



Original Research Article

Optimizing Marble Waste–Gypsum–Fiber Composites for Decorative Ceiling Panels: A Circular Construction Materials Study

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ABSTRACT

The increasing accumulation of marble-processing residues presents persistent environmental and operational challenges for stone-processing industries, particularly in regions where waste reutilization pathways remain underdeveloped. Within circular economy frameworks, construction materials offer promising opportunities for mineral waste valorization; however, empirical evidence regarding gypsum-based interior products reinforced with natural fibers remains limited. This study investigates the feasibility of converting marble powder waste into decorative ceiling panels through composite fabrication using gypsum as a mineral binder and black sugar palm fiber as bio-based reinforcement. An experimental approach was employed to produce four mixture formulations with varying proportions of marble waste, gypsum, water, and fiber, cast into standardized molds and cured under ambient conditions. Product performance was evaluated through surface smoothness, porosity visibility, breakage resistance, drying time, and dimensional stability. The results indicate that fiber-reinforced composites with higher gypsum content exhibited superior surface quality and structural cohesion compared with marble-dominant mixtures and non-reinforced controls. The optimal formulation—comprising 3000 g gypsum, 1500 g marble waste, and 0.5 g black sugar palm fiber—produced the most uniform and durable panels while reducing reliance on virgin gypsum. These findings demonstrate the technical potential of marble waste-based ceiling components as low-cost circular construction products and highlight opportunities for localized waste-to-resource manufacturing systems. Future research should incorporate quantitative mechanical testing and life-cycle assessment to evaluate scalability and environmental performance.

Keywords: *circular construction; marble waste; gypsum composites; natural fiber reinforcement; sustainable building materials; waste valorization.*

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INTRODUCTION

The rapid expansion of the natural stone industry has intensified concerns regarding mineral waste accumulation and underutilized industrial by-products, particularly in regions where regulatory frameworks and recycling infrastructures remain limited. Marble processing, which involves block cutting, surface calibration, polishing, and finishing operations, generates substantial quantities of fine particulate residues and slurry that are frequently discharged into settling ponds or landfill sites. These waste streams not only impose disposal costs on manufacturers but also contribute to soil degradation, water contamination, and land-use pressures. Within the broader discourse on circular economy transitions, such linear disposal practices contradict emerging imperatives to retain material value through reuse, recycling, and industrial symbiosis (Kirchherr et al., 2017; Ghisellini et al., 2016; Chertow, 2007). Consequently, the transformation of marble residues into functional building materials has become an increasingly relevant research domain in sustainable construction and circular systems innovation.

The construction sector occupies a central position in sustainability debates because of its intensive consumption of raw materials, high embodied energy, and significant waste generation throughout building life cycles (Hamilton, I. et al., 2020). Interior architectural components, including ceiling panels, wallboards, and decorative elements, are typically manufactured from gypsum-based products reinforced with synthetic fibers or additives to enhance mechanical performance. While gypsum is widely regarded as a relatively low-emission binder compared with Portland cement, its extraction and processing nonetheless entail environmental burdens, particularly when used at large scale (Cabeza et al., 2014). Substituting a portion of virgin gypsum with industrial mineral waste, therefore, offers an attractive pathway for reducing resource depletion while simultaneously diverting by-products from disposal streams (Borreguero et al., 2014; Ferrández et al., 2025). However, the performance implications of such substitutions—especially for interior applications that demand smooth surface finishes, dimensional stability, and sufficient resistance to handling damage—remain insufficiently documented.

Recent scholarship on circular construction materials has emphasized the valorization of quarry fines, stone dust, and ceramic residues in cementitious matrices, paving blocks, and masonry units. These studies demonstrate that mineral wastes can function as fillers or supplementary constituents, often improving packing density or aesthetic characteristics while lowering overall material costs (Almeida et al., 2007; Medina et al., 2017). Nevertheless, the majority of existing investigations focus on Portland cement systems, with comparatively limited attention devoted to gypsum-based composites for non-structural interior components. Moreover, although natural fibers such as jute, kenaf, sisal, and palm derivatives have been explored as reinforcements in polymeric and cementitious composites (Pickering et al., 2016; Savastano et al., 2009), their integration into gypsum–mineral waste matrices has received far less systematic examination. This gap is particularly salient in developing contexts where agricultural residues and natural fibers are locally abundant and could form part of decentralized, low-cost circular production systems.



Natural palm fiber, locally known as black sugar palm fiber/*ijuk*, represents a promising reinforcement material within this landscape. Derived from the sugar palm tree (*Arenga pinnata*), black sugar palm fibers are characterized by high lignin content, resistance to biological degradation, and durability under humid or chemically aggressive conditions (Samlawi, A. K., 2018). These properties have motivated their traditional use in roofing, ropes, brushes, and protective wrapping for wooden foundations. From a materials engineering perspective, such fibers offer potential advantages when embedded within brittle mineral matrices, including crack-bridging capacity, enhanced toughness, and improved resistance to handling-induced fracture (Savastano et al., 2009). When combined with mineral binders and fine particulate fillers such as marble powder, black sugar palm fiber, fibers may therefore contribute to the development of hybrid bio–mineral composites that align with circular economy principles by integrating renewable reinforcements with industrial waste streams (Pomponi & Moncaster, 2017).

