

Original Research Article

Valorization of Marble Waste through Resin-Based Composite Tile Development: Exploratory Assessment of Formulation-Dependent Fragmentation

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ABSTRACT

Marble processing generates substantial quantities of powder and stone residues that can potentially be recovered as secondary materials for construction-related applications. This study explores the valorization of marble-processing waste powder as a mineral filler in resin-based composite tiles and compares the fragmentation responses of three tested formulations. An exploratory experimental design was employed using 20 × 20 cm composite tiles fabricated from marble powder, resin, and catalyst. Three formulations were prepared: S1 (250 g marble powder and 250 g resin), S2 (200 g marble powder and 300 g resin), and S3 (150 g marble powder and 350 g resin). Three specimens were prepared for each formulation, resulting in nine specimens. Each specimen was subjected to an 8 kg load dropped from a height of 140 cm, and the resulting fragmentation was assessed qualitatively based on visible breakage and the presence of small fragments. S2 exhibited relatively limited fragmentation and fewer small fragments, whereas S1 and S3 showed more extensive breakage. The findings indicate that the tested formulations exhibited different fragmentation responses and that marble powder proportion did not show a simple monotonic relationship with fragmentation under the applied test conditions. However, because catalyst quantities also varied among the formulations, the observed differences cannot be attributed solely to marble powder content. The study provides preliminary evidence for converting marble-processing residue into resin-based composite tiles as a potential secondary-material utilization pathway. Further research should employ controlled formulation, standardized mechanical testing, material characterization, durability assessment, and environmental and economic evaluation.

Keywords: *marble waste; waste valorization; marble powder; resin composite; composite tile; impact-induced fracture; circular material utilization.*

Received: 21-09-2026. Accepted: 01-10-2026. Published: 02-10-2026

INTRODUCTION

The construction sector is a major consumer of natural resources and generator of material waste, creating increasing pressure to reduce dependence on virgin resources and retain materials in productive use. Circular-economy approaches seek to move beyond the conventional linear model of resource extraction, production, use, and disposal by promoting strategies that retain material value through reuse, recycling, recovery, and other forms of resource circulation (Geissdoerfer et al., 2017; Kirchherr et al., 2017, 2023). Within this context, the conversion of industrial residues into secondary material inputs represents one potential pathway for reducing waste while creating new product value. Marble-processing residues are particularly relevant because cutting, shaping, and polishing operations generate substantial quantities of powder, dust, slurry, and stone fragments that can potentially be recovered for composite materials. Recent research identifies marble waste as a promising secondary resource while emphasizing that technical performance, standardization, and scale-up remain important requirements for broader utilization (Luhar & Luhar, 2026).

Waste marble powder (WMP) has been investigated as a secondary material in cement-based systems, including concrete, mortar, and other cementitious composites. Reviews have examined its potential as a partial cement substitute and its effects on the properties of cement-based composites (Prakash et al., 2023), as well as its role in alkali-activated materials and their fresh and hardened properties (Rashad, 2026). The performance of WMP varies with the matrix, formulation, and proportion incorporated. Consequently, increasing the quantity of marble waste does not necessarily result in proportional improvement in material performance. This formulation-dependent behavior is important when considering marble waste not simply as a material to be incorporated in the largest possible quantity, but as a secondary resource whose utilization must remain compatible with the functional requirements of the resulting product.

An alternative pathway is the incorporation of marble powder into polymer- or resin-based composites. In these systems, the resin acts as a binding matrix for particulate mineral fillers and can enable waste-derived powders to be transformed into consolidated products such as slabs, panels, and other construction-related materials. Heriyanto et al. (2019) demonstrated the feasibility of producing powder–resin composite materials from waste-derived fillers and highlighted the importance of particle characteristics and powder–resin interactions in determining composite performance. Studies have also investigated marble waste in different polymer matrices, including low-density polyethylene composites (Khan et al., 2020) and epoxy-based systems. Research on marble-filled epoxy composites has examined a range of mechanical properties, including flexural, hardness, compressive, and wear performance (Arunkumar et al., 2023; Jayaraman et al., 2023; Priyadarshini et al., 2023; Faroque et al., 2023). For example, Priyadarshini et al. (2023) reported improved tensile and flexural performance at a particular marble-powder loading but reductions in these properties at a higher loading, illustrating that increasing mineral filler content does not necessarily improve all performance characteristics simultaneously.

