

SUSTAINABLE GYPSUM COMPOSITES: INCORPORATING CONSTRUCTION AND DEMOLITION WASTE FOR INTERIOR APPLICATIONS

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ABSTRACT

The construction industry is one of the largest generators of solid waste worldwide, primarily construction and demolition waste (CDW). Integrating these materials into new products is a key strategy to promote circular economy principles and reduce environmental impact. This study presents the development and characterization of an innovative gypsum-based composite incorporating cardboard and glass fiber waste, aiming to assess its feasibility for use in interior cladding panels and suspended ceilings.

Experimental tests were conducted to determine the physical, chemical, and mechanical properties of the material, including strength, durability, density, stiffness, and water absorption, as well as compliance with UNE-EN 13279-1:2009 standards. Results show that hardness increases with the addition of waste, while flexural and compressive strengths decrease, particularly with cardboard, although glass fibers mitigate this reduction. Density remains similar to the reference material, and water absorption decreases due to the lower porosity of the added waste. Stiffness improves with CDW incorporation, likely due to particle size and internal cohesion.

Among the tested formulations, mixtures containing 20% glass fibers and 10% cardboard by weight of gypsum achieved the best balance between mechanical performance and sustainability, meeting minimum regulatory requirements. These characteristics enable their application in cladding panels and suspended ceilings, offering a viable alternative that reduces costs and environmental impact without compromising functionality.

In conclusion, while the composite does not exhibit significant enhancements compared to conventional gypsum, it proves suitable for interior applications and supports waste reduction and resource efficiency, reinforcing the adoption of circular economy practices in the construction sector.

PALABRAS CLAVE: circular economy, construction and demolition waste, gypsum, glass fibers, cardboard, sustainability.

1. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and one of the main generators of waste worldwide, generating 25–35% of total solid waste globally [1]. According to the European Environment Agency report (2002), construction and demolition waste (CDW) represents a significant fraction of municipal solid waste, posing considerable environmental and management challenges [2]. The improper disposal of this waste in landfills not only entails the loss of potentially reusable materials but also contributes to the depletion of natural resources and environmental degradation [3,4].

Construction is one of the most important productive activities worldwide, contributing more than 10% to global gross domestic product. Beyond its economic significance, it also stands out for its social impact and its contribution to human development. Through scientific and technological progress, human activity has progressively transformed the geographical environment through economic activities aimed at the exploitation and transformation of natural resources. However, this process has caused significant environmental alterations, leading to irreversible damage to ecosystems [5].

Buildings consume between 20% and 50% of natural resources, depending on their context, with construction being a major consumer of resources such as timber, minerals, water, and fossil fuels. For example, this sector accounts for 12% of global potable water consumption and generates 36-37% of global greenhouse gas emissions [6]. The indiscriminate exploitation of natural resources has multiple negative effects on both the economy and the environment. Non-renewable resource reserves, such as minerals and energy resources, are finite, while the improper management of renewable resources such as timber produces adverse environmental effects, including the reduction of water sources [7].

Moreover, once completed, buildings continue to be a direct source of pollution due to their emissions and their impact on land use, as well as an indirect source of pollution through the energy and water consumption required for their operation [8].

Therefore, in order to achieve its primary objectives, sustainable construction is based on a series of essential principles: reducing, reusing, recycling, protecting the environment, eliminating toxic materials, reducing costs throughout the life cycle, and ensuring building quality [9]. These principles must be applied to the different resources involved, such as land, materials, water, energy, and ecosystems. Furthermore, they must be implemented at all stages of the construction process: planning, development, design, construction, use and operation, maintenance, refurbishment, and deconstruction [10].

In this context, the rehabilitation, renovation, or transformation of existing buildings into more sustainable, ecological, and environmentally friendly structures is actively pursued [11].

To contribute to more sustainable development, reduce pollution to a minimum, and meet the objectives set by the European Union, a series of strategies is proposed as a starting point for change, which in recent years have become an essential part of construction planning [12].

The growing generation of construction and demolition waste (CDW) has driven extensive research into its reuse in construction materials in order to reduce the environmental impact of the sector. Several studies have demonstrated the technical feasibility of incorporating CDW into concrete,

mortars, and prefabricated products, achieving materials with acceptable mechanical performance for non-structural applications [13-15].

