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Flexural Behavior of Jute Fiber Mat-Reinforced Gypsum/Perlite Composites: Effects of Loading Rate and Reinforcement

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ABSTRACT

This study investigates the flexural performance of sustainable gypsum composites reinforced with jute fiber mat and expanded perlite filler. Through systematic experimentation at varying loading rates (2, 100, and 500 mm/min), we demonstrate how jute fiber reinforcement transforms the inherently brittle gypsum matrix into a pseudo-ductile material with superior energy absorption capacity. The incorporation of expanded perlite reduces composite density while maintaining structural integrity, creating a multifunctional material suitable for modern construction needs. Key findings reveal that jute fiber reinforcement enhances flexural toughness by up to approximately 700% compared to unreinforced specimens, with progressive fiber/yarn pull-out mechanisms preventing catastrophic failure. Although perlite addition decreases flexural strength (from 3.82 MPa to 1.19 MPa in unreinforced samples), the hybrid composites exhibit an optimal balance between mechanical performance and lightweight characteristics. Notably, the composites maintain 30–50% residual load capacity even at 15 mm displacement, demonstrating exceptional damage tolerance across all loading rates. These results demonstrate the potential of jute fiber mat-reinforced perlite-gypsum composites for seismic-resistant interior applications, offering a sustainable alternative to conventional building materials. The study provides a foundation for developing eco-friendly construction materials with enhanced mechanical and functional properties. Future work should evaluate seismic performance under cyclic loading to evaluate their performance and further improvement.

Keywords: Fiber-reinforced gypsum, Lightweight construction materials, Pseudo-ductile failure, Eco-friendly building materials, Seismic retrofit.

1 Introduction

Gypsum-based composites (GCs) are widely utilized as building materials, particularly for interior applications such as walls and ceilings [1]-[3]. Their prevalence is attributed to several advantageous characteristics, including their low cost, ease of manufacture and application, desirable decorative properties (being naturally white), rapid setting and hardening without requiring accelerated curing, lightweight nature, and excellent fire and sound resistance [1]-[3]. The abundant availability of gypsum resources, including natural gypsum and industrial by-products like phosphogypsum and flue gas desulfurization (FGD) gypsum, further enhances their popularity and contributes to economic and environmental benefits through waste utilization [1],[2].

Despite these benefits, conventional gypsum products possess notable limitations, which restrict their broader application in construction. These drawbacks include brittleness, inferior mechanical properties, and low water resistance [1],[2],[4]. To overcome these shortcomings and expand their applicability, extensive research has focused on modifying gypsum properties through the incorporation of various additives and reinforcing elements [1],[2].

One primary strategy for enhancing gypsum performance involves the addition of fibers. Fibers are widely recognized for their ability to remarkably improve the comprehensive behavior of quasi-brittle matrices in a cost-effective manner, leading to enhanced mechanical, thermal, and acoustic properties in fiber-reinforced gypsum-based composites (FRGCs) [1]. Fibers used in FRGCs are broadly categorized into natural fibers and man-made (synthetic) fibers [1],[4]. Common man-made fibers include glass, polypropylene (PP), and polyvinyl alcohol (PVA) fibers, which have been extensively studied [1],[4],[5]. Natural fibers, such as hemp, sisal, cotton, coconut, straw, date palm, coir, and wood fibers, are also increasingly explored due to their sustainable and renewable nature, offering benefits like higher tensile strength, lower abrasiveness, and reduced cost compared to inorganic reinforcements [4],[6].

Flexural properties, in particular, are significantly influenced by fiber reinforcement. When subjected to external tensile stress, fibers create a "bridging effect" within the gypsum matrix, which delays crack initiation and limits crack propagation, transforming the material's failure mode from brittle to ductile [7]-[10]. This bridging effect increases the deformation energy required for fracture and the composite's toughness [8],[11]. For instance, adding polypropylene (PP) fibers has been shown to increase flexural strength, with optimal additions observed to enhance properties before a decrease at higher concentrations due to weakened bonding or increased porosity [5],[7],[12],[13]. Glass fibers also demonstrably improve flexural strength and toughness [8],[11]. Hemp fibers have been shown to improve flexural strength and compressive strength significantly, with a 12 vol% fiber content and 15 mm length improving flexural strength by 268% and compressive strength by 109.8% compared to neat gypsum [14]. Hemp fiber reinforcement also transforms the brittle failure of pure gypsum into a ductile behavior, enhancing toughness [11].

