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Impact of Fiber Length on the Mechanical and Thermo-Physical Attributes of Banana Fiber Reinforced Gypsum Composites

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Abstract- In recent years, considering growing ecological concerns, environmentally responsible solutions have become increasingly important, including the use of natural fiber composites. This study focuses on an experimental approach to evaluate the impact of fiber length on the thermo-physical and mechanical properties of banana fiber composites reinforced with gypsum. For the preparation of composites, banana fibers were added to the gypsum at three variations, i.e. 2.5%, 5% and 7.5%, while length variations were also done in 25mm long and 100mm long fibers. Mechanical properties in terms of compressive and flexural strength were measured using a universal testing machine with a maximum loading capacity of 25KN, while thermophysical properties were examined by calculating bulk density, water absorption, and thermal conductivity through a thermal conductivity tester apparatus. The results demonstrated that though fiber length has no significant influence on thermal efficiency, it improves the structural integrity of composited by enhancing flexural capacity by 61%. Ideal results are found in the case of 100 mm length with 5% of gypsum weight, showing optimization among thermomechanical properties. This research promotes the utilization of natural fibers in the development of composites and provides sustainable solutions for the building industry.

Keywords- Natural Fiber, Sustainability, Composites, Gypsum, Thermal, Mechanical

I. INTRODUCTION

For the sustainable growth in the building sector, one of the most important challenges is the development of innovative materials based on natural or renewable resources, which will not only address global pollution but also cater to the demands of the ever-increasing population. [1]. To meet the goals of reducing greenhouse gas emissions from the building industry, multiple research projects are underway to develop less harmful, more sustainable materials. Global efforts are focusing on solutions that have reduced environmental impact and more eco-compatibility for the building industry, to minimize reliance on non-renewable resources and to protect the health of inhabitants. [2]. Another question is the development of new technological standards, which can be employed as a benchmark for evaluating buildings' energy and environmental efficiency. [3]. In ecologically conscious planning, special emphasis must be paid to the choice of low environmental impact materials, or materials that release no harmful substances into the environment, have high thermo-physical properties, and have a low energy content. [4]. A sustainable environment includes the usage of natural and local materials to reduce the carbon footprint and enhance biodiversity. [5]. Thus, environmentally friendly materials should be used in the building industry.

According to a research report, the energy utilized in the building industry accounts for around 50% of total energy consumption [6-7]. As a result, the building industry has a considerable influence on the environment. As a result of its environmental friendliness, adopting bio-based and renewable composites in the building industry is critical for fostering sustainability. The exploration of utilizing plant-based aggregates as building materials has become a popular trend in ecologically responsible construction [8]. One of the primary issues for future buildings is a reduction in energy usage throughout their life cycle, from construction to destruction. It is expected that energy consumption in the building sector, if no action is taken, may rise to 90% shortly [9].

The building industry accounts for more than 30% of Pakistan's energy consumption, with annual growth rates of 2.5% for commercial structures and 4.7% for residential ones. [10]. Over the last few years, Pakistan has dealt with an energy dilemma that has hindered the nation's economic growth. The primary priority of all tenants is that the house be insulated (keep a proper temperature in the summer and winter). In Pakistan, where the per capita yearly average energy usage is roughly 475 kWh, heating and cooling account for 60 to 80% of overall energy costs [11-12]. According to the report, fossil fuels will account for almost 75% of total energy production by 2035. A 2012 assessment of the building sector's expected underutilization of about four-fifths of its potential energy efficiency shows that investing in this area is the most fascinating method for reducing negative environmental consequences [13]. High population growth and climate change have enhanced the energy consumption demand within buildings due to extreme climates. [14]. Pakistan is facing a serious inflation rate, which is adding a burden to its economy in the form of energy bills. [15]. It is the responsibility of the architects and engineers to design buildings for a sustainable environment in the future.[16]