In the case of gypsum and plaster, materials widely used in interior finishes, multiple research lines have focused on the incorporation of recycled waste to improve their sustainability and functional performance [16]. The addition of industrial by-products and waste such as recycled gypsum, metallic residues, polymers, plastics, wood, crushed glass, or rubber generally leads to a reduction in material density and improvements in thermal and acoustic insulation, although often accompanied by a decrease in mechanical strength [17,18]. Nevertheless, several authors agree that these composites are suitable for lightweight construction elements, contributing to improved building energy performance and the valorization of difficult-to-manage waste [19-23].

On the other hand, although fewer studies have addressed the incorporation of cardboard, paper, or cellulose waste into gypsum- or cement-based matrices, available research shows that these materials can improve lightness, workability, and certain thermal properties [24,26,27]. However, an increase in water absorption and, in some cases, a reduction in mechanical strength has also been observed, limiting their use to specific non-structural applications [25,28]. Even so, these materials are highlighted and economically viable alternative to conventional materials.

Finally, the use of reinforcing fibers—particularly glass fibers and mineral fibers derived from construction waste—has proven to be an effective strategy for improving the mechanical properties of gypsum. The incorporation of small amounts of fibers significantly enhances flexural strength, elasticity, and material integrity without negatively affecting workability, while also providing improvements in thermal and acoustic performance and fire behavior [3,29,30].

For all these reasons, the present study aims to build upon previous research, provide new sustainable solutions, and offer viable alternatives for the recovery of inert waste, thereby contributing to the closure of material life cycles and the promotion of a circular economy in the construction sector [31].

2. METHODOLOGY

This research evaluates the mechanical and physical performance of gypsum-based composites incorporating construction and demolition waste (CDW), specifically corrugated cardboard waste and glass fiber residues (Figure 1). The experimental program evaluated the effect of residue incorporation at 10% and 20% by volume to gypsum (Table 1: G1-20/20; G2-10/20; G3-20/10). A control mixture without additions was produced for comparison (Table 1: REF). The water-to-gypsum ratio (w/g) was fixed at 0.8 for all mixtures to isolate the influence of residue incorporation.

Commercial gypsum plaster E-35 Iberyola (Placo) was used as the binder. The material is classified as type A gypsum binder according to UNE-EN 13279-1, with a fineness of 0–0.2 mm, purity >92%, and flexural strength >3.5 N/mm². Mixing water consisted of potable tap water supplied by Canal de Isabel II (Madrid, Spain), compliant with UNE-EN 13279-2 requirements.

Cardboard waste was obtained from post-consumer corrugated packaging (≤ 2 mm thickness) with a unidirectional internal structure. The material was mechanically shredded into strips approximately 5 mm wide and subsequently cut to a maximum length of 10 mm. Cutting was performed perpendicular

to the corrugation direction to enhance mechanical interlocking and facilitate gypsum paste penetration into internal voids.

Glass fiber waste originated from discarded thermal insulation panels. The material was mechanically disintegrated until fiber agglomerations were eliminated and individual fibers could be manually separated, promoting homogeneous dispersion within the matrix.



Figure 1. Cardboard waste (a); Glass fiber waste (b)

Prismatic specimens (160 × 40 × 40 mm) were manufactured in accordance with UNE-EN 13279-2. Four mixtures were produced: reference (REF), 10% residue addition, and 20% residue addition. Residues were incorporated as additions without gypsum replacement and without modifying the w/g ratio. Prior to water addition, gypsum and residues were dry-mixed to improve homogeneity.

Mixing was performed manually for 3 min. Gypsum (and dry-blended residues) was gradually added to water over 30 s and allowed to soak for 60 s. The mixture was then manually stirred for 30 s, rested for 30 s, and mixed for an additional 30 s to achieve a homogeneous paste while minimizing entrapped air. The paste was immediately cast into oiled steel molds. Air voids were reduced by gently lifting and releasing the molds (~10 mm) five times. Casting was completed within 10 min from the start of mixing.