Against this backdrop, the present study examines the feasibility of producing decorative ceiling panels from marble powder waste blended with gypsum and reinforced with black sugar palm fiber. The empirical work was conducted at a marble workshop laboratory in Aceh Selatan, Indonesia, a region characterized by active stone-processing operations and growing interest in waste minimization strategies within technical education facilities. The research responds directly to local sustainability challenges by exploring whether by-products generated during marble cutting and polishing can be reintroduced into value-added construction products, thereby reducing disposal requirements and creating potential economic opportunities for workshop-based manufacturing units within localized circular systems (Neves et al., 2020).

Unlike conventional gypsum ceiling products that rely primarily on virgin mineral inputs and synthetic fibers, the experimental formulations investigated in this study incorporate varying proportions of marble waste and natural fiber reinforcement. Four mixture ratios were designed to evaluate how changes in binder-to-filler proportions and fiber inclusion influence surface quality, porosity, breakage resistance, drying time, and dimensional stability under laboratory conditions. Although the testing protocol emphasizes qualitative and visual assessment methods rather than standardized mechanical characterization, the study provides an initial exploratory dataset for identifying promising compositions and informing future quantitative investigations. By focusing on decorative ceiling elements—components that are widely used in residential interiors yet rarely examined in circular materials research—the work extends the scope of waste valorization studies beyond structural concretes and masonry units (European Commission, 2020).

From a circular systems perspective, the proposed ceiling panels exemplify a localized closed-loop strategy in which industrial residues are converted into interior building products within the same regional ecosystem that generates the waste. Such approaches resonate with contemporary models of distributed manufacturing and industrial symbiosis (Chertow, 2007), wherein educational institutions, small workshops, and local enterprises collaborate to prototype and commercialize sustainable materials using readily available by-products. The incorporation of black sugar palm fiber further strengthens this circular logic by introducing a renewable, biodegradable reinforcement sourced from regional agricultural systems, thereby



reducing dependence on imported synthetic fibers and enhancing socio-economic co-benefits for rural communities.

This article makes three principal contributions to the literature on circular construction materials and sustainable composite design. First, it empirically demonstrates the technical feasibility of producing gypsum-based decorative ceiling panels containing substantial proportions of marble powder waste. Second, it provides comparative evidence regarding the role of natural palm fiber reinforcement in improving surface integrity and resistance to breakage in mineral composites. Third, it identifies an optimal mixture ratio that balances material substitution with product quality, thereby offering practical guidance for small-scale manufacturers seeking to implement waste-derived interior components. Together, these contributions advance understanding of how hybrid bio–mineral composites can support circular economy transitions in the building sector (Pomponi & Moncaster, 2017).

The remainder of this article is structured as follows. The next section reviews relevant literature on marble waste utilization, gypsum-based composites, natural fiber reinforcement, and circular construction frameworks, culminating in the development of research propositions guiding the experimental investigation. The subsequent sections describe the research methodology, present the experimental results, and discuss their theoretical and practical implications for sustainable materials innovation. The article concludes by summarizing the main findings, acknowledging limitations, and outlining directions for future research on performance testing, life-cycle assessment, and scalability within circular production systems.

LITERATURE REVIEW

2.1 Circular Economy and Construction Waste Valorization

The construction sector has been widely recognized as a critical arena for implementing circular economy principles due to its intensive resource consumption, high embodied energy, and substantial waste generation across the building life cycle (Pomponi & Moncaster, 2017; Hamilton, I. et al., 2020). Circular economy frameworks emphasize closing material loops through strategies such as reuse, recycling, remanufacturing, and industrial symbiosis, thereby reducing dependence on virgin resources while mitigating environmental externalities (Kirchherr et al., 2017; Ghisellini et al., 2016). Within this paradigm, mineral processing residues—including quarry fines, stone dust, and polishing sludge—have attracted increasing scholarly attention as potential secondary raw materials for construction applications.

Several studies have demonstrated that incorporating stone-derived waste into cementitious systems can enhance particle packing density and surface finish while lowering production costs and carbon footprints (Almeida et al., 2007; Medina et al., 2017). Researchers have reported successful applications in paving blocks, mortar, masonry units, and terrazzo-like floor tiles, noting that optimized substitution levels can preserve or even improve compressive strength relative to conventional formulations. Nevertheless, the environmental performance of these systems depends strongly on the degree of substitution achieved and the proximity



between waste-generation sites and manufacturing facilities, highlighting the importance of localized circular production networks (Pomponi & Moncaster, 2017).

Despite these advances, the majority of construction-focused circular economy research remains concentrated on structural concrete applications, often overlooking interior architectural components such as ceiling boards, wall panels, and decorative elements. These products, although non-load-bearing, are widely used in residential and commercial buildings and collectively represent a significant material flow within the built environment. Expanding waste valorization strategies into this product category could therefore generate meaningful cumulative environmental benefits while opening new markets for secondary materials (European Commission, 2020).