The filler–matrix relationship is therefore an important consideration in the development of particulate polymer composites. Increasing filler incorporation can increase the proportion of



secondary material utilized and reduce the relative requirement for polymer matrix. However, excessive or insufficient filler content may alter particle packing, matrix continuity, interfacial bonding, void formation, and stress transfer. Experimental studies of marble-filled polymer composites have reported different responses depending on the filler level and the property being evaluated. Abenojar et al. (2021), for example, investigated polyester composites containing substantial marble-particle content using standardized flexural, Charpy impact, compression, and wear tests, demonstrating the potential of marble particles as a component of polymer composites while also illustrating the importance of controlled mechanical characterization.

From a circular-material perspective, the conversion of marble-processing residue into resin-based composite tiles has two related dimensions. First, it represents waste valorization, because a residual material is transformed into a potentially useful product input. Second, it represents a potential form of circular material utilization, because a secondary material may partially substitute for virgin material in a new product. These concepts should not, however, be equated with demonstrated circular-economy performance. Evidence of broader circularity would require assessment of environmental impacts, resource efficiency, economic feasibility, durability, service life, and end-of-life recovery. Circular material utilization therefore involves a potential trade-off: increasing the amount of waste incorporated into a product may improve waste diversion but could also compromise functional performance if the resulting formulation becomes more susceptible to damage or failure (Geissdoerfer et al., 2017; Kirchherr et al., 2017). This trade-off provides an important rationale for examining formulation-dependent performance rather than simply maximizing marble-waste incorporation.

The practical motivation for the present study is the availability of marble-processing residue in South Aceh, Indonesia. The study explores whether this residue can be incorporated into small-format resin-based composite tiles and whether different formulations exhibit distinguishable fragmentation responses under a simple manual drop-load condition. Previous research has investigated marble waste in cementitious and polymer-based composites, but those studies commonly employ different matrices, filler ranges, specimen geometries, processing procedures, and standardized mechanical tests (Abenojar et al., 2021; Priyadarshini et al., 2023; Faroque et al., 2023). Consequently, their findings cannot be directly transferred to the specific small-format marble-powder/resin tile investigated in the present study without experimental assessment.

The research gap addressed here is therefore specific rather than broad. Existing studies establish the feasibility of marble waste utilization in cementitious and polymer composites, but evidence remains limited regarding formulation-dependent fragmentation behavior in small-format resin-bound tiles under a simple, locally reproducible drop-load condition. The present study addresses this gap through an exploratory comparison of three marble powder–resin formulations. Importantly, the formulations also use different catalyst quantities in proportion to the resin quantity. Therefore, the experiment is interpreted as an assessment of combined formulation-dependent behavior, rather than as an isolated causal test of marble powder content.



Accordingly, this study aims to evaluate the feasibility of valorizing locally available marble-processing waste as a mineral filler in resin-based composite tiles and to compare the observed fragmentation responses of three formulations under the same nominal load-drop condition. The study addresses the following research questions:

1. How can waste marble powder be incorporated as a mineral filler in 20 × 20 cm resin-based composite tiles?
2. How do the three tested marble powder–resin formulations differ in their observed fragmentation responses under the same nominal load-drop condition?
3. Which of the three tested formulations exhibits the least severe observed fragmentation, and what does this preliminary finding imply for subsequent development of marble-waste composite tiles?

The contribution of this study is intentionally positioned as exploratory rather than as product validation. First, it provides experimental evidence concerning the feasibility of converting locally generated marble-processing residue into a resin-bound composite tile. Second, it compares the observed fragmentation responses of three formulations, each represented by three specimens, under a common nominal impact condition. Third, it provides an initial formulation-level indication that greater marble-waste incorporation does not necessarily correspond to less fragmentation under the applied test condition. Finally, the study positions marble-waste tile development within a broader circular-material pathway while recognizing that standardized mechanical testing, controlled material characterization, durability assessment, life-cycle assessment, economic evaluation, and end-of-life analysis are required before the material can be evaluated as a validated construction product.

