

Article

Development of Sustainable Gypsum Composites Incorporating Silica Fume Waste and Fiber Reinforcement for Construction Applications

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Abstract

This study evaluates the feasibility of developing sustainable gypsum composites incorporating silica fume waste and fiber reinforcement for construction applications. The experimental program was divided into two phases. First, silica fume was incorporated into the gypsum matrix at addition levels ranging from 10% to 35% by weight of gypsum using water-to-gypsum ratios of 0.7 and 0.8. Dry bulk density, Shore C hardness, flexural strength, and compressive strength were determined according to standards. Subsequently, the most promising formulations were reinforced with polypropylene and glass fibers at dosages of 2% and 4% by weight of gypsum. Selected specimens were also analyzed by scanning electron microscopy (SEM). The results showed that silica fume can be successfully incorporated at levels of up to 35% while complying with the requirements established by UNE-EN 13279. Silica fume addition increased bulk density by up to 9.64% and improved surface hardness. Fiber reinforcement further enhanced mechanical performance, with the best formulation reaching compressive strength values close to 14 MPa, representing an increase of 27.14% compared with the corresponding silica-fume matrix. SEM observations confirmed matrix densification and satisfactory fiber–matrix adhesion. These findings demonstrate that the combined use of silica fume waste and fiber reinforcement is a viable strategy for producing gypsum composites with improved performance while promoting industrial waste valorization.

Keywords: gypsum; silica fume; polypropylene fiber; glass fiber; mechanical properties; sustainability; construction materials



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1. Introduction

The construction sector is one of the largest consumers of natural resources worldwide and is responsible for significant environmental impacts throughout the entire life cycle of buildings. According to the European Commission, the construction sector accounts for approximately 50% of all extracted raw materials, generates around 36% of the total waste produced in the European Union, and is responsible for nearly 40% of final energy consumption. Furthermore, buildings and construction activities contribute to approximately 35% of energy-related greenhouse gas emissions, highlighting the urgent need to develop more sustainable production and construction practices [1–3].

In response to these challenges, the principles of the circular economy have gained increasing relevance in recent years. European policies and strategies promote waste prevention, resource efficiency, and the incorporation of secondary raw materials into new products to reduce the consumption of virgin resources while minimizing environmental impacts [4–6]. Within this framework, the valorization of industrial by-products and waste materials has emerged as an effective strategy for developing more sustainable construction materials, contributing simultaneously to waste reduction, resource conservation, and the transition toward a low-carbon construction sector [7].

Among the various industrial residues currently under investigation, ashes and silica-rich by-products have attracted considerable attention due to their potential to improve the performance of cementitious and gypsum-based materials while simultaneously reducing waste disposal requirements. Previous studies have demonstrated the feasibility of incorporating different industrial ashes into construction materials, obtaining composites with satisfactory physical and mechanical performance [7–13].

In recent years, increasing amounts of synthetic gypsum generated from flue gas desulfurization processes, together with gypsum waste produced during construction and demolition activities, have created significant environmental challenges. While natural gypsum is extracted from quarries, the continuous accumulation of gypsum waste has increased the need for recycling and valorization strategies. Consequently, gypsum has become a key material within the circular economy framework, encouraging the development of sustainable composites that reduce landfill disposal and the consumption of virgin raw materials.

Gypsum-based materials are particularly attractive for the development of sustainable composites due to their widespread use in building construction, low toxicity, good fire resistance, and favorable indoor environmental performance [14,15]. Consequently, numerous researchers have investigated the incorporation of industrial by-products into gypsum matrices to improve their properties and enhance their environmental profile.

One of the most promising residues is silica fume (SF), also referred to as microsilica, an ultrafine by-product generated during the production of silicon metal and ferrosilicon alloys in electric arc furnaces. This material consists primarily of amorphous silicon dioxide (SiO_2) particles with a very high specific surface area and particle fineness [16]. Due to its physical characteristics, silica fume has been extensively used in cement-based materials, where it contributes to matrix densification and improvements in mechanical performance. Its incorporation into construction materials also represents an environmentally beneficial alternative to landfill disposal.

Table 1 shows the key findings of each research work conducted to incorporate different ash waste in cement or gypsum composites. In particular, many researchers have analyzed the incorporation of waste ashes from different industries for the production of gypsum composites due to their outstanding characteristics, such as low hygroscopicity, good fire resistance, and very low toxicity [14,15].

Several authors have investigated the incorporation of silica fume into gypsum-based composites. Al-Ridha et al. [17] reported that additions between 2.5% and 10% by weight of gypsum increased compressive strength by up to 23.5% while reducing setting time. Magallanes-Rivera et al. [18] studied mixtures containing blast furnace slag, silica fume, and fly ash, observing improvements in mechanical performance without compromising compressive strength. Similarly, Khalil et al. [19] found that silica additions modified the physical properties of gypsum composites, affecting density, porosity, workability, and mechanical behavior.

Table 1. Key findings from previous studies incorporating industrial ashes in building materials.

Reference	Base Material	Waste Addition (%)	w/g Ratio	Key Findings
[20]	Cement	Fly ash (10–15%)	0.2/0.4	- Viable method to achieve stability/solidification of metals - The material could be used as a repair mortar in roads and pavements.
[13]	Cement	Ashes (25%)	-	- Increased porosity, which reduces mechanical performance, while thermal and acoustic insulation improves.
[21]	Cement	Coal ash (3–5%)	-	- It is possible to use coal ash and gypsum residues as agents with mechanical resistance. - This new utility model emerges as a sustainable alternative.
[22]	Cement	Silica fume (10%)	0.5	Increasing the dose of silica fume up to 10% caused the improvement of positive force.
[17]	Gypsum	Silica fume (2.5–10%)	0.5	- With SF the compressive strength increases by 23.5% and reduces setting time by 68%.
[18]	Gypsum	Blast furnace slag, silica fume and fly ash (10–25%)	0.2	- Compression resistance is maintained, mechanical resistance improves.
[19]	Gypsum	Sand, Silica gel and fume (0.2–10%)	0.1	- Apparent density decreased and fluidity, setting time, apparent porosity and, to a lesser extent, compressive strength increased.
[23]	Cement	Ladle Furnace Slag (66%)	-	- Despite its high porosity, it had good dimensional stability when exposed to humid environments.
[24]	Gypsum	Bagasse ash (10%)	0.65/0.75	- Improved performance of the panels and boards. - Better fire resistance is obtained with cement and gypsum panels with bagasse fibers.
[25]	Gypsum	Wooden biomass ash (25%)	0.8	Wooden biomass ash can be incorporated up to 25% in gypsum composites complying with the standards.

In parallel, fiber reinforcement has been widely investigated as a strategy to overcome the brittle nature of gypsum-based materials (Table 2). Polypropylene and glass fibers have proven particularly effective in improving toughness, crack control, and flexural behavior. García [26,27] reported improvements in the mechanical performance of gypsum composites reinforced with polypropylene fibers, while Gonçalves et al. [28] and Lucolano et al. [29] demonstrated the potential of glass fibers to enhance the structural performance of gypsum-based materials. More recently, Tasán [30] confirmed the beneficial effect of polypropylene fibers on fracture energy and overall mechanical behavior.

Table 2. Key findings from previous studies incorporating fibers in gypsum composites.