Natural fiber-based materials derived from regenerative raw material sources are quickly gaining popularity as a competitive alternative to conventional construction materials. Compared to conventional fibers, natural fibers provide numerous benefits, including low cost, low density, light weight, biodegradability, renewability, nontoxicity, combustibility, and high specific mechanical characteristics. [17]. Because of their superior environmental compatibility compared to more complicated materials that might be subject to chemical modifications or high-energy activities, it may be feasible to site them near the locations of utilization. [18]. Natural fibers offer outstanding acoustic and heat insulation characteristics, which are frequently greater and more helpful than synthetic fibers, due to their low mass density and cell structure. [19]. Natural fibres have the following two categories: firstly, wood, which includes pine, spruce, oak, maple, etc., with excellent mechanical properties, and secondly, non-wood jute, hemp, flax, sisal, and kenaf, which both offer various advantages over synthetic fibres, such as lower density, biodegradability, and renewable sourcing. [20]. Research has shown that banana peel added as an additive enhances flexural modulus, split tensile strength, and compressive strength of concrete.[21]. Gypsum is commonly used in construction due to its simplicity of use, low cost, and thermal properties. However, it is brittle, which may be remedied by adding fibers [22]. Despite its thermal insulation capabilities, gypsum's mechanical strength is sometimes a constraint. Fibers enhance the flexural, compressive, and impact resistance of gypsum composites [23]. Gypsum-reinforced composites were examined by Esan [24], who also emphasized the materials' potential for environmentally friendly building. By using agricultural waste, adding banana fibers to gypsum composites enhances structural performance while simultaneously advancing environmental sustainability. Epoxy and banana fiber-based bio-composites with a fiber rate of 0% to 20% and a step of 5% variation were investigated by Balaji [25]. Thermo-gravimetric analysis was used to test the mechanical properties, and the results show that banana epoxy-fiber composites perform better mechanically at 15% of the ideal additive ratio. They also show the effects of applying an alkaline treatment with NaOH and lengthening the composite banana fibers, with 20 mm being preferred over 10 mm.

Bananas are one of the most common fruits cultivated in tropical countries and consumed globally. The world's tropical and subtropical regions produce over 70 million metric tons of bananas annually. [26]. After harvesting the banana from the plant, the banana tree and its leaves are discarded. [27]. Even though some of the tree's components are employed as organic fertilizer in the plantations, the vast amount of trees, in particular banana fields, results in extra disposal costs for the farmer [28]. The long banana fiber makes it a good alternative for thermal insulation in buildings since it is easily woven into an insulation batt and does not require binders. Banana fiber is a natural, biodegradable material made mostly of cellulose, hemicellulose, and lignin. Its tensile strength, lightweight design, and environmental benefits make it an appealing reinforcing material. [29]. However, application as thermal insulation will depend on thermal insulating characteristics ranging from 0.02 to 0.06 W/m.K., which will require additional investigation and financing. [30].

In another study, three mix ratios of recycled polyester (r-PET) and banana fiber were utilized to produce chemically bonded and needle-punched nonwovens: 50% banana/50% r-PET, 70% banana/30% r-PET, and 90% banana/10% r-PET. Thermal insulation and biodegradation characteristics were used to describe the created nonwovens. The findings demonstrated that every produced nonwoven performs exceptionally well as insulation; the thermal resistance value falls between 0.299 and 0.248 m2K/W [31]. In comparison to plaster alone, thermal diffusivity and effusivity show gains of 40% and 25%, respectively, depending on the volume fraction and distribution type of banana fiber. In terms of flexural strength, the volume fraction of banana fibers utilized can be up to 20% higher than that of plaster's flexural strength. The ideal amount of banana fiber addition was determined by the dimensionless coefficient analysis, which suggested using it for artificial walls or ceilings. [32].

Banana fibers have multiple advantages, including better mechanical properties, cost-effectiveness, and a renewable supply. These fibers can also improve moisture absorption capacity. [33]. As banana crops are available in bulk production, and these can be reused as an environmentally friendly solution instead of burning. Multiple research studies have used banana fiber in the building industry too, for example, in one research, bricks with 4% banana fibers and lime show improvement in compressive strength by 35.19% in comparison to traditional bricks, based on increased porosity and minor improvement in water absorption. [34]. The results reflect that the addition of banana fibers improves the mechanical performance of composites, particularly their compressive strength. [35].

The length of natural fibers significantly influences the mechanical properties of reinforced composites. Longer fibers show more tensile strength and ductility based on their ability to transfer stress more uniformly between fibers and the matrix, and the shorter fibers ensure more homogeneity. [36]. In comparison, fiber length does not improve compressive strength linearly, as lengthy fibers cause agglomeration, decreasing the homogeneity. [37]. Another research demonstrates that fiber length helps to spread stresses in a wider area, improving the flexural strength and toughness of gypsum composites. [38].