LITERATURE REVIEW

2.1 Marble Waste and Waste Valorization

Marble processing generates considerable quantities of waste in the form of powder, dust, slurry, and stone fragments. Although commonly treated as a residual material, its mineral characteristics make it suitable for recovery as a secondary raw material. Recent studies increasingly emphasize the valorization of marble waste through incorporation into construction and composite products rather than disposal. Luhar and Luhar (2026) identified marble waste as a promising secondary resource for sustainable construction and highlighted recycling, performance optimization, standardization, and scale-up as important requirements for wider implementation. Andriani et al. (2026) examined the technical viability of fabricating decorative ceiling panels from marble powder waste. The authors demonstrated that these marble-based components offer a cost-effective, circular alternative for the construction sector and highlighted prospects for regionally based waste-to-resource production models

Thus, marble-waste valorization can be understood as the transformation of an underutilized residue into a functional material with added value, although technical, environmental, and economic feasibility must still be demonstrated for specific applications.



2.2 Waste Marble Powder in Construction Materials

Waste marble powder (WMP) has been widely investigated as a mineral constituent in cement-based materials, including concrete, mortar, and cementitious composites. Its fine particles can provide a filler effect and modify the physical and mechanical properties of the matrix, although its influence depends strongly on the amount incorporated. Reviews have reported that moderate WMP contents can provide beneficial effects, whereas excessive replacement may reduce mechanical performance because of dilution and changes in matrix structure. While these studies establish the technical potential of WMP, the dominant focus on cementitious systems leaves opportunities for investigating alternative matrices, particularly polymer or resin systems for value-added products such as composite tiles.

2.3 Marble Powder in Polymer and Resin Composites

Polymer-based composites offer an alternative pathway for marble-waste utilization by incorporating marble powder as a mineral filler within a resin matrix. Heriyanto et al. (2019) demonstrated the feasibility of waste powder–resin composite products and reported that such materials could achieve performance comparable with natural and engineered stone in selected applications. More recent studies have also shown that WMP can influence the mechanical properties of epoxy-based composites, although the response varies with filler content and composite formulation. These findings support the feasibility of using marble powder in resin-based products while indicating that appropriate formulation is necessary to obtain acceptable composite performance.

2.4 Filler–Matrix Ratio and Composite Performance

The proportion of filler and matrix is a critical factor in particulate composite development. Increasing marble powder content can increase waste utilization and reduce the relative amount of polymer required, but excessive filler may negatively affect matrix continuity, particle bonding, and stress transfer. Studies of marble-filled epoxy composites have demonstrated that improvements in one property may occur only within a particular filler range, while further increases can adversely affect other mechanical properties. Therefore, the relationship between marble powder content and composite performance should be established experimentally. In the present study, this principle provides the basis for comparing three different marble powder–resin formulations and their relative resistance to impact-induced fracture.

2.5 Circular Material Utilization

Circular material utilization seeks to retain resources in productive use by reducing dependence on virgin materials and converting waste into secondary material inputs. Within broader sustainability and resource-recovery research, recycling, waste management, and material recovery are increasingly recognized as interconnected pathways for retaining value from discarded materials (Amri et al., 2025). In construction, the incorporation of industrial residues into new products represents one practical pathway toward this objective. The conversion of marble-processing waste into resin-based composite tiles therefore represents a potential circular-material pathway because a residual material is redirected into a value-added product. However, this study does not claim to demonstrate complete circularity



because environmental impacts, life-cycle performance, economic feasibility, durability, and end-of-life recovery are not evaluated. Its contribution is limited to demonstrating the technical potential for secondary utilization of marble waste in a composite construction-related product.

2.6 Research Gap and Conceptual Framework

The literature reviewed above identifies several areas that remain insufficiently addressed. First, substantial research has examined marble waste in cement-based construction materials, while polymer/resin systems have received comparatively less attention in relation to simple, small-format tile products intended for localized waste valorization (Prakash et al., 2023; Luhar & Luhar, 2026).

