

Article

Sustainable Innovation in Ceiling: Exploring the Environmental Benefits of a New Plaster–Rock Wool Layered Recycled Composite

Manuel Álvarez * , Daniel Ferrández , Patricia Guijarro-Miragaya and Carlos Morón 

Departamento de Tecnología de la Edificación, Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, Avda Juan de Herrera 6, 28040 Madrid, Spain; daniel.fvega@upm.es (D.F); patricia.guijarro.miragaya@alumnos.upm.es (P.G.-M.); carlos.moron@upm.es (C.M.)

* Correspondence: manuel.alvarezd@upm.es

Abstract: This paper presents a new layered plaster-based material for building purposes. First, a new manufacturing machine was designed to make the elaboration process easier. This manufacturing machine and the way it works are described. In this study, perlite and recycled glass wool (RGW) were added to traditional plaster with the aim of improving the performance of this material. Two series (with and without perlite) and three different layer configurations were developed and assessed. Recycled glass wool layered materials were subjected to both physical and mechanical characterisation to determine their suitability for precast elaboration. The addition of perlite resulted in a significant improvement in flexural strength. Moreover, the addition of RGW also gave rise to extra flexural strength when added. The two-layered samples performed better than the one-layered samples. Mechanical properties increased up to 75% when both the perlite and RGW layers were added. Potential Global Warming Potential (GWP 100) savings were also analysed, reporting up to 49% savings. A complementary cost analysis was performed, aimed at establishing potential savings in production costs; thus, 13–57% potential cost savings were reported. After that, a comparative analysis within the literature was conducted to contextualise the results obtained in this study.

Keywords: manufacturing process; plaster-based materials; waste management; construction and demolition waste



Citation: Álvarez, M.; Ferrández, D.; Guijarro-Miragaya, P.; Morón, C. Sustainable Innovation in Ceiling: Exploring the Environmental Benefits of a New Plaster–Rock Wool Layered Recycled Composite. *Appl. Sci.* **2024**, *14*, 5055. <https://doi.org/10.3390/app14125055>

Academic Editor: Edyta Plebankiewicz

Received: 10 May 2024
Revised: 3 June 2024
Accepted: 8 June 2024
Published: 10 June 2024



Copyright: © 2024 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

After the COVID-19 pandemic, in 2021, the building sector returned to pre-pandemic levels not only in most major economies, but also in more emerging economies thus increasing their use of fossil fuel gases in the process [1].

Population growth led to new constructions and an increase in the demand of resources [2]. As a result, energy consumption rose by 4%, its largest increase in 10 years [3]. In this sense, the Sustainable Development Goals (SDG) have been set in place to try and reduce this problem within the building sector while improving people's quality of life through SDG 7, 9, and 12 [4].

Buildings are responsible for 40% of the world's energy consumption and related CO₂ emissions, which is one of the main factors to be considered in climate change [5]. This consumption includes both operational and embodied energy. Despite industrialisation modifying building construction processes, there is still a lack of implementation [6]. Traditional materials like bricks and concrete are still being largely used due to their low price and good mechanical performance. However, these materials need vast amounts of energy to be produced and have low thermal conductivity properties [7]. Therefore, it is necessary to design energy-efficient buildings that use more sustainable materials and consider the integration of renewable energies sources. Traditional construction methods must be replaced with precast materials and industrialised buildings to achieve the aim of minimising environmental impact.

Operational energy consumption is mostly produced by the air conditioning in buildings, especially in housing and office buildings [8]. This is due to a deficiency in the performance of the building materials and their main properties.

With this context, plaster-based materials have been raised as a major solution and source of possibilities to improve the hygroscopic conditions inside buildings, as well as reduce operational energy consumption [9]. Plaster-based materials are versatile, cheap, and have a good workability, all of which make them suitable to work with. This fact has led to the development of several experimental studies aimed at improving their main properties, while maintaining the characteristics that make it suitable.

To reduce this material's thermal conductivity, the literature shows two schools of thought. On the one hand, matrix modification which pertains to making the material foamed or lighter; on the other hand, through differently shaped additions. Foaming is achieved using chemical additions. A study presented by Capasso et al. used a mixture of natural solutions to foam the final material [10]. Zaragoza-Benzal dissolved extruded polystyrene (XPS) and expanded polystyrene (EPS) to lighten their final material [11]. Meanwhile, Umponparanat et al. used aluminium sulphate and sodium bicarbonate as gas-producing additives to activate the reaction [12]. These reactions produce bubbles while setting, making the final material more porous. Despite this great advantage, all these products become flammable following this process and their use in buildings is not entirely safe. The use of synthetic polymers as a partial replacement in the plaster matrix also achieves a lighter material as well as reduces its thermal conductivity. Most studied materials include EPS and XPS. Several studies have used grain-sized polystyrene as a lightener [13–16]. The main benefits are the apparent density and reduction in thermal conductivity, although it also produces a considerable decrease in mechanical strength. Because of this, fibres are the other most studied shaped addition in plaster-based materials. Its apparent density is slightly bigger than in foamed plasters, but the mechanical properties are less affected. Natural fibres, such as palm fibre, Posidonia, cellulose, and wood, have been studied and shown to result in better flexural strength behaviour and a reduction in thermal conductivity [17–20]. Synthetic fibres have also been widely studied, reporting a remarkable reduction in thermal conductivity and better mechanical behaviour when added. Glass fibre is one of the most studied fibres due to its great mechanical performance, achieving up to a 20% increase in mechanical strength upon addition [21–23]. Polymeric fibres are also widely studied as they are easy to obtain and have a decent performance. Even though polymers can be bio-based, most of them are still fuel-based, which does not contribute to a reduction in energy consumption within its elaboration process [24]. For this reason, most of the studies have compared its performance in plaster-based materials with that of natural fibres, thus proving the feasibility of replacing synthetic polymers with natural ones [25–28]. All the solutions presented have similar elaboration processes, and the materials sometimes comprise a heterogeneous mixture. Even those chemically modified composites sometimes have certain difficulties with homogeneous distribution along the sample. The lack of correct additive distribution within developed materials presents a terrific opportunity to work on a new elaboration process. Thus, the findings will have a positive impact on manufacturing processes and cost savings.

Improving the thermal conductivity of these materials has a direct impact on the energy consumption in buildings as the energy required to maintain the correct hygrothermal conditions is reduced. For new buildings, it is worth trying to use new materials that perform better while considering the design process. Nevertheless, as most of the energy demand is by the existing buildings, it is necessary to focus on cheaper, sustainable, and operational solutions [4,29].

Considering ceilings as one of the places in buildings where the most energy is lost, it is worth reconsidering the materials used in its construction [30,31]. In this sense, the use of plaster-based composites in ceilings would be one of the main solutions and strategies to reduce energy consumption in buildings. Studies show that the addition of different elements, such as polymers [32] and both natural and synthetic fibres [33,34], is the main

alternative for decreasing energy demand and reaching the zero-energy goal included in the SDG [35].

