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Groundnut shell and coir reinforced hybrid bio composites as alternative to gypsum ceiling tiles

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ABSTRACT

Ground nut shells (GNS) and coir are agricultural byproducts available in large quantities at low cost and are sustainable and renewable resources. Gypsum based false ceiling tiles were developed by using the shells and coir as reinforcement individually and also as blends to improve the performance properties. Various ratios of the shells and coir were added into gypsum and made into tiles. Flexural properties at different temperatures and humidities, thermal and sound absorption, morphology of the samples and flammability were tested. Groundnut shells did not improve strength or modulus compared to pure gypsum whereas a 35% higher strength was noticed with the addition of 10% coir. Hence, hybrid gypsum composites containing both shells and coir were developed leading to better properties than pure gypsum and commercially available gypsum boards. The hybrid composites showed unique sound absorption peaks and a higher thermal resistance between 0.092 and 0.150 m^2k/W. Presence of the reinforcement provided considerably high resistance to humidity suggesting that the bio based ceiling tiles will be suitable for applications in most conditions. Hybrid GNS and coir reinforced gypsum boards match or exceed the properties of similar gypsum-based tiles in commercial use. The shells, coir and other residues provide a sustainable and green alternative to replace gypsum for false ceiling, partition boards and other applications.

1. Introduction

Utilization of agricultural residues in particular and renewable and sustainable biomass in general for green building applications is increasingly rapidly [1]. Green building materials market is estimated to be about USD 19 billion in 2021 (https://www.mordorintelligence.com/industry-reports/green-building-materials-market). Green building materials are used for both outdoor and interiors such as insulation, framing, siding, roofing and other applications. Lignocellulosic agricultural residues are not only available in large quantities and low cost but are also renewable and sustainable sources. In addition, many of the agricultural residues and biomasses have unique properties that provide excellent thermal, noise insulation and other properties desirable for building applications [2]. Biobased materials have been used as reinforcement for gypsum plasters, as binder for cement based structural elements [3] and also as replacement for cement [4]. Biobased building materials offer better insulation to sound and heat, reduce density and hence have been used to reinforce concrete as well [5,6].

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Ceiling tiles are one of the most prominent materials used for buildings, particularly for commercial spaces. Ceiling tiles not only provide aesthetics but also have functional properties such as reducing noise and heat levels and also as deterrent during fire hazards. Studies have also shown that ceiling tiles and gypsum boards can absorb or diffuse formaldehyde in indoor environments [7]. Although gypsum is widely used for building applications, it has several limitations. Gypsum tiles are considerably brittle and are easily prone to damage by humidity and water [8]. Hence, several attempts have been made to develop alternatives or improve the properties of gypsum based tiles. For instance, adding even 4.9% by weight of recycled polyurethane into gypsum resulted in 25% lower water and 14% less energy consumption during manufacturing compared to gypsum tiles without the recycled content [9].

Crop residues are inevitably generated and are available in large quantities at low cost. In addition, the residues contain cellulose and lignin which are durable and renewable polymers. Many residues have unique properties such as hollow structures, low-density and hierarchical arrangement which provides good heat, noise insulation and other properties [10]. For example, adding 1–3% of *Typha angustifolia* fibers in various orientations into natural latex and combining it with gypsum provided high compressive strength, thermal shock resistance and low thermal conductivity of 0.0796±0.0005 W/mK compared to conductivity of 0.546–0.126 W/mK for various construction materials [10]. In another study, rice husk, vine pruning residues, cork and prickly pear (*Opuntia basilaris P.*) were made into ceiling tiles as a sustainable and environmentally friendly alternative to gypsum. The residues were made into panels by binding with a water based acrylic resin. The panels had good mechanical properties and good sound absorption coefficient of 0.80 in the frequency range between 200 Hz and 6400 Hz [11]. It is evident that agricultural residues and specifically crop residues are an ideal source for building materials including ceiling tiles that can be a replacement for gypsum tiles. Completely biodegradable insulating boards were developed using sunflower stalks as reinforcement and chitosan as the binder. Depending on the ratio of sunflower stalk to chitosan, the composites had optimum thermal conductivity of 0.056 W/mK and maximum strength of 2 MPa and acoustic absorption coefficient of 0.2 which was considered to be similar to that of insulation boards available on the market [12]. Performance properties of biobased materials can also be modified through physical and chemical modifications. Thermal insulation properties of tree bark were found to improve considerably from 0.065 to 0.045 W/mK after treating with alkali [13].

In previous researces, the feasibility of using poultry feathers, sheep wool, rice husk, groundnut shells, sugarcane bagasse, coffee husks and even mulberry stems as potential replacements for ceiling tiles has been demonstrated [14–18]. The ceiling tiles demonstrated better tensile properties, excellent noise and heat insulation and resistance to humidity and water. Composites obtained by addition of coffee husks had highest sound absorption coefficient of 0.9 and thermal insulation coefficient of 0.0518 W/mK [18]. Similarly, insulation panels containing up to 90% wool and 10% polypropylene were developed with conductivity between 0.058 and 0.083 W/mK and noise absorption coefficient of up to 0.86 [16]. In another study, it was found that addition of poultry feathers (5%) to gypsum reduced thermal conductivity from 0.52 to 0.36 W/mK and decreased the density by about 12% [19]. Addition of 5% feathers to external walls and roofs was found to decrease energy consumption for cooling by 24.8%, heating by 29% and also reduced CO_2 emissions by 408 kg/unit area [20]. Up to 70% reduction in greenhouse gas emissions was reported to be possible when hemp fibers were used as insulation for external building walls [21]. Composite panels (12 mm thickness and density of 1200 kg/m^3) intended for insulation applications were developed by combining coir fibers and Scott pine particles with cement as binder. The panels had densities between 1000 and 1337 kg/m^3 and modulus of rupture between 6.2 and 8.0 MPa [22]. As seen from the literature, addition of biobased materials undoubtedly improves the performance of materials intended for building applications. However, the extent of improvement in properties is dependent on the type, proportion and inherent characteristics of reinforcement and binders used.