Among natural fibers, jute fibers are particularly relevant due to their abundance and established use in reinforced composites [15]. Studies on gypsum-bonded particleboard

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(GPB) reinforced with jute fibers have shown that both the length and content of jute fibers significantly impact mechanical properties, including internal bond strength (IB) and modulus of rupture (MOR), which is a measure of flexural strength [16]. Longer jute fibers (e.g., 12 mm) have demonstrated an advantage in increasing MOR compared to shorter fibers [16]. Jute fabric reinforcement in plaster can also improve ductility and tenacity in bending and compression, providing structural stability after the brittle rupture of the plaster matrix [9]. The rough surface morphology of jute fibers enhances adhesion with plaster crystals, ensuring mechanical interlocking rather than significant chemical bonding [9],[15].

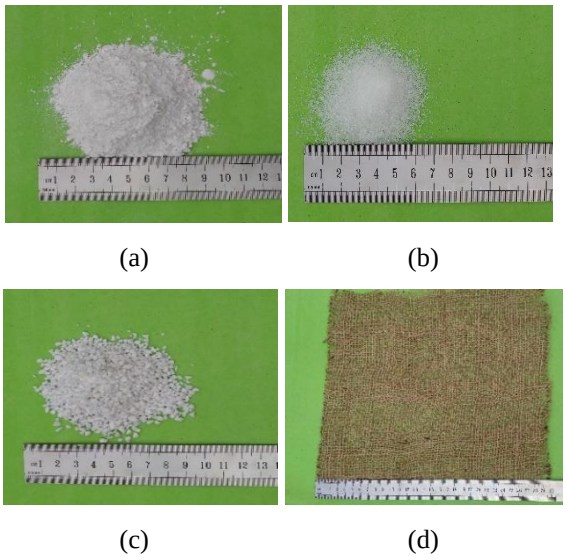
Another crucial approach to modify gypsum's properties is the incorporation of lightweight fillers. These fillers reduce the material density, which in turn enhances its thermal and sound insulation capabilities [2],[17]-[19]. Expanded perlite (EP), an amorphous volcanic silicate/alumina rock, is a widely used lightweight aggregate in building materials [17]-[22]. Its highly porous structure, formed by heating raw perlite, results in a low bulk density (0.05 to 0.40 g/cm^3) and excellent thermal insulation properties due to trapped air [18]-[24]. The incorporation of expanded perlite typically leads to a reduction in the material's mechanical performance, including flexural and compressive strength, largely due to the air cavities within the perlite particles [17]-[24]. For example, high doses of expanded perlite (e.g., 6.5 wt.%) have been shown to considerably reduce flexural and compressive strength by approximately 20% compared to control samples [17]. This reduction can be attributed to the lower strength of perlite particles and a decreased volume fraction of the binding gypsum matrix [23]. However, perlite-filled gypsum composites often still meet minimum strength requirements for plaster applications [17],[23]. While flexural strength may decrease, the flexural modulus and toughness can be remarkably enhanced due to perlite addition, as the cellular walls of perlite particles progressively break down under compression, increasing toughness [23].

The combination of lightweight fillers and fiber reinforcement presents a promising avenue for developing multi-functional gypsum composites. While lightweight fillers primarily enhance thermal and acoustic properties at the expense of strength, fibers can compensate for this strength reduction and improve the ductility and toughness [23]. Studies investigating the combined effect of perlite and fibers, such as glass fibers, have shown improved mechanical performance [23]. More recently, research has explored the combination of expanded perlite filler with jute fiber reinforcement in gypsum composites. Initial findings indicate that while jute fiber reinforcement in pure gypsum may decrease flexural strength, it significantly increases flexural toughness and improves post-failure load-bearing capacity by shifting the failure mode from brittle cracking to fiber pull-out [24]. The addition of perlite in these jute-reinforced composites further influences density and flexural properties, often showing a complex interplay where flexural modulus increases with perlite content, even as flexural strength might show a decreasing trend [23].