With this, the aim of this work is to design, characterise, and assess the suitability of a new plaster-based and RGW-layered material for ceiling elaboration. This material is characterised through a physical, chemical, and mechanical analysis. A new elaboration process is also presented and validated.

2. Materials and Methods

2.1. Materials, Dosages, and Samples Elaborated

This study was conducted using the elements shown in Figure 1 and are described as follows:

- E-35 Plaster: Supplied by Placo-Saint Gobain (Madrid, Spain). This binder has a pureness index of >90% and particle size of \varnothing 0–0.2 mm and main characteristics are shown in Table 1. Thermal conductivity value is set between 250 and 300 mW/m·K. This product meets the standard 13279-2:2014 [36] requirements. The material's main composition, set using X-ray fluorescence analysis, is as follows: CaSO₄ (99.7%), Al (0.022%), Fe (0.035%), Si (0.068%), Sr (0.157%), and P (0.01%).

Table 1. E-35 Iberyola main properties.

Fire Resistance	Thermal Conductivity	pH	Granulometry	Water Vapor Diffusion	Flexural Strength	Purity Index
Euro class AY	250–300 mW/m·K	>6	0–0.2 mm	$\mu = 6$	>3.5 N/mm ²	>92%

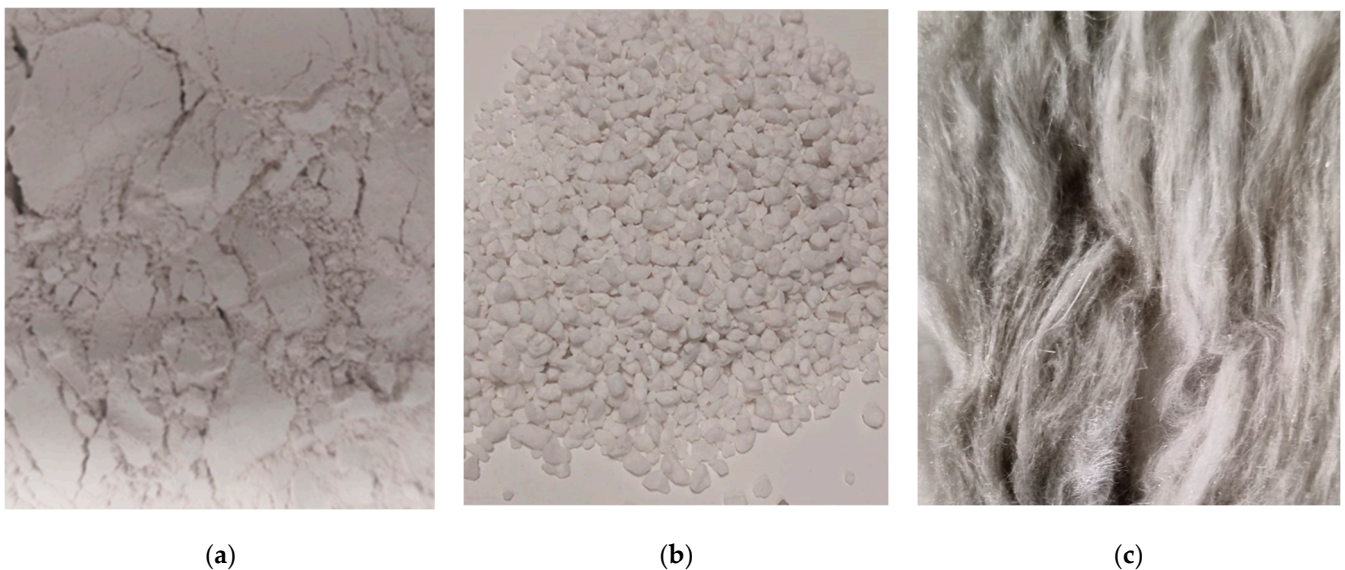



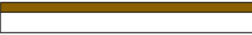

Figure 1. Materials used in this study. (a): E-35 Plaster; (b) Recycled Glass Wool; (c) Expanded Perlite.

- Water: Canal de Isabel II water was used in this study. The Canal de Isabel II is the public company responsible for the management of the integral water cycle in the Community of Madrid. The main properties of this water include an average hardness (25 mg CaCO₃/L); pH between 7 and 8.5; and chloride content between 1 and 1.5 mg/L. It also contains other compounds, such as nitrate (0.6 mg/L), nitrite (<0.05 mg/L), sulphate (5.3 mg/L), calcium (17.8 mg/L), Fe₂O₃ (0.01 mg/L), and copper (<0.005 mg/L) [37].
- Perlite (P): Supplied by Semillas Batlle S.A., (Barcelona, Spain). The expanded perlite is a glassy volcanic rock mainly composed of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, CaO, MgO,

Na₂O, and K₂O. Particle size is >Ø2 mm. This material has no reaction when mixed with plaster and has an impressive performance, both physical and mechanical [38].


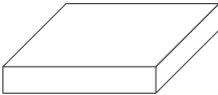
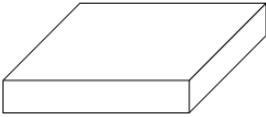
- Recycled glass wool (RGW): Provided by URSA, S.A. (Madrid, Spain) [39]. The glass wool is mainly composed of sand, soda ash, dolomite, limestone, ulexite, and anhydrite, and it is a widely used for insulation in buildings. This material comes from construction and demolition waste, thus this application extends its useful life. Its regular thickness is around 30–50 mm but for this study, the glass wool was manually divided into 5–10 mm thick layers.
- The samples are named as follows: E-00-A-LL, where E is for E-35 plaster used, 00 is for water/plaster ratio, A is for aggregate, depending on whether it contains perlite, and LL corresponds to the number of RGW layers and its position. This can be 1L for one layer, 2L for two layers, and 1LU for a sample with the layer on top. Table 2 shows dosages and amounts of material used along with their configurations.

Table 2. Samples dosages, composition, and configuration. Weight in grams.

Name	E-35 Plaster (g)	Water (g)	Perlite (g)	RGW Layer (N° of Layers)	Configuration
E-0.7	1000	700	-	-	(A)
E-0.7-P	850	595	50	-	
E-0.7-1LU	1000	700	-	1	(B)
E-0.7-P-1LU	850	595	50	1	
E-0.7-2L	1000	700	-	2	(C)
E-0.7-P-2L	850	595	50	2	

- To conduct this study, different-sized samples were established within the context of the tests performed. Samples were elaborated according to the EN 13279-2:2014 Standard [40]. The tests performed and samples used in each test are shown in Table 3.

Table 3. Samples size and tests performed.

