [CrossRef]
24. Erbs, A.; Nagalli, A.; Querne de Carvalho, K.; Mymrin, V.; Hermes Passig, F.; Mazer, W. Properties of recycled gypsum from gypsum plasterboards and commercial gypsum throughout recycling cycles. *J. Clean. Prod.* **2018**, *183*, 1314–1322. [CrossRef]
25. Erbs, A.; Nagalli, A.; de Carvalho, K.Q.; Mazer, W.; Erbs, M.d.M.; Paz, D.H.; Lafayette, K.P. Development of plasterboard sheets exclusively from waste. *J. Build. Eng.* **2021**, *44*, 102524. [CrossRef]
26. Puerto, J.D.; Uribe, S.; Ayala, L.; Padilla, A.; Rodriguez, A. Reliability of Reusing Gypsum Flat Board Grinded Waste as a Conventional Plaster Replacement for Buildings. *Sustainability* **2024**, *16*, 7889. [CrossRef]
27. Li, Z.; Xu, K.; Peng, J.; Wang, J.; Zhang, J.; Li, Q. Influence of the Heating Temperature and Fineness on the Hydration and Mechanical Property of Recycled Gypsum Plaster. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 7520378. [CrossRef]
28. Weimann, K.; Adam, C.; Buchert, M.; Sutter, J. Environmental Evaluation of Gypsum Plasterboard Recycling. *Minerals* **2021**, *11*, 101. [CrossRef]
29. Santos, T.; Wulani Luijten, N.; Santos Silva, A.; Dinis Silvestre, J.; Faria, P. Earthen plasters hygrothermal and mechanical performance: Effect of adding recycled gypsum from plasterboards and raw hemihydrate. *J. Build. Eng.* **2024**, *98*, 111407. [CrossRef]
30. Jafari, A.; Sadghian, P. Influence of biochar and recycled gypsum on the strength and microstructure of conventional and sustainable cementitious composites. *Constr. Build. Mater.* **2023**, *408*, 133715. [CrossRef]
31. European Council. European Green Deal. Available online: https://www.consilium.europa.eu/es/policies/green-deal/ (accessed on 26 December 2024).
32. Merino, M.d.R.; Moreira, C.G.; Sáez, P.V. Mechanical behaviour of a gypsum material with additions of recycled waste from absorbent hygienic products. *Constr. Build. Mater.* **2023**, *367*, 130247. [CrossRef]
33. Saint-Gobain Placo Ibérica, S.A. IBERYOLA E35. Available online: https://www.placomat.com/ficha-tecnica/PL114.pdf (accessed on 12 November 2024).
34. Reglamento (UE) nº 305/2011 del Parlamento Europeo y del Consejo. Available online: https://www.boe.es/buscar/doc.php?id=DOUE-L-2011-80721 (accessed on 12 November 2024).
35. *UNE-EN 13279-1:2009*; Gypsum Binders and Gypsum Plasters—Part 1: Definitions and Requirements. Asociacion Espanola de Normalizacion: Madrid, Spain, 2009.
36. SIGNUS ECOVALOR, S.L. Available online: https://www.signus.es/esquema-reciclaje/ (accessed on 13 November 2024).
37. Herrero, S.; Mayor, P.; Hernández-Olivares, F. Influence of proportion and particle size gradation of rubber from end-of-life tires on mechanical, thermal and acoustic properties of plaster–rubber mortars. *Mater. Des.* **2013**, *47*, 633–642. [CrossRef]
38. López-Zaldívar, O.; Lozano-Díez, R.; Herrero del Cura, S.; Mayor-Lobo, P.; Hernández- Olivares, F. Effects of water absorption on the microstructure of plaster with end-of-life tire rubber mortars. *Constr. Build. Mater.* **2017**, *150*, 558–567. [CrossRef]
39. Morón, A.; Ferrández, D.; Saiz, P.; Vega, G.; Morón, C. Influence of Recycled Aggregates on the Mechanical Properties of Synthetic Fibres-Reinforced Masonry Mortars. *Infrastructures* **2021**, *6*, 84. [CrossRef]

40. Canal de Isabel II. Available online: https://www.canaldeisabelsegunda.es/calidad-del-agua (accessed on 12 November 2024).
41. *UNE-EN 13279-2:2014*; Gypsum Binders and Gypsum Plasters—Part 2: Test Methods. Asociacion Espanola de Normalizacion: Madrid, Spain, 2014.