Second, previous polymer-composite studies demonstrate that marble filler content can produce different material responses depending on the filler level and formulation. However, most studies evaluate performance using standardized mechanical, physical, thermal, or wear tests, whereas relatively little attention has been given to simple visual fragmentation assessment of small-format resin-bound tiles under a locally reproducible drop-load procedure (Abenojar et al., 2021; Priyadarshini et al., 2023; Faroque et al., 2023).

Third, there is a practical gap between laboratory-based characterization of marble-filled composites and exploratory waste-to-product applications using locally available marble-processing residues. Recent circular-construction literature also emphasizes that technical performance and material quality are essential prerequisites for the broader utilization of secondary materials (Ranasinghe et al., 2024).

The present study addresses this gap through an exploratory comparison of three resin-based composite-tile formulations. Each formulation uses marble powder and resin with a nominal catalyst dosage of approximately 2% relative to the resin quantity. Three specimens were prepared for each formulation, giving a total of nine specimens.

METHOD

3.1 Research Design

This study employed an exploratory experimental design to investigate the feasibility of incorporating marble-processing waste into resin-based composite tiles and to compare the observed fragmentation responses of three tested formulations. An experimental approach was appropriate because the study involved the preparation of composite specimens followed by exposure to a common manual load-drop condition. The study was conducted at the Marble Workshop of Politeknik Aceh Selatan over approximately two months. The experimental workflow consisted of marble-waste preparation, weighing and sieving, formulation of marble powder and resin, addition of catalyst, manual mixing, molding, drying, and load-drop testing.

The study should be interpreted as a formulation-level exploratory assessment rather than an isolated test of marble powder content. Although the marble powder and resin quantities were varied systematically, the catalyst quantity also varied according to the resin quantity.



Consequently, differences observed among the formulations cannot be attributed exclusively to marble powder content. The experiment instead evaluates the combined response of the three tested material formulations under a common nominal load-drop condition.

3.2 Materials and Experimental Formulations

The principal materials were marble-processing waste, resin, and catalyst. The marble waste was prepared by breaking down agglomerated material, drying it, and sieving it before weighing. The resin functioned as the polymer matrix, while the catalyst was added to facilitate curing.

Three formulations were prepared while maintaining a total marble-powder–resin mass of 500 g for each formulation. The formulation levels were selected to provide three different proportions of marble powder relative to resin. The formulations used in the experiment are presented in Table 1.

Table 1. Experimental formulations

Sample	Marble powder (g)	Resin (g)	Catalyst (g)	Marble proportion (mL)
S1	250	250	5 (2%)	50 %
S2	200	300	6 (2%)	40 %
S3	150	350	7 (2%)	30 %

The catalyst was added at a nominal dosage of approximately 2% relative to the resin quantity, resulting in 5, 6, and 7 mL for S1, S2, and S3, respectively. The three formulations therefore represent 50%, 40%, and 30% marble powder, respectively, based on the combined marble powder and resin mass. The formulation levels were used to explore differences among the tested formulations and were not intended to establish an optimum filler concentration.

3.3 Specimen Preparation

The preparation procedure began with conditioning the marble-processing waste. Agglomerated material was broken down, dried, and sieved before the required quantities were weighed according to Table 1. For each formulation, the specified amount of marble powder was combined with the corresponding quantity of resin and catalyst. The materials were manually stirred until they were considered sufficiently distributed and were subsequently transferred into a mold measuring 20 × 20 cm.

Each formulation was prepared as three specimens, resulting in a total of nine specimens: 1) S1a, S1b, S1c; 2) S2a, S2b, S2c; and 3) S3a, S3b, S3c. The composite mixture was distributed and leveled within the mold to produce relatively uniform tile specimens before drying.

3.4 Impact-Induced Fracture Assessment

After drying, each specimen was subjected to a manually conducted load-drop test. An 8 kg load was raised to a height of 140 cm and released onto the surface of the composite tile. The same nominal load and drop height were applied to all three formulations, with three specimens tested for each formulation, resulting in nine tested specimens in total. The corresponding gravitational potential energy of the falling load can be estimated as approximately 110 J using $E=m.g.h$.



