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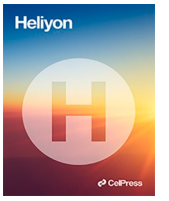

Effect of fibre loading on mechanical properties of jute fibre bundle reinforced gypsum composites

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ABSTRACT

Gypsum plasterboards are widely used in interior decoration like false ceilings, wall partitioning etc. The main component of this plasterboard is gypsum, which is a mineral material. These boards contain poor mechanical strength with lower durability. The addition of natural fibres in these plasterboards can be useful to achieve better mechanical properties. Since Jute fibre is abundant in Bangladesh and its usability in reinforced composites is well established, for this reason, jute fibre was selected to do the research. The aim of this study was to evaluate the impact of jute fibre on the mechanical properties of the gypsum plasterboard. To make this board, Plaster of Paris and water were thoroughly mixed to make a suspension first. Different fibre loadings of 2, 4, 6, and 8% were incorporated into gypsum composites. Reinforcement of 6% fibre provided the highest tensile properties, but 8% fibre loading showed inferior tensile and flexural properties. Impact test results showed a gradually improving nature with fibre loading, and hardness values showed a decreasing trend in hardness with higher fibre loading. FTIR results and SEM images confirmed that no significant chemical bonding took place in the composites, instead, the composite depended mainly on the mechanical bonding among the reins crystals and between the fibre and gypsum matrix.

1. Introduction

Gypsum boards are being used very frequently for interior decoration as well as for functional uses such as false ceilings, wall partitioning etc. The use of a false ceiling not only increases the aesthetic property of a space but also reduces the area of the living space, which is very much needed to reduce the conditioning cost and also saves a lot of energy incurred by an air conditioner. Since gypsum itself possesses low mechanical properties, such as it is brittle in nature, reinforcement with fibre can be a solution to this problem [1].

The main objective of this research work is to evaluate the probability of using jute fibre as a reinforcement in gypsum composites and also to improve the mechanical performance of existing gypsum plasterboard by using natural fibre.

Jute fibre is widely being used successfully by researchers as a reinforcing material in both thermoplastic and thermoset

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composites. Jute fibres are generally found in bundle form instead of an individual fibre and those bundles are used in all these applicaitons in composite production. Kumar et al. stated that after the addition of jute fibre tensile, flexural, and compression strength of jute-epoxy composite increased, and the author suggested that this composite can be used in partition boards, walls, floors, windows, and door frames [2]. Dobah et al. developed a jute-polyester composite in the hand-laying method, where a jute-woven fabric was used to reinforce the composite laminate. From the test result, authors suggested that this composite can be used in car or aircraft interiors which will surely reduce cost, weight as well as carbon footprint while maintaining performance [3]. Researchers also reveal that jute-epoxy composites show better tensile and flexural properties than jute polyester composites [4].

Researchers also investigated the effect of jute fibre incorporation into a thermoplastic matrix like polypropylene, PVC etc., due to their low cost, low thermal expansion, and recycling ability [5]. Gon et al. stated that jute-thermoplastic composites are suitable for making any moulded plastic object. He also suggested using wood flour as filler for better performance which can replace wooden products [6]. Barbosa et al. investigated the property of bio-composite made from jute and thermoplastic resin and found that the incorporation of jute fibre positively influences the composite but also increases the damping capacity [7].

Khan et al. investigated the characteristics of jute-PVC composite, where hessian jute fabric was incorporated. They also found improvements in mechanical properties after fibre incorporation [8].

Jute fibre has been applied successfully in hybrid composites, too, where along with other natural or synthetic fibres, jute is added as reinforcement. Researchers have hybridized jute with various natural and synthetic fibres. Ramnath et al. investigated the mechanical property of jute banana hybrid composite and stated that better result is found in hybrid composite compared to composite reinforced by jute or banana alone [9]. Ranakoti et al. hybridized jute with tasar silk waste to make an epoxy composite and found that the addition of tasar silk waste increases the mechanical strength of the composite, and the addition of 12% provided the best result [10]. Jawaid et al. investigated the effect of jute fibre loading in oil palm epoxy composite and found improved tensile and mechanical properties and stated that the jute oil palm epoxy hybrid composite might replace the use of synthetic fibres, and this hybrid composite can be applied in automobile, construction and aerospace industry [11].

Researchers have been trying to hybridize jute fibre with high-performance synthetic fibres due to higher cost, non-biodegradable nature as well as their complex manufacturing system. Maharana et al. studied the mechanical property of jute-Kevlar-fume silica hybrid composite with different layer sequences. They tried this study with 4 layers of composite and found that the Jute-Kevlar-jute-Kevlar structure was able to reach 76.35% of maximum tensile strength compared to the Kevlar-Kevlar-Kevlar-Kevlar structure [12]. Ramana et al. studied the tensile, flexural, and impact behaviour of the jute-carbon epoxy hybrid composite and compared it to the carbon epoxy composite. They found that the jute-carbon hybrid can replace the carbon epoxy composite with a minimal loss in tensile and flexural properties but with improved ductility and impact strength [13]. Jha et al. fabricated jute E-glass epoxy composite by hand layup technique and investigated the erosion and mechanical behaviour. They observed that this hybridization offers better mechanical and wear properties [14].

Gypsum has been used in building and construction materials widely since ancient times. Gypsum is a mineral material named calcium sulfate dihydrate ($CaSO_4.2H_2O$). After mining the raw gypsum, it is crushed and heated to form calcium sulfate hemihydrate ($CaSO_4.0.5H_2O$). It is recyclable, provides good thermal insulation, and it is easily available too. But it is brittle in nature, and it also shows poor mechanical properties. Reinforcing the gypsum plasterboards with natural fibres is being done by researchers as a solution of this problem. Haba et al. developed gypsum-based composite reinforced with date palm fibre. They extracted the fibre from date palm trees which are abundant in Middle East Asia and North Africa region. Various mechanical as well as chemical treatments can be done for the extraction process like alkali treatment with NaOH, retting and boiling etc. [15,16] After that, researchers made a dispersion with the ratio water/gypsum ratio: 0.6 and prepared the final composite according to hand laying method. They revealed that the inclusion of finer grade date palm fibre strongly improves the insulation behaviour of the composite - 5% fibre inclusion reduces the 55% thermal conductivity - but it also decreases the compressive strength by 14% with the same rate of reinforcement. Haba et al. concluded that the date palm fibre-reinforced gypsum composite can be very much useful as construction and building materials due to their great thermal insulation biodegradability [17].

An approach to improve the fracture toughness of gypsum matrix by reinforcing with natural fibre was made by Fantilli et al. They compared the performance of both sheep wool and hemp fibre as reinforcement. 1% in volume of sheep wool and hemp fibres were added to the gypsum paste. Mechanical test results revealed that the fracture toughness of wool-reinforced gypsum composite was found to be more than that of the hemp-reinforced sample. The wool fibre was found to show better adhesion with gypsum matrix than hemp [18].

Alcaraz et al. studied the mechanical behaviour of jute fabric-gypsum composite and got improved ductility and tenacity [1]. Iucolano et al. tested the thermo-mechanical character of hemp-reinforced gypsum composites and concluded that the addition of hemp increases the tenacity under load [19]. Coelho et al. manufactured sisal-gypsum composite by binder jetting technique and investigated the mechanical strength and porosity of the manufactured parts. They reported that the presence of fibre in infiltrated portions has a positive influence on the mechanical property but a loss of strength was observed in the green parts due to the presence of porous areas [20].