Despite these advancements, a comprehensive and detailed investigation into the flexural properties of gypsum composites reinforced with jute fiber mats and filled with expanded perlite is limited in the existing literature. Specifically, understanding the precise load-displacement behavior, crack propagation mechanisms, and the synergistic effects of jute fiber mats (as opposed to loose fibers or fabrics) and perlite on the overall flexural performance and toughness of these hybrid composites requires further exploration. Such an investigation would provide valuable insights for optimizing these eco-friendly materials for building applications, balancing mechanical performance with desirable lightweight and insulating characteristics.

2 Materials

The composite was fabricated using gypsum as the matrix, perlite as the filler, and jute fiber mat as the reinforcement. Expanded perlite was sourced from Xinyang Caster New Material Company Ltd., located in Henan Province, China. To ensure consistency in particle size, the perlite was sieved to remove dust and fine powders, retaining particles between 2 mm and 5 mm. Based on the manufacturer's specifications, the chemical composition of the perlite includes 70–75% SiO_2 (primarily in the amorphous silica form, which is non-hazardous), 12–16% Al_2O_3, 2.5–5% Na_2O, 1–4% K_2O, 0.1–2% CaO, 0.15–1.5% Fe_2O_3, and 0.2–0.5% MgO. The gypsum powder was obtained from Shahenoor Corporation in Dhaka, Bangladesh. According to the technical datasheet, it consists of 23.3% calcium and 18.5% sulfur. The reinforcing jute fiber mat was supplied by Jashore Jute Products in Daulatpur, Khulna, Bangladesh, with an areal density of 0.0267 g/cm^2. Additionally, citric acid was procured from Haiko Consumer Products in Dhaka for use in the composite preparation. The photographs of the materials used in this work are given in Fig. 1.



(a) (b)

(c) (d)

Fig. 1 Photographs of (a) Gypsum powder (b) Citric acid (c) Expanded perlite, and (d) Jute fiber mat used in this work

3 Methodology

3.1 Sample preparation

The composites were manufactured both with and without jute fiber mat reinforcement on the lower side of the panels, with perlite content serving as an additional variable. Four different perlite concentrations were tested for each configuration (reinforced and unreinforced). Sample identification followed a systematic notation where the number after "P" indicated the grams of perlite added per 390 g of gypsum (e.g., P80 denotes 80 g perlite), while samples without perlite were labeled with "P0".

A custom mold was fabricated using glass as the base and wooden frames secured with glue to create a 300 mm × 300 mm × 12 mm cavity. Jute fiber mats were trimmed to 300 mm × 300 mm dimensions using scissors. For pure gypsum panels, the preparation began by mixing distilled water with citric acid (quantities as specified in Table 1), followed by two minutes of stirring. Gypsum powder was then gradually added and mixed for five minutes. The mixture was poured into the mold and

allowed to cure for 24 hours before being dried in an electric oven (Gallenkamp OHG097 XX.2.5 Size 2).

Gypsum-perlite panels followed a similar procedure, with pre-measured perlite incorporated into the gypsum-water solution and mixed uniformly for five minutes using a steel rod. The mixture was then cast into the mold and dried identically to the pure gypsum panels. For jute mat-reinforced panels, an initial layer of 400 g gypsum-water mixture was poured into the mold, after which the jute mat (one ply only) was placed and pressed with a grooved roller to ensure complete impregnation. The remaining gypsum or gypsum-perlite mixture (Table 1) was then added, and the drying process repeated. Once dried, all panels were cut to the required dimensions for flexural testing.

Table 1 Mix proportion constituents.

Case	Sample ID	Gypsum, g	Water, g	Perlite, g	Jute Fiber Mat (/cm^2), g	Citric Acid at per 100g of Water, g
Unreinforced	P0	390	300	0	0	0.05
	P40			40		
	P60			60		
	P80			80		
Jute mat-reinforced	P0			0	0.0267	
	P40			40		
	P60			60		
	P80			80		

3.2 Physical and Mechanical Test Methods

The physical dimensions (length, width, and thickness) of each sample were measured using digital slide calipers, while sample mass was determined using a precision weighing scale. These measurements were then used to calculate density according to the formula:

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

where ρ represents density (g/cm³), M is mass (g), and V is volume (cm³). The calculated density values for all samples are presented in Table 2.

The flexural properties were evaluated using a Shimadzu AGX-300kN universal testing machine in accordance with ASTM C393 standard with specimen dimension of 240 mm × 25 mm × thickness. The three-point bending tests were conducted at three different crosshead speeds (2 mm/min, 100 mm/min, and 500 mm/min) with a constant support span length of 150 mm. During testing, data including force, deflection, stress, and strain were recorded at 0.05-second intervals for subsequent analysis.