The thermal performance capacity of fibers varies with variation in the length of fibers. Short fibers develop a more even thermal barrier, while as the length of fibers increases, their distribution becomes uneven, badly impacting their thermal performance [39]. Fiber length can also affect the thermal expansion and heat capacity of composites. Longer fibers help to stabilize the composite during temperature variations, lowering thermal expansion [40]. A study explores that at certain temperatures, banana fibers help to maintain temperature. Longer fibers may help in the improvement of thermal performance, but reduce fire resistance [41].

It is essential to determine ideal fiber length, as too short fibers may not improve mechanical strength, but too long fibers hamper the structural homogeneity and result in ineffective stress distribution. [42]. The length-to-diameter ratio of natural fibers affects both mechanical and thermal properties. An appropriate ratio helps in developing better thermos-mechanical properties and balanced material behaviour. [43].

Generally, it is difficult to maintain a uniform distribution of fibers in a gypsum matrix, especially in the case of longer fibers, as they will get clumped and develop stress concentrations. [44]. Thermo-mechanical properties can be improved with surface treatment (alkali treatment/ chemical bonding agents) of fibers. [45]. Experimental investigations reveal that composites with tailored fiber lengths have higher mechanical strength and heat resistance. Comparative research with other natural fibers (e.g., jute, sisal) emphasizes the banana fiber's unique properties in composite materials. [46].

II. Methodology

Commercial natural gypsum with a volumetric mass of 900 kg/m3 was used in this investigation. Banana stems were used as cellulosic fibers; they were first dried and placed in the sun for 40-50 days to aid in the natural retting process. [7]. After this procedure, the banana fibers were automatically separated and cooked in water for 1 hour to dissolve lignin and remove any dust associated with it. The fibers were then sun-dried and chopped with a cutting machine into two sizes, 25 mm and 100 mm on average.

2.1 Composite Preparation

Four reference gypsum samples were made with a water plaster ratio of 1:0.75, and the material was mixed with helical motions using a mixer for around 60 seconds. The slurry was then placed into molds and molded after 3 hours. They were maintained indoors at room temperature for one day before being exposed to direct sunshine for seven days until they gained a steady weight. Then, the samples were measured and tested.

Figure 1: Composite Preparation Protocol
(a) Banana Fibers, (b) Gypsum Plaster, (c) Mould, (d) Moulding, (e) Moulded Composite Samples

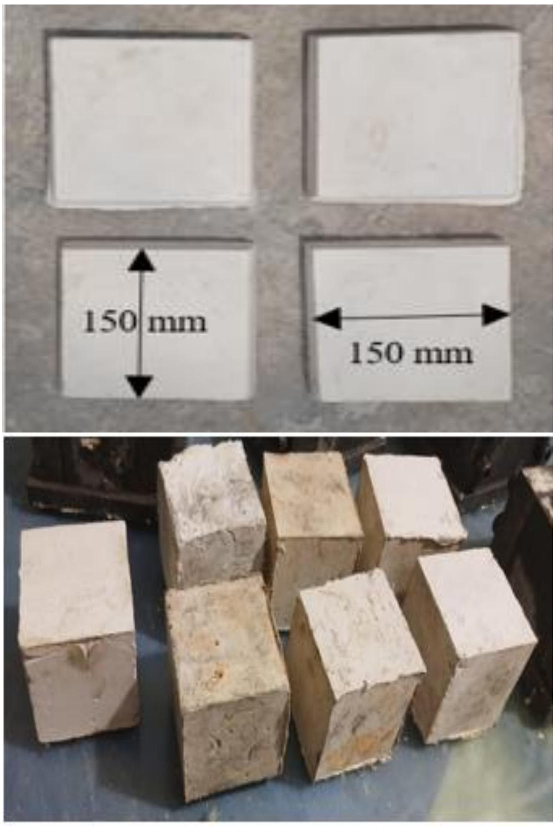

Figure 2: Image of Prepared Composites
(a) Plate Samples 150 x 150 x 25 mm,
(b) Cube Samples 50 x 50 x 50 mm

The banana fiber with fiber length variations of 25 mm and 100 mm was utilized for separate samples and was blended in three different ratios (2.5%, 5%, and 7.5%) of gypsum weight to create a homogenous combination of matrix and fibers. First, fibers were dry mixed with plaster, and then water was added at varying ratios as mentioned in Table 1. The mixture was well stirred by hand for 60-90 seconds. Then they were molded in a mold. To guarantee the tests' reproducibility, four replications of each sample were generated.