Author	Base Material	Fiber Type (%)	w/g	Key Findings
[26]	Gypsum	Polypropylene (2–5–10%)	0.7	- Increase in mechanical strength values under flexural stresses.
[27]	Gypsum	Polypropylene (2%)	0.7	- Allows reducing density compared to plain gypsum and laminated gypsum boards.
[28]	Gypsum	Glass fiber (6%)	1.7	- The addition of recycled fibers in the gypsum matrix modified material behavior, avoiding purely brittle failure and increasing flexural strength.
[29]	Gypsum	Glass fiber (1–2%)	0.7	- Gypsum samples reinforced with 1 and 2% glass fiber were successfully produced.
[30]	Gypsum	Polypropylene fibers	0.7/0.8	- Significant improvements in mechanical behavior and fracture energy were found with the addition of polypropylene fibers in gypsum composites.

Despite the promising results reported for silica fume additions and fiber reinforcement individually, studies evaluating the combined effect of both strategies in gypsum composites remain limited. Understanding the interaction between silica fume incorporation and fiber reinforcement may contribute to the development of gypsum-based materials with improved performance while promoting the valorization of industrial by-products.

Although previous studies have investigated silica fume or fiber reinforcement separately, limited research has evaluated the combined influence of high silica fume contents (up to 35 wt.%), different water-to-gypsum ratios, and two fiber types on the physical, mechanical, and microstructural performance of gypsum composites. This integrated approach constitutes the main scientific contribution of the present work.

Therefore, the objective of this study is to evaluate the feasibility of developing sustainable gypsum composites incorporating silica fume waste and fiber reinforcement. The influence of silica fume content and fiber type on the physical and mechanical properties of gypsum-based materials is experimentally investigated. Unlike previous studies, which mainly evaluated silica fume or fiber reinforcement separately, the present research analyses their combined effect using silica fume contents of up to 35 wt.% together with polypropylene and glass fibers. The results provide practical information for the development of high-performance gypsum composites while promoting industrial waste valorization and reducing the consumption of virgin raw materials in accordance with circular economy principles. The study seeks to determine whether the combined use of these materials can improve the performance of gypsum composites while contributing to resource efficiency and waste valorization within the construction sector.

2. Materials and Methods

2.1. Materials

The experimental program was carried out using commercial gypsum plaster (E-35), silica fume (SF), polypropylene fibers (PP), glass fibers (GF), and potable water:

- The gypsum plaster was supplied by Placo Saint-Gobain (Madrid, Spain). According to the manufacturer, the material presents a purity higher than 90% and is classified as a normal-setting gypsum binder in accordance with EN 13279-1.

- Silica fume (SF) was used as a recycled mineral addition obtained as a by-product during the production of silicon metal and ferrosilicon alloys in electric arc furnaces. It consists predominantly of amorphous silicon dioxide (SiO_2) with ultrafine spherical particles, typically smaller than $1\mu\text{m}$, a specific surface area of approximately $15\text{--}30\text{ m}^2/\text{g}$, and a density of about 2.20 g/cm^3 . Owing to its high fineness and pozzolanic activity, silica fume has been extensively investigated as a supplementary material capable of improving the microstructure and mechanical performance of cementitious and gypsum-based composites.
- Two types of fiber reinforcement were evaluated: polypropylene fibers (PP) and alkali-resistant glass fibers (GF) supplied by Sika (Madrid, Spain). Polypropylene fibers, with a density of approximately 0.91 g/cm^3 , were selected because of their high chemical stability, low density, and excellent crack-bridging capacity. These fibers are widely used to improve toughness, reduce crack propagation, and enhance the post-cracking behaviour of gypsum-based composites. In addition, alkali-resistant glass fibers were incorporated due to their high tensile strength, high elastic modulus, and excellent compatibility with gypsum-based matrices. Their incorporation contributes to improved crack control, flexural strength, and the overall mechanical performance of brittle composites.
- Potable water supplied by Canal de Isabel II (Madrid, Spain) was used for the preparation of all mixtures.

Figure 1 shows the materials used throughout the experimental campaign.

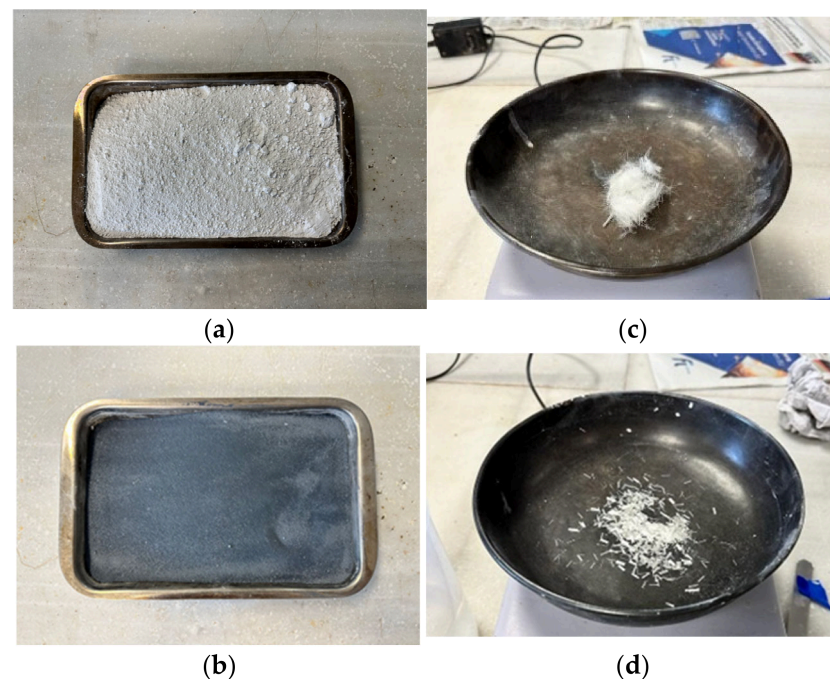


Figure 1. Materials used: plaster E-35 (a), silica fume (b), polypropylene fiber (c), and glass fiber (d).

2.2. Experimental Program

The experimental study was divided into two consecutive phases (Figure 2). In the first phase, the influence of silica fume incorporation on the physical and mechanical properties of gypsum composites was evaluated. In the second phase, the mixtures showing the most promising performance were selected for reinforcement with polypropylene and glass fibers.

