



Development of Eco-Friendly Gypsum Composite Using Gypsum Binder and Gypsum Waste Aggregates

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Abstract. The development of sustainable building materials is increasingly focused on integrating regenerative resources and secondary raw materials obtained through industrial symbiosis. In this context, gypsum composites represent a promising solution for reducing environmental impact in the construction sector. The raw materials used for gypsum composites include not only building gypsum (BG) but also gypsum-based demolition waste (GDW). In this study, gypsum composites were produced using BG binder combined with varying proportions of fine recycled fillers derived from GDW. The primary aim was to evaluate whether incorporating GDW can reduce environmental impact while maintaining mechanical performance comparable to reference gypsum composites without recycled material. BG was substituted with 10, 20, 30, and 40 wt% GDW, and the gypsum-to-water (G/W) ratio varied from 0.5 to 0.7. For each composition, nine samples were tested. The structural and mechanical behavior of the composites was assessed using X-ray diffraction (XRD), scanning electron microscopy (SEM), compressive strength tests, hydration temperature measurements, and loss-on-ignition analysis. The results showed that the proportion of recycled fillers significantly influenced the key material properties. Notably, a slight improvement in compressive strength was observed in the eco-friendly composites: the reference sample achieved 13.85 MPa, whereas the composite containing 10 wt% GDW reached 15.95 MPa. However, higher GDW content led to a reduction in compressive strength. This increase can be attributed to the micro-filler and nucleation effects of GDW, which produced denser microstructure and improved bonding characteristics.

Keywords: Gypsum composite · Secondary raw materials · Building gypsum binder · Gypsum boarding waste aggregates

1 Introduction

Gypsum, a long-used construction material, can significantly improve its sustainability through circular-economy strategies, including recycling and the partial replacement of raw gypsum with various construction and demolition wastes. A study [1] shows that gypsum composites and prefabricated elements can incorporate a wide range of waste materials—such as concrete, ceramics, glass, plastics, and insulation materials—while maintaining viable mechanical performance for building applications. Villiorya et al. [2] showed that adding ceramic, concrete, and expanded polystyrene (EPS) construction waste to gypsum can improve density, mechanical strength, and thermal behavior. Using the best mixture, they produced a sandwich-type gypsum block, demonstrating both performance gains and environmental benefits through waste reuse. A related study [3] tested lightweight fillers such as silica sand, perlite, expanded clay, and waste polyurethane foam. Filler porosity was found to shape the gypsum microstructure, producing smaller, denser crystals around porous particles. Mortar with polyurethane foam had the lowest strength (2.9 MPa at 7 days) but the best thermal conductivity (0.211 W/m·K). Pedreño-Rojas et al. [4] showed that recycled gypsum combined with wood waste can produce eco-efficient gypsum composites with lower density, improved thermal insulation, and adequate mechanical performance for building applications. The study [5] evaluates the incorporation of ceramic and EPS waste into gypsum products, showing that up to 50% ceramic waste maintains core properties while improving hardness and reducing water absorption, and EPS additions lower density and enhance thermal performance, supporting future inclusion in a national recycling database.

Several studies have demonstrated that gypsum derived from construction and demolition waste (GDW) can be effectively reused as a gypsum binder, showing technical feasibility, stable performance across multiple recycling cycles, and compatibility with various additives for producing sustainable construction materials. Bumanis et al. [6] stated that GDW can be recycled into a functional gypsum binder, though its performance depends strongly on gypsum purity, fineness, and the required water-to-gypsum ratio. Laboratory results show that recycled GDW, after separation, crushing, milling, and controlled heat treatment, can achieve strengths up to 3.7 MPa, demonstrating its potential as a secondary raw material within a circular gypsum life cycle. Study made by Erbs et al. [7] shows that gypsum waste can be successfully recycled up to three cycles without significant loss of physical or mechanical performance, confirming the technical viability of repeated reuse. These findings highlight the potential for producing new building components with high recycled-gypsum content, supporting circular-economy strategies and creating new commercial opportunities in the construction sector. Crushed plasterboard waste is a viable sulphate source for activating pozzolanic binders made from slag and cement bypass dust. Hughes et al. [8] showed that a mix containing 15% gypsum, 5% bypass dust, and 80% basic oxygen slag performs on par with conventional cement in road construction, offering a cost-efficient and sustainable reuse route for plasterboard gypsum and other industrial by-products. In a similar study, Zaharieva et al. [9] found that recycled gypsum from plasterboard waste can be effectively used in blended green binders, providing fast-setting behavior and achieving strengths up to 30 MPa when combined with natural zeolite.