Table 1: Prepared Composite Samples

Samples Code	**Banana Fiber Content% %**	**Plaster – Water Ratio**
CG	0	1:0.8
2.5 SBG	2.5% fibers (25 mm length)	1:0.6
5 SBG	5% fibers (25 mm length)	1:0.6
7.5 SBG	7.5% fibers (25 mm length)	1:0.6
2.5 LBG	2.5% fibers (100 mm length)	1:0.6
5 LBG	5% fibers (100 mm length)	1:0.6
7.5 LBG	7.5% fibers (100 mm length)	1:0.6

(CG: Control gypsum samples, SBG: Small banana fiber length with gypsum samples, LBG: Long banana fiber length with gypsum samples)

III. EXPERIMENTATION

3.1 Physical Attributes

3.1.1 Bulk Density

Samples were weighed with electronic weighing equipment. As represented in Table 2, weight was lowered by 20% in the control sample, with the highest reduction occurring at 7.5 SBG. Bulk density decreases as fiber content increases due to increased porosity incorporated by fibers rather than gypsum plaster. The sample that included 7.5% natural fiber had the lowest density.

Table 2: Bulk Density of Prepared Samples

Sr No	Samples	Weight (g) Dry State		%age reduction after drying	Bulk Density (kg/m^3)
		1Day	7th Day		
1	CG	838	638	23.86	1216
2	2.5 SBG	766	550	28.19	1048
3	5 SBG	701	448	36	854
4	7.5 SBG	670	394	41.19	751
5	2.5 LBG	759	508	33	968
6	5 LBG	715	476	33.42	908
7	7.5 LBG	653	433	33.69	825

3.1.2 Water Absorption

The water absorption test was performed by ASTM D5229. The test was carried out by fully immersing samples in water at room temperature. Dry weight was also recorded, and following immersion, the mass development of the samples was observed at regular Intervals.

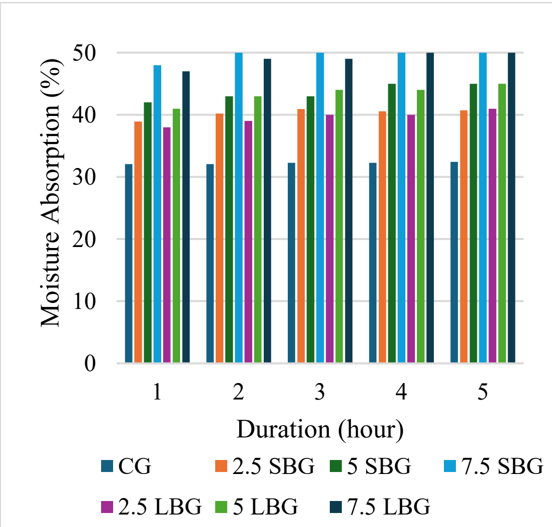

Figure 3: Moisture Absorption

During mass measurement, samples were removed from the tub and softly cleaned with a dry absorbing cloth to eliminate the moisture film before being weighed using digital weighing equipment. Figure 3 indicates that all samples, regardless of composition, absorb the most water within the first 1 hour of immersion. Following that, water absorption was reduced to 1-2 percent. Even after five days of immersion, just two to four percent of the maximum water was absorbed. Among all samples, the control sample had the minimum absorption, while the composite reinforced with fibers absorbed more water. It can be well related to the hydrophilic nature of natural fibers. [47]. The samples with maximum fiber content absorb more water in comparison to samples with fewer fibers, while the behavior of water absorption is not influenced by the fiber length.