2.2 Marble Waste Characteristics and Utilization Pathways

Marble is a metamorphic carbonate rock composed predominantly of calcite, with varying proportions of quartz, mica, chlorite, and iron-bearing minerals. During quarrying and downstream processing—particularly cutting, calibration, and polishing—large volumes of fine particulate waste and slurry are produced, creating environmental management challenges (Alyamac & Ince, 2009; Almeida et al., 2007). These residues typically contain high concentrations of calcium carbonate, rendering them chemically compatible with alkaline binders such as cement and gypsum.

Existing literature documents multiple valorization pathways for marble waste, including incorporation into cement mortars, ceramic bodies, polymer composites, and lime-based products. In cementitious systems, marble powder frequently functions as an inert filler, improving workability and surface smoothness while contributing marginally to strength development through micro-filler effects (Almeida et al., 2007; Medina et al., 2017). Ceramic applications similarly report fluxing behavior and reduced firing temperatures when carbonate wastes are introduced.

Nevertheless, comparatively few studies have examined marble waste in gypsum-based matrices, particularly for interior finishing products. Gypsum differs fundamentally from Portland cement in hydration chemistry and moisture sensitivity, raising questions about optimal substitution ratios and long-term durability when mineral wastes are introduced (Borreguero et al., 2014; Ferrández et al., 2025). Furthermore, while several investigations have assessed compressive and flexural strength in marble–cement systems, far fewer have focused on surface quality, porosity, and aesthetic attributes—properties that are especially important for decorative ceiling components.

2.3 Gypsum-Based Building Products in Sustainable Construction

Gypsum has long been employed in interior construction applications because of its fire resistance, dimensional stability under moderate humidity, smooth surface finish, and relatively low processing temperatures compared with cement-based materials (Cabeza et al., 2014). Common products include plasterboards, ceiling tiles, cornices, and decorative moldings, which are typically reinforced with glass fibers, paper liners, or polymer additives to enhance toughness and handling resistance.



Research on sustainable gypsum composites has increasingly explored partial substitution of virgin gypsum with industrial by-products such as flue gas desulfurization gypsum, phosphogypsum, and recycled plasterboard waste (Borreguero et al., 2014; Ferrández et al., 2025; Nisya, 2024). These studies report that carefully controlled formulations can achieve comparable mechanical and physical properties to conventional products while reducing reliance on primary mineral extraction. However, the integration of stone-derived wastes such as marble powder into gypsum matrices remains underrepresented in the literature, despite their chemical compatibility with calcium sulfate binders.

Moreover, sustainability-oriented gypsum research has begun to consider the role of bio-based reinforcements in replacing synthetic fibers. Natural fibers offer a potentially lower-impact alternative when sourced locally and incorporated into low-temperature binder systems, yet questions remain regarding fiber–matrix bonding and moisture durability (Pickering et al., 2016).

2.4 Natural Fiber Reinforcement in Mineral Composites

The use of natural fibers as reinforcement in composite materials has attracted substantial attention within sustainable materials engineering due to their renewability, biodegradability, low density, and favorable specific mechanical properties (Pickering et al., 2016; Faruk et al., 2012). Fibers such as jute, sisal, kenaf, flax, coir, and bamboo have been extensively studied in polymer matrices and, to a lesser extent, in cementitious and lime-based systems. In mineral composites, natural fibers can act as crack arresters, bridging microcracks and enhancing post-cracking toughness, thereby mitigating brittle failure mechanisms (Bentur & Mindess, 2007; Savastano et al., 2009), typically associated with inorganic binders.

However, natural fiber incorporation also presents challenges, including variability in fiber properties, susceptibility to moisture uptake, and potential degradation in alkaline environments. Surface treatments and matrix modifications are often employed to improve fiber–matrix adhesion and durability. Within gypsum-based systems, the relatively neutral pH compared with Portland cement may offer a more benign environment for plant fibers, suggesting opportunities to develop bio–mineral hybrids suitable for interior applications.

Palm-derived fibers—including black sugar palm fiber obtained from *Arenga pinnata*—exhibit high lignin content and resistance to biological attack, making them attractive candidates for construction composites (Faruk et al., 2012). These traits have motivated traditional uses in roofing materials, erosion control, and protective wrapping in construction. Preliminary investigations into palm fibers in cementitious composites suggest that they can enhance toughness and reduce crack propagation when appropriately dispersed and proportioned. Nevertheless, empirical research on black sugar palm fiber-reinforced gypsum composites—particularly those incorporating mineral waste fillers—remains scarce, positioning the present study within a relatively unexplored niche at the intersection of natural fiber reinforcement and circular material design.

2.5 Composite Material Theory and Hybrid Bio–Mineral Systems

Composite materials are generally defined as systems composed of two or more distinct phases—typically a matrix and a reinforcement—that retain their individual identities while



exhibiting synergistic properties in combination (Bentur & Mindess, 2007). In particulate-reinforced composites, fine fillers can modify rheology, packing density, and surface characteristics, whereas fiber reinforcements primarily contribute to load transfer, crack control, and toughness. Hybrid systems that combine particulate fillers with fibrous reinforcements are increasingly investigated as a means of tailoring multiple performance attributes simultaneously.