The response was assessed qualitatively from the visible condition of each specimen after loading. The principal observations concerned:

- The extent of overall breakage
- The degree of fragmentation
- The presence of smaller fragments
- The apparent severity of visible damage

3.5 Data Analysis

The analysis was primarily descriptive, comparative, and qualitative. The three formulations were compared based on the observed fragmentation response of their three respective specimens following exposure to the same nominal 8 kg load dropped from 140 cm.

The observations for S1a–S1c, S2a–S2c, and S3a–S3c were considered together to characterize the overall fragmentation response of each formulation. The formulation exhibiting relatively less visible fragmentation across its three specimens was identified as the best-performing formulation among the three tested formulations under the applied experimental condition.

No inferential statistical analysis was conducted because the response variable was qualitative rather than a standardized numerical mechanical property. Importantly, because marble powder, resin, and catalyst quantities vary together across the formulations, the analysis does not attempt to estimate the isolated effect of marble powder content. The findings are interpreted as differences among the tested composite formulations.

3.6 Methodological Framework

The overall experimental sequence can be summarized as:

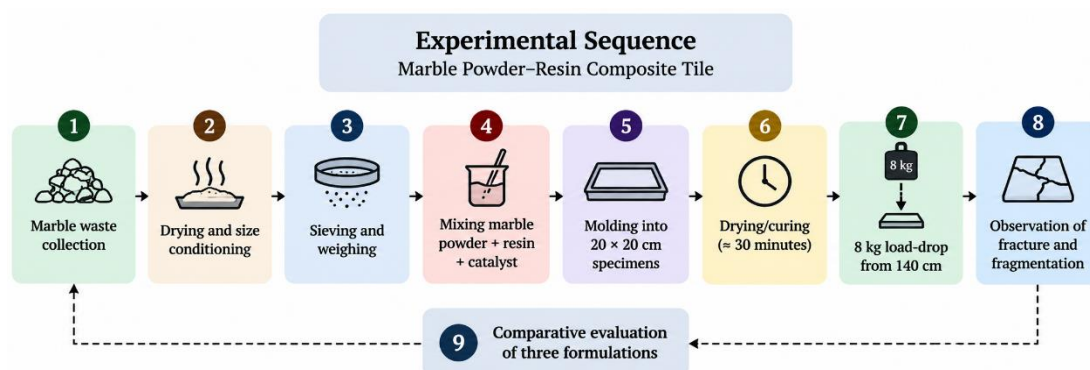


Figure 1. Methodological framework of the study

This methodology provides a direct experimental pathway for examining whether variation in marble powder–resin composition produces observable differences in the integrity of the resulting composite tiles. It also establishes the methodological basis for interpreting the subsequent results within the limited scope of the experiment: the study evaluates relative resistance to impact-induced damage, not standardized mechanical strength or hardness.



RESULT

4.1 Composite Tile Fabrication

The experimental procedure described in Section 3 was used to prepare three marble powder–resin formulations. Each formulation included three specimens, for a total of nine composite-tile specimens. The specimens were fabricated using a 20 × 20 cm mold and subsequently subjected to the same nominal load-drop condition.

The formulations differed in the relative proportions of marble powder and resin. S1 contained 250 g marble powder and 250 g resin, S2 contained 200 g marble powder and 300 g resin, and S3 contained 150 g marble powder and 350 g resin. The corresponding catalyst quantities were 5, 6, and 7 mL, respectively.

Table 2. Composite tile formulations and experimental conditions

Sample	Σ Specimens	Marble powder	Resin	Catalyst	Tile size	Impact condition
S1 x 3	3	250 g	250 g	5 mL (2%)	20×20 cm	8 kg from 140 cm
S2 x 3	3	200 g	300 g	6 mL (2%)	20×20 cm	8 kg from 140 cm
S3 x 3	3	150 g	350 g	7 mL (2%)	20×20 cm	8 kg from 140 cm

4.2 Response to the Load-Drop Test

Each of the nine specimens was subjected to the manual load-drop test using an 8 kg load released from a height of 140 cm. The resulting condition of the specimens was assessed qualitatively based on visible breakage, fragmentation, and the presence of smaller pieces.