Groundnut shells (GNS) are the outer covering that are inevitably generated as byproducts. The shells form about 30% of the entire nut and are made up of cellulose, lignin and hemicellulose. It has a fibrous structure with completely different inner and outer layers. Ground nut shells are treated as waste and generally used for composting or as a source for fuel which are low value applications. Recent studies have considered the possibility of using the shells as a source to produce biodiesel, bioethanol, enzyme and hydrogen production etc [23]. Adding groundnut shells as reinforcement was found to improve the mechanical properties of epoxy and other resins and could be made into composites with desirable properties [24]. Recently, nanocarbons developed by pyrolyzing ground nut shells were found to be suitable as microbial growth inhibitors, bio-imaging and drug delivery [25]. Guna et al. have used a blend of rice husk and groundnut shells to develop biocomposites for green building applications, particularly as replacement for gypsum ceiling tiles. It was demonstrated that an optimum tensile strength of 15.6 MPa and flexural strength of 37.6 MPa could be obtained when the ratio of groundnut shells, rice husk and polypropylene was 20/60/20. Along with good sound absorption and thermal insulation properties, the composites had 85% lower water absorption than commercially available ceiling tiles. However, the matrix used in this research was polypropylene which is non-renewable and also hydrophobic which may provide good resistance of water but will have limited compatibility with the reinforcements. Polypropylene is from non-renewable sources and developing composites with polypropylene requires higher temperatures and compression molds which are not necessary to prepare composites with gypsum.

In this study, ground nut shell reinforced gypsum biocomposites (defined in this study as composites containing a major proportion of renewable resources i.e. agricultural residues) have been developed as potential replacement for commercially available gypsum tiles. To further enhance the properties, coconut coir was added and hybrid biocomposites were developed. The biocomposites were studied for their mechanical properties, acoustic and thermal resistance and flammability in comparison to commercial gypsum tiles. Performance of the composites at different temperatures and humidity was also evaluated. The aim of this study is to present the possibility of utilizing agricultural residues as green and sustainable materials for building interior applications.

2. Materials and methods

2.1. Materials

Groundnut shells (GNS) were kindly provided by local farmers and coir was procured from coir industry, in Tamil Nadu, India.

Commercially available gypsum powder used as matrix was purchased from local vendors. Initially both GNS and coir were cleaned and dried in a hot air oven for 48 h to remove moisture. Coir fibers were carded many times to untangle the coir fibers which were later cut into small fibers (5–10 mm) and GNS was powdered to pass through a 5 mm size mesh. Both the reinforcements were used without any further chemical treatment. Digital images of the gypsum, coir and GNS composites containing the individual reinforcement and their blends are shown in Fig. 1.

2.2. Composite fabrication

The parameters listed in Table 1 were used to fabricate different ratios of GNS/coir fiber reinforced individual and hybrid composites. The dry mixture containing both binder and reinforcement was first homogenized in a Remi (RQ-121) homogenizer, followed by addition of distilled water (67% v/w i.e. 67 ml of water and 33 g of binder and reinforcement per 100 g of the mixture) and stirring was continued for approximately 5 min at 1000rpm. Amount of water to be added was chosen depending on the mass of the reinforcement and gypsum and the consistency (workability) of the mixture that could ensure easy and uniform spreading across the mold. Excess water delayed setting of the gypsum and caused uneven surfaces and formation of cracks in the composites whereas low water content did not allow uniform mixing of the materials. After combining the gypsum and reinforcements, the homogenized mixture was cast into open molds (160x40x40mm) and tapped from the sides to fill cavities. All plasters had a setting time of around 20 min, independent of the presence of fillers. Samples with dimensions of 160x40x40 mm were prepared for the flexural properties, 300x300 mm for thermal conductivity and 29.5 and 99.5 mm for acoustic absorption. All samples were removed from the mold and treated in a hot air oven for 48 h at 40 °C before characterization when about 11.8% of moisture was removed.

2.3. Surface morphology

The morphology of the samples, and the fracture surface of the composites were investigated using a Hitachi SU3500 model Scanning Electron Microscope (SEM). Due to their non-conductive nature, samples were sputter coated with gold for 30 s using an ion sputter coater. SEM images at various magnifications were obtained in secondary electron (SE) mode at a voltage of 10 kV.

2.4. Flexural strength

Three-point bending tests were used to determine the reinforcement's capacity to increase ultimate strength and toughness. Flexural tests on materials measuring 160x40x40 mm were conducted using a Universal Testing Machine (MTS Exceed E43) equipped with a 500 N load cell in accordance with UNI EN 1015–11. The crosshead was set at a speed of 5 mm/min. Tests were done after conditioning the samples at different temperature and humidity for at least 24 h in an environmental chamber (Memmert CTC 256). For each condition, at least 10–15 samples were evaluated, and the average results were given along with standard deviation.