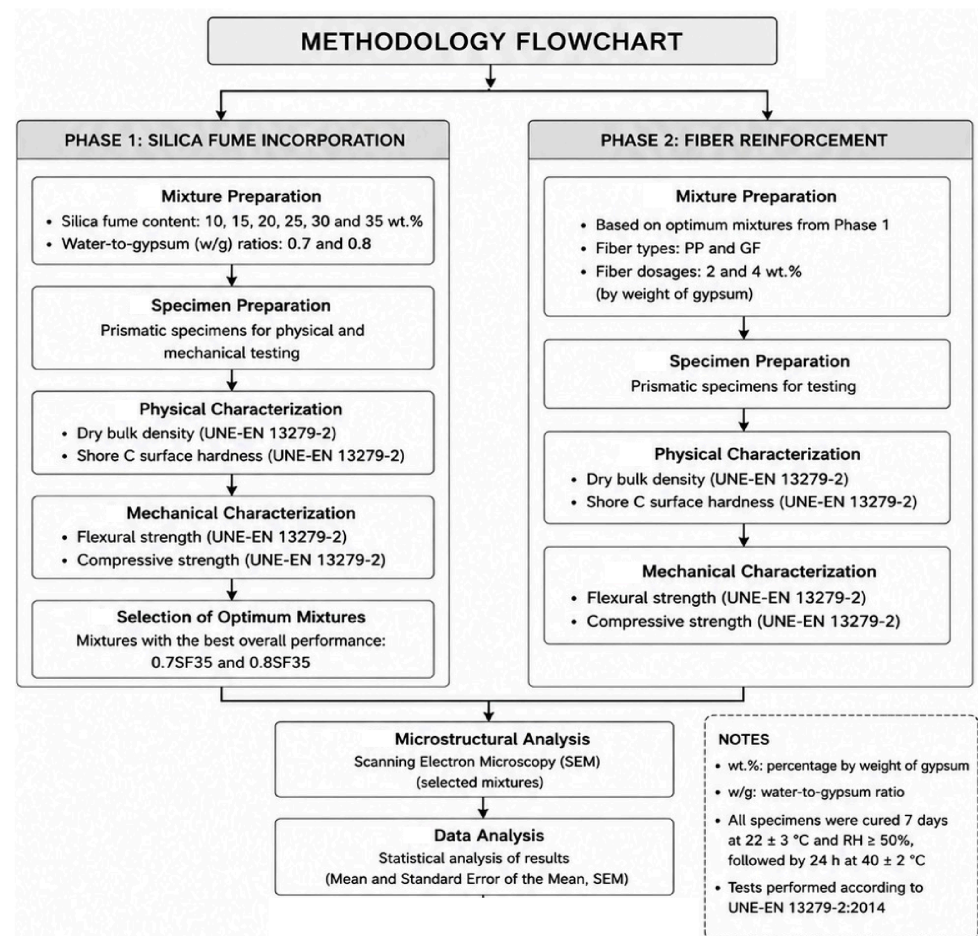


Figure 2. Flowchart of the experimental plan.

The experimental variables and dosage ranges were established based on previous studies reported in the literature and preliminary experimental work carried out by the authors. Silica fume incorporation levels ranging from 10 to 35 wt.% were selected because this interval has been identified as representative for evaluating the influence of silica-rich additions on gypsum-based materials while maintaining adequate workability. Water-to-gypsum (w/g) ratios of 0.7 and 0.8 were chosen to investigate the influence of water content on the behavior of the composites under two representative mixing conditions. Likewise, polypropylene and glass fibers were incorporated at dosages of 2 wt.% and 4 wt.% of gypsum to evaluate both a commonly reported reinforcement level and a higher dosage close to the practical incorporation limit, where changes in workability and mechanical performance become more evident. Therefore, the objective of the present study was not to optimize each experimental variable individually, but to investigate the combined effect of silica fume incorporation and fiber reinforcement using representative mixture compositions.

2.2.1. Phase 1: Silica Fume Addition

Reference gypsum specimens were produced using water-to-gypsum (w/g) ratios of 0.7 and 0.8. These ratios were selected to ensure adequate workability in accordance with UNE-EN 13279-2:2014 requirements [31].

Silica fume was incorporated at incorporation levels of 10%, 15%, 20%, 25%, 30%, and 35% by weight of gypsum. For each formulation, three prismatic specimens measuring $40 \times 40 \times 160 \text{ mm}^3$ were manufactured. The composition and designation of all mixtures are presented in Table 3.

Table 3. Specimen composition and designation for Phase 1.

Designation	Gypsum [g]	Silica Fume [g]	Water/Gypsum Ratio (w/g)	Water [g]
E0.7	1000	-	0.7	700
0.7SF10	1000	100	0.7	700
0.7SF15	1000	150	0.7	700
0.7SF20	1000	200	0.7	700
0.7SF25	1000	250	0.7	700
0.7SF30	1000	300	0.7	700
0.7SF35	1000	350	0.7	700
E0.8	1000	-	0.8	800
0.8SF10	1000	100	0.8	800
0.8SF15	1000	150	0.8	800
0.8SF20	1000	200	0.8	800
0.8SF25	1000	250	0.8	800
0.8SF30	1000	300	0.8	800
0.8SF35	1000	350	0.8	800

After casting, the specimens were stored under laboratory conditions (22 ± 3 °C and $50 \pm 5\%$ relative humidity) for seven days. Subsequently, they were oven-dried at 40 °C for 24 h prior to testing.

The physical and mechanical characterization included dry bulk density, Shore C surface hardness, flexural strength, and compressive strength tests, all performed according to UNE-EN 13279-2:2014 [31]. The average value obtained from the three specimens was considered for each property.

2.2.2. Phase 2: Fiber Reinforcement

Based on the results obtained in Phase 1, the mixtures containing 35% silica fume (0.7SF35 and 0.8SF35) were selected for further investigation.

Polypropylene and glass fibers were incorporated at dosages of 2% and 4% by weight of gypsum. A total of eight reinforced formulations were produced, as summarized in Table 4.

Table 4. Specimen composition and designation incorporating polypropylene fibers (PP) and glass fibers (GF).

Designation	Gypsum [g]	Silica Fume [g]	Water/Gypsum Ratio (w/g)	Water [g]	Fibers [g]
0.7SF35PP2	1000	350	0.7	700	20
0.7SF35PP4	1000	350	0.7	700	40
0.7SF35GF2	1000	350	0.7	700	20
0.7SF35GF4	1000	350	0.7	700	40
0.8SF35PP2	1000	350	0.8	800	20
0.8SF35PP4	1000	350	0.8	800	40
0.8SF35GF2	1000	350	0.8	800	20
0.8SF35GF4	1000	350	0.8	800	40

The specimens were manufactured and conditioned following the same procedure described for Phase 1. The resulting composites were subjected to the same physical and mechanical characterization tests in order to evaluate the influence of fiber reinforcement on material performance.

2.3. Test Methods and Data Analysis

The physical and mechanical properties of the developed gypsum composites were evaluated in accordance with UNE-EN 13279-2:2014 [31], which specifies the test methods for gypsum binders and gypsum plasters. For each formulation, three specimens were tested and the average value was considered for the analysis.

2.3.1. Dry Bulk Density

The dry bulk density was determined after oven drying the specimens at 40 °C for 24 h and calculated using Equation (1):

$$\rho = \frac{m}{V} \quad (1)$$

where

- ρ is the dry bulk density (kg/m³).
- m is the dry mass of the specimen (kg).
- V is the specimen volume (m³).

2.3.2. Surface Hardness

Surface hardness was measured using a Shore C durometer according to the procedure established in UNE-EN 13279-2:2014 [31]. The reported value corresponds to the average of the three specimens tested for each mixture.

2.3.3. Flexural Strength

Flexural strength was determined by means of a three-point bending test and calculated using Equation (2):

$$R_f = \frac{3FL}{2bh^2} \quad (2)$$

where

- R_f is the flexural strength (MPa).
- F is the maximum applied load (N).
- L is the span between supports (mm).
- b is the specimen width (mm).
- h is the specimen height (mm).

2.3.4. Compressive Strength

The compressive strength was determined using the two halves obtained after the flexural test and calculated according to Equation (3):

$$R_c = \frac{F}{A} \quad (3)$$

where

- R_c is the compressive strength (MPa).
- F is the maximum applied load (N).
- A is the loaded area (mm²).