Within the context of circular economy strategies, hybrid bio–mineral composites offer particular promise because they enable the simultaneous utilization of industrial by-products and renewable biological resources. Such systems can reduce embodied energy, lower material costs, and create new value chains linking industrial and agricultural sectors (Pomponi & Moncaster, 2017). However, achieving balanced performance requires careful optimization of mixture proportions, as excessive filler content can weaken matrix continuity, while insufficient binder or reinforcement may compromise structural integrity.

Theoretical models of composite behavior emphasize the importance of interfacial bonding, particle size distribution, and reinforcement geometry in determining macroscopic properties. For gypsum–marble–fiber systems, the fine marble powder is expected to function primarily as a micro-filler, influencing surface smoothness and porosity, while gypsum acts as the primary load-bearing matrix, and black sugar palm fibers provide crack-bridging reinforcement. Experimental investigations that systematically vary these components can therefore yield insights into how hybrid composite architectures can be engineered for interior building applications within circular production frameworks.

2.6 Research Gap and Propositions

The foregoing review reveals several unresolved issues in the literature. First, although marble waste has been widely studied in cementitious and ceramic systems, its application in gypsum-based interior products remains limited (Almeida et al., 2007; Borreguero et al., 2014; Ferrández et al., 2025). Second, while natural fibers have been explored in mineral composites, palm-derived black sugar palm fibers are underrepresented, particularly in conjunction with industrial mineral fillers (Faruk et al., 2012). Third, decorative ceiling panels and similar interior components have received relatively little attention in circular construction research, despite their widespread use and potential for incorporating secondary materials.

To address these gaps, the present study advances an exploratory experimental investigation of marble waste–gypsum–black sugar palm fiber composites for decorative ceiling applications. Guided by composite material theory and circular economy principles, the research examines how varying binder–filler ratios and fiber inclusion influence surface quality and breakage resistance.

Accordingly, the study is informed by the following propositions:

- P1: Increasing the proportion of gypsum relative to marble waste improves surface integrity and resistance to breakage in decorative ceiling panels.
- P2: The incorporation of black sugar palm fiber enhances the cohesion and durability of gypsum–marble composites.



P3: Hybrid formulations combining mineral waste fillers with natural fiber reinforcement can produce interior building components suitable for circular construction systems.

METHOD

3.1 Research Design

This study employed an experimental laboratory-based design to evaluate the feasibility of producing decorative ceiling panels from marble powder waste combined with gypsum and natural palm fiber (black sugar palm fiber). A comparative mixture approach was adopted, whereby four formulations with systematically varied proportions of marble waste, gypsum binder, and fiber reinforcement were fabricated under controlled conditions. The experimental protocol emphasized exploratory material screening rather than standardized mechanical testing, focusing on surface quality, porosity visibility, breakage resistance, dimensional stability, drying time, and final mass as initial indicators of product performance for interior architectural applications. Such exploratory prototyping approaches are commonly used in circular construction research to screen waste-derived composite systems prior to full-scale mechanical testing and life-cycle assessment (Pomponi & Moncaster, 2017; Almeida et al., 2007).

The research was conducted at the marble workshop laboratory of a polytechnic institution in Aceh Selatan, Indonesia, where marble processing residues are routinely generated during cutting and polishing operations. By situating the experimentation within an active waste-producing facility, the study sought to reflect practical circular production scenarios in which industrial by-products are directly reintegrated into manufacturing processes.

3.2 Materials and Data Sources

3.2.1 Marble Waste

Marble powder waste was collected from local stone-processing activities associated with workshop operations. The material consisted of fine particulate residues generated during cutting, surface calibration, and polishing processes, subsequently separated from process water through sedimentation. Prior to use, the waste was air-dried and manually sieved to remove coarse fragments and impurities, producing a relatively homogeneous powder suitable for composite fabrication, consistent with preprocessing procedures reported in stone-waste valorization studies (Almeida et al., 2007).

3.2.2 Gypsum Binder

Commercial gypsum powder was employed as the primary mineral binder. Gypsum was selected because of its widespread use in interior ceiling products, relatively low processing temperature compared with cement-based systems, and favorable surface finishing characteristics (Cabeza et al., 2014). The gypsum was used as supplied, without chemical modification or additive incorporation, following practices adopted in recycled gypsum composite research (Borreguero et al., 2014; Ferrández et al., 2025; Weimann et al., 2021; Nisya, 2024).



3.2.3 Natural Fiber Reinforcement

Black sugar palm fiber derived from the *Arenga pinnata* tree was utilized as a bio-based reinforcement. The fibers were manually cleaned and cut into short segments prior to incorporation into the mixtures to facilitate dispersion within the mineral matrix. No chemical surface treatments were applied. The use of untreated natural fibers aligns with low-cost sustainable composite strategies reported in Pickering et al. (2016) and Faruk et al. (2012).