2. Materials & methods

2.1. Materials

The intention was to use raw materials which are easily available so that the final product be cheap and easy to manufacture. The list of raw materials used in this research with basic specifications is given below.

a) Gypsum powder

Product Name: BK 90 gypsum powder.
Manufacturer: B.K Plaster & Gypsum Corporation.
Country of origin: Thailand.

b) Jute fibre bundle

Commercial Class: Tossa
Species: Corchorus olitorius.
Length: 2.1 m.
Strength: 27.4 g/tex.
Fineness: 3.1tex.

c) Water

Water is an essential element in making the Jute Gypsum (JG) composite. Distilled water was used to prepare the Gypsum suspension.

d) Sodium Hydroxide

Product concentration: 5% NaOH solution.
Molecular formula: NaOH.
Molecular weight: 39.997 g/mol.

e) Acetic Acid

Concentration: 1 g/l solution.
Molecular formula: CH_3COOH
Molecular weight: 60.05 g/mol.

2.2. List of samples

Five samples were prepared using the percentages stated in Table 1 to make samples for different tests.

2.3. Composite fabrication

Fabrication of composite samples was started with surface modification to increase the interfacial bond. Fibre bundle batts were prepared manually. Each batt weighs 2 g which reinforces gypsum-water dispersion. Each step is described below.

2.3.1. Fibre bundle preparation

Firstly, Fibre bundles were cut down into around 25 mm lengths by a hand-cutting machine. Fibre bundle length was selected according to the previous researchers [21]. The individual fibre bundle diameter varied around 200 μm, while the fibre bundles were found in bundles. Then, to increase the openness and fluffiness of the fibre bundle, the fibre bundles were treated in a trash analyzer. After that, fibre bundles were submerged into a 5% NaOH solution for 8 h at 30° Celsius. The material: liquor ratio was 1:15. Excess alkali solution was drained off and then neutralized by a dilute acetic acid solution of 1 g/l.

P^H level 7 was maintained. At last, drying was done for 48 h in room temperature. These procedures are done based on the findings of previous researchers [4]. The alkali treatment was carried out to improve the roughness of the surfaces of the fibre bundles, which generally helps matrix molecules to adhere on to the surface so that the interfacial bonding between fibre bundle and matrix can be improved [22,23]. Fig. 1(a) shows the comparatively smooth surface of the jute fibre bundes filled with hemicellulose, wax, etc., while Fig. 1(b) shows the roughened surface of the jute fibre bundles of the study which would help the interfacial bonding in the composites.

Table 1
List of samples.

Test name	Variation in fibre bundle percentage	Number of samples
Tensile strength	0%, 2%, 4%, 6% and 8%	05
Flexural strength	0%, 2%, 4%, 6% and 8%	05
Impact strength	0%, 2%, 4%, 6% and 8%	05
Hardness	0%, 2%, 4%, 6% and 8%	05
FTIR	6%	01

2.3.2. Preparation of fibre bundle batt

2 g of fibre bundles were spread by hand on the mould as evenly as possible. When a batt is formed, it was collected from the mould carefully. Water was used to bind the fibre bundles together, and this process was helped by the interfacial bonding between the fibre bundles and also the waviness of the fibre bundles [23,24]. The fibre bundle batt is shown in Fig. 2.

2.3.3. Matrix preparation

We made a Water-Plaster of Paris (POP) dispersion first. When POP powder in the form of calcium sulfate hemihydrate gets mixed with water, it turns into a white colour dispersion of calcium sulfate dihydrate, and a few hours later, it becomes a hard solid. It cures very quickly and does not need any external heating arrangement. The overall strength of gypsum plasterboard varies greatly on this POP-water ratio. If more water is added while mixing, the dispersion will be diluted, increasing the fluidity of the dispersion and the hardening time. On the other hand, the addition of less amount of water makes the dispersion more viscous and dries quickly, and it becomes tough to work with that dispersion. The ratio of the dispersion was 20:13 (Gypsum: Water).

2.3.4. Composite fabrication

The hand-laying method was used for composite development. A flexible plastic-made mould was taken, which is 177.8 mm long, 127 mm wide, and 10 mm in height. Required no. of fibre bundle batts of 2 g each were laid.1 layer of suspension matrix suspension was followed by 1 layer of fibre bundle batt.

Fig. 3 shows the mixture of the fibre bundle batt and gypsum matrix before curing of the composites.

2.3.5. Curing

Gypsum-water suspension dries very quickly, and it is possible to cure it at room temperature. The samples were cured for 72 h at room temperature. The mass of samples was measured once every 8 h. No mass change was observed after 72 h.

Fig. 4 is showing a cured fibre bundle reinforced gypsum plasterboard.

2.3.6. Cut into the required shape

As each test requires a different particular dimension according to the particular standard, after curing, the solid gypsum board was cut according to the desired shape. A wood-cutting machine was used for this purpose.

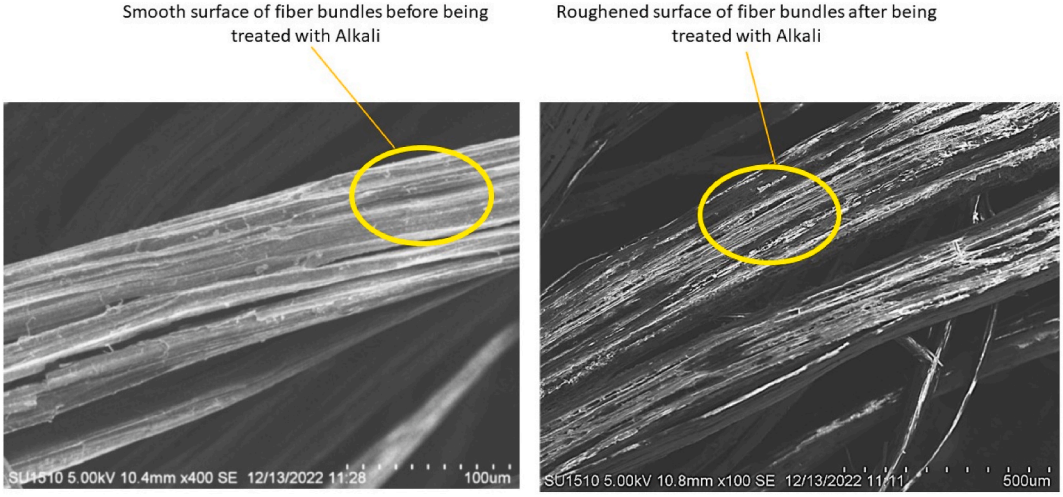
2.4. Testing machines and test methods

The samples underwent several tests. The specifications of the tests are shown in Table 2. Standard condition (25 ± 2 °C temperature and 65 ± 2% RH were maintained).

3. Results and discussion

3.1. Microscopic images of the composites

SEM (scanning electron microscopic) images shown in Fig. 5(a–h) are showing in the structures of the composites. The images in



a) Untreated fibre bundle b) Alkali treated fibre bundle

Fig. 1. Effect of alkali treatment on fibre bundle properties.

Fig. 2. Cut and surface modified jute fibre bundle batt.