2.3.5. Statistical Analysis

For each formulation, three independent specimens were tested. The reported values correspond to the arithmetic mean of the experimental measurements. The variability of the results was evaluated using the standard error of the mean (SEM), calculated as Equation (4):

$$SEM = \frac{SD}{\sqrt{n}} \quad (4)$$

where

- SEM is the standard error of the mean.
- SD is the standard deviation of the experimental measurements.
- n is the number of tested specimens ($n = 3$).

Statistical Analysis. For each formulation, three independent specimens were manufactured and tested following the procedures established in UNE-EN 13279-2:2014. The reported values correspond to the arithmetic mean of the experimental measurements. The variability of the results was evaluated using the standard error of the mean (SEM), calculated from the three independent measurements for each formulation. Error bars will be shown to represent the SEM and were included in the results to illustrate the uncertainty associated with the experimental measurements.

2.4. Microstructural Analysis

To support the interpretation of the experimental results, selected specimens were analyzed using a FEI Teneo scanning electron microscope (SEM).

Microstructural observations focused on the interaction between silica fume particles, gypsum crystals, and reinforcing fibers, with the aim of identifying potential mechanisms responsible for the observed variations in physical and mechanical behavior.

3. Results and Discussion

3.1. Results for Phase 1: Effect of Silica Fume Incorporation

3.1.1. Bulk Density Results

The incorporation of silica fume resulted in an increase in the dry bulk density of all gypsum composites, regardless of the water-to-gypsum ratio employed (Figure 3).

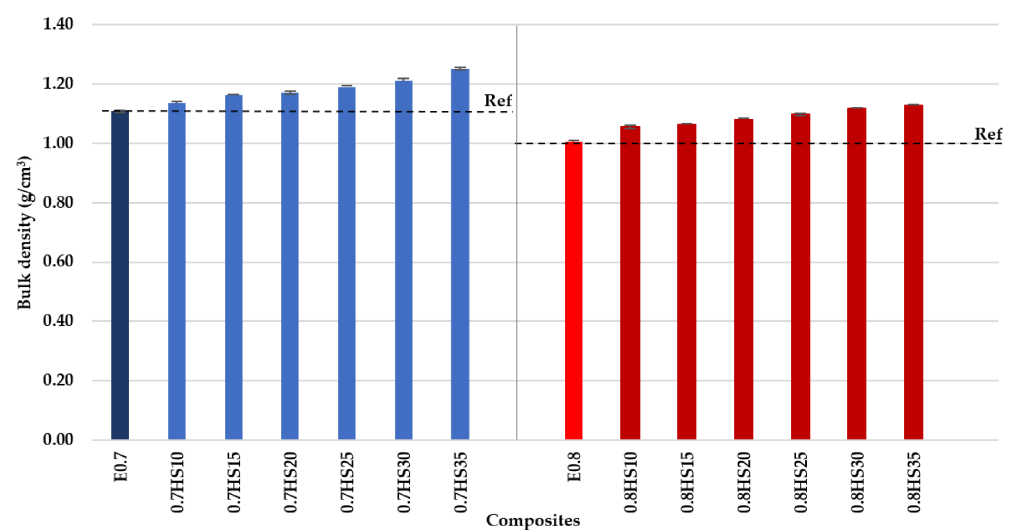


Figure 3. Results for dry bulk density for Phase 1 mixtures with water/gypsum ratios of 0.7 (left) and 0.8 (right).

The effect became progressively more pronounced as the silica fume content increased, with the highest density values being obtained for mixtures containing 35% silica fume.

For the w/g ratio of 0.7, the density increased from approximately 1.14 g/cm³ for the reference mixture to values close to 1.25 g/cm³ for the 0.7SF35 formulation. A similar trend was observed for the w/g ratio of 0.8, although the absolute density values remained lower due to the higher water content of the mixtures.

This behavior can be attributed to the extremely fine particle size of silica fume, which promotes a filler effect within the gypsum matrix. The silica particles occupy voids between gypsum crystals, reducing internal porosity and generating a more compact microstructure. As a consequence, the overall density of the hardened composites increases as the proportion of silica fume rises.

These results indicate that silica fume can effectively modify the internal structure of gypsum composites, producing denser materials without compromising the workability requirements established by UNE-EN 13279-2 [31].

The increase in bulk density observed in the present study is consistent with previous investigations on silica-based gypsum composites. Khalil et al. [19] reported that the incorporation of silica materials reduced the apparent porosity of gypsum matrices due to the filler effect produced by ultrafine particles, resulting in denser composites. Similarly, Al-Ridha et al. [17] found that silica fume enhanced the compactness of gypsum-based materials, contributing to improvements in their mechanical behaviour. In the present work, the higher density achieved with 35 wt.% silica fume confirms that the fine particles effectively filled the interstitial voids between gypsum crystals, producing a more compact internal structure.

3.1.2. Surface Hardness Results

The incorporation of silica fume also produced a consistent improvement in Shore C surface hardness (Figure 4).

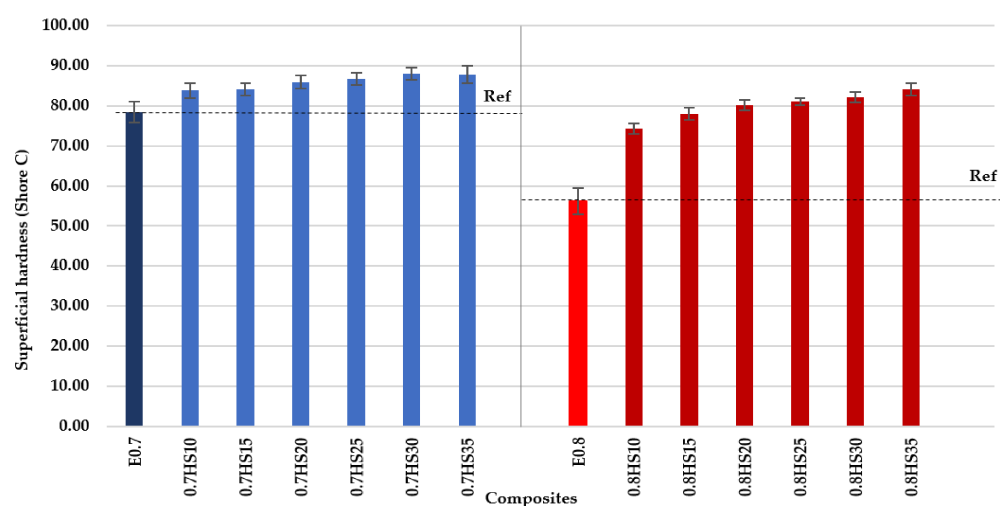


Figure 4. Results for Shore C hardness for Phase 1 mixtures with water/gypsum ratios of 0.7 (left) and 0.8 (right).

All mixtures containing silica fume exhibited higher hardness values than the corresponding reference specimens, with the greatest increases observed for the formulations incorporating 35% silica fume.

The effect was particularly evident for the w/g ratio of 0.8, where hardness increased by almost 28 Shore C units compared with the reference mixture. Similar improvements, although less pronounced, were observed for the w/g ratio of 0.7.

The increase in hardness is consistent with the densification effect previously identified in the density results. The incorporation of ultrafine silica particles contributes to the formation of a more compact surface layer, reducing the presence of voids and improving resistance to localized penetration. Consequently, the material develops a harder and more resistant surface.