The flexural strength was calculated using the following equation:

$$\sigma_f = \frac{3PL}{bd^2} \quad (2)$$

where P is the peak load (N) obtained from the load-deflection curve beyond the linear region, L is the span length (mm), b is the specimen width (mm), and d is the specimen depth (mm).

The energy absorption capacity was determined by calculating the area under the load-displacement curve:

$$W = \int_0^d F(x)dx \quad (3)$$

where $F(x)$ represents the applied force (N) at displacement x (mm), and d is the maximum displacement (mm) achieved during the test.

4 Results and discussion

4.1 Density

Table 2 presents the density measurements of gypsum composite panels with varying perlite contents, comparing unreinforced and jute mat-reinforced samples. The density is also plotted in Fig. 2 for various perlite content for better visualization. The unreinforced P0 (pure gypsum) sample showed the highest density at 1.02 ± 0.03 g/cm³, while the unreinforced P80 sample exhibited the lowest density at 0.72 ± 0.03 g/cm³.

Jute-reinforced samples consistently demonstrated slightly higher densities than their unreinforced counterparts at equivalent perlite contents. The most notable difference occurred in P60 composites, where reinforcement increased density from 0.78 ± 0.02 g/cm³ to 0.89 ± 0.02 g/cm³. The increase in density of jute mat-reinforced panels is due to the reinforced bottom layer without any porous perlite particles. However, all perlite filled panels showed lower density due to the incorporation perlite particles.

Table 2 Density comparison of composite panels

Sample ID	Density (g/cm³)	
	Unreinforced Composite	Jute Fiber Mat-reinforced Composite
P0	1.02 ± 0.03	1.01 ± 0.04
P40	0.84 ± 0.03	0.90 ± 0.02
P60	0.78 ± 0.02	0.89 ± 0.02
P80	0.72 ± 0.03	0.86 ± 0.03

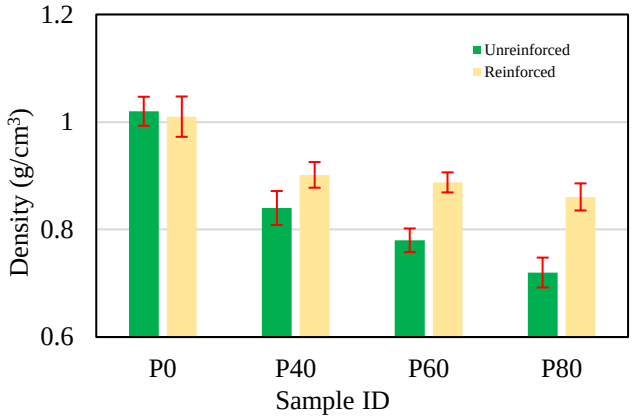


Fig. 2 Density of the unreinforced and jute fiber mat-reinforced gypsum panels with various perlite contents (Standard deviations are shown as error bars).

4.2 Flexural Strength at Different Crosshead Speeds

The maximum load in the load-displacement curves up to a crosshead displacement of 15 mm was considered to calculate the flexural strength of the gypsum composite panels. The flexural strength of both unreinforced and reinforced gypsum-perlite composites was evaluated at three crosshead speeds (2, 100, and 500 mm/min), with results presented in Table 3 and Fig. 3. For unreinforced samples, a consistent reduction in strength was found with increasing perlite content for all testing speeds because of the incorporation of lightweight and low strength perlite particles. At 2 mm/min, the flexural strength declined from 3.82 MPa (P0) to 1.19 MPa (P80), while at 100 mm/min, values decreased from 2.70 MPa (P0) to 1.12 MPa (P80) as

shown in Table 3. Notably, the unreinforced specimens exhibited significant rate dependence, with P0 strength increasing from 2.70 MPa at 100 mm/min to 5.49 MPa at 500 mm/min showing approximately 103% increase.

Jute fiber reinforcement essentially changed this behavior. Reinforced samples not only maintained higher strength values but also demonstrated less sensitivity to both perlite content and loading rates. At 100 mm/min, reinforced P40 and P60 specimens achieved identical peak strengths of 3.49 MPa which 128% greater than their unreinforced counterparts. The 500 mm/min tests revealed an optimal reinforcement effect at P40 (4.09 MPa), with P60 (3.98 MPa) and P80 (3.64 MPa) showing gradual reductions. Interestingly, while 2 mm/min testing showed parallel strength reduction trends between reinforced and unreinforced samples, the reinforced samples showed consistently higher strength by 35-117% across all perlite contents.