2.5. Thermal conductivity

Thermal conductivity tests were done according to the ISO 8301:1991 (2014) standard in an HFM 436 Lambda instrument supplied by NETZSCH (Erich Netzsch Gmbh & Co. Holding Kg, Selb, Germany). Thermal conductivity was determined in each ratio using a minimum of three samples 300 mm x 300 mm x 10 mm each. Briefly, the test sample is placed between a heating and cooling plate, which maintains a consistent temperature differential and allows heat to pass over the sample at a constant pace. Thermal conductivity

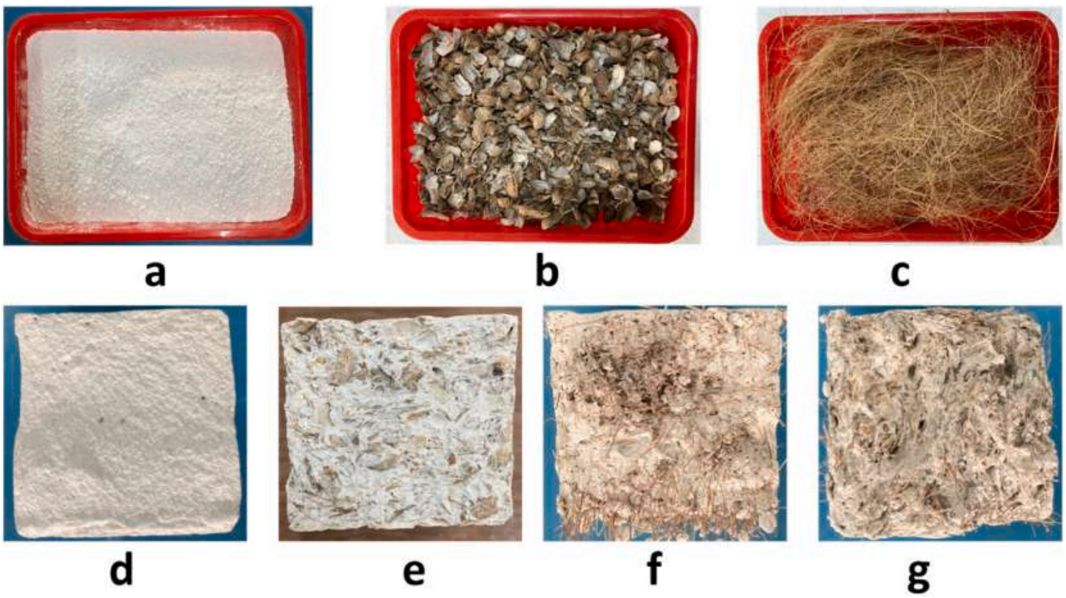

Fig. 1. Digital images of (a); Gypsum powder (b); GNS (C); Coir fibre (d); Pure Gypsum (e); Gypsum/GNS composite (f); Gypsum/Coir composite (g); Gypsum/GNS/Coir Hybrid composite.

Table 1
Conditions used to prepare the Groundnut/coir/gypsum composites.

Sample		Gypsum (g)	Water (g)	W/G Ratio	GN (g)	Coir (g)
Reference		1000	670	0.67	–	–
Gypsum/GN	90/10	900	603	0.67	100	–
	80/20	800	536	0.67	200	–
	70/30	700	469	0.67	300	–
Gypsum/Coir	90/10	900	603	0.67	–	100
	80/20	800	536	0.67	–	200
	70/30	700	469	0.67	–	300
Coir/GN/Gypsum	10/20/70	700	469	0.67	100	200
	15/15/70	700	469	0.67	150	150
	20/10/70	700	469	0.67	200	100

was determined based on the resistance of the material to the flow of heat reported in terms of W/mK.

2.6. *Sound absorption*

The sound absorption coefficient of the composites was determined using the ASTM E1052-12 two-microphone impedance tube technique. The impedance tube shown in Fig. 2 was utilized to determine the acoustic absorption of the gypsum panels used in this study. The frequency range covered by the results was 2000 Hz–6000 Hz. The inner diameter of the impedance tube was 29 mm in this research, frequencies between 2 kHz and 6 kHz were designated as high-frequency spectrum. To confirm repeatability of the data, the measurement was repeated three times on a single sample, and the variability was small.

2.7. *Flammability*

The vertical flame test technique was used to evaluate the flammability of pure and mixed gypsum boards in accordance with UL-94 standards. The samples measured 125x15x10mm. Briefly, the samples were introduced into the flame for 10 Secs and then allowed to burn naturally. Surgical cotton was put under the sample to observe any dripping of burnt sample. The flammability grade was determined based on the time required to extinguish the flame. To ensure repeatability of the ratings, the flammability of five samples for each ratio/condition was tested and the ratings were assigned.