Samples	Tests
 15 × 15 × 2 cm ³	To set thermal conductivity value following Guarded Hot plate method using a λ-Meter EP500e from Lambda-Meßtechnik GmbH Dresden (Dresden, Germany), according to EN 12664 and EN 1946-2 standards [41,42].
 24 × 24 × 2 cm ³	To set thermal conductivity value using the heat flux meter (HFМ) method according to EN 12664 and EN 1946-3 [42,43] standard.
 30 × 40 × 2 cm ³	Impact, surface hardness, and flexural strength tests to determine mechanical and complementary physical properties requires by EN 12859:2012 and EN 14246:2007 [44,45] standards. For this, Proeti, S.A., (Madrid, Spain) bending test equipment was used.

2.2. Manufacturing Process

This study presents a new manufacturing system developed to reduce the elaboration time and simplify the process. This structure is placed over the sample mould and moved along the sample on rails with a pouring hopper to homogeneously distribute the plaster. Through a four-step process, the sample is produced. Figure 2 shows, in a longitudinal cross-section, the distinct parts of the machine.

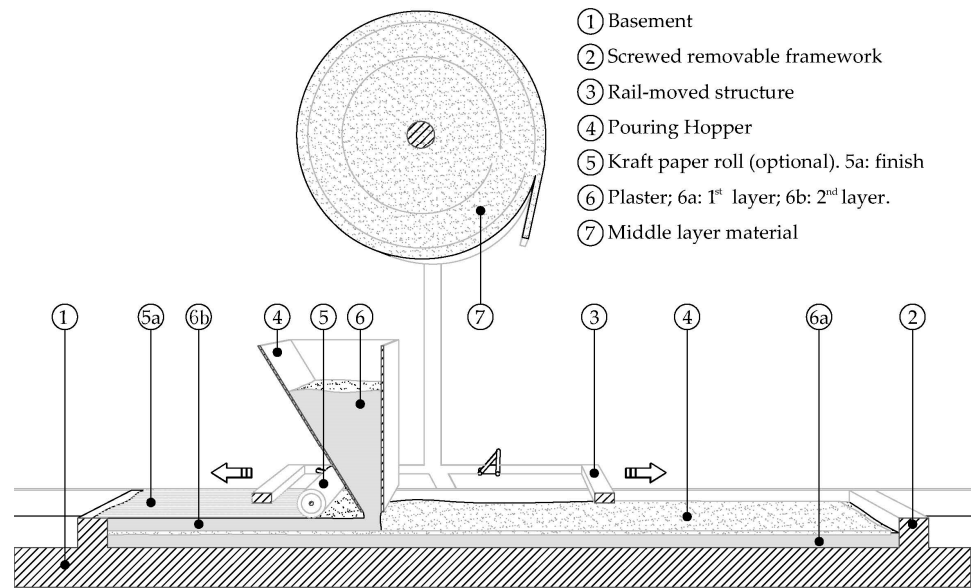


Figure 2. Cross-section of the manufacturing system developed.

The four-step process is shown in Figure 3 and consists of the following:

- Step 1: The structure is placed such that the pouring spout is at the beginning of the mould. Plaster is then poured into the hopper and as it falls, the structure moves along the mould until it reaches the end, creating the first layer.
- Step 2: The middle layer material is placed on the roller.
- Step 3: The structure moves back until it reaches the beginning while the middle layer is being laid. The weight of the roller presses down on the middle layer material, thus ensuring a homogeneous placement.
- Step 4: Plaster is again poured into the hopper and as it falls, the structure moves along the mould until it reaches the end, creating the second layer. Optionally, a second roller, provided with kraft paper, can be placed and used for a more attractive finish and extra bending strength.

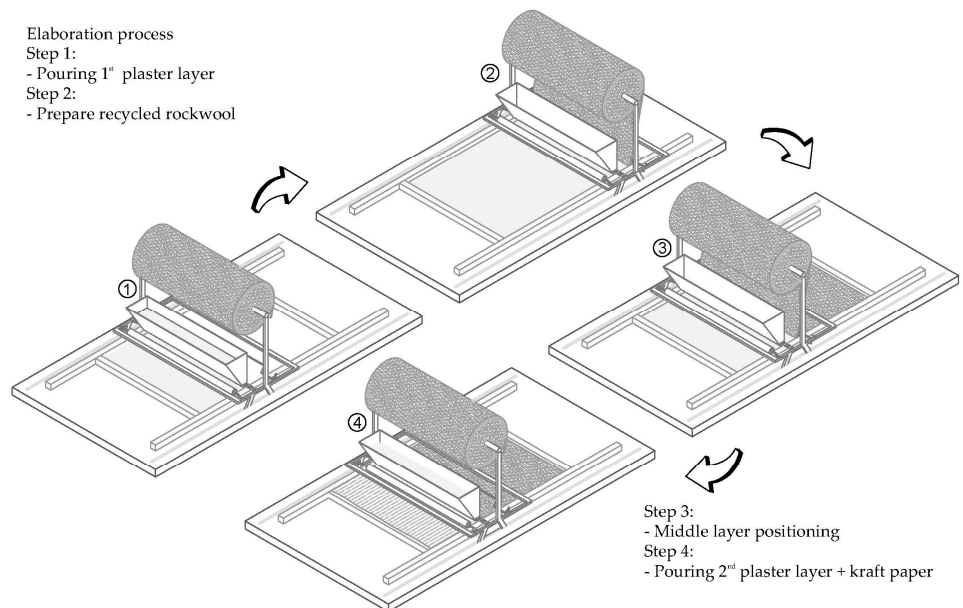


Figure 3. Four-step elaboration process.

After Step 4, the structure is placed outside the mould. Once the sample is set, the framework is removed and sample is taken out of the mould to let it dry.

2.3. Sustainability and Opportunities

Raw material cost analysis was conducted. First, the manufacturing process costs, including the materials and resources needed, were determined using unitary prices. For this, the amount of raw materials required was set, and then the costs were obtained.

On the other hand, aimed at maintaining the sustainability of this new material, an environmental analysis was conducted to quantify CO₂ potential savings following the Life Cycle Assessment (LCA) standard ISO 14040 [46]. This standard states four analysis phases as follows: goal and scope definition, inventory analysis, Life Cycle Impact assessment, and interpretation. As different amounts of perlite and RGW do not affect the environmental results, the LCA considers any binders and additives. For this study, a cradle-to-gate assessment was the most relevant, as it covers the phases from extraction to manufacturing.

This procedure has been previously validated in the literature [47]. The environmental product declaration (EPD) data of RGW, E-35 plaster, and expanded perlite were used to calculate the environmental benefits derived from this new composite production. Furthermore, the Intergovernmental Panel on Climate Change 2023 report (IPCC) was used to calculate GWP 100 potential savings [48].

Once the EPD for each component was obtained, precise measurements were required to set the amount of material used during the elaboration process of this new material. To calculate the CO₂ emissions associated with each element, information within the different EPDs and components quantities were taken. With this, the CO₂ emissions associated to each component produced were set.

3. Results

3.1. Physical–Mechanical Properties

As this material is going to be used for ceiling elaboration, the EN 14246 [45] standard mechanical requirements were assessed. Apparent density, shore C hardness, and thermal conductivity results are shown below.