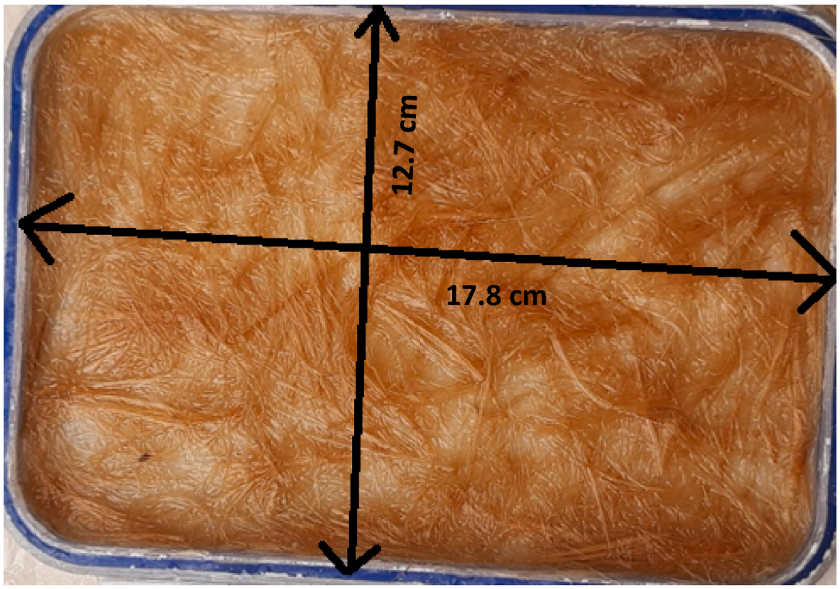


Fig. 3. Jute fibre bundle batt-gypsum dispersion mixture for composite production.

Fig. 5(a–f) show that the structures are porous with a lot of pores. It was evident in the sample containing no fibre bundle also. The hand layup process tends to make a porous structure due to the application of less uniform pressure than required. But at the same time, gypsum board is also porous in nature. It is down to the nature of gypsum. Gypsum does not form a continuous film like other polymers, instead, it forms needle-like crystals which are mechanically interlocked to form the board [25]. It leaves pores in between the crystals.

On the other hand, composites are made of two types of bonding, namely, mechanical and chemical bonding. Chemical bonding is generally found within the same molecules, like the molecules of the gypsum matrix or fibre bundle. But when a fibre bundle-reinforced composite is made, the main bonding between the fibre bundle and the gypsum matrix is generally the mechanical bonds. The mechanical bonds are created by the interfacial bonding between the fibre bundle and rein [23]. The amount of fibre bundle has not been too high in the composites of this study as the density of jute and gypsum are not far from each other (about 600–1000 kg/m^3 for gypsum and 1300 kg/m^3 for jute [26,27]). But the images in Fig. 5(g and h) show that a good amount of gypsum crystals are adhering to the surface of the fibre bundles, which means good interfacial bonding between fibre bundle and the gypsum matrix. But since gypsum board is made of mechanical interlocking itself, the interfacial bonding between the fibre bundles and gypsum crystals interrupts the mechanical bonds among the gypsum crystals, and the increasing amount of fibre bundle would disrupt the mechanical bonds within the gypsum crystals even more. For this reason, the increasing fibre bundle loading would be expected to affect the mechanical properties of the composites negatively until the reduction of bonds among the gypsum crystals reaches the

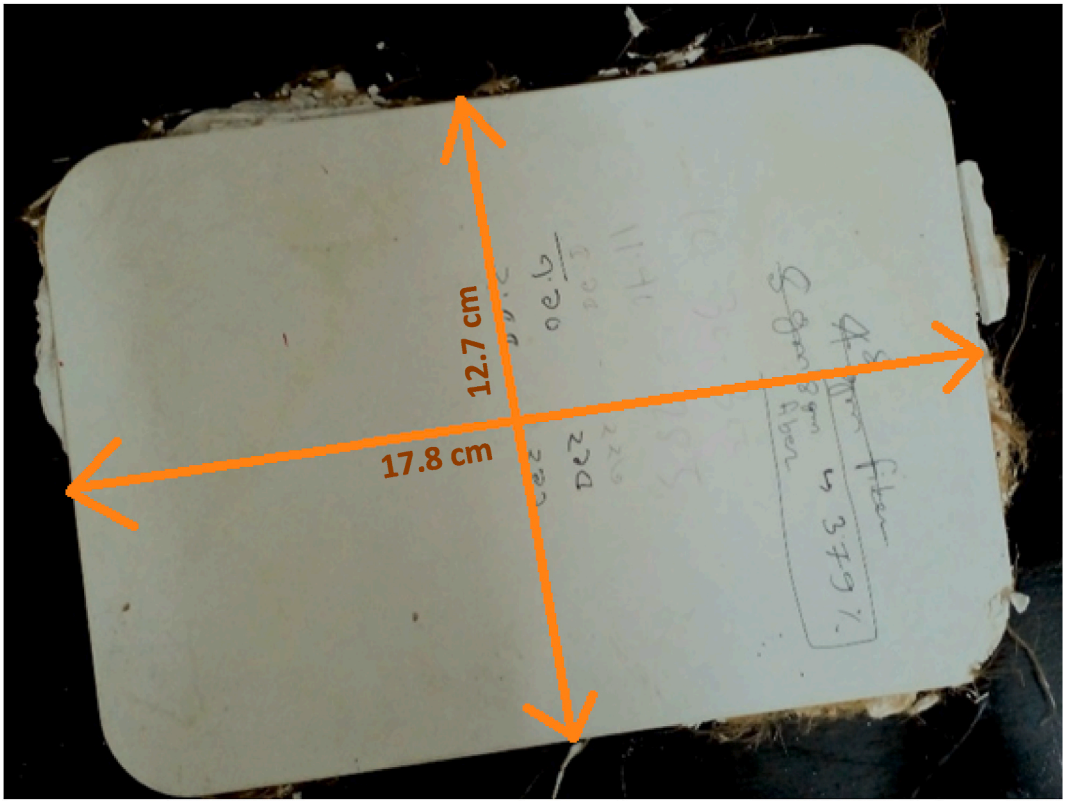
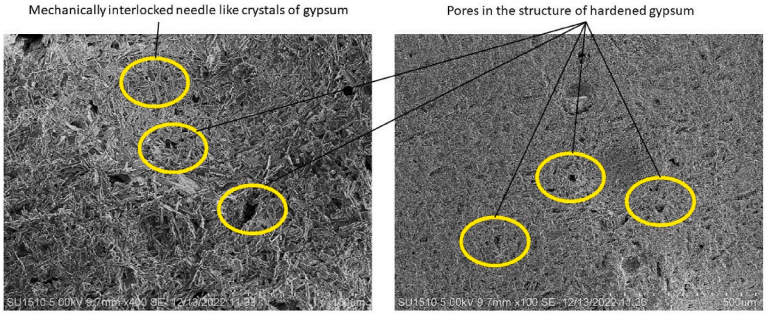


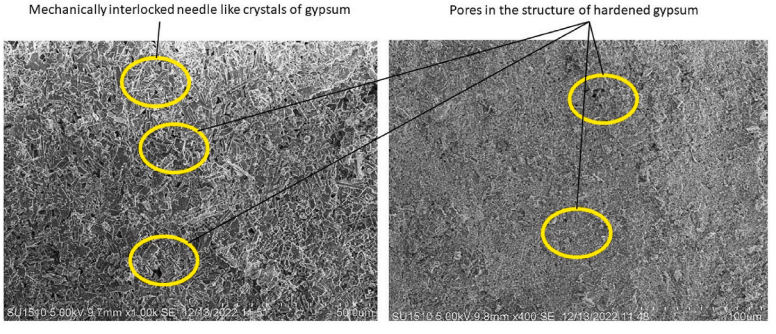
Fig. 4. Fibre bundle loaded Gypsum Plasterboard.