3. Results and discussion

3.1. *Influence of groundnut shells and coir on flexural strength*

Adding groundnut shells and coir as reinforcement for gypsum has shown contrasting results for both flexural strength and modulus. Pure gypsum boards had flexural strength of 2.3 MPa and flexural modulus of 226 MPa. Addition of 10% groundnut shells decreased the strength by 22% and modulus by 17% whereas an increase in strength by about 35% and 9% decrease in modulus occurred due to the addition of coir fibers (Fig. 3). Further increase in the reinforcement to 20 and 30% drastically decreased the strength and modulus of the groundnut shell reinforced composites whereas a steady increase is noticed for the composites containing coir fibers. A highest strength of 5.6 MPa and modulus of 286 MPa was obtained when gypsum was reinforced with 30% coir. The drastically different behavior of groundnut shells and coir in terms of improving the flexural properties of gypsum should mainly be due to the difference in their structure and properties. Coir is fibrous and thin in nature and is also highly flexible whereas groundnut shells are thick and sheet-like. In this study, the groundnut shells were powdered to pass through a 5 mm mesh. The particulate shells create a barrier and a discontinuous network for gypsum to bind to the reinforcements which affects the flexural properties. Since gypsum and the shell particles are both relatively brittle, the tiles break easily when subject to bending. The fibers can be more uniformly mixed with gypsum than the shells and the continuous fibers provide flexibility to the comopsites and hence, they can support higher flexural loads as seen from Fig. 3.

Since ground nut shells provided relatively poor strength and modulus to the composites compared to coir, we developed hybrid

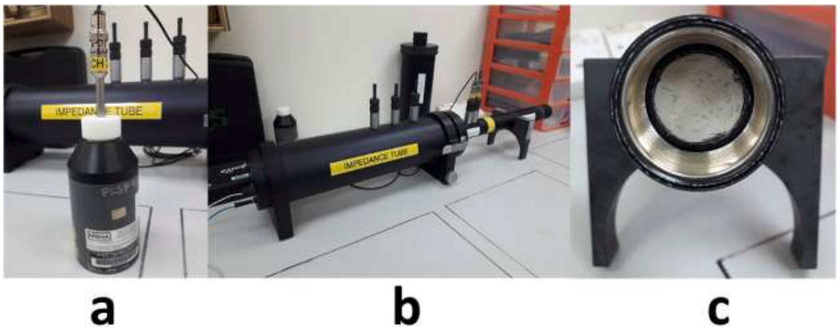

Fig. 2. Equipment to perform the sound absorption coefficient (a); Calibration of Microphone (b); impedance tube & (c); Sample holder.

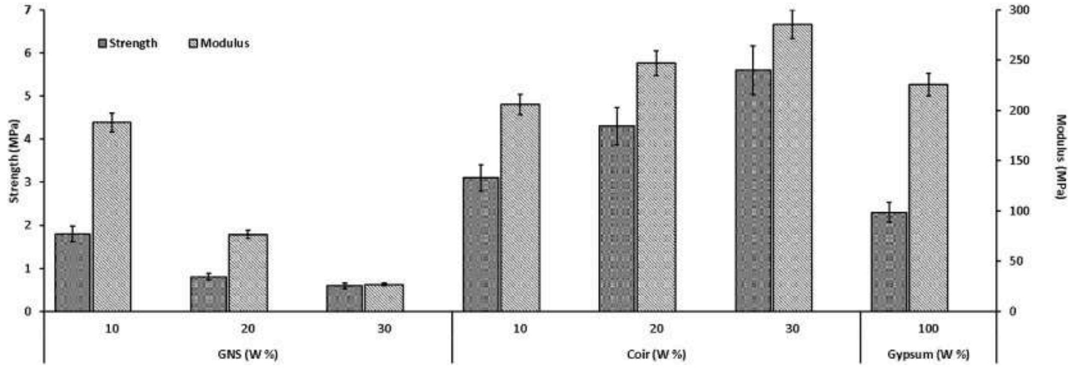

Fig. 3. Influence of addition of 10, 20 or 30% (w/w) of groundnut shells (GNS) or coir into gypsum on the flexural strength and modulus of the ceiling tiles (bio-composites). The density of the composites was between 932 and 1269 kg/m^3.

composites of ground nut shells and coir. As seen from Fig. 4, adding coir continually increases the strength of the composites. At 10% coir, the strength and modulus were 2.1 MPa and 159 MPa, respectively which is similar to the strength of pure gypsum but with 30% lower modulus. At the highest concentration (20%) of coir used, the strength was 3.6 MPa, about 56% higher than that of pure gypsum but about 17% lower than that of gypsum reinforced with 20% coir alone which suggests that addition of the ground nut shells did not favor the improvement in flexural strength. It should be noted that the overall percentage of reinforcement was maintained at 30% and it was not possible to increase further due to the difficulties in mixing the gypsum uniformly. Previous studies have shown significant improvement in the strength of gypsum boards even after the addition of 2% hemp fibers which were considered as green and sustainable alternatives to replace glass fibers used to reinforce gypsum [26]. Fibrous reinforcements change the behavior of plaster from brittle to non-linear and hence provides better properties. However, some other studies have shown a decrease in the elastic properties of gypsum after reinforcing with hemp or flax fibers due to the introduction of defects and trapping of air in the gypsum [27]. European standard EN-13279/1 specifies that gypsum based materials used for construction applications should have a minimum flexural strength of 1 MPa and compressive strength of 2 MPa. It is apparent from Figs. 3 and 4 that the pure and blended composites developed in this research satisfy this requirement. Previous studies have reported that addition of various sizes and shapes of extruded polyurethane foams into gypsum resulting in flexural strength between 1.5 and 2.9 MPa and compressive strength between 1.5 and 5.7 MPa [28].