3.2 Thermal Performance

The DRX-IPB thermal conductivity apparatus was used to evaluate the thermal performance of the control sample and the test samples in accordance with ASTM C-518. As we place the sample in the apparatus, three thermocouples, TC1, TC2, TC3, are connected to the cold brass end, and TC4, TC5, TC6 are attached to the sample, and the last three, TC7, TC8, TC9, are near the hot brass. Cold water supply was given to remove excessive heat, and power was supplied for the provision of continuous heat. The sample was retained in the apparatus for 20-30 minutes, and then temperature values were calculated at all nine points. After this, the following equation (Eq.1) was used to calculate thermal conductivity.

$$K = \frac{Q.dx}{A.dT} \quad (1)$$

Q is the heat flow (watts), A is the area (m^2), dx is the distance between thermocouples (m), and dT is the temperature difference (K)

Table 3: Temperature Measurement at the Thermocouples Using the Heat Transfer Apparatus

Thermocouples	**TC1**	**TC2**	**TC3**	**TC4**	**TC5**
Distances (mm)	**10.0**	**20.0**	**30.0**	**40.0**	**50.0**
CS	68	65	64	57	51
2.5 SBG	73	71	69	59	53
5 SBG	79	76	75	61	54
7.5 SBG	79	77	73	68	52
2.5 LBG	71	68	67	55	46
5 LBG	73	71	70	61	52
7.5 LBG	79	77	74	67	56
Thermocouples	**TC6**	**TC7**	**TC8**	**TC9**	
Distances (mm)	**60.0**	**70.0**	**80.0**	**90.0**	
CS	42	32	31	30	
2.5 SBG	41	35	32	30	
5 SBG	38	34	33	30	
7.5 SBG	37	33	32	29	
2.5 LBG	39	35	32	30	
5 LBG	37	34	33	30	
7.5 LBG	34	31	30	29	

Using the values of temperature at all thermocouples shown in Table 3, thermal performance was evaluated. TC1-TC3 reflect the temperature of the hot brass plate, TC4-TC6 indicate values of thermal gain by the samples, and TC7-TC9 provide the temperature of the cold plate. The average temperature of the first three points was 74°C, and that of the last three thermocouples is recorded as 30°C, the same as the ambient temperature. These average values are plotted in Figure 5.

Figure 4: Heat Conduction Apparatus

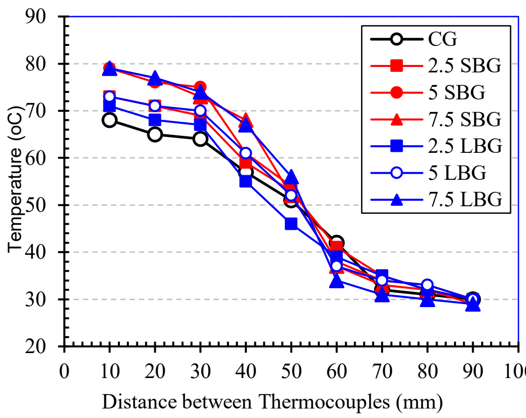

Figure 5: Thermal Gradient Profile of the Investigated Samples at Nine Thermocouples

The thermal conductivity of samples including recycled and natural fibres was compared to the control sample for each specimen, as shown in Figure 6. The control sample has the highest thermal conductivity, which decreases when fibers are added. Natural fibers have to be added to the gypsum matrix in order to reduce the thermal conductivity of the reinforced composites. For example, a 29% improvement in thermal insulation was achieved by reducing the thermal conductivity from 0.229 to 0.162 W/m.K. by adding 2.5% banana fiber. The reduction in heat conductivity is caused by the microporous nature and low thermal conductivity of the plant fibers.

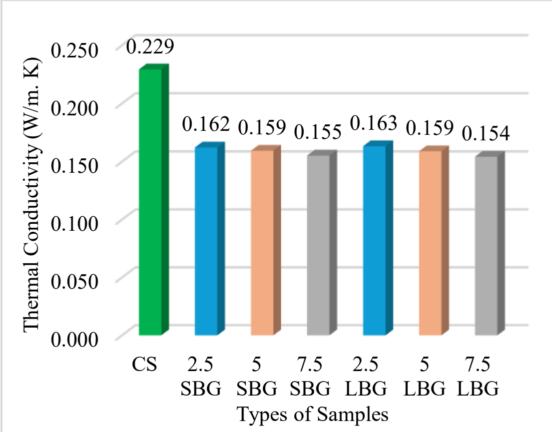

Figure 6: Insulating Performance in Terms of Thermal Conductivity

Furthermore, reinforced gypsum's uniform banana fiber dispersion contributes to a higher level of heat distribution throughout the material, lowering thermal conductivity. This mixture enhances thermal insulation, lowers heat transmission through the material, and aids in the creation of areas with greater thermal resistance. The fact that the banana fibers utilized have the same physicochemical characteristics explains why there is no influence of fiber length on heat conductivity. However, the rate of fiber inclusion dominantly influences the thermal performance. [48]. It's also important to keep in mind that adding plant fibers can effectively regulate a building's temperature by reducing heat transfer.