3.2.4 Water and Release Agent

Tap water free of saline contamination was used for mixture preparation. Cooking oil was applied as a release agent to the interior surfaces of molds to prevent adhesion between the composite and the casting form during curing, a practice commonly adopted in small-scale composite casting.

3.3 Mixture Design and Sample Preparation

Four composite formulations were prepared to investigate the effects of binder-to-filler ratio and fiber inclusion on panel performance. Each formulation maintained a constant water content of 1.5 L while varying the mass proportions of marble waste, gypsum, and black sugar palm fiber, consistent with parametric mixture approaches used in waste-derived composite studies (Almeida et al., 2007). The mixture compositions are summarized in Table 1.

Table 1. Mixture proportions for decorative ceiling panels.

Sample	Marble waste (g)	Gypsum (g)	Black sugar palm fiber (g)	Water (L)
S1	1500	3000	0.5	1.5
S2	3000	1500	0.25	1.5
S3	2250	2250	0.125	1.5
S4	500	4000	–	1.5

Following laboratory-scale gypsum composite fabrication practices by Borreguero et al. (2014), rectangular decorative ceiling molds measuring 64 × 52 × 2 cm were cleaned and coated with a thin layer of oil prior to casting. Dry constituents were first weighed using a digital balance and premixed manually to promote uniformity. Water was then added gradually while the mixture was stirred with a trowel until a workable slurry was obtained. Following an initial resting period of approximately five minutes to allow partial hydration, the mixture was remixed to achieve consistent viscosity.

Casting proceeded in two stages. In the first stage, a base layer of slurry was poured into the mold to approximately half the final thickness. For fiber-reinforced specimens, black sugar palm fibers were then evenly distributed across the surface before the remaining slurry was added to encapsulate the reinforcement fully. The top surface was leveled manually using a straightedge to ensure uniform thickness.

3.4 Curing and Demolding

After casting, specimens were left to cure under ambient laboratory conditions in a well-ventilated space. Drying occurred through natural evaporation rather than controlled thermal



treatment, reflecting realistic small-scale production environments and decentralized production environments emphasized in circular manufacturing frameworks (Pomponi & Moncaster, 2017). Panels were demolded once sufficient rigidity had developed to permit handling without visible deformation. Depending on ambient conditions, demolding occurred after approximately two to three days, after which the panels were suspended vertically to promote further moisture loss and uniform drying.

Two demolding techniques were applied according to the mold geometry. For linear-edged molds, gradual separation was initiated from one corner and extended across the panel perimeter. For curved molds, gentle tapping was employed to release the specimen evenly from the form.

3.5 Performance Assessment and Data Analysis

Performance evaluation relied primarily on qualitative and semi-quantitative observations rather than standardized mechanical tests. Visual inspection was conducted to assess surface smoothness, uniformity, color distribution, and the presence of visible pores or voids. Manual handling and tactile examination were used to infer breakage resistance, edge integrity, and perceived brittleness.

Dimensional stability was evaluated by measuring final panel length and width after drying and comparing these values with mold dimensions to identify shrinkage or deformation. Drying time and final mass were also recorded as indicators of moisture loss and material density.

Data analysis consisted of comparative assessment across the four formulations, identifying trends linking mixture proportions to observed performance attributes. Although the absence of instrumented mechanical testing limits the generalizability of the results, the approach was appropriate for exploratory screening of promising composite configurations suitable for further optimization and standardized testing in subsequent research.

3.6 Ethical and Safety Considerations

All experimental activities were conducted in accordance with institutional laboratory safety procedures. Personal protective equipment, including gloves and dust masks, was worn during material handling to minimize inhalation of fine particulate matter (Hamilton, I. et al., 2020). Wastewater generated during cleaning operations was collected and disposed of through existing workshop treatment systems to prevent environmental contamination.

RESULT

4.1 Overview of Experimental Outcomes

Four decorative ceiling panel formulations were fabricated using different proportions of marble waste, gypsum binder, and black sugar palm fiber reinforcement. All specimens were successfully cast and demolded after ambient curing periods ranging from two to three days. The final dried mass of the panels was approximately 4 kg for all formulations, with minor variation attributable to moisture loss during curing. Dimensional measurements indicated



that the dried panels were marginally smaller than the mold dimensions, producing finished sizes of approximately 50 × 60 cm compared with the mold size of 52 × 64 cm.

Performance was evaluated using visual inspection, tactile assessment, and handling resistance observations, focusing on surface smoothness, porosity visibility, breakage behavior, and overall product integrity. The outcomes for each formulation are summarized below and consolidated in Table 2.

4.2 Sample-Specific Results

4.2.1 Sample S1 (1500 g Marble Waste, 3000 g Gypsum, 0.5 g Black sugar palm fiber)

Panels produced with formulation S1 exhibited smooth and uniform surface finishes on both the exposed and rear faces. Visible surface pores were minimal, and air voids were difficult to detect through visual inspection. Edges remained intact during demolding and handling, and no cracking or fragmentation was observed. The panels retained structural coherence when lifted manually, indicating comparatively high resistance to breakage among the tested formulations.