3.2. Effect of relative humidity on the properties of the composites

Although ground nut shells did not improve the flexural properties significantly compared to coir, it was hypothesized that the shells would provide better performance in terms of stability to varying temperatures and humidities and other properties. Both flexural strength and modulus are affected by humidity and temperature as seen from Fig. 5. Inherent moisture sorption of gypsum (11% moisture content) also influences the properties of the composites. Performance of the hybrid gypsum composites was studied at three different relative humidities (30, 60 and 90%) at 20°C to cover practical use conditions in different settings and environmental conditions. Increasing humidity substantially decreases both strength and modulus and the extent of decrease also depends on the proportion of shells and coir in the composites. At 30% humidity, changing the proportion of the shells or the coir fibers does not show any significant change whereas the modulus increases from 199 to 286 MPa when coir content is increased from 10 to 15% but decreased to 234 MPa when the amount of coir was 20%. Both strength and modulus were observed to have a drastic decrease with increase in humidity to 60 and further to 90% irrespective of the proportion of the shells or coir. Composites containing equal proportion of the coir and shells had about 40% decrease in strength and 18% decrease in modulus when the humidity is increased from 30 to 60%. Further increase in humidity to 90% saw the composites have 60% lower strength and 72% decrease in modulus compared to

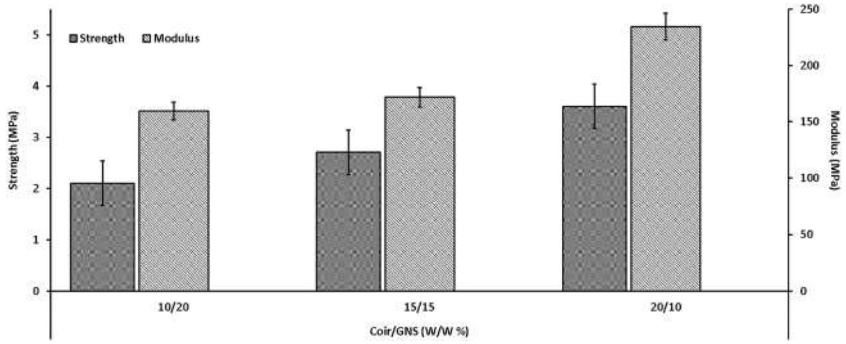

Fig. 4. Changes in the flexural strength and modulus of hybrid 70 (W %) gypsum composites reinforced with coir and groundnut shells.

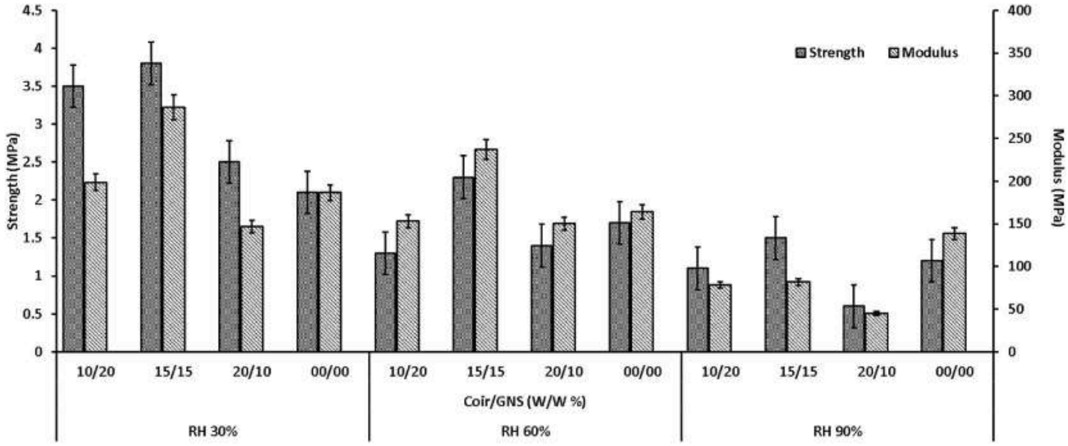

Fig. 5. Changes in the strength and modulus of gypsum reinforced with different proportions of ground nut shells and coir at 20°C and different humidities.

the properties at 30% humidity. As humidity increases, the amount of water sorbed by the materials, particularly gypsum, increases. Moisture decreases the interactions between the gypsum and reinforcements and also reduces the strength and modulus of the coir fibers. Hence, there is a decrease in the tensile and flexural modulus. However, there was no particular trend in the change in strength or modulus probably because the distribution of the reinforcement was non-uniform. However, it should be noted that only the hybrid composites (15/15/70%) had substantially higher strength and modulus compared to pure gypsum at the different humidities although the % decrease in properties was similar compared to pure gypsum. Pure gypsum had strength and modulus of 2.1 MPa and 186 MPa at 30% humidity, respectively which decreased to 1.2 MPa and 139 MPa (63% and 26% decrease in strength and modulus, respectively).