3.3 Mechanical Performance

In cube samples (2" x 2" x 2") and plate samples (6" x 6" x 1"), the mechanical behavior of the control sample and different composites was examined.

Figure 7: Universal Testing Machine (Max Load 250 KN) for Compressive Strength Testing

For accurate findings, flexural testing was conducted using a Universal Testing Machine (UTM) with a maximum load of 30 KN, and uniaxial compression tests were conducted on a UTM with a maximum load of 250 KN. Samples having a material age of more than seven days underwent testing for flexural and compressive strength.

Figure 8: Universal Testing Machine (Max. Load 30 KN) for Flexural Strength Testing

The nonlinear compressive stress-strain curves for various compositions are shown in Figures 8 and 9 in contrast to the control sample. These numbers were used to compute the Young Modulus, the slope of the elastic zone, and the compressive strength of different formulations. Because a greater amount of binder was utilized on the reference samples, the compressive strength is higher than that of the fiber composites, as predicted. The experiment also shows that adding fibers spontaneously improves the brittleness of gypsum plaster.

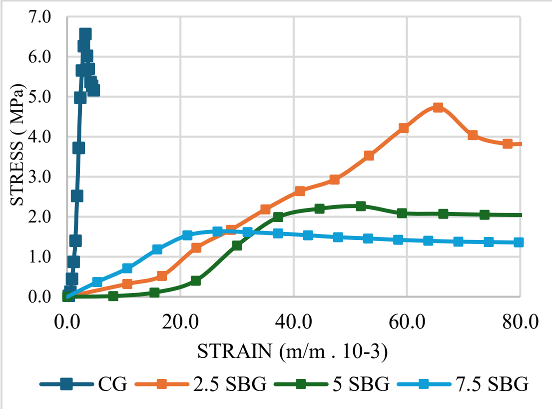

Figure 9: Compressive Strength Behavior of 25 mm Banana Fiber Composites

Banana fiber-reinforced gypsum (BFG) composites with varying fiber concentrations (2.5%, 5%, and 7.5%) and lengths (25 mm and 100 mm) exhibit distinct patterns in stress-strain behavior in their compressive strength data. The peak compressive strength reduces as the amount of banana fiber increases. For example, at comparable strain levels, a composite containing 7.5% short banana fiber (SBG) may withstand up to 1.63 MPa of stress, but a composite containing 2.5% SBG can withstand 4.725 MPa. Longer fibers may not be better under compressive stress, as seen by the decreased compressive strength of long banana fibers (LBG), which drops to 3.80 MPa at 2.5% LBG. Higher fiber content composites have a more ductile post-peak response, indicating that adding banana fibers improves the material's ability to withstand deformations before failing. The composite containing 7.5% LBG exhibits better energy absorption and robustness against brittle failure, sustaining greater stresses after peak compared to control samples.