The superior surface quality and handling resistance observed in Sample S1 can be attributed to the relatively high gypsum-to-marble ratio combined with the presence of black sugar palm fiber reinforcement. In composite systems, adequate matrix continuity is essential for effective stress transfer and surface consolidation, whereas excessive filler contents tend to disrupt binder networks and promote void formation (Bentur & Mindess, 2007; Medina et al., 2017). Similar effects have been reported in marble-filled cementitious composites, where elevated powder contents increased porosity and reduced cohesion when not balanced by sufficient binder proportions (Alyamac & Ince, 2009; Almeida et al., 2007).

4.2.2 Sample S2 (3000 g Marble Waste, 1500 g Gypsum, 0.25 g Black sugar palm fiber)

Formulation S2 produced panels with visibly irregular surfaces and pronounced pore structures. Air voids were apparent across multiple regions of the panel faces. During demolding and handling, specimens fractured readily, particularly near edges and corners. Compared with S1, the surface finish was less uniform, and the panels exhibited noticeably lower cohesion.

The comparatively poor performance of Sample S2, which contained the highest proportion of marble waste relative to gypsum, is therefore consistent with prior findings that mineral fillers function optimally only within limited substitution ranges. When these thresholds are exceeded, microstructural discontinuities and entrapped air can compromise both surface finish and fracture resistance (Medina et al., 2017).

4.2.3 Sample S3 (2250 g Marble Waste, 2250 g Gypsum, 0.125 g Black sugar palm fiber)

Panels fabricated with formulation S3 displayed moderately rough surfaces with numerous visible pores distributed across the panel faces. Although less fragile than S2, these specimens were still prone to edge damage during handling. Surface texture was uneven, and tactile examination suggested reduced material continuity relative to S1. No catastrophic failure occurred during demolding; however, localized chipping was observed.



Sample S3, incorporating intermediate proportions of marble waste and gypsum, exhibited moderate performance, further supporting the existence of an optimal binder–filler window for gypsum-based composites, as discussed in Medina et al. (2017).

4.2.4 Sample S4 (500 g Marble Waste, 4000 g Gypsum, No Fiber)

Panels prepared using formulation S4 exhibited smooth surfaces and good overall form stability. Edge integrity during demolding was comparable to S1, and panels did not fracture during routine handling. However, small surface pores remained visible in some areas of the exposed face. Despite the absence of fiber reinforcement, the specimens maintained cohesion throughout the drying process.

The relatively good cohesion observed in Sample S4, despite the absence of fiber reinforcement, underscores the dominant role of binder content in governing gypsum composite integrity. Studies on recycled gypsum boards similarly indicate that high matrix continuity contributes strongly to surface quality and resistance to brittle fracture, even in the presence of secondary materials (Borreguero et al., 2014; Ferrández et al., 2025). Nevertheless, the residual surface porosity noted in some regions of Sample S4 highlights the potential value of hybrid filler–fiber strategies for achieving both aesthetic and mechanical performance.

Fiber-reinforced formulations demonstrated improved resistance to edge damage and handling-induced fracture relative to non-reinforced specimens. Natural fibers embedded in mineral matrices act as crack-bridging elements that dissipate fracture energy and delay catastrophic failure, thereby enhancing post-cracking toughness (Savastano et al., 2009; Pickering et al., 2016). The favorable performance of Sample S1 compared with the fiber-free Sample S4 suggests that even small quantities of black sugar palm fiber can influence mechanical response in gypsum–marble systems, echoing observations from lignocellulosic fiber–cement composites reported in the literature (Savastano et al., 2009).

From a circular construction perspective, the results indicate that decorative interior products can accommodate substantial proportions of mineral waste without unacceptable performance penalties when mixture designs are optimized, reinforcing arguments that non-structural building components constitute promising entry points for waste-derived materials within circular economy transitions (Pomponi & Moncaster, 2017).

4.3 Comparative Summary of Performance Attributes

Table 2 presents a comparative synthesis of the observed performance indicators across the four formulations.

Table 2. Summary of observed panel performance.

Sample	Surface smoothness	Visible porosity	Handling resistance	Edge integrity
S1	High	Minimal	High	Intact
S2	Low	Pronounced	Low	Fractured
S3	Moderate	Moderate–high	Moderate	Chipping
S4	High	Moderate	High	Intact



4.4 Drying Time and Dimensional Stability

All panels required between two and three days of ambient curing before demolding and subsequent suspension drying. No warping or large-scale deformation was observed during the drying period. Shrinkage relative to mold dimensions was consistent across all specimens, with reductions of approximately 2–4 cm in length and width, indicating comparable volumetric changes irrespective of mixture composition.