The aim of this study is to examine how incorporating gypsum-based demolition waste (GDW) as a recycled filler influences the key physical, mechanical, and microstructural properties of gypsum-based building composites, and to determine whether these changes support the development of more sustainable construction materials.

2 Materials and Methods

2.1 Characterization of Initial Materials

The X-ray diffraction pattern of the commercial building gypsum shows reflections characteristic of calcium sulfate hemihydrate (bassanite, $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$), confirming that the material is predominantly in the semihydrate form (Fig. 1a). The main diffraction peaks appear at approximately $2\theta \approx 14.7^\circ$, 25.5° , 29.7° , and 31.2° , corresponding to the most intense bassanite planes. Some residual peaks of dolomite ($\text{CaMg}(\text{CO}_3)_2$), are detected as well. In the building gypsum system, the semihydrate phase remained predominant despite the incorporation of dolomite.

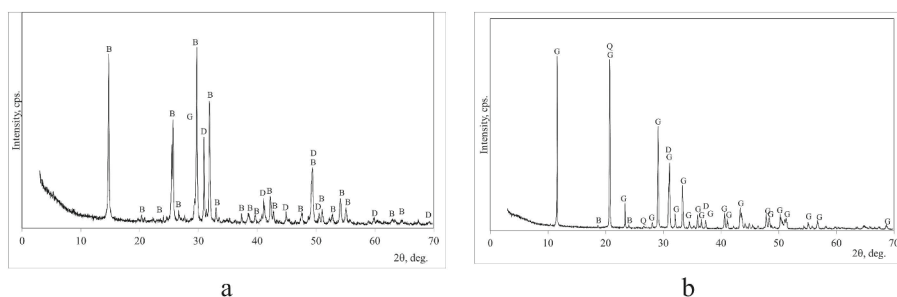


Fig. 1. X-ray diffraction patterns of building gypsum (a) gypsum-based demolition waste (b): G - gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (33–331), B - bassanite $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$ (33–310), D - dolomite $\text{CaMg}(\text{CO}_3)_2$ (74–1687), Q - quartz SiO_2 (72–916).

For the gypsum-based demolition waste (Fig. 1b), the hydrated mineral forms were identified as being dominated by the $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ dihydrate phase, accompanied by only minor amounts of dolomite and quartz. The loss on ignition (LOI) for GDW consisted of 16.36.

SEM images (Fig. 2a) show that BG exhibits sharp-edged, plate-like crystals forming a structure composed of particles of varying size. The crystals are typically a few micrometers in size and display an irregular morphology characteristic of β -type hemihydrate. A similar form of building-gypsum crystals, such as flaky particles composed of small intergrown crystals, was also reported by Singh et al. [10]. In contrast, the GDW (Fig. 2b) displays a markedly more homogeneous microstructure. The crystalline framework is disrupted, characterized by fragmented needle-like forms and irregular particle boundaries. The dry bulk density of the GDW is 581.01 kg/m^3 .

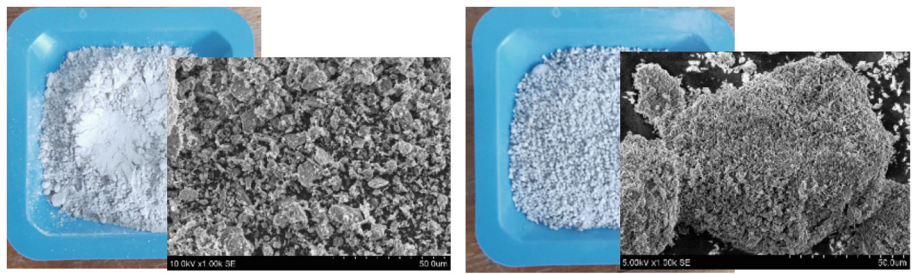


Fig. 2. Microstructure of building gypsum (a) and gypsum-based demolition waste (b).

2.2 Preparation for Forming Mixtures

Table 1 outlines the formulation of the gypsum composites prepared using varying proportions of building gypsum (BG) and gypsum-based demolition waste (GDW). The mixtures range from a reference sample composed entirely of BG (0GDW) to blends containing up to 40% GDW (40GDW).

Table 1. The composition of initial materials for gypsum composite.

Sample	BG (%)	GDW (%)	W/G
0GDW	100	0	0.5
10GDW	90	10	0.5
20GDW	80	20	0.5
30GDW	70	30	0.6
40GDW	60	40	0.7

As the GDW content increases, the **water-to-gypsum ratio (W/G)** is gradually adjusted to ensure workable consistency. Samples with lower GDW content (10–20%) maintain a constant W/G ratio of 0.5, while higher GDW substitutions require increased water demand (0.6–0.7) associated with recycled gypsum waste.