Table 2
Sample size, Testing machines, and machine specifications.

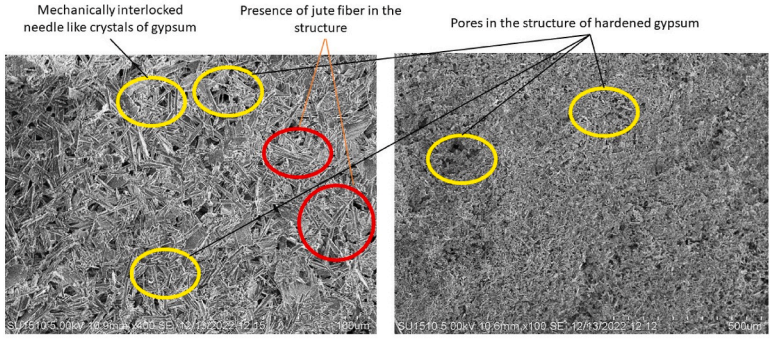
Name of the test	Method	Sample size & machine specification
Microscopic Imaging	Scanning Electron Microscope	Machine Name: Hitachi Scanning Electron Microscope Model No.: SU 1510 Manufacturer: Hitachi Origin: Japan Sample size: N/A
Tensile properties	ASTM D638	Instrument: Universal Testing machine Model No.: H10KS Manufacturer: Hounsfield Test speed: 2 mm/min. Sample size: 10 cm × 0.6 cm
Impact properties	ASTM D256- IZOD Impact Test	Instrument: Universal Analogue Impact Tester Model No.: HT-8041B IZOD Manufacturer: Hung Ta Instrument CO. Ltd Sample size: 10 cm × 1.2 cm
Flexural properties	ASTM D790	Instrument: Universal Testing machine Manufacturer: Hounsfield Model: H10KS Sample size: 10 cm × 1.2 cm
Hardness properties	ASTM A956	Instrument: Leeb Hardness Tester Manufacturer: Qualitest Model: H 1000 Sample size: N/A
FTIR Spectroscopy		Instrument: FTIR spectrometer Manufacturer: Shimadzu Model No: IRAffinity1 Country of origin: Japan Frequency: 4000–650 cm^{-1} Sample size: N/A



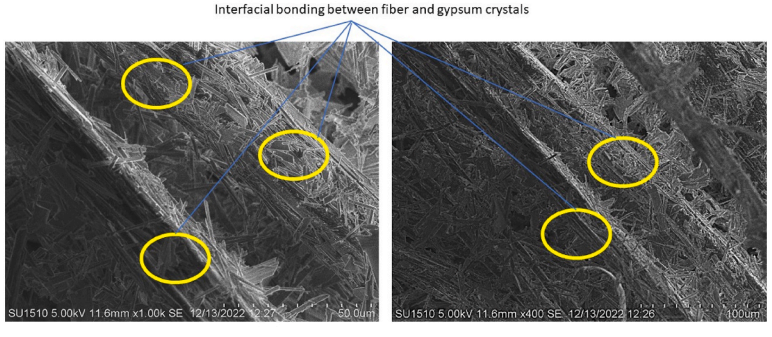
a) Cross sectional view (0% fibre bundle sample) b) Surface view (0% fibre bundle sample)



c) Cross sectional view (2% fibre bundle sample) d) Surface view (2% fibre bundle sample)



e) Cross sectional view (6% fibre bundle sample) f) Surface view (6% fibre bundle sample)



g) Surface view (4% fibre bundle sample) h) Surface view (4% fibre bundle sample)

Fig. 5. SEM Images of different JG composites.

maximum level and overcomes the strength provided by the interfacial bonding among the fibre bundles.

3.2. Effect of fibre bundle loading on tensile properties of Jute-Gypsum composite

The tensile test result shows how much stress the composites can bear if they are pulled until the breaking point. Fig. 6 shows that it requires more stress to break the samples after the addition of fibre bundles up to 6%.

Here, the added fibre bundles acted positively because they could provide some resistance against the tensile force. This demanded more stress to break the specimen. In addition, the surface modification with alkali removes the lignin, wax, pectin etc. from the outer surface and makes the fibre bundle surface rough. This rough surface creates better interlocking with the gypsum matrix creating interfacial bonds [28,29]. At the same time, the increase of the bulk of the fibre bundles is also helping increase the strength as the strength of the fibre bundle bulk is improved. But with the addition of 8% fibre bundle, the disruption of bonding among the gypsum crystals reached a point where the slight improvement of the strength in the fibre bundle bulk could not improve the overall strength of the composite, instead, the interfacial bonding between the fibre bundles and gypsum crystals caused lack of mechanical interlocking among the gypsum crystals and that resulted in a reduction of the strength of the composite. This would have continued if further addition of fibre bundle was made.

On the other hand, the elongation property shows a similar trend as tensile strength. Fig. 7 indicates an increase in the elongation of composite samples up to 6% fibre bundle reinforcement. The addition of jute fibre bundle affects the elongation positively due to fibre bundle's elongation capability. But when we added 8% fibre bundle to the elongation value, goes down. When more fibre bundles were added than the optimum limit, the jute fibre bundles had a more specific surface area over the amount of matrix dispersion, and as a result, the matrix got reduced inside the composite. The reason for the lack of matrix crystals to get bonded to each other has already been discussed in the previous section. And due to an inadequate amount of matrix, the uneven Jute-gypsum bond formation could not sustain the elongation due to stress. As a result, after 8% fibre bundle loading composite sample breaks with a lower elongation value. So, according to the results, 6% fibre bundle loading was found as the optimum limit of fibre bundle addition.

In addition to the above discussion, the modulus shown in Fig. 8 also matches the concept also. Here, the modulus decreased till 4% fibre bundle loading, but later, with the addition of fibre, the values increased gradually. Modulus is measured by the ratio of applied stress or force to the change in dimension or strain onto the material [22,30]. If the stress value is lower while keeping the strain constant, which means the material is needing lesser force to be deformed, then the modulus value decreases. It increases if the required force or stress is increased for the same amount of strain. And in case, both values are changing, the resultant modulus will depend on the percentage of change in each value in respect to the other value. In case the change in the stress is less but that stress is resulting in relatively high strain in the material, then the modulus value will be lower than materials that are undergoing less strain. It means the value of modulus is generally lower for materials that show higher elongation unless the required force responsible for the deformation is significantly more than the deformation.