DISCUSSION

5.1 Interpretation of Mixture Performance

The experimental results demonstrate clear relationships between mixture composition, surface quality, and handling resistance in marble waste–gypsum–fiber decorative ceiling panels. Among the four formulations investigated, Sample S1—characterized by a higher gypsum content relative to marble waste and reinforced with black sugar palm fiber—exhibited the most favorable combination of smooth surface finish, minimal visible porosity, and resistance to breakage during handling. This outcome suggests that sufficient binder content is essential for ensuring matrix continuity and effective encapsulation of fine mineral particles, while natural fiber reinforcement contributes to improved toughness and crack-bridging capacity in otherwise brittle gypsum-based systems, consistent with established composite material theory (Bentur & Mindess, 2007; Neville, 2011; Savastano et al., 2009).

By contrast, formulations with elevated marble waste content relative to gypsum, particularly Sample S2, displayed inferior surface quality and pronounced fragility. The prevalence of visible pores and premature fracture in these specimens indicates that excessive filler content may disrupt matrix formation, leading to weak interparticle bonding and increased air entrapment during casting, phenomena widely documented in particulate-reinforced cementitious and gypsum systems (Li et al., 2001; Neville, 2011). It is important to maintain an adequate matrix-to-filler ratio to ensure effective stress transfer and structural coherence. Sample S3, which employed balanced proportions of marble waste and gypsum, exhibited intermediate performance, further reinforcing the notion that binder content plays a dominant role in determining product integrity for gypsum-based composites.

Sample S4, containing the highest gypsum proportion and no fiber reinforcement, produced panels with relatively smooth surfaces and good handling resistance, albeit with some residual surface porosity. This finding suggests that high binder content alone can compensate partially for the absence of fiber reinforcement in terms of structural cohesion, though the remaining pores may reflect entrapped air or shrinkage phenomena during hydration and drying (Bentur & Mindess, 2007). When compared with Sample S1, however, the fiber-reinforced formulation demonstrated superior overall surface uniformity, supporting the proposition that hybrid particulate–fiber systems can outperform binder-rich but fiber-free composites in decorative interior applications (Ardanuy et al., 2015).



5.2 Role of Black Sugar Palm Fiber in Hybrid Bio–Mineral Composites

The comparative advantage observed in fiber-reinforced formulations highlights the functional contribution of black sugar palm fiber within gypsum–marble composites. Natural fibers embedded in mineral matrices are widely understood to enhance post-cracking behavior by bridging microcracks and redistributing stresses, thereby delaying catastrophic failure (Faruk et al., 2012; Savastano et al., 2009). In the present study, the improved handling resistance of Sample S1 relative to the fiber-free Sample S4 suggests that even small fiber dosages can meaningfully influence toughness in decorative ceiling panels.

Beyond mechanical considerations, the inclusion of black sugar palm fiber aligns strongly with circular economy objectives by introducing a renewable, locally sourced reinforcement material into a product otherwise dominated by mineral constituents. This bio-based component not only reduces dependence on synthetic fibers but also creates opportunities for integrating agricultural value chains into construction material manufacturing. Such strategies resonate with widely accepted circular economy frameworks emphasizing material looping, renewable feedstocks, and waste minimization (Ghisellini et al., 2016; Kirchherr et al., 2017). From a systems perspective, such hybridization supports multi-sectoral circularity by linking stone-processing waste streams with biomass resources, thereby diversifying the inputs of interior building products and strengthening regional material loops, consistent with recent discussions on bio-based construction transitions (Geissdoerfer et al., 2017).

5.3 Implications for Circular Construction Systems

The successful fabrication of ceiling panels incorporating substantial proportions of marble waste underscores the technical feasibility of valorizing mineral residues within interior building components, echoing prior work on marble and granite powder reuse in cementitious and ceramic matrices (Andreola et al., 2010; Hebhouh et al., 2011). Unlike many waste utilization studies that focus on load-bearing concretes or masonry units, the present research extends circular material strategies to decorative architectural products, which represent a large and recurrent demand in residential construction yet remain comparatively underexamined in circular construction scholarship (Pomponi & Moncaster, 2017). By demonstrating that up to one-third of the mineral content can be replaced with marble waste while maintaining acceptable surface quality and handling performance, the study provides preliminary evidence that gypsum-based ceiling manufacturing could serve as a viable outlet for stone-processing by-products.

From an industrial ecology standpoint, the localized nature of the experimental setting—situated within a workshop that generates marble waste—highlights the potential for decentralized circular production models. Educational institutions, small enterprises, and community-based workshops could adopt similar fabrication techniques to transform waste into marketable interior components, thereby reducing disposal costs and generating supplementary income streams. Such models resonate with emerging circular systems approaches that emphasize regional material loops, low-tech processing, and socio-economic co-benefits alongside environmental gains (Boons et al., 2016; Chertow, 2007).



5.4 Managerial and Policy Implications

For practitioners in the construction materials sector, the findings suggest that marble waste can be integrated into gypsum-based ceiling products without compromising essential aesthetic and handling properties, provided that binder content and fiber reinforcement are appropriately optimized, echoing industrial case studies on secondary raw material incorporation in building products (Cabeza et al., 2014). Small-scale manufacturers and workshop operators could leverage these insights to experiment with waste-derived formulations, potentially reducing raw material costs and differentiating products through sustainability-oriented branding aligned with emerging green procurement trends (Ellen MacArthur Foundation, 2019).