3.1.1. Physical Characterisation

After sample elaboration, the main physical properties were collected and are shown in Table 4.

Table 4. Physical values obtained from physical characterisation tests.

Sample	Surface Hardness (Shore C)	ρ (kg/m ³)	$\Delta \rho$	λ (mW/m·K)	$\Delta \lambda$
E-0.7	85.0 ± 4	1100.0	-	300.00	-
E-0.7-P	89.0 ± 3	1000.0	−9%	225.00	−25%
E-0.7-1LU	85.0 ± 3	798.6	−27%	216.67	−28%
E-0.7-2L	88.0 ± 3	736.1	−33%	203.85	−32%
E-0.7-P-1LU	89.0 ± 4	580.6	−47%	183.24	−39%
E-0.7-P-2L	87.0 ± 2	555.6	−49%	146.83	−51%

Surface hardness was measured using a Baxlo Shore C durometer (Barcelona, Spain). As RGW was placed at the top of the 1LU samples, surface hardness measurements are similar to those without the RGW layers. The main difference occurs when RGW is placed in the middle of the sample. E-0.7-P obtained the highest value (89 ± 3 Shore C) and E-0.7 attained the lowest value (85 ± 4 Shore C). This property remained almost the same for all the samples depending on perlite addition.

Apparent density and thermal conductivity are the most important physical properties as they establish the suitability and viability of developing and commercialising this material. There exists a correlation between both values. The bigger the apparent density, the higher the thermal conductivity. In this study, the apparent density was reduced by

up to 49% in E-0.7-P-2L (555.6 kg/m^3) compared to E-0.7. The addition of RGW led to a 27–33% reduction in apparent density. In terms of apparent density, there is no significant difference observed whether one or two RGW layers were added.

Regarding thermal conductivity, there is a progressive decrease as the RGW was being added. This difference increased when both perlite and RGW were added. E-0.7's thermal conductivity value ($300 \text{ mW/m}\cdot\text{K}$) was the highest, while E-0.7-P-2L ($146.83 \text{ mW/m}\cdot\text{K}$) was the lowest. This leads to a potential thermal conductivity reduction of up to 51%. Perlite addition reduced this value by up to 25%, while RGW reached a 32% reduction. With this, all the samples assessed passed the EN 14246 standard [45] requirements related to thermal conductivity. These results will be discussed and compared with the literature results in the Discussion section.

3.1.2. Flexural Strength

Figure 4 shows three samples of each dosage elaborated and assessed following the EN 14246 standard [45] requirements, while the test results are shown in Table 4.



Figure 4. Samples elaborated for flexural strength test. (a) Dried samples; (b) test performed.

First, all the assessed samples passed the minimum load required in EN 14246 [45], set at 0.18 kN. The flexural behaviour is linked to the apparent density and thermal conductivity. The RGW addition had a slight impact on flexural strength, increasing the performance of E-0.7-2L up to 12%. Samples containing two RGW layers performed better than those with one. When the RGW layer was placed at the top of the sample, a lower interaction between the plaster and RGW was achieved, leading to a similar performance to those samples without RGW.

On the other hand, samples containing two RGW layers with plaster placed in the middle produced a greater interaction and a better performance. As both sides of the RGW layers are connected to plaster, the strength significantly increased.

The perlite addition resulted in a flexural strength increase of up to 77%. When added, perlite homogeneously mixed with the plaster, leading to a strong structural connection. As shown in Table 5, when both the elements, perlite and RGW, are added, the flexural strength is slightly lower than E-0.7-P. As the thickness remains the same (2 cm), a higher RGW volume results in the sample using less plaster than in the samples without RGW.

Despite this slight decrease, the values achieved are over the standard required values. The E-0.7-P-2L value obtained is 0.51 kN, increasing the flexural strength value up to 75% when compared to E-0.7. Furthermore, E-0.7-P-1LU obtained a value of 0.43 kN, which is 49% higher in terms of flexural strength than E-0.7. None of the samples surpassed E-0.7-P, but samples containing both perlite and RGW achieved similar values. Again, these results confirm this material's suitability for precast elaboration.

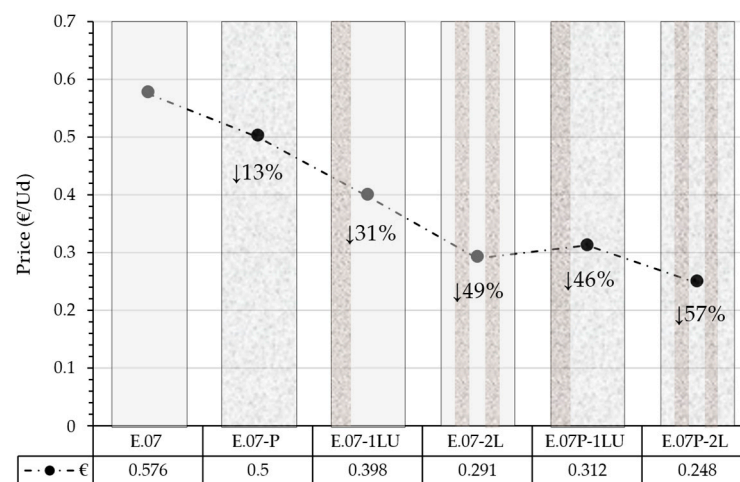
Table 5. Sample sizes and tests performed.

Sample	Load (kN)	Average (kN)	Δ Load	EN 14246 Min. Value [45]	Passed Test
E-0.7	0.26	0.29	-	0.18 kN	YES
	0.29				YES
	0.31				YES
E-0.7-P	0.50	0.51	\uparrow 77%	0.18 kN	YES
	0.52				YES
	0.50				YES
E-0.7-1LU	0.33	0.31	\uparrow 2%	0.18 kN	YES
	0.30				YES
	0.31				YES
E-0.7-2L	0.30	0.32	\uparrow 12%	0.18 kN	YES
	0.32				YES
	0.34				YES
E-0.7-P-1LU	0.40	0.43	\uparrow 49%	0.18 kN	YES
	0.43				YES
	0.45				YES
E-0.7-P-2L	0.52	0.50	\uparrow 75%	0.18 kN	YES
	0.49				YES
	0.50				YES

3.2. Cost Analysis

A cost analysis derived from product manufacturing was conducted and the profitability was studied. After that, an analysis of the CO₂ emissions derived from the production of the material was conducted, establishing the environmental impact during the production process.

Regarding how much money these new configurations can save compared to commercial precast materials, the base prices of each material were established and are presented in Figure 5. This study has considered the commercial prices in the calculation of production costs, since it is not possible to access the prices that different producers have with various companies. Even using commercial prices, the potential savings are significant and may therefore be increased when considering supplier prices.