3.3. Comparison of the flexural properties with commercial gypsum boards

Composites developed using the individual reinforcements and their blends were compared against commercially available gypsum boards and also with the gypsum used in this study. Table 2 shows that the flexural strength and modulus of the commercial gypsum boards are very similar to that of the coir-gypsum hybrid composites when tested at 30% humidity. At this humidity, the ground nut shell composites have considerably lower strength (68%) and modulus (35%) compared to the coir composites and commercial gypsum. A substantial decrease in strength by 77% and modulus by 45% was observed for commercial gypsum boards when the humidity was increased from 30 to 60%. Susceptibility of the commercial gypsum boards to humidity is evident when the tests were done at 90% humidity with only 5% strength and 20% modulus being retained. Comparatively, the gypsum powder used in this study had better stability and lost about 29% strength but 56% modulus at 90% humidity. Composites reinforced with only ground nut shells (GNS/GYP) showed a decrease of 50% in strength and 53% in modulus, composites reinforced with only coir fibers (Coir/GYP) had decrease in strength by 54% and modulus by 49%. The hybrid composites showed 61% lower strength and 72% lower modulus compared to the respective properties at 30% humidity. Changes in the strength and modulus of the composites and gypsum board with humidity should be due to the inherent ability of the gypsum and reinforcements to absorb moisture and also due to the changes in the structural arrangement of the reinforcement within the matrix. Compared to commercially used gypsum boards, it is evident that addition of coir improves the resistance to moisture. It is also interesting to note that the decrease in properties of the composites co-relate well to the decrease in the properties of the GYP used to prepare the composites suggesting that the coir fibers or the ground nut shells were relatively unaffected by the humidity. Including fibers, particularly coir not only leads to enhancing the mechanical properties but will also help to enhance the resistance of the composites to temperature and humidity which is critical for ensuring suitability of the composites for false ceiling applications under different conditions.

3.4. Acoustic absorption

Reinforcing gypsum with groundnut shells and coir shows considerably different behavior in terms of sound absorption coefficient.

Table 2
Changes in the strength and modulus of the commercially available gypsum (GYP) boards, gypsum-based composites containing ground nut shells (GNS), coir or both and the boards made from the gypsum used for preparing the composites.

	30% RH		60% RH		90% RH	
	Strength, MPa	Modulus, MPa	Strength, MPa	Modulus, MPa	Strength, MPa	Modulus, MPa
Commercial GYP	5.6±0.4	275 ±10	1.3± 0.2	179 ±16	0.3±0.02	54 ±12
GNS/GYP	1.8± 0.2	188 ±16	1.5± 0.3	151 ±14	0.9±0.1	91 ±16
Coir/GYP	5.6± 0.4	286 ±11	4.0± 0.7	265 ±19	2.6±0.6	146 ±15
Coir/GNS/GYP	3.8± 0.6	286 ±13	2.3± 0.3	237 ±18	1.5±0.4	82 ±14
GYP	2.1± 0.4	186 ±19	1.7± 0.4	164 ±17	1.1±0.3	65 ±10

Broad and narrow peaks were observed throughout the frequency range depending on the particular frequency or the proportion of the reinforcement. Highest absorption coefficient of 0.07–0.75 was observed between 2000 and 2750 Hz when 10% coir and 20% ground nut shells were used as reinforcement. Two similar broad peaks were observed for the 20/10 coir/groundnut shells and 30% ground nut shells. However, the composites containing equal proportion of coir and ground nut (15/15%) had a distinct and sharp peak at 5250 Hz which was not seen in the other samples (Fig. 6). Noise absorption depends not only the characteristics of the raw materials used but also on the physical condition i.e. the thickness, size and uniformity of the reinforcement etc. It is clearly seen that the samples containing only ground nut shells have a broad and relatively lower intensity peaks. Among all the samples, those containing 10% coir and 20% shells and also those with equal proportion of the reinforcement having strong absorption coefficient of up to 0.75. Previous studies on reinforcing gypsum with orange pruning fibers found that reinforcement above 20% caused transmission losses in the medium and high frequency range [29]. Reinforcing gypsum with wool and coir have shown major absorption peaks between 4000 and 6000 Hz [14]. Such sharp peaks are not observed in this study probably due to the lack of resonance of the sound waves when they are incident on the sample's surface. The shape and size of the shells and rough surface of coir fibers also influences the sound penetration. Hence, major changes in position and intensity of the peaks are seen as the proportion of the shells, coir and their blends are varied. Inherent variations in sound absorption can also be attributed to the type of agricultural waste used as reinforcement. For example, rice husk was reported to have a sound absorption coefficient between 0.02 and 0.8 compared to 0.86 to 0.99 for sunflower stalks. Such variations are due to the differences in composition and the morphological and physical structure of the byproducts. Sheep wool with unique scales on its surface and low density has sound absorption coefficient between 0.056 and 1.12 and coir fibers between 0.2 and 0.75 [30]. Overall, it can be concluded that addition of the reinforcement benefits noise reduction and among the two, groundnut shells appear to be more preferable than coir fibers [18].