Three specimens were produced per mixture. After initial setting, excess material was removed using a straightedge. Specimens were demolded after sufficient hardening, weighed, and stored under controlled laboratory conditions (23 ± 2 °C; 50 ± 5% RH) for 7 days. Subsequently, specimens were oven-dried at 40 ± 2 °C for 24 h until constant mass and cooled to room temperature prior to testing.

Table 1. Composition of the mixtures proposed in the research

Designation	Gypsum (g)	Water (g)	%CDW on gypsum by volume		Density (g/cm ³)
			Cardboard	Fibers	
REF	1000	800	---	---	0.989
G1-20/20	1000	800	20%	20%	0.976
G2-10/20	1000	800	10%	20%	0.991
G3-20/10	1000	800	20%	10%	0.995

2.1. Physical tests

Physical characterization included hardened density, dynamic Young's modulus, and capillary water absorption:

Hardened density was determined according to UNE 102042 by dividing dry mass by geometric volume (256 cm³). Mean values were calculated from three specimens per mixture.

Dynamic Young's modulus was determined by ultrasonic pulse velocity in accordance with UNE-EN 12504-4 using an Ibertest Ultrasonic Tester E46 in direct transmission mode. A coupling gel ensured proper acoustic contact between transducers and specimen surfaces. Pulse velocity V (km/s) was calculated as:

$$V = L / T$$

where L is the transmission path (mm) and T is the transit time (μ s).

The dynamic modulus E_D (MN/m²) was calculated as:

$$E_D = V^2 \cdot \rho$$

where ρ is the density (kg/m³).

Capillary water absorption was evaluated according to RILEM RC 25-PEM. Oven-dried specimens were placed vertically with a water contact depth of 10 ± 1 mm. Capillary rise was recorded at 1-min intervals over 10 min, and final penetration heights were measured and averaged.

All tests were conducted in the Materials Laboratory of the Escuela Técnica Superior de Edificación (Universidad Politécnica de Madrid). Results are presented as mean values with corresponding standard deviations. Statistical analysis was performed using one-way analysis of variance (ANOVA) to assess the significance of residue incorporation level on mechanical and physical properties, considering a significance level of $p < 0.05$.

2.2. Mechanical tests

Mechanical characterization included Shore C surface hardness, flexural strength, and compressive strength:

Shore C hardness was determined according to UNE 102042 using a calibrated durometer. Five measurements were taken on each longitudinal face of each specimen, resulting in 60 measurements per mixture. Measurement points were spaced at least 20 mm apart. Outliers exceeding 2.5 standard deviations were excluded. Results are reported as mean values.

Flexural strength was determined by three-point bending in accordance with UNE-EN 13279-2 using an Ibertest Autotest 200-10SW universal testing machine. The span between supports was 100 mm, and load was applied centrally at a constant rate until failure. The flexural strength P_F is given by the formula:

$$P_F = 0.00234 \times P$$

where P_F is the flexural strength in N/mm², and P is the average breaking load in N of at least three obtained values.

Compressive strength was determined using the halves obtained after flexural testing, applying load over a 40 × 40 mm cross-section. Specimens were positioned such that molded faces were in contact with the loading plates. The compressive strength load R_c is given by the formula:

$$R_c = \frac{F_c}{1600}$$

where F_c is the maximum failure load (N) and 1600 mm² is the loading area. Some halves were reserved for capillarity testing and were not included in compressive testing.