These results revealed two critical observations: firstly, the jute fiber mat reinforcement effectively mitigates the strength reduction imposed by perlite addition, particularly at higher loading rates, and secondly an apparent optimal perlite content exists near P40 (40g perlite/390g gypsum) for jute mat-reinforced composites under dynamic loading conditions.

Table 3 Flexural strength of the composites at various crosshead speeds.

Crosshead speed, mm/min	Condition	Flexural Strength, MPa			
		P0	P40	P60	P80
2	Unreinforced	3.82 ± 0.28	2.39 ± 0.16	1.78 ± 0.22	1.19 ± 0.25
	Reinforced	3.42 ± 0.32	3.22 ± 0.33	2.99 ± 0.58	2.59 ± 0.32
100	Unreinforced	2.70 ± 0.44	1.53 ± 0.11	1.23 ± 0.20	1.12 ± 0.17
	Reinforced	3.02 ± 0.35	3.49 ± 0.30	3.49 ± 0.30	3.07 ± 0.37
500	Unreinforced	5.49 ± 0.54	3.40 ± 0.37	2.52 ± 0.44	2.15 ± 0.45
	Reinforced	3.93 ± 0.58	4.09 ± 0.40	3.98 ± 0.39	3.64 ± 0.27

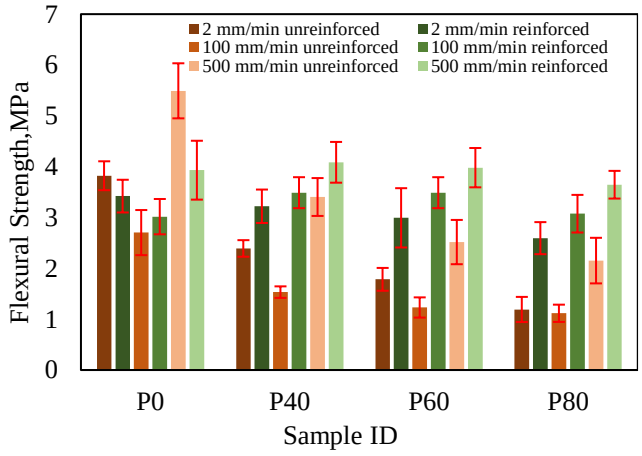


Fig. 3 Flexural strength of the composites at different crosshead speeds (Standard deviations are shown as error bars)

4.3 Energy Absorption at Different Crosshead Speeds

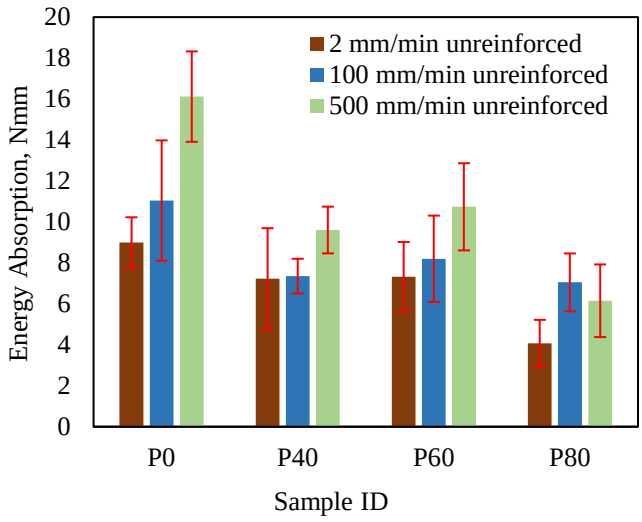
The energy absorption was calculated as the area under the load-displacement curve up to 15 mm crosshead displacement. The energy absorption characteristics of unreinforced and reinforced gypsum-perlite composites were evaluated at three crosshead speeds (2, 100, and 500 mm/min), with results presented in Fig. 4 and Table 4.