From a practical perspective, these improvements may contribute to enhanced durability and wear resistance in gypsum-based construction applications, particularly in elements exposed to frequent contact or abrasion.

The increase in Shore C hardness agrees with the densification mechanism observed in the density results. Al-Ridha et al. [17] also reported improvements in the mechanical behaviour of gypsum composites incorporating silica fume, attributing this behaviour to the refinement of the gypsum matrix. The higher hardness values obtained in this study indicate that silica fume contributes to the formation of a more compact surface with fewer defects, thereby increasing the resistance of the material to localized penetration.

3.1.3. Flexural Strength Results

The influence of silica fume on flexural strength depended on the water-to-gypsum ratio employed (Figure 5).

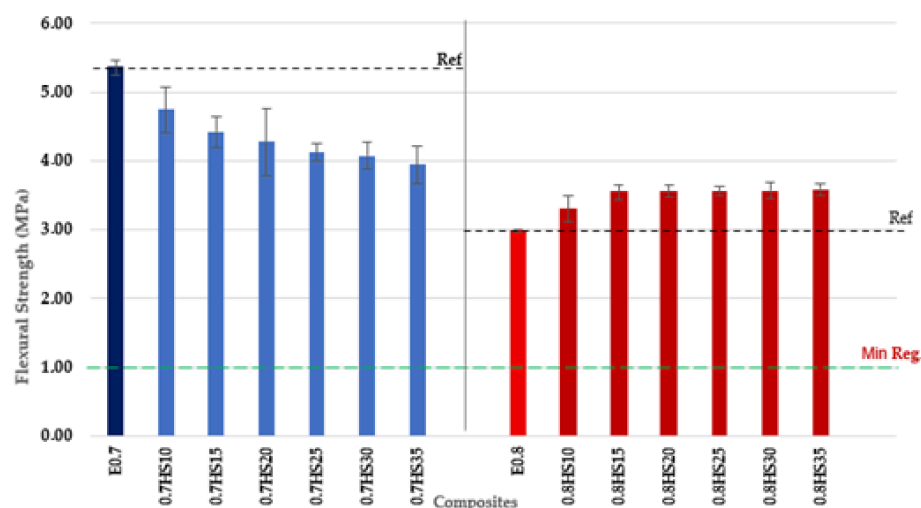


Figure 5. Results for Flexural Strength for Phase 1 mixtures with water/gypsum ratios of 0.7 (left) and 0.8 (right). Error bars represent the standard error of the mean (SEM) calculated from three independent specimens.

For mixtures produced with a w/g ratio of 0.7, flexural strength showed a gradual reduction as the silica fume content increased. Although all composites remained well above the minimum value required by the standard, the incorporation of high silica fume contents did not result in improvements in flexural performance.

Conversely, mixtures prepared with a w/g ratio of 0.8 exhibited a progressive increase in flexural strength with increasing silica fume content. The highest values were obtained for the formulations containing 30–35% silica fume, indicating that the beneficial effect of matrix densification compensated for the higher initial porosity associated with the larger water content.

These results suggest that the influence of silica fume on flexural behaviour is not governed exclusively by the presence of the residue itself, but also by the interaction between silica particles, gypsum crystals, and the amount of mixing water. Therefore, the effectiveness of silica fume as a reinforcing addition appears to be strongly dependent on mixture design.

The different flexural behaviour observed for the two water-to-gypsum ratios suggests that the effectiveness of silica fume depends on the mixture composition and water content. Similar observations were reported by Magallanes-Rivera et al. [18], who found that silica-rich additions improved the mechanical behaviour of gypsum composites without adversely affecting their structural performance. In contrast, the slight reduction in flexural strength observed in some mixtures with a w/g ratio of 0.7 may be related to the higher silica fume incorporation levels evaluated in the present study compared with those commonly investigated in previous research.

3.1.4. Compressive Strength Results

The compressive strength results are presented in Figure 6.

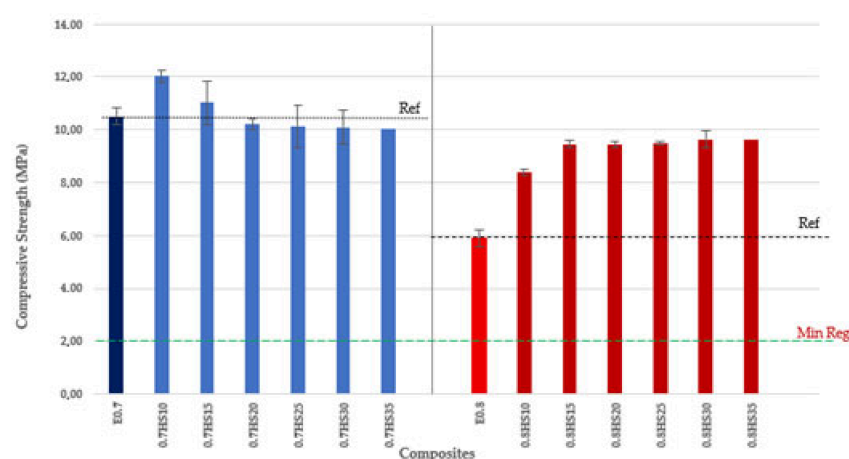


Figure 6. Results for Compressive Strength for Phase 1 mixtures with water/gypsum ratios of 0.7 (left) and 0.8 (right). Error bars represent the standard error of the mean (SEM) calculated from three independent specimens.

In general, all mixtures satisfied the minimum requirements established by UNE-EN 13279-1 [32], confirming the technical feasibility of incorporating silica fume at the investigated incorporation levels.

For the w/g ratio of 0.7, the incorporation of 10% silica fume produced the highest compressive strength values. Further increases in silica fume content resulted in a slight reduction in strength; however, the differences remained relatively small and all mixtures maintained satisfactory mechanical performance.

A different trend was observed for the w/g ratio of 0.8. In this case, compressive strength generally increased as the silica fume content increased, with the highest values corresponding to the mixtures incorporating 30–35% silica fume. This behaviour suggests that the beneficial filler effect of silica fume becomes more significant when higher water contents are employed, partially compensating for the increased porosity typically associated with these mixtures.

The overall results indicate that silica fume can be incorporated in relatively high proportions without adversely affecting compressive performance. Moreover, the improvements observed in density and surface hardness, together with the stable compressive strength values obtained, support the suitability of silica fume as a sustainable addition for gypsum-based composites.

The compressive strength results are in agreement with previous studies evaluating silica fume in gypsum composites. Al-Ridha et al. [17] reported compressive strength increases of up to 23.5% with silica fume additions between 2.5% and 10%, while Khalil et al. [19] observed slight improvements associated with the filler effect and the reduction

in internal porosity. Although the present study investigated significantly higher silica fume contents (up to 35 wt.%), all mixtures maintained satisfactory compressive strength, demonstrating that high incorporation levels can be successfully incorporated without compromising the mechanical integrity of the material.

3.2. Results for Phase 2: Effect of Fiber Reinforcement

Following the results obtained during Phase 1, the mixtures containing 35 wt.% silica fume (0.7SF35 and 0.8SF35) were selected for fiber reinforcement because they exhibited the best overall balance between physical and mechanical performance while maximizing the utilization of industrial waste. The upper limit of 35 wt.% was selected to evaluate a high silica fume incorporation level while maintaining adequate mixture workability. Polypropylene (PP) and glass fibers (GF) were incorporated at dosages of 2 wt.% and 4 wt.% in order to evaluate their influence on the behavior of the optimized gypsum composites.