Here, the modulus values have been found to decrease when the fibre loading was increasing at the beginning till 4% fibre loading. This happened because of the change in dimension or strain in those samples on the higher side which is evident in the elongation results that increased gradually with the fibre loading. The required force or stress is on the rise as well with the fibre loading but the change in the stress was less significant in comparison to strain. But the modulus increased for the sample containing 6% fibre because this sample showed the highest strength value among the samples which was significant in comparison to the deformation it showed. It means the hardness of the sample along with compact and solid structure due to the increased percentage of fibre in the structure. But

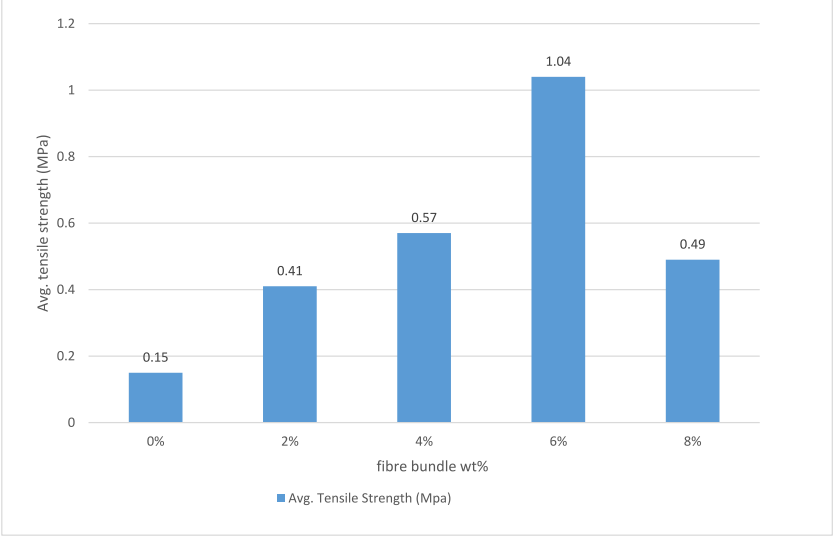


Fig. 6. Average tensile strength of JG composite samples.

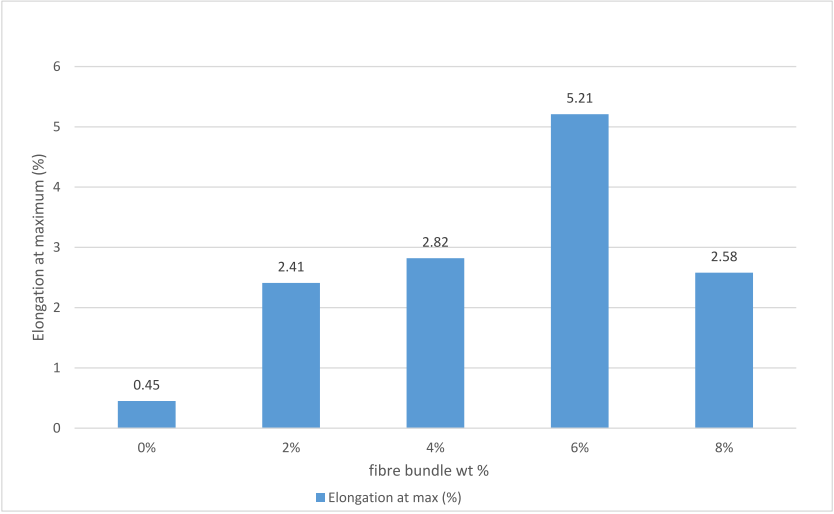


Fig. 7. Average elongation at max % of JG composites.

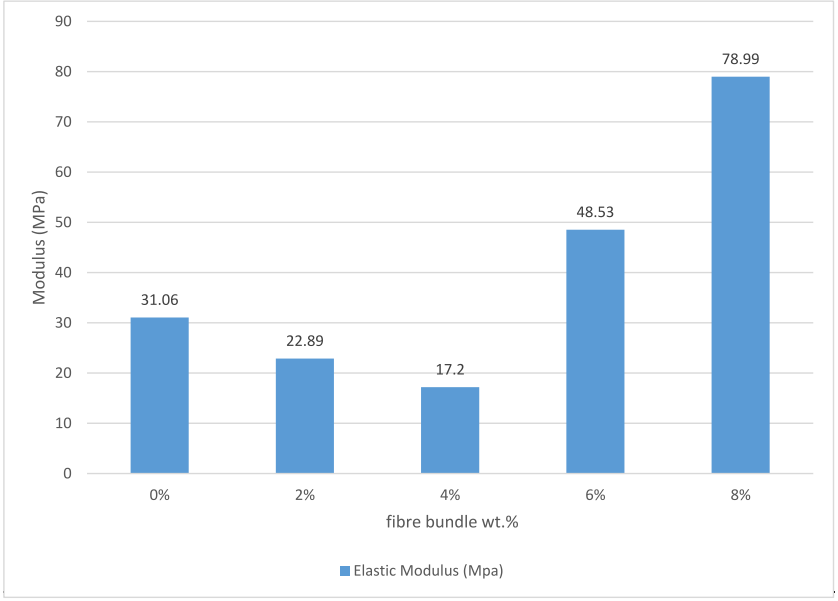


Fig. 8. Average modulus of JG composites.

the decrease in the modulus value in the sample with 8% fibre loading is an indication of a very rigid structure with the least deformation which is also evident in elongation results (Fig. 7). The negative change in modulus even after the required stress or force means the very rigid nature of the sample that is caused by the increased compactness of the structure with the fibre loading.

3.3. Effect of fibre bundle loading on flexural strength

The effect of fibre bundle loading on flexural properties is shown in Fig. 9.

Flexural strength is the highest stress faced by the sample until it ruptures against flexing. When fibre bundle is incorporated into the composite, flexural strength decreases up to 8% loading of fibre bundle. This occurs due to weak interlocking among the matrix molecules and due to the existence of voids inside the composite [31,32].

Actually, the flexural strength results of the samples of this study are different to tensile strength results (Fig. 6). The tensile strength increased gradually with the addition of fibre while the flexural strength has been found in decreasing trend as shown in Fig. 9. The measurement of tensile and flexural strength is different. The tensile test is done by putting the stress on to the sample where the whole dimension of the sample responds against the stress put during the test. On the other hand, the flexural test done in three-

point bending process puts more stress on a single point and the stress mainly works on half of the sample instead of the whole structure. Since the localized weakness in the fibre-reinforced composite is generally high due to the difference in the mechanical properties of fibre and matrix, it becomes difficult for the composites to withstand stress put on specific points or areas instead of the whole area if the bonding between the fibre and matrix are not strong enough [33]. The composites made in this study depend solely on the mechanical bonding between the fibre and matrix which was able to show a slight improvement in tensile strength but localized weakness in the structure caused the composites to fail in the flexural test and as a result, the flexural strengths of all the samples decreased with a gradual increase in the fibre loading.

3.4. Effect of fibre bundle loading on impact resistance

The impact test result from Fig. 10 provides the energy absorbed by the specimen expressed in Joules/meter. The figure shows a gradual increase in the impact strength of composite samples. This happens because more incorporation of fibre bundles induces better fibre bundle-to-fibre bundle interaction, which can increase the impact strength. This also increases the toughness of the composite sample enabling it to resist fracture under sudden stress. The alkali-treated fibre bundles also provide a better interfacial bond between the fibre bundle and the matrix [34]. The softness of the bundle fibre bundles enables the composite to absorb sudden stress to show higher impact resistance in the composites [23].

3.5. Effect of fibre bundle loading on surface hardness

Leeb rebound hardness test measures the loss of energy when an impact body impacts a test surface. A hard material shows a higher rebound velocity which indicates a higher hardness value. A lower hardness value indicates softer material [35].