The energy absorption characteristics showed distinct patterns between unreinforced and reinforced composites. For unreinforced specimens, the energy absorption decreased with the addition of perlite in gypsum regardless of loading rate which is prominent at P80. At 2 mm/min, the energy absorption values dropped from 8.99 N·mm (P0) to 4.07 N·mm (P80), while at the faster 500 mm/min rate, the energy absorption declined from 16.12 N·mm to 6.16 N·mm. This reduction occurs because the porous structure of perlite particles introduces voids that diminish the energy absorption capability which is aligned with the findings for flexural strength as shown in Fig. 3. P40 and P60 shows approximately similar energy absorptions indicating a threshold for perlite addition in terms of energy absorption.

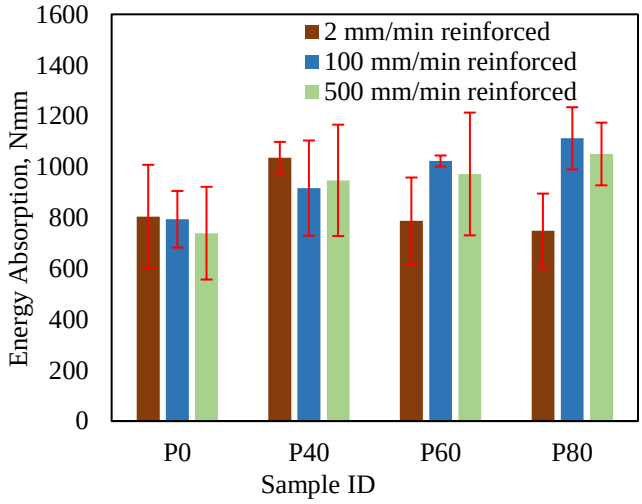
In contrast, jute fiber reinforcement significantly improved energy absorption, showing approximately 70- to 150-fold improvement compared to unreinforced samples across all compositions. The reinforced composites at 2 mm/min, the peak energy absorption occurred at intermediate perlite contents (P40), while at higher loading rates (100 and 500 mm/min) showed consistent improvement with increasing perlite addition, reaching a maximum absorption of 1112.11 N·mm for P80 at 100 mm/min, surpassing the performance of pure gypsum. The honeycomb structure of perlite enhances energy dissipation at higher loading rates through multiple synergistic mechanisms. Under dynamic loading, the thin, porous cell walls undergo sequential buckling and collapse rather than instantaneous failure, creating a sustained energy absorption pathway. The trapped air within the cellular structure compresses viscoelastically, converting kinetic energy into heat through viscous damping - an effect amplified at increased strain rates. The irregular pore geometry forces propagating cracks to branch and deflect, significantly extending the fracture path and energy absorption per unit volume. This are the reason for enhanced energy absorption at higher loading rate through resistance to crack propagation due to the jute fiber mat reinforcement at the tension side of the composite panel as well as rapid material response during cracking through perlite particles. The effect is most noticeable under dynamic loading conditions (100-500 mm/min), where increasing perlite content continuously improves energy absorption, while static loading (2 mm/min) demonstrates optimal reinforcement at moderate perlite levels (P40). These findings show how jute fiber mat reinforcement can effectively mitigate the energy absorption limitations imposed by perlite addition, particularly under dynamic loading conditions.

Table 4 Energy absorption (N·mm) of composite panels at different crosshead speeds

Crosshead speed, mm/min	Condition	Energy absorption, N.mm			
		P0	P40	P60	P80
2	Unreinforced	8.99 ±1.24	7.23 ±2.48	7.33 ±1.69	4.07± 1.16
	Reinforced	804.7 ±203.38	1036.48 ±61.85	787.53 ±170.56	748.93 ±145.87
100	Unreinforced	11.05 ±2.94	7.36 ±0.85	8.2 ±2.11	7.05 ±1.42
	Reinforced	793.85 ±111.4	916.6 ±187.16	1022.77 ±21.85	1112.11 ±122.49
500	Unreinforced	16.12 ±2.21	9.61 ±1.14	10.74 ±2.13	6.16 ±1.78
	Reinforced	739.07 ±182.38	946.91 ±219.03	971.92 ±241.49	1050.66 ±123.4



(a)



(b)

Fig. 4 Energy absorption of (a) unreinforced and (b) reinforced composite panels at different crosshead speeds (Standard deviations are shown as error bars).