Figure 7 illustrates the relationship between bulk density and the flexural and compressive strengths of the reinforced composites.

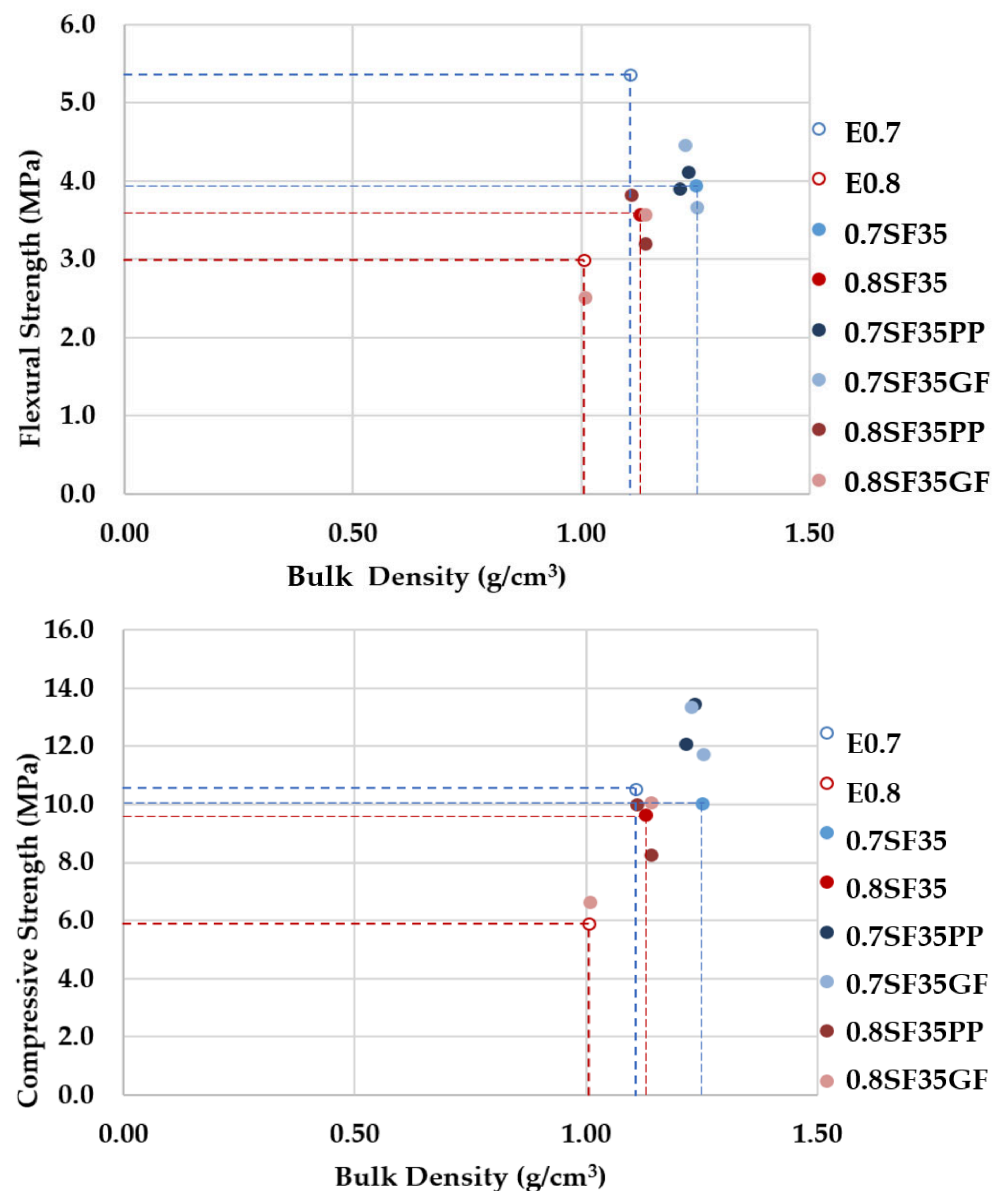


Figure 7. Relationship between bulk density and flexural/compressive strength for Phase 2 mixtures.

In all cases, fiber incorporation produced an increase in bulk density compared with the corresponding silica-fume matrices. For mixtures prepared with a water-to-gypsum ratio of 0.7, density increased from approximately 1.13 g/cm^3 to values between 1.21 and 1.23 g/cm^3 , whereas for the w/g ratio of 0.8 the density increased from approximately 1.04 g/cm^3 to values close to 1.14 g/cm^3 . Although these increases were moderate, they indicate that the incorporation of fibers contributed to producing a more compact internal structure.

The improvement in density was accompanied by an enhancement of the mechanical properties, although the relationship was not strictly proportional. The increase in density alone cannot explain the mechanical behavior of the composites, since fiber type, dosage, orientation, and fiber–matrix interaction also played a significant role. Consequently, the mechanical response resulted from the combined influence of matrix densification promoted by silica fume and crack-control mechanisms provided by the reinforcing fibers.

Regarding flexural performance, glass fiber reinforcement exhibited the most favorable behavior. The mixture 0.7SF35GF4 achieved the highest flexural strength among all reinforced formulations, demonstrating the effectiveness of glass fibers in resisting tensile stresses generated during bending. This behavior is attributed to the high elastic modulus of glass fibers and their ability to bridge developing cracks, delaying crack propagation and increasing the energy required for failure. Similar observations have been reported by Gonçalves et al. [28] and Lucolano et al. [29], who concluded that glass fibers significantly improve the flexural behavior of gypsum-based composites through effective crack bridging and enhanced load transfer.

A different response was observed under compressive loading. The highest compressive strengths were obtained for the mixtures reinforced with 2 wt.% polypropylene fibers and 4 wt.% glass fibers at a water-to-gypsum ratio of 0.7, reaching values close to 14 MPa. Compared with the corresponding silica-fume matrix, the best-performing formulation exhibited an increase of approximately 27.14% in compressive strength after seven days. These results indicate that polypropylene fibers contribute effectively to delaying crack propagation and redistributing internal stresses, thereby reducing brittle failure under compression. Similar improvements have been reported by García [26,27] and Tasán [30], who observed that polypropylene fibers enhance the toughness and post-cracking behavior of gypsum composites.

The results also demonstrate that silica fume and fiber reinforcement act through complementary mechanisms rather than independently. During Phase 1, silica fume promoted matrix densification by filling the voids between gypsum crystals, producing a more compact microstructure. Subsequently, the incorporation of fibers improved crack control and stress redistribution during loading. Consequently, the denser matrix generated by silica fume enhanced the effectiveness of the reinforcing fibers by improving the fiber–matrix interaction and facilitating stress transfer. This synergistic effect explains the superior overall performance of the reinforced composites compared with the silica-fume matrices without fibers.

Overall, the experimental results confirm that the combined incorporation of silica fume and fiber reinforcement constitutes an effective strategy for improving the performance of gypsum composites. While silica fume primarily enhances the compactness of the matrix, polypropylene and glass fibers contribute to controlling crack propagation and increasing mechanical resistance. The microstructural mechanisms responsible for these improvements are further discussed in the following section through SEM observations.

3.3. Microstructural Analysis Results

Representative SEM micrographs of the developed composites are shown in Figure 8.