3. RESULTS AND DISCUSSION

3.1. Physical properties

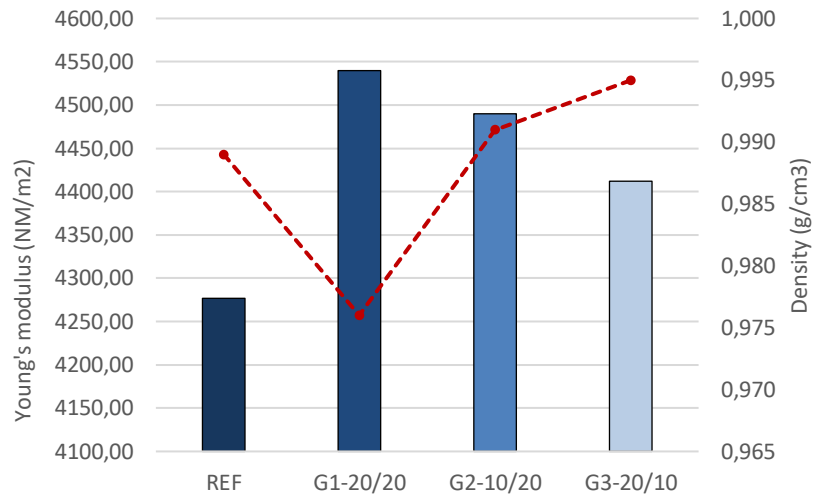
Table 2 summarizes the hardened density, dynamic Young’s modulus and capillary water absorption results of the tested composites. Hardened density values remained practically constant across all mixtures, with average values ranging between 0.976 and 0.995 g/cm³. The reference mixture (REF) showed a mean density of 0.989 g/cm³, while mixtures incorporating residues exhibited negligible variations (<1%). The lowest mean density was observed in G1-20/20 (0.976 g/cm³), corresponding to the highest total waste content (20% cardboard + 20% fibers), indicating a slight reduction attributable to the lower specific gravity of the incorporated waste materials. It is reasonable to conclude that the hardened density remains within a relatively narrow range and decreases slightly as the waste content increases, due to the lower specific gravity of these materials. This is consistent with the results reported in other studies of plasters with rubber/felt and recycled polymer fibers [32-33].

Table 2. Results of physical properties tests

Designation	Hardened density (g/cm ³)	Dynamic Young’s modulus (MN/m ²)	Capillary water absorption (mm)
REF	0.989	4276.80	46.10
G1-20/20	0.976	4539.77	32.30
G2-10/20	0.991	4489.92	36.20
G3-20/10	0.995	4412.04	37.80

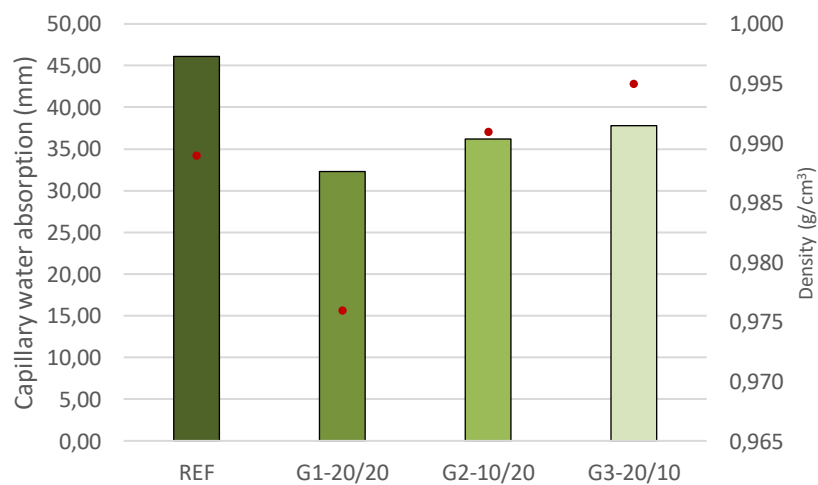
In contrast, the dynamic Young's modulus showed an increase in stiffness in all modified mixtures compared to the reference (Graphic 1). The control mixture exhibited a mean modulus of 4276.80 MN/m². The incorporation of waste increased stiffness by +6.15% in G1-20/20 (4539.77 MN/m²), +4.99% in G2-10/20 (4489.92 MN/m²), and +3.16% in G3-20/10 (4412.04 MN/m²). The greatest increase in stiffness was observed in the mixture with the highest combined waste content (G1-20/20). The results indicate that the addition of waste, particularly when the fiber content is higher, increases the dynamic stiffness of the hardened matrix despite minimal density changes. These trends are in line with previous studies on gypsum-based composites, where the incorporation of glass fibers and other

waste fibers has been shown to increase the stiffness and mechanical performance of the gypsum matrix with only limited changes in bulk density [34-36].