**Figure 5.** Elaboration prices (€/plate) for each sample. Own elaboration.

Considering the amount of material needed for the sample elaboration, a potential 49% could be saved just by adding RGW to this material. Moreover, the perlite addition would lead to a potential 57% in savings. On the other hand, in addition to the costs derived from

the material, we must estimate both the fixed and variable indirect costs derived from the manufacturing, which may be defined as follows:

- Variable indirect costs: These may change according to the demand, and they include the payment of electricity, bills, and salaries.
- Fixed indirect costs: These are costs such as utilities, which may include security services, maintenance, cleaning, and insurance.

All these costs may vary according to the facilities and means of the company manufacturing the product, considering that the resources may change depending on the company.

3.3. Potential CO₂ Emissions Savings through LCA

An analysis of the carbon footprint has been conducted using various materials' EPDs. This document contains information about every single process the different elements go through during their elaboration, i.e., energy consumption, chemical processes involved, and transport.

A total of 1 m³ of final material was used per unit and the results are shown in Table 6. As expected, the perlite replacement in the plaster-based material led to an 18% reduction in embodied carbon emissions. Despite perlite also producing emissions during its manufacturing process, these emissions are lower than those of plaster. The RGW addition led to another decrease of up to 11–13% in the samples without perlite, depending on the layers placed, although the results were similar.

Table 6. Embodied carbon analysis and potential savings.

	Plaster (kg)	Water (kg)	Perlite (kg)	RGW (kg)	CO ₂ (kg/m ³)	Δ of CO ₂
E-0.7	647.06	452.94	-	-	45.29	-
E-07-P	530.46	371.32	10.83	-	37.13	−18%
E-0.7-1LU	527.93	369.55	-	2.53	40.23	−11%
E-0.7-2L	496.16	347.31	-	6.53	39.56	−13%
E-0.7-P-1LU	521.62	365.13	10.65	2.55	32.67	−28%
E-0.7-P-2L	486.23	340.36	9.92	6.53	30.49	−33%

Emissions of the samples with both perlite and RGW additions were reduced up to 28–33%. Again, most of the reduction was caused by perlite, while the RGW layers led to a slight 5% decrease in CO₂ emissions when an extra layer was added. E-0.7-P-2L achieved the lowest emissions, placing this sample as the most sustainable material in this study. Plaster had the greatest environmental impact in all the samples, which means that a reduction in its use will always lead to a better environmental performance.

There are other variables that significantly affect this analysis. A reduction in the samples' apparent density has a significant impact on the stages of construction, including transportation and installation. During the useful life stage, thermal conductivity contributes to reduced energy consumption, which is still mainly achieved with materials from non-renewable sources. This further produces a significant reduction in embodied carbon emissions.

4. Discussion

Following evaluation, the results can be compared and discussed with other studies found in the literature. To contextualise these results, thermal conductivity, apparent density, and flexural strength are compared. Thermal conductivity and apparent density are strongly linked, as can be seen in Figure 6.

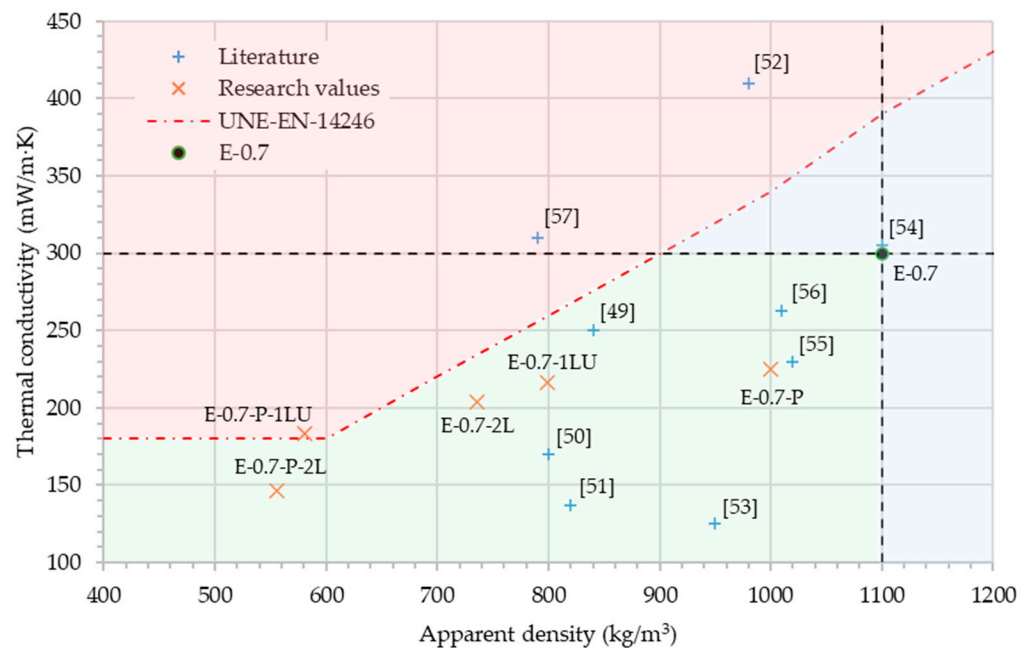


Figure 6. Comparison between the apparent density and thermal conductivity resulting values. [49]: Sheep wool; [50]: Groundnut and coir; [51]: Typha angustifolia; [52]: Microencapsulated PCM; [53]: Cork; [54]: Chicken feathers; [55]: Plastic cables; [56]: Mineral wool; [57]: Cellular glass. Own elaboration.

This chart demarcates three key regions based on potential material suitability. The red zone encompasses values exceeding the established maximum as dictated by EN 14246 [45]. The red dashed line represents the limiting values. The black dashed line implies the E-0.7 reference point. The blue area encompasses materials with values that are within the standard range but exceed the E-0.7 reference, indicating a relative decline in one or both properties. Finally, the green zone highlights materials that could potentially enhance E-0.7 performance.

Within this framework, the research data points were plotted and compared with the existing literature. As illustrated in Figure 6, the E-0.7-P-1LU material does not satisfy the minimum apparent density-to-thermal conductivity ratio required for ceiling applications. While this does not necessarily negate its potential as a building material, its suitability for such applications warrants reevaluation. Materials incorporating cellular glass [57] and microencapsulated phase change material (PCM) [52] exhibit a similar trend, suggesting a better fit for partition walls. Materials containing mineral wool [55] and plastic cable waste [56] exhibit a performance comparable to that of E-0.7, with slightly higher thermal conductivity. Natural additives like Typha angustifolia [51] and cork [53] result in a significant decrease in thermal conductivity; however, their apparent density surpasses the values obtained in this study. Chicken feathers [54] display a performance equivalent to that of E-0.7, offering no improvement in either property. Finally, the remaining natural additives, sheep wool [49] and groundnut and coir [50], exhibit similar apparent densities to those of the RGW and perlite composites evaluated here, but with inferior thermal conductivity values.

Figure 7 shows the mechanical performance over apparent density values for both the current research samples and those in the literature.