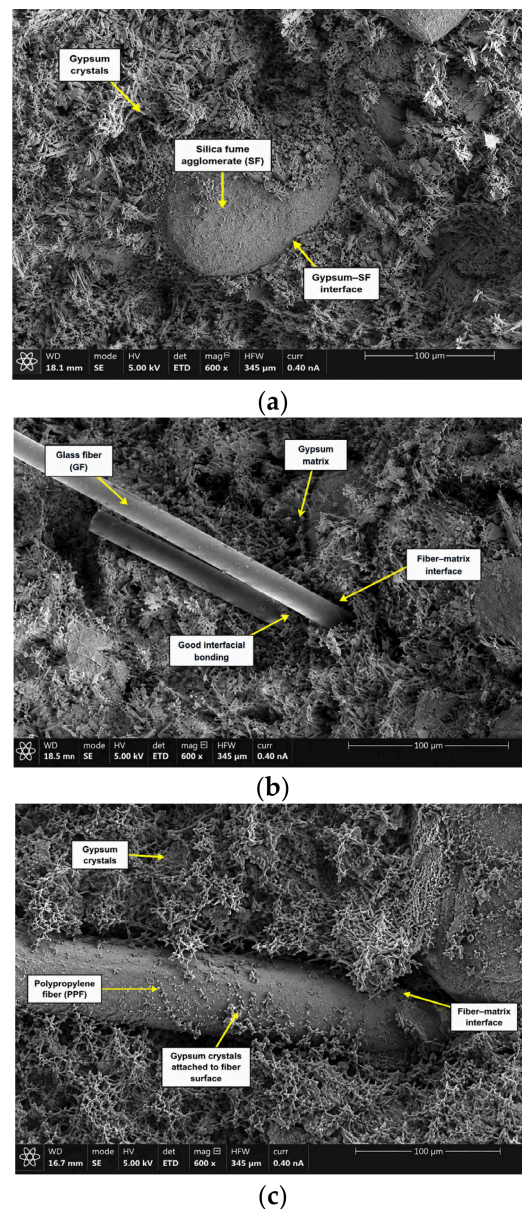


Figure 8. SEM micrographs showing: (a) interaction between gypsum crystals and silica fume particles; (b) glass fiber embedded in the gypsum matrix, illustrating the fiber–matrix interface; and (c) polypropylene fiber surrounded by gypsum hydration products, showing the interfacial bonding between the reinforcement and the matrix.

The observations provide valuable information regarding the interaction between the gypsum matrix, silica fume particles, and the reinforcing fibers, helping to explain the mechanical behaviour observed during experimental testing.

Figure 8a reveals a relatively compact microstructure in the gypsum composites incorporating silica fume. The ultrafine silica particles appear to be distributed throughout the matrix, occupying voids between gypsum crystals and contributing to a denser internal structure. This observation is consistent with the increase in bulk density recorded during the experimental campaign and supports the hypothesis that silica fume acts primarily through a filler effect.

The SEM image corresponding to the glass fiber-reinforced composite (Figure 8b) shows good contact between the fiber surface and the surrounding gypsum matrix. No significant interfacial gaps or debonding zones are observed, suggesting effective stress transfer between both phases. This behaviour may explain the favourable flexural performance

achieved by the mixtures reinforced with glass fibers, particularly those incorporating the highest fiber dosage.

Similarly, the polypropylene fiber-reinforced composite (Figure 8c) exhibits adequate fiber embedding within the gypsum matrix. Although the fiber surface appears smoother than that of the glass fibers, a continuous contact zone between the matrix and the reinforcement can still be identified. This interaction contributes to limiting crack propagation and improving the overall mechanical behaviour of the composite.

Overall, the SEM observations confirm that the incorporation of silica fume promotes matrix densification, while both types of fibers achieve satisfactory adhesion with the gypsum matrix. The combined action of these mechanisms contributes to the improved physical and mechanical performance observed in the developed composites, particularly in terms of density, flexural strength, and compressive strength.

The SEM observations provide microstructural evidence supporting the experimental results. Similar microstructural behaviour was reported by Khalil et al. [19], who observed that silica particles occupied the voids between gypsum crystals, producing denser matrices with reduced porosity. Likewise, Al-Ridha et al. [17] associated the improved mechanical performance of silica-fume gypsum composites with matrix refinement. In the present study, the good adhesion observed between both fiber types and the gypsum matrix explains the improvements in flexural and compressive strength obtained during the experimental campaign.

The SEM observations support the mechanical results discussed in Section 3.2. The incorporation of silica fume produced a denser gypsum matrix by reducing interstitial voids between gypsum crystals. Furthermore, satisfactory adhesion between the reinforcing fibers and the surrounding matrix was observed, promoting efficient stress transfer during loading. These microstructural characteristics explain the improvements recorded in density, flexural strength, and compressive strength after fiber reinforcement.

4. Conclusions

This study investigated the development of sustainable gypsum composites incorporating silica fume waste and fiber reinforcement through a two-phase experimental program. Based on the experimental and microstructural results, the following conclusions can be drawn:

- Silica fume was successfully incorporated into gypsum composites at addition levels of up to 35% by weight of gypsum while maintaining adequate workability and complying with the minimum mechanical requirements established by UNE-EN 13279.
- The incorporation of silica fume produced a densification of the gypsum matrix, resulting in increased bulk density and surface hardness. The highest density values were obtained for the mixtures containing 35% silica fume, reaching increases of up to 9.64% compared with the corresponding reference specimens.
- The influence of silica fume on mechanical performance depended on the water-to-gypsum ratio. While all mixtures satisfied the regulatory requirements, the most favourable overall behaviour was observed for the formulations incorporating the highest silica fume contents, particularly at a w/g ratio of 0.8.
- Based on the results obtained during the first phase, the mixtures containing 35% silica fume were selected for fiber reinforcement. The incorporation of polypropylene and glass fibers further increased the density of the composites, producing values of up to 1.23 g/cm³.
- Fiber reinforcement improved the overall mechanical behaviour of the developed composites. Glass fibers showed the most favourable response under flexural loading,

whereas polypropylene fibers contributed positively to compressive performance. The best-performing formulations achieved compressive strength increases of up to 27.14% compared with the corresponding silica-fume composites.

- SEM observations confirmed the densifying effect of silica fume and revealed satisfactory adhesion between the gypsum matrix and both types of fibers. These microstructural observations support the mechanical improvements recorded during the experimental campaign.

Overall, the results demonstrate that silica fume and fiber reinforcement act through complementary mechanisms. Silica fume enhances matrix compactness by reducing porosity and improving the packing of gypsum crystals, whereas the reinforcing fibers contribute to crack control and more efficient stress transfer during mechanical loading. The sequential optimization strategy proposed in this study successfully combines both mechanisms, resulting in gypsum composites with improved physical, mechanical, and microstructural performance while enabling the incorporation of significant amounts of industrial by-products.

From a sustainability perspective, the developed composites provide an effective route for the valorization of silica fume as an industrial by-product, reducing the consumption of virgin raw materials and supporting circular economy principles in the construction sector. Therefore, this methodology represents a promising approach for the development of more sustainable gypsum-based materials without compromising their engineering performance.

Future research should focus on evaluating the long-term durability of the developed composites through water absorption, capillary absorption, ageing, and freeze–thaw tests. In addition, life cycle assessment (LCA) and carbon footprint analyses should be performed to quantify the environmental benefits associated with silica fume valorization and to further support the application of these composites in sustainable construction.