Figure 3 presents the prepared gypsum composite specimens containing increasing proportions of GDW. The size of samples was 4 × 4 × 4 cm.

2.3 Test Methods

X-ray diffraction (XRD) analysis was performed using a Bruker AXS D8 diffractometer with CuK α radiation and a 0.02 mm Ni filter. The detector step size was 0.02°, counting time 0.5 s, and the operating conditions were 40 kV and 40 mA. The amount of bound water (loss on ignition) was determined by heating the material to 400 °C. The microstructure was examined using an FEI Quanta 200F SEM equipped with a Schotky field-emission gun (FEG). Imaging was performed in high-vacuum mode at 5 kV. Compressive strength tests were conducted after 7 days of curing according to LST EN 12390-3:2019, using 4 × 4 × 4 cm cubic specimens and a Zwick Roell testing machine.

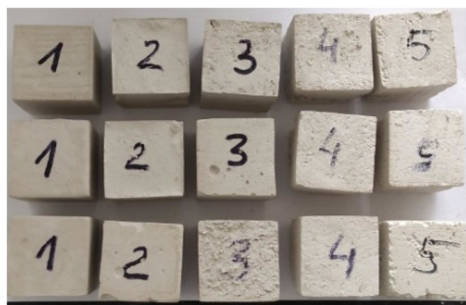


Fig. 3. The picture of gypsum composites samples.

3 Results and Discussions

Figure 4 illustrates the evolution of hydration temperature for the gypsum composite mixtures incorporating increasing proportions of GDW.

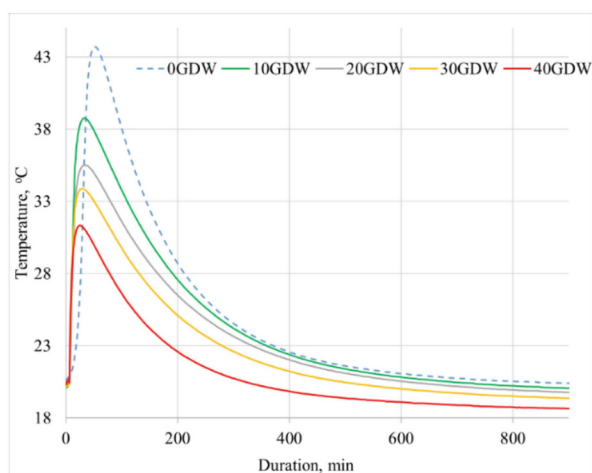


Fig. 4. Hydration temperature of gypsum composites samples.

The reference sample (0GDW) exhibits the highest temperature (43.6 °C), reflecting the typical exothermic behavior of pure building gypsum during setting. As the GDW content increases, the peak hydration temperature gradually decreases, with the 40GDW mixture reaching only 31.25 °C, and the temperature curve becomes more attenuated. This reduction in hydration temperature indicates a lower amount of gypsum binder. The duration of the main hydration peaks is also closely linked to the proportion of GDW in the mixture. As the GDW content increases, the hydration peaks shift toward shorter durations, which may be attributed to the accelerating effect of calcium sulfate dihydrate, as this phase acts as a setting accelerator within the system [11].

The density curve (Fig. 5a) shows that the sample with lowest amount of GDW exhibits the highest density (1389 kg/m³), while higher amount of GDW leads to a gradual reduction, reflecting the lower density and more porous nature of samples.

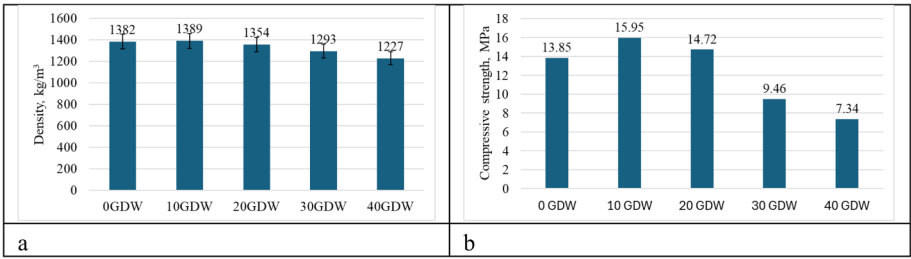


Fig. 5. The influence of the amount of GDW on the density and compressive strength of gypsum composites samples.