4.4 Failure Behavior

The failure behavior of unreinforced and jute fiber-reinforced gypsum composites was systematically investigated for three loading rates (2, 100, and 500 mm/min) along with load-displacement curves and photographs of failed specimens as shown in Fig. 5 - Fig. 7. The unreinforced panels consistently exhibited brittle failure at all loading rates (Fig. 5(a), Fig. 6(a), Fig. 7(a)), characterized by linear elastic region followed by sudden, catastrophic fracture with complete specimen separation (Fig. 5(c), Fig. 6(c), Fig. 7(c)). This is consistent with previous findings [3],[17],[22]-[24].

In contrast, jute fiber mat-reinforced composites demonstrated pseudo-ductile failure behavior across all loading conditions (Fig. 5(b), Fig. 6(b), Fig. 7(b)), indicated by progressive crack formation and fiber/yarn pull-out rather than immediate rupture. The load-displacement curves of reinforced specimens showed multiple load drops (Fig. 5(b), Fig. 6(b), Fig. 7(b)) corresponding to sequential fiber/yarn pull-out and matrix cracking events (Fig. 5(d), Fig. 6(d), Fig. 7(d)), with the composite maintaining significant residual load bearing capacity even at 15 mm displacement.

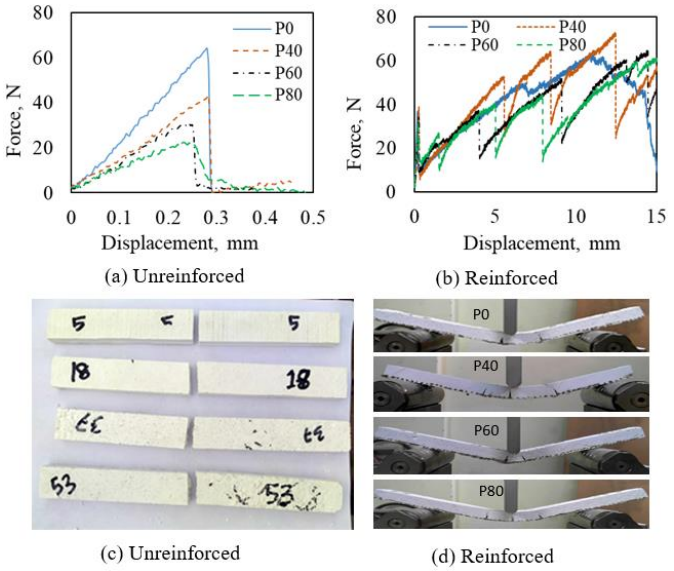


Fig. 5 Typical load-displacement curves of (a) unreinforced and (b) jute fiber mat-reinforced samples at **2 mm/min** crosshead speed and photographs of failed specimens for (c) unreinforced and (d) jute fiber mat-reinforced specimens.

The failure mechanisms exhibited clear rate-dependence as illustrated in Fig. 5-Fig. 7: at 2 mm/min (Fig. 5(b)), distinct "sawtooth" load fluctuations indicated gradual fiber/yarn pull-out, while 500 mm/min tests (Fig. 7(b)) revealed smoother load redistribution suggesting enhanced fiber-matrix interaction under dynamic loading. Intermediate loading rates (100 mm/min, Fig. 6(b)) displayed transitional behavior, balancing characteristics of both quasi-static and dynamic responses. It can be seen that the yarns of jute fiber mat bridged cracks through gradual pull-out at low rates (Fig. 5(d)), while at high rates (Fig. 7(d)), rapid load transfer activated energy-absorbing mechanisms in the cellular structure of perlite particles.