Table 3. Observed fracture response of the composite tiles

Sample	Marble powder (g)	Resin (g)	Visual observed fracture response		
			a	b	c
S1	250	250			
					
					
S2	200	300			
S3	150	350			



The observations indicated different fragmentation patterns among the three formulations. S1, containing 250 g of marble powder and 250 g of resin, exhibited extensive breakage accompanied by several small fragments. S2, containing 200 g of marble powder and 300 g of resin, exhibited relatively limited fragmentation and fewer small fragments. S3, containing 150 g of marble powder and 350 g of resin, exhibited extensive breakage, with more small fragments and a relatively severe fragmentation pattern.

Table 4. Overall observed fracture response of the composite tiles

Sample	Marble powder	Load	Drop height	Overall observed fracture response
S1	250 g	8 kg	140 cm	Extensive breakage; several small fragments
S2	200 g	8 kg	140 cm	Relatively limited fragmentation; fewer small fragments
S3	150 g	8 kg	140 cm	Extensive breakage; more small fragments and severe fragmentation

4.3 Comparative Performance of the Three Formulations

The three formulations exhibited distinguishable fragmentation patterns under the same nominal 8 kg load and 140 cm drop height. S2 retained relatively larger pieces and produced fewer small fragments than S1 and S3. S1 and S3, in contrast, showed more extensive breakage and fragmentation.

Among the three tested formulations, S2 (200 g marble powder and 300 g resin) exhibited the least severe observed fragmentation under the applied experimental conditions. S1 (250 g marble powder and 250 g resin) and S3 (150 g marble powder and 350 g resin) exhibited greater visible fragmentation.

The observed pattern does not indicate a simple linear relationship between marble powder proportion and fragmentation. The formulation with the highest marble content (S1) and the formulation with the lowest marble content (S3) both exhibited more extensive fragmentation than S2. Thus, within the limited experimental range examined, the results indicate formulation-dependent fragmentation behavior rather than a monotonic relationship with marble powder content.

DISCUSSION

5.1 Formulation-Dependent Fragmentation Response

The principal finding of this study is that the three tested marble powder–resin formulations exhibited different fragmentation responses under the same nominal load-drop condition. S2, containing 200 g of marble powder and 300 g of resin, exhibited relatively limited fragmentation and fewer small fragments, whereas S1 (250 g marble powder/250 g resin) and S3 (150 g marble powder/350 g resin) exhibited more extensive breakage.

This result indicates that the observed fragmentation response was not monotonic across the three tested formulations. The formulation with the highest marble powder proportion did not exhibit the same response as the intermediate formulation, while the formulation with



the lowest marble powder proportion also showed relatively extensive fragmentation. Therefore, the results are more appropriately interpreted as formulation-dependent behavior than as evidence that increasing or decreasing marble powder content alone improves resistance to impact-induced damage.

This interpretation is consistent with previous studies showing that the response of marble-filled polymer composites depends on formulation and that increasing filler content does not necessarily improve all material properties simultaneously. Priyadarshini et al. (2023), for example, reported improved tensile and flexural properties up to 8 wt.% marble dust in epoxy/glass-fiber composites, followed by a decline at 10 wt.%. Their study also observed increasing void formation with increasing marble-dust content. Similarly, Upadhyay et al. (2023) found that increasing marble-dust loading in epoxy composites produced different trends across tensile, flexural, compressive, hardness, and wear properties rather than a uniform improvement in all properties.

The present findings therefore support the broader principle that waste-filler incorporation must be evaluated in relation to the complete composite formulation rather than by filler quantity alone.

5.2 Possible Role of Filler–Matrix Balance

One possible explanation for the observed difference among the formulations is the balance between mineral filler and polymer matrix. S1 contained approximately 50% marble powder and 50% resin, S2 contained approximately 40% marble powder and 60% resin, and S3 contained approximately 30% marble powder and 70% resin based on the combined marble-powder–resin mass.

Particulate composite behavior depends on factors such as filler dispersion, matrix continuity, particle–matrix interaction, porosity, and processing conditions. At sufficiently high filler loading, the ability of the polymer matrix to adequately surround and bind particles may become an important consideration. Conversely, reducing the filler fraction does not necessarily guarantee improved performance because the resulting behavior also depends on the properties and structure of the matrix and the quality of the composite produced.