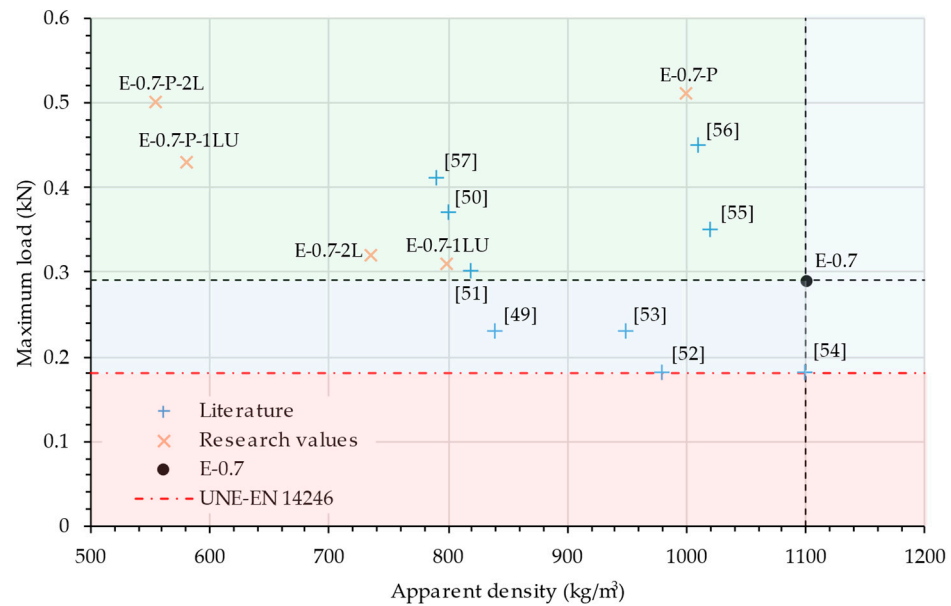


Figure 7. The apparent density over maximum load value results compared. [49]: Sheep wool; [50]: groundnut and coir; [51]: Typha Angustifolia; [52]: Microencapsulated PCM; [53]: Cork; [54]: Chicken feathers; [55]: Plastic cables; [56]: Mineral wool; [57]: Cellular glass. Own elaboration.

The areas are again highlighted following the Figure 6 criteria. All the materials compared are over the minimum rate requirements of the standard. The closer and higher to the Y axis the point is, the better the material's performance. Again, the chicken feathers studied by Ouakarrouch et al. [54] performed worse than the rest of the materials analysed. Samples with perlite and RGW performed the best once again, with E-0.7-P-2L being the best sample of all those studied. The perlite addition significantly improves flexural strength, while the mineral wool studied by Villoria et al. [56] also attained better flexural strength performance. When compared with E-0.7-1LU and E-0.7-2L, sheep wool and cellular glass performed similar to E-0.7-P-1LU, although their apparent density was higher.

5. Conclusions

This study investigated the development and characterisation of a novel plaster-based layered composite incorporating recycled glass wool (RGW) and perlite. A series of mechanical and physical tests were conducted to evaluate the material's performance. The obtained results were then analysed and compared with the relevant literature.

- Perlite addition significantly enhanced the investigated physical and mechanical properties. This demonstrates its effectiveness as a lightweight filler for plaster-based materials without compromising performance. Furthermore, perlite's ease of acquisition and minimal pre-use treatment make it an ideal choice for this application.
- Recycled glass wool (RGW) improved the composite's bulk density, flexural strength, and thermal conductivity. Notably, the RGW exhibited no degradation after its initial service life, demonstrating its suitability and effectiveness for this application.
- The newly designed manufacturing system facilitated reduced production times, enhanced material homogeneity, and greater versatility in producing samples of varying sizes. Large-scale implementation of this system would translate to ease of production, potentially leading to significant business opportunities when combined with raw material cost savings.
- Four composite formulations were evaluated. As all the formulations, except E-0.7-P-1LU, satisfied the EN 14246 requirements for ceilings, all the formulations can be employed in the construction of partition walls when reinforced with cardboard. The E-0.7-P-2L sample exhibited the most significant improvement across all the investigated properties, while E-0.7-1LU displayed the least improvement.

- Regarding flexural performance, all the composite samples demonstrated improved flexural resistance exceeding the minimum regulatory requirements. RGW played a critical role in significantly enhancing flexural strength across all samples, with perlite contributing an additional 10% increase.
- The conducted cost analysis revealed a potential reduction in the final material cost compared to conventional ceilings. Even a minor reduction in plaster usage significantly impacted the purchase price per sample. The E-0.7-P-2L formulation achieved the most substantial cost savings, reaching up to 49% on the final product price.
- This study demonstrated a potential reduction in embodied carbon emissions of up to 33% in the E-0.7-P-2L sample. Plaster has a high embodied carbon footprint, limiting the sustainability of this versatile material. The analysis results confirm a significant improvement in embodied carbon values, promoting a more sustainable construction approach aligned with sustainable development goals.

This study was conducted regarding the application of the aforementioned material in ceiling elaboration. Within this context, some properties could be assessed to fully characterise this material. Complementary to that, X-ray diffractometry as well as SEM could also be performed for a better understanding of this material's behaviour.

Author Contributions: Conceptualisation, M.Á. and D.F.; methodology, M.Á. and P.G.-M.; software, D.F.; validation, M.Á. and P.G.-M.; formal analysis, M.Á. and D.F.; investigation, M.Á. and P.G.-M.; resources, D.F. and C.M.; data curation, M.Á. and D.F.; writing—original draft preparation, M.Á. and P.G.-M.; writing—review and editing, M.Á. and D.F.; visualisation, D.F. and C.M.; supervision, D.F. and C.M.; project administration, C.M.; funding acquisition, C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank Laboratorio de Materiales y Geotecnia from Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, as well as URSA, S.A for their collaboration. This work would have not been possible without them.