Fig. 11 shows that 100% gypsum board contains more hardness than the fibre bundle-reinforced samples. The reason behind this behaviour is the stiffness of gypsum. When fibre bundle is added to gypsum, the composite becomes softer, and gradually the hardness value drops down from 8.07 to 6.9 [36]. When more fibre bundle is added to gypsum during composite formation, fibre bundles become more and more prominent than gypsum. For this reason, intermolecular attraction among the gypsum decreases, and the composite becomes softer, which can absorb more impact energy showing a lower hardness value [37].

The Leeb's hardness test assesses the hardness of the materials on the surface and the composites produced in this study contained fibres within the structure. The tensile test results which included the modulus results that are shown in Fig. 8 showed that the modulus of the samples decreased till 4% fibre loading while it increased due to the compactness of the structures in samples with 6% fibre loading. The tensile test involves the whole structure in the test while Leeb's hardness test involves only the surfaces of the samples. Since the fibres were introduced to the composites which were placed beneath the surfaces of the composites, the layer of gypsum got thinner with increasing amounts of fibre. This caused the surfaces to become softer even though the materials were found compact and rigid in tensile test results. The surfaces still showed elastic nature during the tests which match the tensile test results that are described before.

3.6. FTIR analysis

The spectra of the Jute-Gypsum composite sample show a number of bands in Fig. 12. The peaks are listed in Table 3. A broad band at 3245 cm^{-1} (peak no.9) occurs due to the stretching and vibration of water molecules after absorption by O–H [38]. It was found as a broader peak than a sharp peak because of the existence of weak hydrogen bonds between the molecules in the composite. It means hydrogen bonds were formed between the fibre bundles and the water molecules of the gypsum crystals. But the nature of this bond makes this insignificant in case of any improvement in the mechanical properties of the materials. The absorbance peak found at 1621 cm^{-1} is almost similar to the characteristic band of lignin, which absorbs at 1633 cm^{-1}. The presence of SO_4^{2-} was also detected by their characteristic band. Peaks at 600 and 674 cm^{-1} occur due to the bending vibration, and peaks at 1004 cm^{-1} were found due to the stretching vibration of the Sulfate group. Bands at wavenumber 2115cm-1 and 2236 cm^{-1} appeared as new bands due to the bending vibration of H_20 [39], which can be occurred due to the hydrogen bond formation between the fibre bundle and the matrix.

So, the above discussion shows the existence of the jute and gypsum in the structure, but no new chemical bonding other than hydrogen bonds has been detected, while no significant change in the chemical structure of any material has been detected either. The hydrogen bonds were formed between the fibre bundles and the water molecules that existed in the gypsum. In fact, nothing new was expected in this part as the whole structure depended mainly on mechanical bonding instead of any chemical bonding, which has been evident in the previous results.

4. Conclusion

This study reveals that the addition of jute fibre bundle influences the performance of gypsum plasterboards positively. Test results support the possibility of successful jute fibre bundle inclusion into currently available gypsum plasterboards, which are brittle and also contain poor mechanical properties. Loading of jute fibre bundle can provide a solution to these problems.

After analyzing all the data, the following conclusions can be drawn:

- Mechanical bonding has been found as the main bonding force among the gypsum crystals and also between the fibre bundle and gypsum crystals in the composite, while no new strong chemical bonds have been found in the structure.

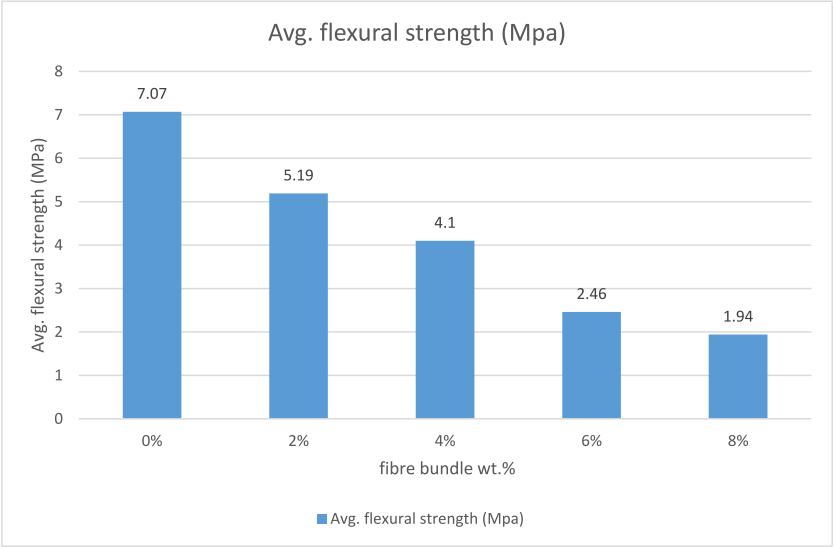


Fig. 9. Average flexural strength of JG composites.

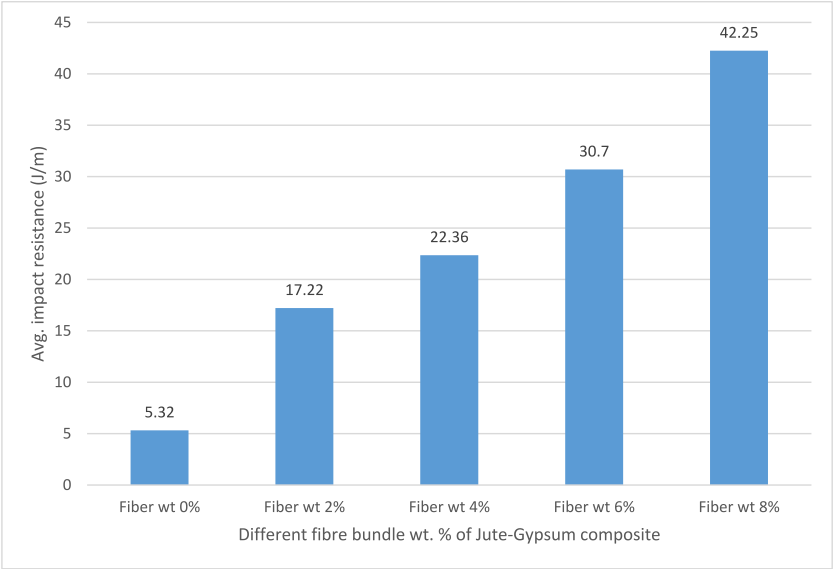


Fig. 10. Average impact resistance of JG composites.

- 6% jute-reinforced gypsum composite provides the best tensile strength. The alkali-treated reinforcing fibre bundles increase the interfacial bond. Elongation at break% of the samples follows the same trend. The high modulus of the sample containing 6% fibre bundle indicated the strong nature of the composite, which is an evidence of optimum fibre bundle loading in that structure.
- Minimum flexural strength is seen from 8% jute reinforced sample due to weak mechanical bond and the presence of void in the structure.
- Composite's impact strength becomes higher with the gradual inclusion of fibre bundle. 8% jute-reinforced composite shows the maximum impact strength. It happened due to the ability of bundle fibre bundles to absorb sudden impacts better than hard and rigid gypsum crystals.
- More incorporation of jute results negatively in terms of hardness. As gypsum is more rigid than jute fibre bundle, hardness decreases with the increase of reinforcing fibre bundle.
- FTIR shows a large area of peak of hydrogen bond which is an indicator of hydrogen bonding between jute fibre bundle and the present water molecules in the matrix.