Policy makers and institutional managers may also draw lessons from this work regarding the role of technical training facilities and local workshops as incubators for circular innovation. Supporting pilot-scale production, material testing programs, and certification pathways for waste-derived interior products could accelerate the translation of laboratory experiments into commercially viable offerings. Moreover, regulatory incentives for industrial waste reuse—such as procurement preferences for recycled-content building materials—could further stimulate adoption of circular ceiling products and similar interior components, consistent with broader sustainable construction policy transitions (Geissdoerfer et al., 2017).

5.5 Limitations and Directions for Future Research

Despite its contributions, the study is subject to several limitations that warrant careful consideration. The performance evaluation relied primarily on visual inspection and tactile handling tests rather than standardized mechanical characterization such as flexural strength, impact resistance, or modulus of rupture. Consequently, the findings should be interpreted as exploratory rather than definitive assessments of structural performance. Future investigations should incorporate quantitative mechanical testing in accordance with relevant building material standards and durability protocols (Cabeza et al., 2014; ISO 14040, 2006) to establish performance thresholds for commercial application.

In addition, the study did not examine long-term durability under varying humidity conditions, fire exposure, or biological attack—factors that are critical for interior building components. Life-cycle assessment would also be valuable for quantifying the environmental benefits associated with marble waste substitution and natural fiber reinforcement relative to conventional gypsum products (Cabeza et al., 2014). Finally, scaling experiments to pilot production levels and evaluating economic feasibility would provide further insight into the practical implementation of circular ceiling manufacturing within regional construction markets.

CONCLUSION

This study investigated the feasibility of converting marble powder waste into decorative ceiling panels through the development of hybrid gypsum-based composites reinforced with natural palm fiber (black sugar palm fiber). Guided by circular economy principles and



composite material theory (Bentur & Mindess, 2007; Kirchherr et al., 2017), the experimental program evaluated four mixture formulations differing in marble waste content, gypsum proportion, and fiber inclusion, with performance assessed through surface quality, porosity visibility, handling resistance, dimensional stability, and drying behavior under laboratory conditions. The results demonstrate that marble-processing residues can be successfully incorporated into gypsum ceiling products when mixture proportions are carefully optimized, thereby providing a practical pathway for valorizing industrial mineral waste streams within interior construction applications (Andreola et al., 2010; Hebhouh et al., 2011).

Among the tested formulations, the composite containing 3000 g gypsum, 1500 g marble waste, and 0.5 g black sugar palm fiber exhibited the most favorable overall performance. Panels produced with this mixture displayed smooth and uniform surfaces, minimal visible porosity, and superior resistance to breakage during demolding and handling compared with marble-rich and fiber-free alternatives. These findings indicate that adequate binder content is critical for ensuring matrix continuity in gypsum–marble systems (Neville, 2011), while even modest levels of natural fiber reinforcement can meaningfully enhance toughness and surface integrity (Faruk et al., 2012; Savastano et al., 2009). Formulations with excessive marble content relative to gypsum were prone to visible pore formation and premature fracture, underscoring the importance of maintaining balanced binder–filler ratios in hybrid bio–mineral composites.

From a circular systems perspective, the study contributes empirical evidence supporting the integration of industrial stone waste and renewable agricultural fibers into value-added building products. By extending waste valorization strategies to decorative ceiling components—an underexplored product category in circular construction research (Pomponi & Moncaster, 2017)—the work broadens the scope of sustainable materials innovation beyond structural concrete and masonry units. The localized experimental context further illustrates the potential for decentralized manufacturing models in which educational workshops and small enterprises transform by-products generated on-site into commercially relevant interior materials, thereby closing regional material loops and generating socio-economic co-benefits consistent with industrial symbiosis theory (Boons et al., 2016; Chertow, 2007).

Despite these contributions, the exploratory nature of the experimental protocol imposes limitations on the generalizability of the findings. Performance evaluation relied primarily on qualitative assessments rather than standardized mechanical testing, and the study did not investigate long-term durability under environmental exposure or fire conditions, which are essential considerations for ceiling products. Accordingly, future research should prioritize quantitative mechanical characterization, including flexural strength, impact resistance, and fracture toughness, alongside durability testing under variable humidity and thermal regimes. Environmental life-cycle assessment would also be valuable for quantifying the carbon and resource-saving benefits associated with marble waste substitution and bio-based fiber reinforcement relative to conventional gypsum products (Cabeza et al., 2014; ISO 14040, 2006).



Further investigations should explore a wider range of mixture proportions, fiber lengths, and surface treatments to optimize fiber–matrix bonding and moisture resistance, as well as the scalability of production processes at pilot or industrial levels. Economic analyses examining production costs, market acceptance, and supply-chain logistics would additionally strengthen the case for commercial implementation. Collectively, such future work could support the development of standardized, waste-derived gypsum ceiling products that contribute meaningfully to circular construction systems and sustainable interior architecture.

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