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

References

1. Hassan, A.M.; Megahed, N.A. COVID-19 and urban spaces: A new integrated CFD approach for public health opportunities. *Build Environ.* **2021**, *204*, 108131. [[CrossRef](#)]
2. Morsy, M.; Fahmy, M.; Elshakour, H.A.; Belal, A.M. Effect of Thermal Insulation on Building Thermal Comfort and Energy Consumption in Egypt. *J. Adv. Res. Appl. Mech.* **2018**, *43*, 8–19.
3. United Nations Environment Programme. 2022 Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Building and Construction Sector. 2022. Available online: www.globalabc.org (accessed on 21 April 2022).
4. United Nations. Goal 12. Responsible Consumption and Production. Sustainable Development Goals. Available online: <https://www.un.org/sustainabledevelopment/es/sustainable-consumption-production/> (accessed on 21 April 2022).
5. Santos, P.; Ribeiro, T. Thermal performance improvement of double-pane lightweight steel framed walls using thermal break strips and reflective foils. *Energies* **2021**, *14*, 6927. [[CrossRef](#)]
6. Bucarelli, N.; El-Gohary, N. Sensor deployment configurations for building energy consumption prediction. *Energy Build.* **2024**, *308*, 113888. [[CrossRef](#)]
7. Fikru, M.G.; Gautier, L. The impact of weather variation on energy consumption in residential houses. *Appl. Energy* **2015**, *144*, 19–30. [[CrossRef](#)]
8. Liu, P.; Wu, W.; Du, B.; Tian, G.H.; Gong, Y.F. Study on the heat and moisture transfer characteristics of aerogel-enhanced foam concrete precast wall panels and the influence of building energy consumption. *Energy Build.* **2022**, *256*, 111707. [[CrossRef](#)]
9. del Río-Merino, M.; Vidales-Barriguete, A.; Piña-Ramírez, C.; Vitiello, V.; Cruz-Astorqui, J.S.; Castelluccio, R. A review of the research about gypsum mortars with waste aggregates. *J. Build. Eng.* **2022**, *45*, 103338. [[CrossRef](#)]
10. Capasso, I.; Pappalardo, L.; Romano, R.A.; Iucolano, F. Foamed gypsum for multipurpose applications in building. *Constr. Build Mater.* **2021**, *307*, 124948. [[CrossRef](#)]
11. Zaragoza-Benzal, A.; Ferrández, D.; Atanes-Sánchez, E.; Saíz, P. Dissolved recycled expanded polystyrene as partial replacement in plaster composites. *J. Build. Eng.* **2023**, *65*, 105697. [[CrossRef](#)]

12. Umponpanarat, P.; Wansom, S. Thermal conductivity and strength of foamed gypsum formulated using aluminum sulfate and sodium bicarbonate as gas-producing additives. *Mater. Struct. /Mater. Et Constr.* **2016**, *49*, 1115–1126. [CrossRef]
13. Astorqui, J.S.C.; Del Río Merino, M.; Sáez, P.V.; Amores, C.P. Analysis of the viability of prefabricated elements for partitions manufactured with plaster and eps from waste recycling. *Dyna* **2019**, *94*, 415–420. [CrossRef]
14. Bicer, A.; Kar, F. Thermal and mechanical properties of gypsum plaster mixed with expanded polystyrene and tragacanth. *Therm. Sci. Eng. Prog.* **2017**, *1*, 59–65. [CrossRef]
15. de Oliveira, K.A.; Oliveira, C.A.B.; Molina, J.C. Lightweight recycled gypsum with residues of expanded polystyrene and cellulose fiber to improve thermal properties of gypsum. *Mater. Constr.* **2021**, *71*, e242. [CrossRef]
16. Bouzit, S.; Merli, F.; Sonebi, M.; Buratti, C.; Taha, M. Gypsum-plasters mixed with polystyrene balls for building insulation: Experimental characterization and energy performance. *Constr. Build Mater.* **2021**, *283*, 122625. [CrossRef]
17. Abdellah, M.Y.; Sadek, M.G.; Alharthi, H.; Abdel-Jaber, G.T.; Backar, A.H. Characteristic properties of date-palm fibre/sheep wool reinforced polyester composites. *J. Bioresour. Bioprod.* **2023**, *8*, 430–443. [CrossRef]
18. Kuqo, A.; Boci, I.; Vito, S.; Vishkulli, S. Mechanical properties of lightweight concrete composed with Posidonia Oceanica fibres. *Zast. Mater.* **2018**, *59*, 519–523. [CrossRef]
19. Romero-Gómez, M.I.; Silva, R.V.; Costa-Pereira, M.F.; Flores-Colen, I. Thermal and mechanical performance of gypsum composites with waste cellulose acetate fibres. *Constr. Build Mater.* **2022**, *356*, 129308. [CrossRef]
20. Iucolano, F.; Boccarusso, L.; Langella, A. Hemp as eco-friendly substitute of glass fibres for gypsum reinforcement: Impact and flexural behaviour. *Compos. B Eng.* **2019**, *175*, 107073. [CrossRef]
21. Evans, T.J.; Majumdar, A.J.; Ryder, J.F. A semi-dry method for the production of lightweight glass-fibre-reinforced gypsum. *Int. J. Cem. Compos. Lightweight Concr.* **1981**, *3*, 41–44. [CrossRef]
22. Dharmasastha, K.; Samuel, D.G.L.; Nagendra, S.M.S.; Maiya, M.P. Experimental investigation of thermally activated glass fibre reinforced gypsum roof. *Energy Build.* **2020**, *228*, 110424. [CrossRef]
23. Wang, S.; Pancheti, J.; Xi, Y.; Mahendran, M. Lightweight composite gypsum boards with clay mineral and glass fibre for enhanced fire-resistance. *Compos. B Eng.* **2023**, *266*, 111044. [CrossRef]
24. Suárez, F.; Felipe-Sesé, L.; Díaz, F.A.; Gálvez, J.C.; Alberti, M.G. On the fracture behaviour of fibre-reinforced gypsum using micro and macro polymer fibres. *Constr. Build Mater.* **2020**, *244*, 118347. [CrossRef]
25. Di Bella, G.; Fiore, V.; Galtieri, G.; Borsellino, C.; Valenza, A. Effects of natural fibres reinforcement in lime plasters (kenaf and sisal vs. Polypropylene). *Constr. Build Mater.* **2014**, *58*, 159–165. [CrossRef]
26. Westgate, P.; Paine, K.; Ball, R.J. Physical and mechanical properties of plasters incorporating aerogel granules and polypropylene monofilament fibres. *Constr. Build Mater.* **2018**, *158*, 472–480. [CrossRef]
27. Gencil, O.; Del Coz Diaz, J.J.; Sutcu, M.; Koksall, F.; Rabanal, F.P.Á.; Martínez-Barrera, G. A novel lightweight gypsum composite with diatomite and polypropylene fibers. *Constr. Build Mater.* **2016**, *113*, 732–740. [CrossRef]
28. Romero-Gómez, M.I.; Pedreño-Rojas, M.A.; Pérez-Gálvez, F. Rubio-de-Hita, Characterization of gypsum composites with polypropylene fibers from non-degradable wet wipes. *J. Build. Eng.* **2021**, *34*, 101874. [CrossRef]
29. Department, E. Energy Efficiency in Buildings. Brussels. 2020. Available online: https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/documents/in_focus_energy_efficiency_in_buildings_en.pdf (accessed on 5 May 2022).
30. Agency, I.E. Technology Roadmap Energy Efficient Building Envelopes. 2013. Available online: www.iea.org (accessed on 21 April 2022).
31. Li, Q.; Zhang, L.; Zhang, L.; Wu, X. Optimizing energy efficiency and thermal comfort in building green retrofit. *Energy* **2021**, *237*, 121509. [CrossRef]
32. Pedreño-Rojas, M.A.; Rodríguez-Liñán, C.; Flores-Colen, I.; de Brito, J. Use of Polycarbonate Waste as Aggregate in Recycled Gypsum Plasters. *Materials* **2020**, *13*, 3042. [CrossRef] [PubMed]
33. Pedreño-Rojas, M.A.; Morales-Conde, M.J.; Pérez-Gálvez, F.; Rodríguez-Liñán, C. Eco-efficient acoustic and thermal conditioning using false ceiling plates made from plaster and wood waste. *J. Clean. Prod.* **2017**, *166*, 690–705. [CrossRef]
34. Álvarez, M.; Santos, P.; Lopes, P.; Abrantes, D.; Ferrández, D. Performance Characterisation of a New Plaster Composite Lightened with End-of-Life Tyres' Recycled Materials for False Ceiling Plates. *Materials* **2022**, *15*, 5660. [CrossRef]
35. United Nations. Goal 11. Sustainable Cities and Communities. Sustainable Development Goals. Available online: <https://www.un.org/sustainabledevelopment/es/cities/> (accessed on 21 April 2022).
36. UNE-EN 13279-1; Yesos de Construcción y Conglomerantes a Base de Yeso para la Construcción. Parte 1: Definiciones y Especificaciones. UNE: Madrid, Spain, 2006.
37. de Isabel, C., II. Características Medias del Agua de Consumo en el Sistema de Distribución. 2021. Available online: <https://www.canaldeisabelsegunda.es/calidad-del-agua> (accessed on 21 April 2022).
38. Kapeluszna, E.; Kotwica, Ł.; Pichór, W.; Nocuń-Wczelik, W. Cement-based composites with waste expanded perlite—Structure, mechanical properties and durability in chloride and sulphate environments. *Sustain. Mater. Technol.* **2020**, *24*, e00160. [CrossRef]
39. URSA Insulation, S.A. *Especificaciones Técnicas URSA TERRA T18R/T18P*; URSA Insulation, S.A.: Madrid, Spain, 2022.
40. UNE-EN 13279-2:2014; Construction Plasters and Gypsum Binders for Construction. Part 2: Test Methods. UNE: Madrid, Spain, 2014.