3.5. Thermal conductivity

Having good thermal resistance i.e. low thermal conductivity for the ceiling tiles assists in controlling the temperature and heat and humidity losses. A thermal insulating material is considered to be good or classified as an insulator if the conductivity is less than 0.1 W/mK according to TS 805 EN 601 standards [12,31]. Pure gypsum had a thermal conductivity of 0.122 ± 0.03 W/mK which decreased up to 0.066 ± 0.02 W/mK with the addition of the coir and ground nut shells in equal proportions. As seen from Table 3, ground nut shells provide about 25% lower conductivity than coir fibers when added in similar proportions. Interestingly, a blend of the two reinforcements in equal proportions has provided the lowest thermal conductivity in this study. Thermal conductivity not only depends on the inherent properties of the raw materials but also on the distribution of the raw material within gypsum and the presence/absence of air gaps and voids. Groundnut shells particles will be more evenly distributed and create lower gaps and voids in the composites compared to coir. Even better distribution and covering of gypsum would have happened when the blends are added which leads to the lowest thermal conductivity among the conditions studied here. Hybrid composites developed using wool and coir had thermal conductivity in the range of 0. 17–0. 305 W/mK [14] which is considerably higher than that provided by groundnut shells and coir. Thermal conductivity of gypsum based composites was reported to be highly dependent on the density, size of particles and type of waste used for reinforcement [28]. For example, thermal conductivity of gypsum reinforced with corn stalk particles varied from 0.1 to 0.199 W/mK depending on the amount of stalks and the density of the composites [31]. Considerable variations have been reported in the thermal conductivity of various agricultural wastes. Flax, hemp and pineapple wastes had thermal conductivity of about 0.066–0.108 W/mK compared to 0.10–0.14 W/mK for corn wastes [32]. Coir and bagasse were cut into various sizes and combined in various ratios to develop insulating materials with gum Arabic as the binder. Thermal conductivity varied depending on the size and proportion of the reinforcement. A lowest thermal conductivity of 0.01467 W/mK was obtained for 1 mm particle coir and 0.5 mm size sugarcane bagasse compared to 0.01832 W/mK for polyurethane used for food packaging (insulation) applications [33].

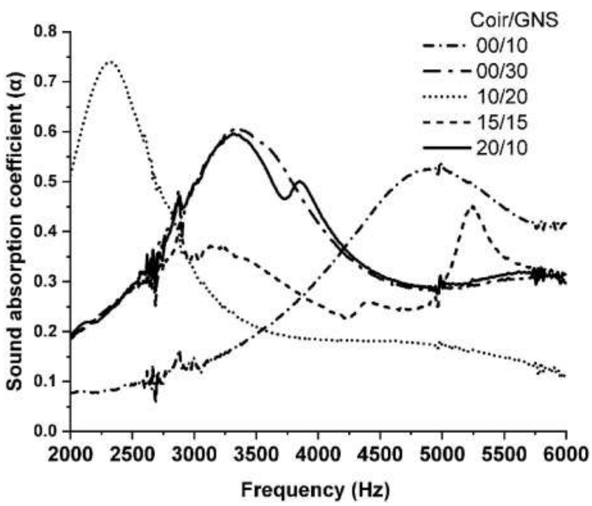

Fig. 6. Changes in the sound absorption of pure gypsum and gypsum reinforced with ground nut shells, coir and their blends in different proportions.

Table 3
Thermal conductivity of the hybrid and non-hybrid composites.

Coir/GNS (w/w %)	Thermal Conductivity (W/mK)
00/00	0.122 ± 0.03
30/00	0.108 ± 0.02
00/30	0.080 ± 0.01
15/15	0.066 ± 0.02

Based on these observations, it is proposed that the decrease in thermal conductivity due to addition of coir and GNS should be due to the decrease in the porosity, density of the composites and inherent resistance of the reinforcement.

3.6. Surface morphology

Pure gypsum is in particulate form as seen from image 7a. Pieces of GNS have been entrapped within the gypsum and appear to have limited interaction or binding with the matrix (Fig. 7b) as observed from the voids between the shell pieces and the matrix. Coir fibers, however, are well blended in the matrix and do not show any fiber pull out or apparent breaking suggesting good compatibility (7C). Addition of GNS creates defects (spaces and holes) which is due to the hydrophobicity and smooth surface of GNS compared to coir (7d). Although the defects may decrease mechanical properties, there may be improvement in the noise and thermal insulation due to the presence of air gaps.

3.7. Flammability

Adding biomass (GNS and/or coir) which are flammable reduces the overall flame resistance ratings of the gypsum from V0 to V2. GNS provided better flame resistance compared to coir and the hybrid composites had V1 rating as seen from Table 4. Groundnut shells have inherently better flame resistance and hence the composites have higher flammability rating. Since it is expected that false ceiling tiles have high flame resistance, it may be necessary to add flame retardant chemicals and further improve the flame resistance of the GNS and coir reinforced gypsum composites. Previous studies have shown that addition of various flame retardant chemicals can improve the flame resistance and make biocomposites suitable for most industrial applications [34–36].

3.8. Comparison with other bio composites

Composites developed in this study as replacement for gypsum-based ceiling tiles have properties comparable to that of composites manufactured from other biobased resources and also to commercially available gypsum board. As seen from Table 5, at similar densities, the Coir/GNS/gypsum composites have flexural strength between 0.6 and 5.6 MPa and modulus between 26 and 285 MPa which is similar to or better compared to other biomass-based composites and to commercially available gypsum boards. Further, the thermal conductivity and sound absorption are well within the acceptable range for false ceiling and acoustic paneling applications. Inherent characteristics of coir and GNS such as good tensile strength of coir, presence of hemicellulose and lignin, network and dense structure of GNS cause decrease in porosity of the composites, good interaction between the reinforcement and gypsum leading to enhanced properties compared to commercially available gypsum tiles. These properties can be further enhanced depending on specific requirements.