Previous research provides evidence for such formulation dependence. Priyadarshini et al. (2023) found that increasing marble-dust content initially improved selected mechanical properties but that further addition reduced tensile and flexural performance, accompanied by increased void formation. Faroque et al. (2023), in contrast, reported systematic changes in the physical and mechanical behavior of marble–epoxy composites with increasing filler loading and used microstructural characterization to investigate filler–matrix interaction. These findings demonstrate that the response of marble-filled polymer composites can depend strongly on formulation and material structure.

However, the present experiment did not measure particle distribution, porosity, interfacial bonding, or microstructure. Therefore, the explanation that S2 performed differently because of a more favorable filler–matrix balance should be regarded as a plausible interpretation rather than a demonstrated mechanism.



5.3 Relationship with Previous Marble–Polymer Composite Studies

The present findings are consistent with the broader literature demonstrating the feasibility of incorporating marble waste into polymer-based composites. Heriyanto et al. (2019) showed that waste powder can be incorporated into resin-based composite products and highlighted the importance of filler characteristics and powder–resin interaction. More recent studies have investigated waste marble powder in epoxy systems using mechanical, thermal, physical, and wear characterization.

Abenojar et al. (2021), for example, developed polyester composites containing 50 wt.% marble particles and evaluated flexural, Charpy impact, compression, wear, and fire-resistance characteristics. Their study demonstrates that marble-containing polymer composites can be evaluated using standardized mechanical and impact-related methods. Faroque et al. (2023) similarly investigated marble–epoxy composites using systematic filler variation and combined mechanical characterization with FTIR, SEM, TGA, XRD, and micromechanical modeling.

The present study differs from these investigations in both scale and measurement approach. Rather than attempting to quantify standardized mechanical properties, it provides a preliminary visual assessment of fragmentation in small-format composite tiles fabricated from locally available marble-processing residue. Consequently, its findings should not be numerically compared with published tensile, flexural, compression, hardness, or Charpy impact values.

The contribution is instead preliminary: the experiment demonstrates that marble-processing residue can be incorporated into a resin-bound tile and that the three tested formulations produce visibly distinguishable fragmentation patterns. This provides an initial basis for subsequent material characterization using standardized procedures.

5.4 Interpretation of the S2 Response

Among the three tested formulations, S2 exhibited the least severe observed fragmentation. S2 contained 200 g of marble powder and 300 g of resin, corresponding to approximately 40% marble powder and 60% resin based on the combined marble–powder–resin mass.

The observation may indicate that the particular combination of filler and matrix used in S2 produced a comparatively favorable structural response under the applied load-drop condition. However, the present data are insufficient to establish why S2 performed better. Possible contributing factors include filler distribution, matrix continuity, particle–matrix interaction, porosity, curing behavior, specimen thickness, and mixing quality. These factors were not directly measured in the present experiment. Furthermore, catalyst quantities differed among S1, S2, and S3. Consequently, the observed response of S2 cannot be attributed specifically to its 40% marble powder proportion.

Accordingly, the appropriate interpretation is: S2 was the best-performing formulation among the three tested formulations under the applied experimental condition, but the experiment does not establish 40% marble powder as an optimum concentration.



5.5 Implications for Marble-Waste Valorization and Circular Material Utilization

From a waste-valorization perspective, the experiment provides preliminary evidence for converting marble-processing residue into a consolidated resin-based composite product. Rather than treating marble powder exclusively as a waste-management burden, the material can potentially be redirected as a secondary mineral input in a new product.

This pathway is consistent with the broader literature on marble-waste utilization. Recent research identifies marble waste as a potentially useful secondary resource while emphasizing the importance of performance optimization, standardization, and scale-up before wider implementation (Luhar & Luhar, 2026). Research on circular construction similarly emphasizes the importance of material quality, reliable material information, design, and technological conditions in enabling effective secondary-material utilization (Ranasinghe et al., 2024).