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References

1. European Commission. *Level(s): Taking Action on the Total Impact of the Construction Sector*; Publications Office of the European Union: Luxembourg, 2021.
2. United Nations Environment Programme (UNEP). *Global Status Report for Buildings and Construction 2023: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme (UNEP) and Global Alliance for Buildings and Construction (GlobalABC): Nairobi, Kenya, 2023.
3. European Union. *The European Parliament and the Council of the European Union*; State Agency Official Gazette: Madrid, Spain, 2008.

4. EC. *On Resource Efficiency Opportunities in the Building Sector 445 Final*; Publications Office of the European Union: Luxembourg, 2014.
5. Fundacion CONAMA (Ed.) *Economía Circular en el Sector de la Construcción*; Fundacion CONAMA: Madrid, Spain, 2018.
6. Benachio, G.L.F.; Freitas, M.D.C.D.; Tavares, S.F. Circular economy in the construction industry: A systematic literature review. *J. Clean. Prod.* **2020**, *260*, 121046. [\[CrossRef\]](#)
7. Del Rio-Merino, M.; Vidales-Barriguete, A.; Pina-Ramirez, C.; Vitiello, V.; Santa Cruz-Astorqui, J.; Castelluccio, R. A review of the research about gypsum mortars with waste aggregates. *J. Build. Eng.* **2022**, *45*, 103338. [\[CrossRef\]](#)
8. Shen, L.Y.; Lu, W.S.; Yao, H.; Wu, D.H. A computer-based scoring method for measuring the environmental performance of construction activities. *Autom. Constr.* **2005**, *14*, 297–309. [\[CrossRef\]](#)
9. Li, X.; Zhu, Y.; Zhang, Z. An LCA-based environmental impact assessment model for construction processes. *Build. Environ.* **2010**, *45*, 766–775. [\[CrossRef\]](#)
10. Kaur, M.; Arora, S. Environment impact assessment and environment management studies for an upcoming multiplex—A Case Study. *IOSR J. Mech. Civ. Eng. (IOSR/JMCE)* **2012**, *1*, 22–30. [\[CrossRef\]](#)
11. Asif, M.; Muneer, T.; Kelley, R. Life cycle assessment: A case study of a dwelling home in Scotland. *Build. Environ.* **2007**, *42*, 1391–1394. [\[CrossRef\]](#)
12. Tam, C.M.; Tam, V.W.Y.; Tsui, W.S. Green construction assessment for environmental management in the construction industry of Hong Kong. *Int. J. Proj. Manag.* **2004**, *22*, 563–571. [\[CrossRef\]](#)
13. Rodríguez-Álvaro, R.; González-Fontebao, B.; Seara-Paz, S.; Rey-Bouzon, E.J. Masonry mortars, precast concrete and masonry units using coal bottom ash as a partial replacement for conventional aggregates. *Constr. Build. Mater.* **2021**, *283*, 122737. [\[CrossRef\]](#)
14. González Madariaga, F.J. Mezclas de residuos de poliestireno expandido (EPS) conglomerados con yeso o escayola para su uso en la construcción. *Inf. Constr.* **2008**, *60*, 35–43. [\[CrossRef\]](#)
15. Sharma, N.; Sharma, P.; Parashas, A. Incorporation of Silica Fume and Corn Cob Ash Waste into Cement and Concrete. *Mater. Proc.* **2022**, *62*, 4151–4155. [\[CrossRef\]](#)
16. CEDEX. *Humo de Sílice*; Centro de Estudios y Experimentación de Obras Públicas: Madrid, Spain, 2015.
17. Al-Ridha, S.D.; Abbood, A.A.; Hussein, H.H. Improvement of gypsum properties using SF additive. *Int. J. Sci. Res.* **2015**, *6*, 504–509.
18. Guerra-Cossío, M.A.; González-López, J.R.; Magallanes-Rivera, R.X.; Zaldívar-Cadena, A.A.; Figueroa-Torres, M.Z. Anhydrite, blast-furnace slag and silica fume composites: Properties and reaction products. *Adv. Cem. Res.* **2019**, *31*, 362–369. [\[CrossRef\]](#)
19. Khalil, A.A.; Tawfik, A.; Hegazy, A.A.; El-Shahat, M.F. Effect of different forms of silica on the physical and mechanical properties of gypsum plaster composites. *Mater. Constr.* **2013**, *63*, 529–537. [\[CrossRef\]](#)
20. López Zaldívar, O. Desarrollo de Conglomerados con la Incorporación de Cenizas Volantes Procedentes de la Incineración de Residuos Sólidos Urbanos. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2015.
21. Siddique, R. Performance characteristics of high-volume Class F fly ash concrete. *Cem. Concr. Res.* **2004**, *34*, 487–493. [\[CrossRef\]](#)
22. Raja, M.A.; Jude Sujatha, S.; Yadav, A.; Sophia, M. Design of an eco-friendly composite gypsum binder using different mineral admixtures. *Mater. Today Proc.* **2022**, *62*, 5519–5525. [\[CrossRef\]](#)
23. Henríquez, P.A.; Aponte, D.; Ibáñez-Insa, J.; Bizinotto, M.B. Ladle furnace slag as a partial replacement of Portland cement. *Constr. Build. Mater.* **2021**, *289*, 123106. [\[CrossRef\]](#)
24. Srikanth, G.; Fernando, A.; Selvaranjan, K.; Gamage, J.C.P.H.; Ekanayake, L. Development of a plastering mortar using waste bagasse and rice husk ashes with sound mechanical and thermal properties. *Case Stud. Constr. Mater.* **2022**, *16*, e00956. [\[CrossRef\]](#)
25. Pedreño-Rojas, M.A.; Porras-Amores, C.; Villoria-Sáez, P.; Morales-Conde, M.J.; Flores-Colen, I. Characterization and performance of building composites made from gypsum and woody-biomass ash waste: A product development and application study. *Constr. Build. Mater.* **2024**, *419*, 135435. [\[CrossRef\]](#)
26. García Santos, A. Comportamiento Mecánico de Yesos Reforzados con Polímeros Sintéticos. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 1988.
27. García-Santos, A. Lightened plaster reinforced with polypropylene fibres and expanded polystyrene beads. *Mater. Constr.* **2009**, *59*, 105–124.
28. Gonçalves, R.M.; Martinho, A.; Oliveira, J.P. Evaluating the potential use of recycled glass fibers for the development of gypsum-based composites. *Constr. Build. Mater.* **2022**, *321*, 126320. [\[CrossRef\]](#)
29. Lucolano, F.; Boccarusso, L.; Langella, A.; Caputo, D.; Caputo, F. Hemp as an eco-friendly substitute for glass fibres for plaster reinforcement. *Compos. Part B Eng.* **2019**, *175*, 107073. [\[CrossRef\]](#)
30. Tasán, D. Incorporation of Polypropylene Fibers into Gypsum Compounds for Construction Applications. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2023.

31. UNE-EN 13279-2:2014; Building Plaster and Plaster-Based Construction Conglomerates—Part 2: Test Methods. AENOR: Madrid, Spain, 2014.
32. UNE-EN 13279-1:2009; Building Plasters and Plaster-Based Conglomerates for Construction—Part 1: Definitions and Specifications. AENOR: Madrid, Spain, 2009.

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