A similar trend is observed in the compressive strength results (Fig. 5b). The 10GDW sample achieves the highest strength (15.95 MPa), whereas mixtures containing 30–40% GDW show a noticeable decrease in mechanical performance. This reduction is associated with the diminished amount of reactive gypsum binder at higher substitution levels, which weakens the overall microstructure. The slight strength increase observed at 10% GDW can be attributed to a micro-filler and nucleation effect. At low replacement levels, fine GDW particles fill voids within the matrix and provide additional nucleation sites for gypsum crystallization, promoting a denser and more interconnected crystal network. This leads to improved mechanical performance compared with the reference sample. However, once the GDW content exceeds this optimal threshold, the reduced binder fraction and the more heterogeneous nature of the recycled material dominate, resulting in lower strength.

Despite these reductions, the composites containing moderate GDW levels (10%) retain sufficient strength for non-structural applications, highlighting the potential of GDW as a sustainable partial replacement in gypsum-based materials.

XRD analysis was used to determine the mineral composition of the hardened gypsum composites (Fig. 6). The results demonstrated that the mineral composition was nearly identical across all examined samples. Gypsum dihydrate (G) remained the dominant crystalline phase in all mixtures. Dolomite (D) and quartz (Q) were identified as minor phases originating from the GDW and BG. Although these phases do not participate in hydration, their presence contributes to the overall heterogeneity of the system and may influence mechanical performance by acting as non-reactive fillers. Bassanite (B) was also detected in small quantities.

The SEM images in Fig. 6 reveal a microstructure typical of gypsum dihydrate for the composite containing 10 wt% GDW. The material displays a dense and well-interlocked network of acicular gypsum crystals, characteristic of a fully hydrated and structurally cohesive matrix [12]. These needle-like crystals form continuous contact points, which explains the relatively high mechanical strength observed in samples with low GDW content. Overall, the SEM analysis confirms that low GDW additions can still

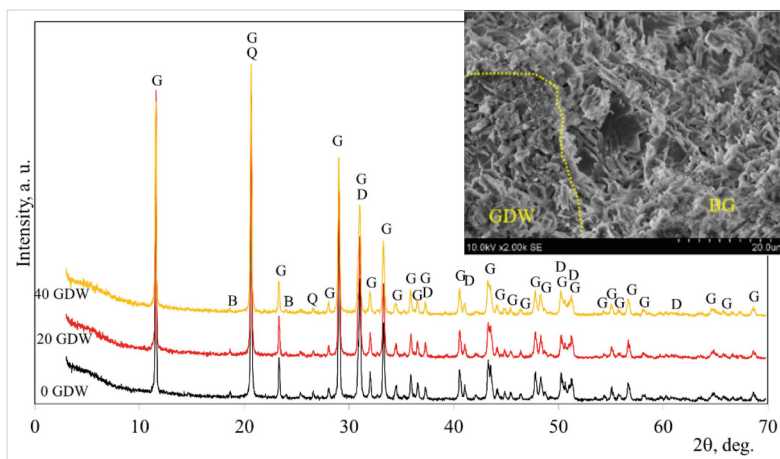


Fig. 6. Mineral composition according to XRD analysis and microstructure (SEM analysis) of gypsum composite samples. Notes: G - gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (33–331), B - basanite $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$ (33–310), D - dolomite $\text{CaMg}(\text{CO}_3)_2$ (74–1687), Q - quartz SiO_2 (72–916).

support the formation of a coherent gypsum matrix, directly influencing the mechanical performance of the composites. The contact zone between the GDW particles and the BG matrix shows the interface remains relatively well integrated, with gypsum dihydrate crystals growing around and partially anchoring the GDW fragments.

4 Conclusions

This study showed that gypsum demolition waste (GDW) can be effectively used as a partial replacement for building gypsum (BG), supporting more sustainable gypsum-based materials. Increasing GDW content reduced hydration-peak temperature and duration due to the lower binder fraction and the accelerating influence of residual calcium sulfate dihydrate. Up to 10 wt% of GDW improved compressive strength through micro-filler and nucleation effects, while higher levels (30–40 wt%) decreased density and strength because of reduced binder content and greater heterogeneity.

XRD confirmed a consistent mineral composition dominated by gypsum dihydrate, with dolomite and quartz from GDW acting as inert fillers. SEM analysis showed a dense, well-interlocked crystal network at low GDW levels and a more heterogeneous structure at higher substitutions. Overall, GDW is a viable and environmentally beneficial component for gypsum composites, particularly at low replacement levels suitable for non-structural applications, supporting circular-economy practices in gypsum-based construction. From a circular economy perspective, the use of gypsum-based demolition waste (GDW) as a partial replacement for building gypsum contributes to reducing construction waste and lowering the demand for primary raw materials. This approach supports material reuse within a closed-loop system and minimizes landfill disposal.

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