41. UNE-EN 1946-2; Thermal Performance of Products and Components for Buildings. Particular Criteria for the Evaluation of Laboratories Measuring Thermal Transmission Properties. Part 2: Measurements by the Protected Hot Plate Method. UNE: Madrid, Spain, 1999.
42. UNE-EN 12664; Construction Materials. Determination of Thermal Resistance by the Saved Hot Plate Method and the Heat Flow Meter Method. Dry and Wet Products with Low and Medium Thermal Resistance. UNE: Madrid, Spain, 2002.
43. UNE-EN 1946-3; Prestaciones Térmicas de los Productos y Componentes Para Edificios. Criterios Particulares para la Evaluación de los Laboratorios que Miden las Propiedades de Transmisión Térmica. Parte 3: Mediciones por el Método del Medidor de Flujo Térmico. UNE: Madrid, Spain, 1999.
44. UNE-EN 12859; Paneles de Yeso. Definiciones, Especificaciones y Métodos de Ensayo. UNE: Madrid, Spain, 2012.
45. UNE-EN 14246:2007; Placas de Escayola para Techos Suspendidos. Definiciones, Especificaciones y Métodos de Ensayo. UNE: Madrid, Spain, 2008.
46. UNE-EN ISO 14040:2006/A1; Environmental Management—Life Cycle Assessment—Principles and Framework—Amendment 1. UNE: Madrid, Spain, 2021.
47. Fenoglio, E.; Fantucci, S.; Serra, V.; Carbonaro, C.; Pollo, R. Hygrothermal and environmental performance of a perlite-based insulating plaster for the energy retrofit of buildings. *Energy Build.* **2018**, *179*, 26–38. [[CrossRef](#)]
48. IPCC. *Climate Change 2023 Synthesis Report*; IPCC: Geneva, Switzerland, 2023. [[CrossRef](#)]
49. Guna, V.; Yadav, C.; Maithri, B.; Ilangovan, M.; Touchaleaume, F.; Saulnier, B.; Grohens, Y.; Reddy, N. Wool and coir fiber reinforced gypsum ceiling tiles with enhanced stability and acoustic and thermal resistance. *J. Build. Eng.* **2021**, *41*, 102433. [[CrossRef](#)]
50. Sheng, D.D.C.V.; Ramegowda, N.S.; Guna, V.; Reddy, N. Groundnut shell and coir reinforced hybrid bio composites as alternative to gypsum ceiling tiles. *J. Build. Eng.* **2022**, *57*, 104892. [[CrossRef](#)]
51. Muntongkaw, S.; Pianklang, S.; Tangboriboon, N. Modifications to improve properties of gypsum ceiling composites as multi-functional construction by embedding *Typha angustifolia* fiber and natural rubber latex compound. *Case Stud. Constr. Mater.* **2021**, *15*, e00658. [[CrossRef](#)]
52. Gencel, O.; Hekimoglu, G.; Sari, A.; Ustaoglu, A.; Subasi, S.; Marasli, M.; Erdogmus, E.; Memon, S.A. Glass fiber reinforced gypsum composites with microencapsulated PCM as novel building thermal energy storage material. *Constr. Build Mater.* **2022**, *340*, 127788. [[CrossRef](#)]
53. Cherki, A.B.; Remy, B.; Khabbazi, A.; Jannot, Y.; Baillis, D. Experimental thermal properties characterization of insulating cork–gypsum composite. *Constr. Build Mater.* **2014**, *54*, 202–209. [[CrossRef](#)]
54. Ouakarrouch, M.; El Azhary, K.; Laaroussi, N.; Garoum, M.; Kifani-Sahban, F. Thermal performances and environmental analysis of a new composite building material based on gypsum plaster and chicken feathers waste. *Therm. Sci. Eng. Prog.* **2020**, *19*, 100642. [[CrossRef](#)]
55. Vidales-Barriguete, A.; Santa-Cruz-Astorqui, J.; Piña-Ramírez, C.; Kosior-Kazberuk, M.; Kalinowska-Wichrowska, K.; Atanes-Sánchez, E. Study of the mechanical and physical behavior of gypsum boards with plastic cable waste aggregates and their application to construction panels. *Materials* **2021**, *14*, 2255. [[CrossRef](#)]
56. Piñeiro, S.R.; Del Río Merino, M.; García, C.P. New Plaster Composite with Mineral Wool Fibres from CDW Recycling. *Adv. Mater. Sci. Eng.* **2015**, *2015*, 854192. [[CrossRef](#)]
57. Sáez, P.V.; Santa, J.; Astorqui, C.; Del, M.; Merino, R. Conglomerados Sostenibles Realizados Con Residuos De Construcción Generados En Obras De Rehabilitación Energética. In Proceedings of the 7th Encuentro Latinoamericano de Economía y Gestión de la Construcción—VII Elagec, Bogotá, Colombia, 15–18 November 2016; pp. 16–17.

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.