The present findings also illustrate an important circularity trade-off. Increasing waste incorporation can increase the quantity of residual material diverted toward productive use, but greater waste incorporation does not automatically produce better functional performance. A circular-material strategy therefore requires an appropriate balance between waste incorporation and product functionality. The study should nevertheless not be interpreted as demonstrating complete circularity. The contribution is therefore limited to demonstrating a preliminary secondary-material utilization pathway for marble waste.

5.6 Methodological Implications and Future Research

The findings provide a basis for a more rigorous second-stage investigation. The current experiment demonstrates formulation-dependent differences, but several methodological improvements are necessary before it is evaluated for construction applications.

First, future experiments should use a controlled formulation design in which the catalyst-to-resin ratio is held constant across treatments. This would allow the effect of filler–matrix proportion to be investigated more clearly. The present experiment cannot isolate the marble powder effect because catalyst quantity changes together with resin quantity. Second, future studies should employ a wider range of formulations and more specimens per treatment. This would allow the relationship between filler proportion and performance to be examined more systematically rather than inferring an optimum from only three formulations.

Third, the qualitative load-drop assessment should be supplemented or replaced by standardized mechanical testing. Appropriate tests could include impact, flexural, compressive, and hardness measurements, depending on the intended application. Abenojar et al. (2021), for example, combined flexural, Charpy impact, compression, and wear testing in their evaluation of marble-containing polymer composites. Fourth, material characterization should include particle-size distribution, density, porosity, water absorption, and microstructural analysis. Such measurements would help determine whether differences in fragmentation are associated with filler dispersion, void formation, or filler–matrix interaction. Previous marble–epoxy research has used SEM and other analytical techniques to investigate these mechanisms.

Finally, subsequent development should extend beyond mechanical performance to include durability, environmental impacts, economic feasibility, and end-of-life management. These



dimensions are necessary before a waste-derived composite tile can be evaluated as a viable circular construction material rather than merely as a laboratory-scale waste-valorization concept.

Therefore, the principal contribution of the study is exploratory. It provides preliminary evidence that locally generated marble-processing residue can be incorporated into a resin-based composite tile and that different formulations can produce distinguishable fragmentation responses. This provides a foundation for subsequent controlled experiments using standardized mechanical testing and more comprehensive material characterization.

CONCLUSION

This study explored the feasibility of utilizing marble-processing waste powder as a mineral filler in resin-based composite tiles and compared the observed fragmentation responses of three tested formulations under a common nominal load-drop condition. Three formulations were prepared using 250, 200, and 150 g of marble powder combined with 250, 300, and 350 g of resin, respectively. Each formulation was represented by three specimens, resulting in a total of nine specimens.

Under an 8 kg load released from a height of 140 cm, the three formulations exhibited different qualitative fragmentation responses. S2, consisting of 200 g marble powder and 300 g resin, exhibited relatively limited fragmentation and fewer small fragments, whereas S1 (250 g marble powder/250 g resin) and S3 (150 g marble powder/350 g resin) exhibited more extensive breakage. Thus, among the three tested formulations, S2 showed the least severe observed fragmentation under the applied experimental condition.

The findings indicate that the tested formulations did not exhibit a simple monotonic relationship between marble powder proportion and observed fragmentation. However, because the catalyst quantity also varied among the formulations, the observed differences cannot be attributed solely to marble powder content. The result should therefore be interpreted as evidence of formulation-dependent fragmentation behavior, rather than as evidence that a specific marble powder percentage represents an optimum composition.

From a circular-material perspective, the study provides preliminary evidence that marble-processing residue can be redirected from a waste stream into a resin-based composite tile. This represents a potential secondary-material utilization pathway consistent with waste valorization. Nevertheless, the study does not establish the environmental, economic, durability, or end-of-life performance required to claim a fully validated circular construction material.

Future research should employ a more controlled experimental design with a constant catalyst-to-resin ratio, a broader range of filler–matrix formulations, and multiple replicated specimens. Standardized impact, flexural, compressive, and hardness tests should be combined with particle-size, density, porosity, water-absorption, and microstructural characterization. Further assessment of durability, environmental impacts, economic feasibility, and end-of-life recovery would also be necessary to determine the potential of marble-waste composite tiles for practical construction applications.



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