The above statements clearly depict the probability of jute inclusion in gypsum plasterboards. Better tensile strength, higher

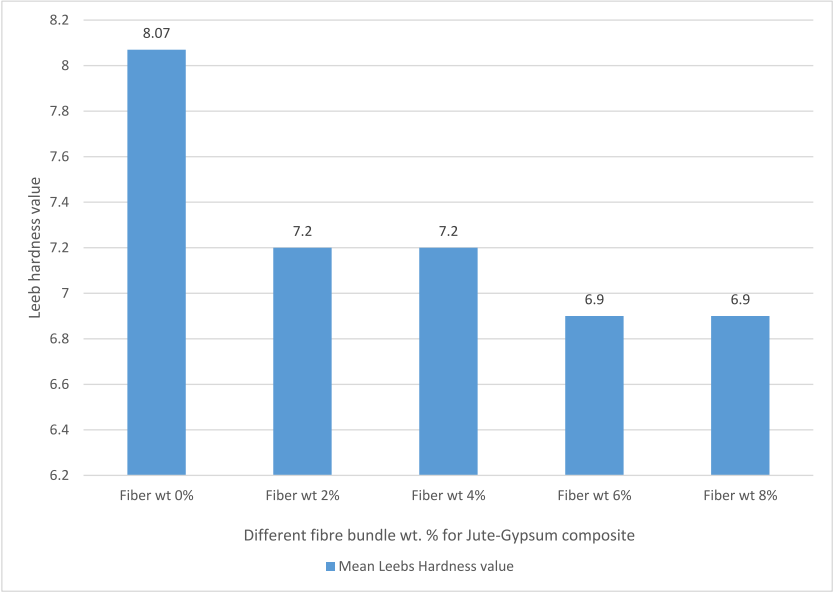


Fig. 11. Leeb's hardness value of JG composites.

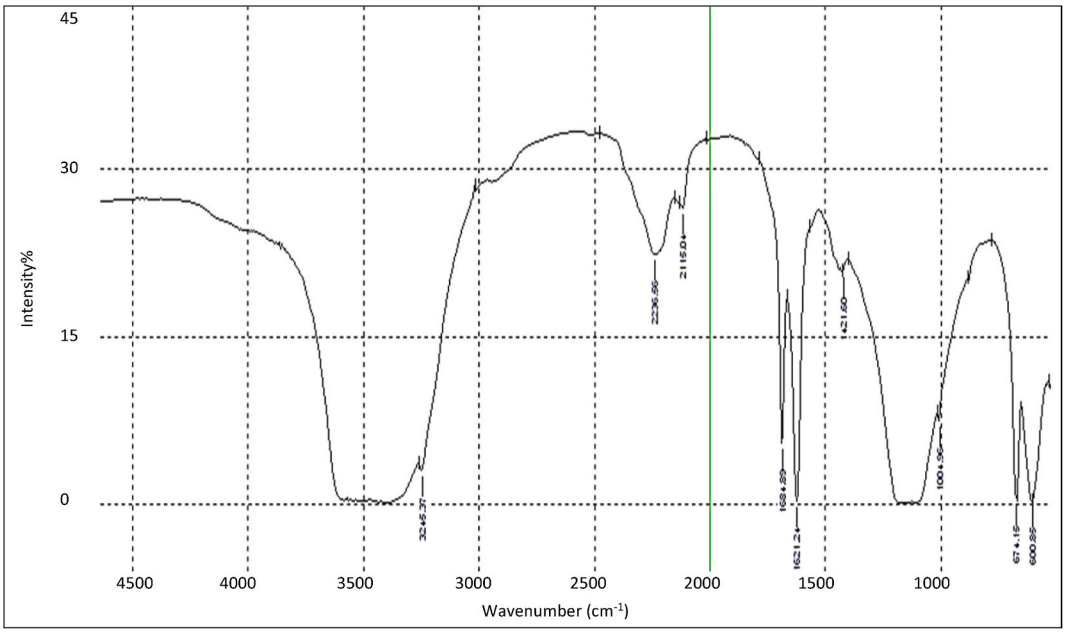


Fig. 12. *FTIR spectra of JG composite.*

breaking elongation %, and more impact resistance with increasing fibre bundle loading are accompanied by poor flexural strength in the composites, which may need further investigation and trials for future applications.

Author contribution statement

Nafis Abir: Conceived and designed the experiments, Performed the experiments, Analyzed and interpreted the data, Contributed reagents, materials, analysis tools or data, and Wrote the paper.

Abu Bakr Siddique; Hosne Ara Begum; Md. Abdul Gafur; Ayub Nabi Khan: Conceived and designed the experiments, Analyzed and interpreted the data, and Wrote the paper.

Md. Arif Mahmud: Performed the experiments, Analyzed and interpreted the data, and Wrote the paper.

Table 3
Wavenumber (cm^{-1}) of peaks from FTIR spectra.

Peak no. (from right to left)	Peak Wavenumber (cm^{-1})
1	600.85
2	674.15
3	1004.96
4	1421.60
5	1621.24
6	1684.89
7	2115.04
8	2236.56
9	3245.37