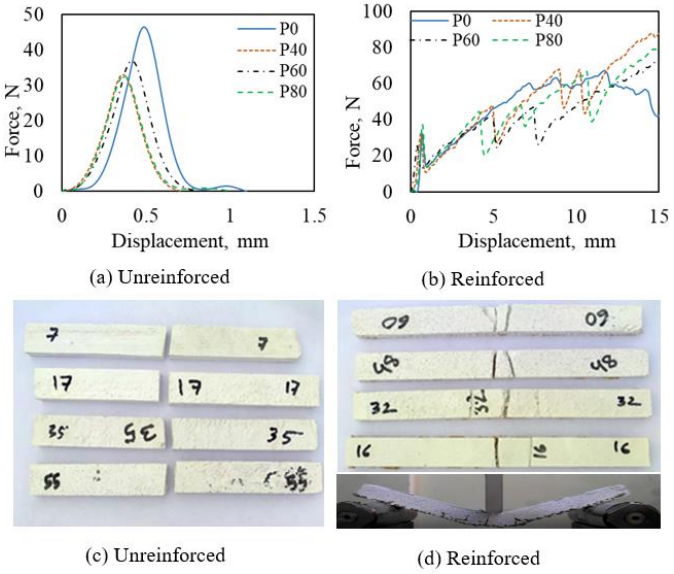


Fig. 6 Typical load-displacement curves of (a) unreinforced and (b) jute fiber mat-reinforced samples at **100 mm/min** crosshead speed and photographs of failed specimens for (c) unreinforced and (d) jute fiber mat-reinforced specimens.

This synergistic behavior explains why reinforced composites maintained approximately 30-50% of peak load capacity at maximum displacement in all test conditions (Fig. 5(b), Fig. 6(b), Fig. 7(b)).

The consistent pseudo-ductile response across all test conditions (Fig. 5 - Fig. 7), coupled with the absence of complete separation in reinforced specimens (Fig. 5(d), Fig. 6(d), Fig. 7(d)), confirms the significant improvement in damage tolerance imparted by jute fiber mat reinforcement. These findings, as visually demonstrated in Fig. 5 - Fig. 7, strongly support the potential application of jute fiber mat-reinforced gypsum composites in seismic-resistant construction, where energy absorption and progressive failure under varying loading conditions are critical performance requirements. The research demonstrates through comprehensive testing that natural fiber reinforcement can effectively transform the inherent brittleness of gypsum into a tunable, damage-tolerant material system suitable for structural applications.

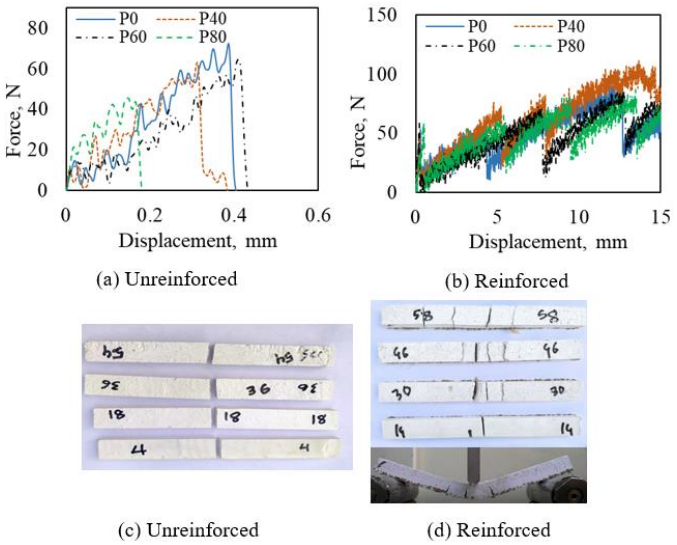


Fig. 7 Typical load-displacement curves of (a) unreinforced and (b) jute fiber mat-reinforced samples at **500 mm/min** crosshead speed and photographs of failed specimens for (c) unreinforced and (d) jute fiber mat-reinforced specimens.

5 Conclusions

This study demonstrates that the jute fiber mat reinforcement effectively transforms brittle gypsum into a more ductile, damage-tolerant composite, while expanded perlite incorporation reduces density without completely compromising mechanical performance. The jute fiber mat-reinforced gypsum composites exhibited remarkable pseudo-ductile behavior across all loading rates, maintaining 30-50% residual load capacity even after extensive cracking - a critical advantage for seismic-resistant applications. While perlite addition predictably decreased flexural strength (from 3.82 MPa to 1.19 MPa in unreinforced samples at 2 mm/min), the jute reinforcement compensated by significantly improving energy absorption (up to 700% increase at 100 mm/min) and preventing catastrophic failure. The performance of the composites was particularly noteworthy under dynamic loading, where the interaction of the cellular structure of perlite particles and jute fiber mats with gypsum improved energy absorption capacity.

For future work, developing multi-layer composite panels with optimized perlite distribution, and conducting full-scale structural tests under simulated seismic loads may be considered.

The findings establish these eco-friendly composites as promising candidates for interior construction, particularly where vibration damping and crack resistance are prioritized over pure strength. With further development, they could significantly expand the applications of gypsum in sustainable building systems.

Acknowledgement

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