Graphic 1. Results of the Density and Young's modulus test

Capillary water absorption results are presented in Graphic 2. The reference mixture exhibited a capillary rise of 46.10 mm after 10 min. All mixtures incorporating CDW showed reduced water absorption. The greatest reduction was observed in G1-20/20 (32.30 mm), corresponding to a decrease of 29.9% relative to the reference. G2-10/20 and G3-20/10 exhibited reductions of 21.5% (36.20 mm) and 18.0% (37.80 mm), respectively. These results demonstrate that residue incorporation significantly reduces capillary water uptake. Mixtures with higher fiber content showed slightly lower absorption compared to those with higher cardboard content. Several studies have shown that replacing part of gypsum with waste materials (plastics, rubber, or vegetable fibres) can significantly reduce water absorption, particularly by capillarity, while maintaining acceptable mechanical strength [37-39]. In some cases, the reduction in capillary water absorption reaches values of 30–50% compared with reference gypsum, which is consistent with the maximum reduction of 29.9% obtained in this study.



Graphic 2. Results of the Density and Young's modulus test

3.2. Mechanical properties

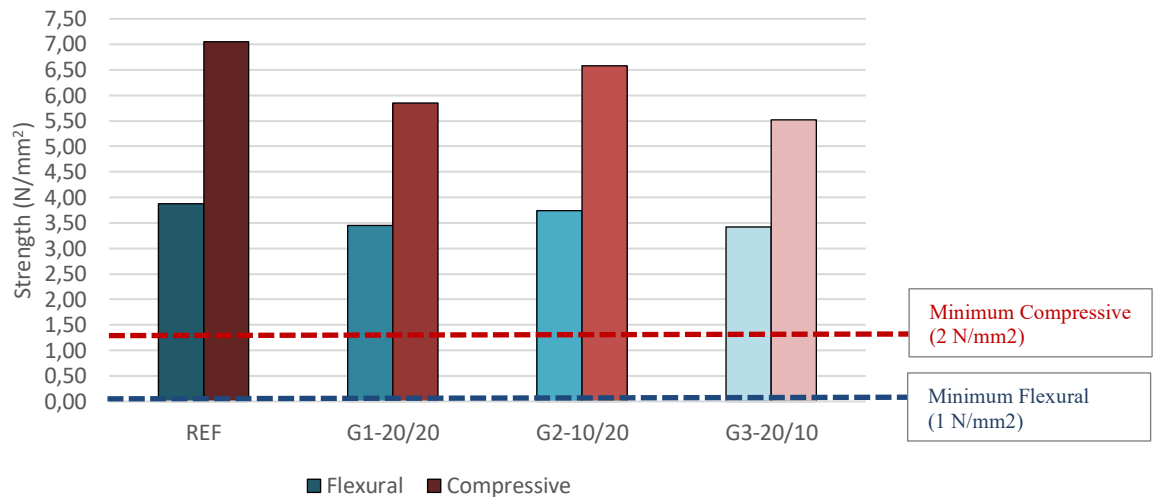
Surface hardness, flexural and compressive strengths are summarized in Table 3. The reference mixture presented an average Shore C hardness of 69.10. All residue-modified mixtures exhibited increased hardness. G1-20/20 achieved the highest mean value (76.80), representing an increase of 11.15% relative to the reference. G2-10/20 and G3-20/10 presented mean values of 75.30 and 74.90, corresponding to increases of 8.97% and 8.38%, respectively. Hardness increased with total residue content and showed slightly higher values in mixtures with greater fiber proportion. The observed trend (hardness increases with total waste content and slightly higher values for mixtures with a higher fiber fraction) aligns with previous findings where inorganic or high-stiffness waste and fibers contribute to greater hardness and strength by refining the pore structure and improving stress transfer in the matrix [40-42]. Therefore, the study is justified as it highlights that engineered eco-gypsum composites not only meet regulatory hardness requirements but can also outperform conventional gypsum in surface strength while incorporating significant waste content.