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J.S. Alcaraz, I.M. Belda, E.J. Sanchis, J.M. Gadea Borrell, Mechanical properties of plaster reinforced with yute fabrics, Compos. B Eng. 178 (2019), 107390, https://doi.org/10.1016/j.compositesb.2019.107390.
[2] A. Kumar, A. Srivastava, Preparation and mechanical properties of jute fiber reinforced epoxy composites, Ind. Eng. Manag. 6 (4) (2017), https://doi.org/10.4172/2169-0316.1000234.
[3] Y. Dobah, M. Bourchak, A. Bezazi, A. Belaadi, F. Scarpa, Multi-axial mechanical characterization of jute fiber/polyester composite materials, Compos. B Eng. 90 (Apr. 2016) 450–456, https://doi.org/10.1016/j.compositesb.2015.10.030.
[4] A. Gopinath, M. Senthil Kumar, A. Elayaperumal, Experimental investigations on mechanical properties of jute fiber reinforced composites with polyester and epoxy resin matrices, in: Procedia Engineering, Elsevier Ltd, 2014, pp. 2052–2063, https://doi.org/10.1016/j.proeng.2014.12.448.
[5] H. Chandekar, V. Chaudhari, S. Waigaonkar, A review of jute fiber reinforced polymer composites, Mater. Today Proc. 26 (xxxx) (2020) 2079–2082, https://doi.org/10.1016/j.matpr.2020.02.449.
[6] D. Gon, K. Das, P. Paul, S. Maity, Jute composites as wood substitute, Int. J. Textil. Sci. 1 (6) (2013) 84–93, https://doi.org/10.5923/j.textile.20120106.05.
[7] L.C.M. Barbosa, G.R.V. Duque, A.C. Ancelotti Junior, Temperature-frequency-dependent properties analysis of a bio-composite based on a new liquid thermoplastic resin reinforced with jute fibers, J. Thermoplast. Compos. Mater. (2020), https://doi.org/10.1177/0892705720959139.
[8] R.A. Khan, et al., Fabrication and characterization of jute fabric-reinforced PVC-based composite, J. Thermoplast. Compos. Mater. 25 (1) (2012) 45–58, https://doi.org/10.1177/0892705711404726.
[9] B. Vijaya Ramnath, et al., Experimental determination of mechanical properties of banana jute hybrid composite, Fibers Polym. 16 (1) (2015) 164–172, https://doi.org/10.1007/s12221-015-0164-0.
[10] L. Ranakoti, P.K. Rakesh, Physio-mechanical characterization of tasar silk waste/jute fiber hybrid composite, Compos. Commun. 22 (2020), 100526, https://doi.org/10.1016/j.coco.2020.100526.
[11] M. Jawaid, H.P.S. Abdul Khalil, A. Hassan, R. Dungani, A. Hadiyane, Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites, Compos. B Eng. 45 (1) (2013) 619–624, https://doi.org/10.1016/j.compositesb.2012.04.068.
[12] S.M. Maharana, A.K. Pradhan, M.K. Pandit, Performance evaluation of mechanical properties of nanofiller reinforced jute-kevlar hybrid composite, J. Nat. Fibers 00 (00) (2020) 1–15, https://doi.org/10.1080/15440478.2020.1777246.
[13] M.V. Ramana, S. Ramprasad, Experimental investigation on jute/carbon fibre reinforced epoxy based hybrid composites, Mater. Today Proc. 4 (8) (2017) 8654–8664, https://doi.org/10.1016/j.matpr.2017.07.214.
[14] K. Jha, B.B. Samantaray, P. Tamrakar, A study on erosion and mechanical behaviour of jute/E-glass hybrid composite, Mater. Today Proc. 5 (2) (2018) 5601–5607, https://doi.org/10.1016/j.matpr.2017.12.151.
[15] A. Bezazi, et al., Alkali Treatment Effect on Physicochemical and Tensile Properties of Date Palm Rachis Fibers 19 (10) (2020) 3770–3787, https://doi.org/10.1080/15440478.2020.1848726.
[16] L.A. Elseify, M. Midani, L.A. Shihata, H. El-Mously, Review on cellulosic fibers extracted from date palms (Phoenix Dactylifera L.) and their applications, Cellulose 26 (4) (2019) 2209–2232, https://doi.org/10.1007/s10570-019-02259-6.
[17] B. Haba, F. Benali, M. Jawaid, 43, no. 11, A Review on Gypsum - Based Composites Reinforced with Palm Fibers in Construction Applications, Springer US, 2022, https://doi.org/10.1007/s10765-022-03086-x.
[18] A.P. Fantilli, J. Daria, P. Denis, Bio-Fibres as a Reinforcement of Gypsum Composites, 2021.
[19] F. Iucolano, B. Liguori, P. Aprea, D. Caputo, Thermo-mechanical behaviour of hemp fibers-reinforced gypsum plasters, Construct. Build. Mater. 185 (2018) 256–263, https://doi.org/10.1016/j.conbuildmat.2018.07.036.
[20] A.W. Fonseca Coelho, R.M. da Silva Moreira Thiré, A.C. Araujo, Manufacturing of gypsum–sisal fiber composites using binder jetting, June, Addit. Manuf. 29 (2019), 100789, https://doi.org/10.1016/j.addma.2019.100789.
[21] M.A. Mansur, M.A. Azizf, A study, of jute fibre reinforced cement composites M A Mansur* and M A Azizf, IABSE congress report 4 (2) (1982) 75–82.
[22] Md A. Mahmud, F.R. Anannya, Sugarcane bagasse - a source of cellulosic fiber for diverse applications, Heliyon 7 (8) (2021), https://doi.org/10.1016/j.heliyon.2021.e07771, 1, 14.
[23] M.A. Mahmud, S.A. Belal, M.A. Gafur, Development of a biocomposite material using sugarcane bagasse and modified starch for packaging purposes, J. Mater. Res. Technol. 24 (2023) 1856–1874, https://doi.org/10.1016/j.jmrt.2023.03.083.
[24] S. Akter, Md M. Helali, The effect of mechanical crimp on the basic properties of jute yarn, Mater. Today Proc. 46 (2021) 425–432, https://doi.org/10.1016/j.matpr.2020.09.431.
[25] T. Nissinen, M. Li, N. Brielles, S. Mann, Calcium sulfate hemihydrate-mediated crystallization of gypsum on Ca2+-activated cellulose thin films, CrystEngComm 15 (19) (2013) 3793–3798, https://doi.org/10.1039/C2CE26814K.
[26] G. Rangasamy, et al., An extensive analysis of mechanical, thermal and physical properties of jute fiber composites with different fiber orientations, Case Stud. Therm. Eng. 28 (2021), 101612, https://doi.org/10.1016/j.csite.2021.101612.

[27] M. Doleželová, J. Krejsová, A. Vimmrová, Lightweight gypsum based materials: methods of preparation and utilization, Int. J. Sustain. Dev. Plann. 12 (2) (2017) 326–335, https://doi.org/10.2495/SDP-V12-N2-326-335.
[28] A. Dilfi K, A. Balan, H. Bin, G. Xian, S. Thomas, Effect of surface modification of jute fiber on the mechanical properties and durability of jute fiber-reinforced epoxy composites, Polym. Compos. 39 (2018) E2519–E2528, https://doi.org/10.1002/pc.24817.
[29] X. Li, L.G. Tabil, S. Panigrahi, Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review, J. Polym. Environ. 15 (1) (2007) 25–33, https://doi.org/10.1007/s10924-006-0042-3.
[30] Md A. Mahmud, Modification of starch using alkali, adipic acid, and mustard oil in search of an improved biomaterial, Discov Mater 2 (1) (2022) 13, https://doi.org/10.1007/s43939-022-00035-1.
[31] V. Mishra, S. Biswas, Physical and mechanical properties of Bi-directional jute fiber epoxy composites, NUiCONE 2012, Procedia Eng. 51 (2013) 561–566, https://doi.org/10.1016/j.proeng.2013.01.079.
[32] C. Dong, I.J. Davies, Flexural properties of wheat straw reinforced polyester composites flexural properties of wheat straw reinforced polyester composites, January (2011), https://doi.org/10.5923/j.materials.20110102.11.
[33] D. Leguillon, É. Martin, M.-C. Lafarie-Frenot, Flexural vs. tensile strength in brittle materials, Compt. Rendus Mec. 343 (4) (2015) 275–281, https://doi.org/10.1016/j.crme.2015.02.003.
[34] I.A.T. Razera, E. Frollini, Composites Based on Jute Fibers and Phenolic Matrices : Properties of Fibers and Composites, 2003.
[35] N.E. Frank S, J. Sommer, Standardization of the Leeb Hardness Testing Method, Krautkrämer GmbH, Hürth, Germany, 1986.
[36] M. Ismail, M. Foisal, A. Kumer, O. Nasrin, M. Islam, The investigations on the physico-mechanical properties of jute fiber reinforced unsaturated polyester resin (UPR) composites, Chemical Science International Journal 22 (1) (2018) 1–14, https://doi.org/10.9734/csji/2018/40021.
[37] Md M. Islam, et al., Study on physio-mechanical properties of rice husk ash polyester resin composite, Int. Lett. Chem. Phys. Astron. 53 (2015) 95–105, https://doi.org/10.18052/www.scipress.com/ilcpa.53.95.
[38] D. Dai, M. Fan, Preparation of bio-composite from wood sawdust and gypsum, Ind. Crop. Prod. 74 (2015) 417–424, https://doi.org/10.1016/j.indcrop.2015.05.036.
[39] A.A. Khalil, A. Tawfik, A.A. Hegazy, Plaster composites modified morphology with enhanced compressive strength and water resistance characteristics, Construct. Build. Mater. 167 (2018) 55–64, https://doi.org/10.1016/j.conbuildmat.2018.01.165.