42. Yi, P.; Du, H.; Chai, C.; Li, Y.; Hu, Y.; Sun, X.; Liu, W.; Xing, F. Potential of desulfurized gypsum as a sulfate alternative in preparing solid waste-based limestone calcined clay cement (LC3) and its effects on early properties. *J. Build. Eng.* **2024**, *98*, 111335. [CrossRef]
43. Gordon, A.M.; Barrio, M.I.P.; Escamilla, A.C.; Matilla, A.L. From waste to resource: Exploring the recyclability and performance of gypsum-graphene nanofibre composites. *Resour. Conserv. Recycl. Adv.* **2024**, *23*, 200222. [CrossRef]
44. Feng, H.; Zhao, J.; Holberg, A.; Habert, G. Where to focus? Developing a LCA impact category selection tool for manufacturers of building materials. *J. Clean. Prod.* **2023**, *405*, 136936. [CrossRef]
45. Paula Junior, A.C.; Jacinto, C.; Oliveira, T.M.; Polisseni, A.E.; Brum, F.M.; Teixeira, E.R.; Mateus, R. Characterisation and Life Cycle Assessment of Pervious Concrete with Recycled Concrete Aggregates. *Crystals* **2021**, *11*, 209. [CrossRef]
46. Teixeira, E.R.; Mateus, R.; Camões, A.; Branco, F.G. Quality and durability properties and life-cycle assessment of high volume biomass fly ash mortar. *Constr. Build. Mater.* **2019**, *197*, 195–207. [CrossRef]
47. Pedreño-Rojas, M.A.; Fořt, J.; Černý, R.; Rubio-de-Hita, P. Life cycle assessment of natural and recycled gypsum production in the Spanish context. *J. Clean. Prod.* **2020**, *253*, 120056. [CrossRef]
48. Romero-Gómez, M.I.; Silva, R.V.; de Brito, J.; Flores-Colen, I. Prototype of alveolar gypsum blocks with plastic waste addition for partition walls: Physico-mechanical, water-resistance and life cycle assessment. *J. Clean. Prod.* **2023**, *432*, 139810. [CrossRef]
49. Zaragoza-Benzal, A.; Ferrández, D.; Santos, P.; Morón, C. Recovery of End-of-Life Tyres and Mineral Wool Waste: A Case Study with Gypsum Composite Materials Applying Circular Economy Criteria. *Materials* **2023**, *16*, 243. [CrossRef] [PubMed]
50. Villanueva, L.; García Santos, A. *Manual Del Yeso*; CIE Inversiones Editoriales Dossat-2000, S.L.: Madrid, Spain, 2001.
51. Strydom, C.A.; Potgieter, J.H. Dehydration behaviour of a natural gypsum and a phosphogypsum during milling. *Thermochem. Acta* **1999**, *332*, 89–96. [CrossRef]
52. Fleck, W.E.P.; Jones, M.H.; Kuntze, R.A.; McAdie, H.G. The differential thermal analysis of natural and synthetic hidrates of calcium sulphate. *Can. J. Chem.* **1960**, *38*, 936–943. [CrossRef]
53. Serna, A.; del Río, M.; Palomo, J.G.; González, M. Improvement of gypsum plaster strain capacity by the addition of rubber particles from recycled tyres. *Constr. Build. Mater.* **2012**, *35*, 633–641. [CrossRef]
54. Álvarez-Dorado, M.; Ferrández, D.; Guijarro-Miragaya, P.; Zaragoza-Benzal, A. Fire behaviour of plaster composite materials lightened with perlite and superabsorbent polymers. *DYNA* **2022**, *98*, 197–201. [CrossRef] [PubMed]
55. Barroso, L.d.S.; Cherene, M.G.P.; Xavier, G.d.C.; de Azevedo, A.R.G.; Vieira, C.M.F. Bibliometric study of the application of gypsum residues and by-products in Portland cement and mortar. *Constr. Build. Mater.* **2023**, *409*, 134072. [CrossRef]
56. Valentini, F.; Pegoretti, A. End-of-life options of tyres. A review. *Adv. Ind. Eng. Polym. Res.* **2022**, *5*, 203–213. [CrossRef]
57. Zhu, C.; Zhang, J.; Yi, W.; Cao, W.; Peng, J.; Liu, J. Research on degradation mechanisms of recycled building gypsum. *Constr. Build. Mater.* **2018**, *173*, 540–549. [CrossRef]
58. Ardebili, A.A.; Sáez, P.V.; Cortina, M.G.; Cruz, D.M.T.; Sáiz, Á.R.; Atanes-Sánchez, E. Mechanical characterization of gypsum mortars with waste from the automotive sector. *Constr. Build. Mater.* **2023**, *370*, 130675. [CrossRef]
59. Zerin, N.H.; Rasul, M.G.; Jahirul, M.I.; Sayem, A.S.M. End-of-life tyre conversion to energy: A review on pyrolysis and activated carbon production processes and their challenges. *Sci. Total Environ.* **2023**, *905*, 166981. [CrossRef] [PubMed]
60. Tamizhdurai, P.; Arthi, P.; Mangesh, V.; Krishnan, P.S.; Kumar, N.S.; Saravanan, P.; Subramani, A.; Sasikumar, P.; Alotibi, M.F.; Alreshaidan, S.B.; et al. Clean energy technology: Hydro-processing of waste tyre pyrolysis oil (WTPO) to diesel fuel in a continuous reactor using Co/SBA-15 catalyst. *Appl. Energy Combust. Sci.* **2025**, *21*, 100305. [CrossRef]
61. SIGNUS Ecovalor, S.L. Aplicaciones de Los Neumáticos Reciclados. Available online: https://www.signus.es/aplicaciones-neumaticos-reciclados/ (accessed on 24 December 2024).
62. Caro, D.; Lodato, C.; Damgaard, A.; Cristóbal, J.; Foster, G.; Flachenecker, F.; Tonini, D. Environmental and socio-economic effects of construction and demolition waste recycling in the European Unión. *Sci. Total Environ.* **2024**, *908*, 168295. [CrossRef] [PubMed]
63. Jiménez Rivero, A.; Sathre, R.; García Navarro, J. Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Unión. *Resour. Conserv. Recycl.* **2016**, *108*, 171–181. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.