4. Conclusions

Groundnut shells and coir fibers provide the desired features for developing environmentally friendly and sustainable false ceiling tiles. The hybrid composite tiles had highest flexural strength of 3.6 MPa and modulus of 234 MPa higher than pure gypsum and satisfied the requirement for gypsum based insulation materials. More importantly, the hybrid composites can withstand high humidity of up to 90% without major loss in flexural properties unlike the gypsum tiles which become soggy and weak. Further, a range of sound absorption with a few broad and a few distinct and sharp peaks were obtained depending on the frequency and proportion of the shells and coir fibers. Having sound absorption coefficients between 0.1 and 0.75, good flame and thermal resistance (thermal conductivity between 0.06 and 0.12 W/mK) make the reinforced composites ideal to replace the gypsum based tiles in current use. Being sustainable, renewable and inexpensive sources available in large quantities, groundnut shells and coir for gypsum-based tiles and partitions would assist in developing green and sustainable buildings and benefit the environment.

Author statement

Authors state that they do not have any conflict of interest and they are willing to share the data in the manuscript upon 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.

Data availability

Data will be made available on request.

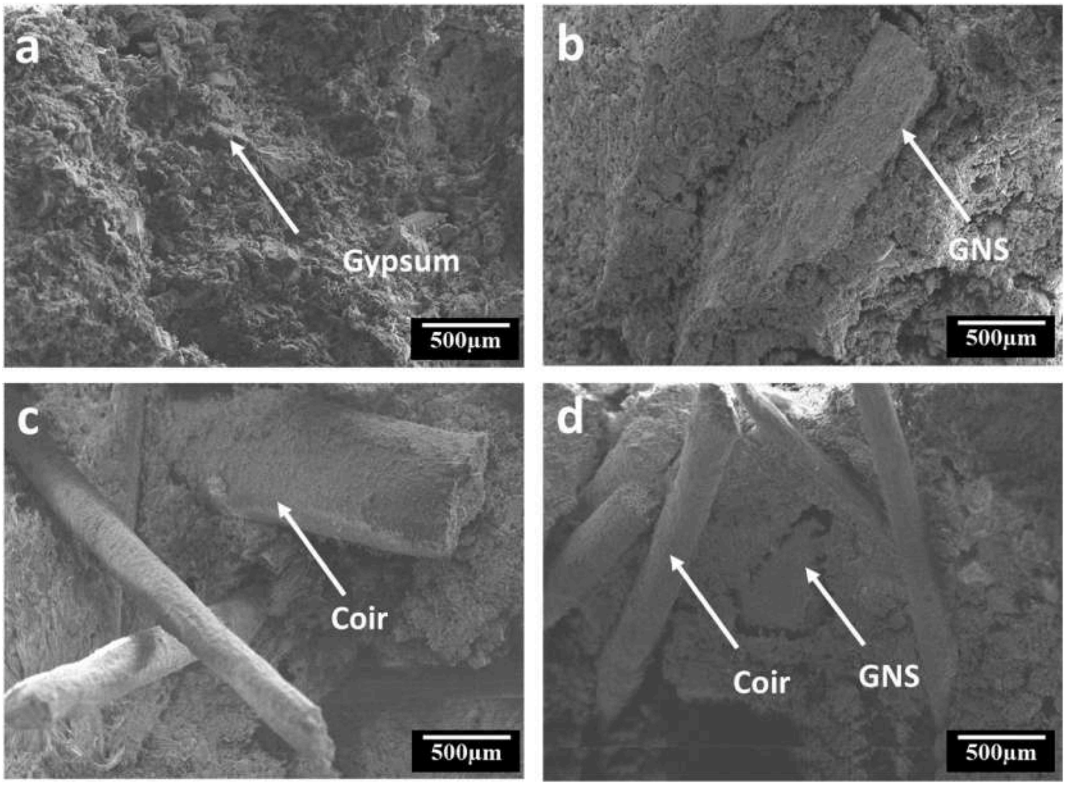

Fig. 7. SEM images of (a–c); cross section view of pure gypsum powder, GNS + Gypsum surface (b), Coir + Gypsum surface (c,d); Cross sectional view showing the matrix and reinforcement bonding in 15/15/70 Coir/GNS/gypsum hybrid composite.

Table 4
Flammability ratings of the hybrid and non-hybrid composites.

Coir/GNS w/w %	Time to Self-Extinguish After Ignition (s)	Observed Dripping	UL-94 Rating
00/00	<30	No	V0
00/30	<30	No	V1
30/00	<30	Yes	V2
15/15	<30	No	V1

Table 5
Properties of Coir/GNS/Gypsum composites compared with other bio composites.

Composite Sample	Density (Kg/ m^3)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Thermal Conductivity (W/mK)	Sound Absorption Coefficient (α)	References
Cork- Gypsum	–	1.82–8.12	–	0.12–0.19	~0.05–0.35	[37]
Coir/SW/Gypsum	420–1200	1.25–3.78	4.90–6.9	0.17–0.30	0.15–0.35	[17]
Commercial Gypsum Board	500–1200	5.14–7.16	179–275	0.17	0.4–0.5	[17]
Wood Waste/Gypsum	702–1307	1.2–4.1	–	0.2–0.5	0.1–0.65	[38]
Sisal Fibre/Gypsum	1020–1200	–	–	0.7–0.9	–	[39]
Coir/GNS/Gypsum	932–1269	0.6–5.6	26–285	0.06–0.12	0.1–0.75	**This Study**

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