Table 3. Results of mechanical properties tests

Designation	Shore C hardness (units Shore C)	Flexural strength (N/mm ²)	Compressive strength (N/mm ²)
REF	69.10	3.88	7.05
G1-20/20	76.80	3.45	5.85
G2-10/20	75.30	3.74	6.58
G3-20/10	74.90	3.42	5.52

Flexural and compressive strengths are reported in Graphic 3. The reference mixture exhibited a mean flexural strength of 3.88 N/mm² and a mean compressive strength of 7.05 N/mm². All modified mixtures showed a reduction in strength compared to the reference.

Flexural strength decreased by 11.10% in G1-20/20 (3.45 N/mm²) and by 11.90% in G3-20/10 (3.42 N/mm²). In contrast, G2-10/20 exhibited only a slight reduction (-3.60%), with a mean value of 3.74 N/mm², indicating improved performance when fiber content was proportionally higher relative to cardboard. Despite these reductions, all mixtures exceeded the minimum requirement established by UNE-EN 13279-2 (1 N/mm²).



Graphic 3. Results of Flexural and Compressive strengths test

Compressive strength reductions were more pronounced. G1-20/20 showed an 17.00% decrease (5.85 N/mm²), G2-10/20 a reduction of 6.70% (6.58 N/mm²), and G3-20/10 the largest decrease of 21.70% (5.52 N/mm²) relative to the reference (6.99 N/mm²). Although compressive strength decreased with residue incorporation, all mixtures remained well above the minimum normative requirement of 2 N/mm².

Failure patterns differed between mixtures. Reference specimens exhibited brittle behavior with clean fracture surfaces under flexural loading. In contrast, residue-modified specimens remained partially bridged after flexural failure, indicating fiber and cardboard reinforcement effects. Under compressive loading, reference specimens displayed the typical pyramidal failure geometry with inclined fracture planes, whereas modified specimens showed more dispersed fragmentation, consistent with reduced compressive cohesion.

These results are corroborated by other studies on gypsum composites reinforced with basalt fibers and braids, where the fibers and meshes restrict crack propagation and prevent a sudden drop in stress, keeping part of the panel still “stitched” together after flexural failure [43-44]. Furthermore, the addition of fibers leads to greater distributed fragmentation, more tensile and shear cracks, reflecting lower effective compressive cohesion but more ductile behavior of the assembly [45-46].

3.3. Statistical analysis

One-way ANOVA revealed statistically significant differences ($p < 0.05$) between the reference and residue-modified mixtures for Shore C hardness, compressive strength, capillary absorption, and dynamic Young’s modulus. Post hoc Tukey tests confirmed that mixtures with higher total residue content exhibited significantly increased hardness and stiffness, while compressive strength reductions were statistically significant primarily in mixtures with higher cardboard proportion.

4. CONCLUSIONS

This study investigates the feasibility of incorporating fibrous and cardboard construction and demolition waste into gypsum-based composites as a sustainable construction solution. To achieve

this, it is guaranteed that the raw materials used comply with the requirements of UNE-EN 13279-1:2009, ensuring the reliability and comparability of the experimental results. The characteristics of the incorporated residues are consistent with those reported in previous studies, taking into account possible variations resulting from prior use.

The experimental results indicate that material hardness increases with higher residue content, attributable to the intrinsic properties of the added materials. However, a reduction in both flexural and compressive strength is observed with the incorporation of fibrous residues or cardboard, with mixtures containing glass fibers showing a less pronounced decrease, particularly in flexural strength. In contrast, composites with higher proportions of cardboard exhibit a more significant deterioration of mechanical performance.

Regarding physical properties, the density of CDW-containing mixtures remains very similar to that of reference material, as the increase in solid content is offset by the low density of the incorporated residues. An increase in material stiffness is also observed in composites containing residues, likely due to particle size, internal cohesion forces, and lower porosity. Additionally, water absorption capacity decreases, as the added residues are less porous than conventional gypsum.

Future research should focus on evaluating the mechanical, physical, thermal, acoustic, and fire performance of the developed composite in plate form, in order to assess its behavior under real application conditions and to further define its suitability for specific building uses.

Overall, the results confirm the technical feasibility of the developed material for non-structural applications such as drywall panels or suspended ceiling boards. The performance achieved is comparable to that of commercial products, while offering the advantages of reduced cost and lower environmental impact, reinforcing the potential of this approach as a sustainable alternative for the construction sector.

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