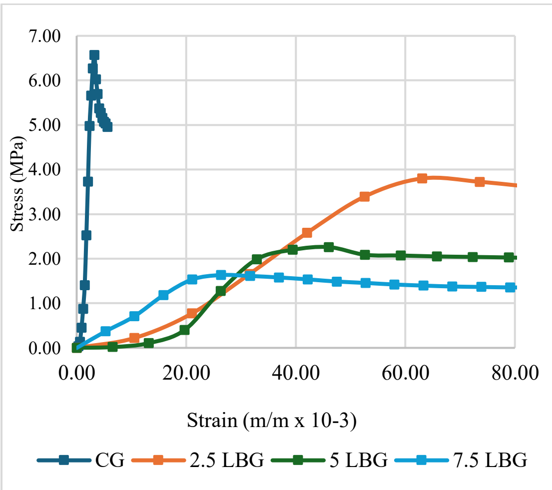

Figure 10: Compressive Strength Behavior of 100 mm Banana Fiber Composites

Higher fiber content composites have a more ductile post-peak response, indicating that adding banana fibers improves the material's ability to withstand deformations before failing. The composite containing 7.5% LBG exhibits better energy absorption and robustness against brittle failure, sustaining greater stresses after peak compared to control samples. As demonstrated by the approximately 65% decrease in strength compared to the control sample for the 5% LBG, the 5% fiber content in long fibers performs better than the 7.5% composite in both post-peak behavior and strain capacity, making it a better choice for applications needing more ductility. A 7.5% addition of fibers results in compressive strength below the minimum standard for building application, so max 5% fibers can be added for optimum performance.

The addition of fibers in gypsum improves flexural load-bearing capability at peak displacement, as shown in Figures 10 and 11. For instance, the 2.5% SBG composite reaches peak loads of around 0.953 KN load at a displacement of 2.625 mm, whereas the 2.5% LBG composite achieves a peak value of 1.789 KN load, which is 60% more than the control sample.

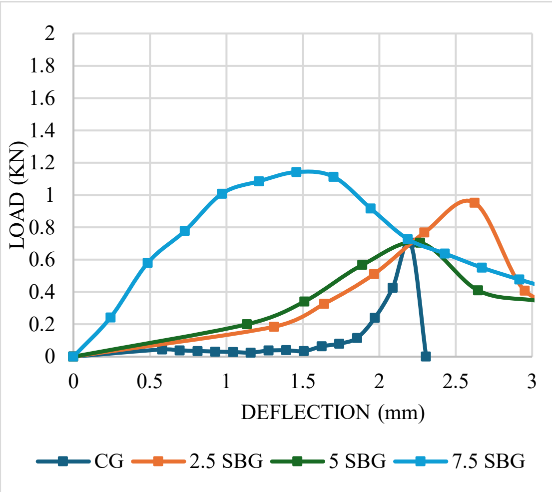

Figure 11: Flexural Behaviour of 25 mm Banana Fiber Composites

Improved flexural capacity is a result of both shorter and longer fibers, although the gain is more noticeable for longer fibers because of their increased capability to distribute load along their length. Higher fiber content composites show less abrupt post-peak reductions in flexural loading, enabling continuous load support even as displacement rises. When it comes to structural applications that are subjected to dynamic loading, the 7.5% fiber composites' ability to sustain flexural strength across a wide displacement range indicates improved ductility and bending resistance. With load-bearing improvements of over 48% above the control at critical displacements, 7.5% LBG composites exhibit the best ductility and flexibility. High-content, long-fiber BFG composites are therefore more appropriate for building projects that call for resilience to bending and distortion.

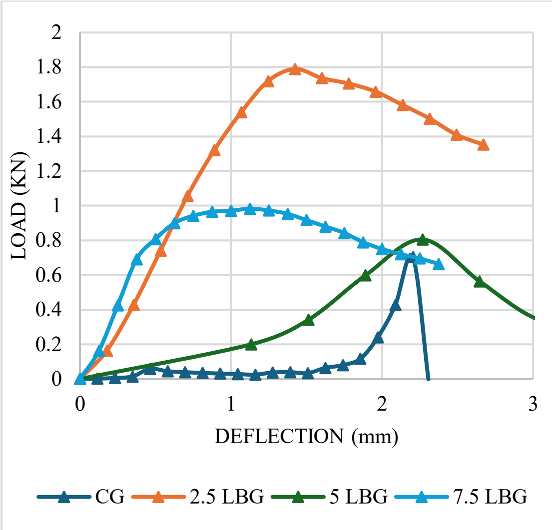

Figure 12: Flexural Behaviour of 100 mm Banana Fiber Composites

With a 5% fiber content and a length of 100 mm, banana fiber-reinforced gypsum composites exhibit optimum compressive and flexural performance, providing higher peak strengths and more ductile post-peak behavior. Long-fiber, high-content BFG composites are ideal for construction applications requiring more durability and flexibility because of their improvement in flexural capacity. Table 4 represents the comparison of compressive and flexural strength along with Young's modulus and modulus of rupture.

Table 4: Mechanical Behaviour of Banana Fiber Reinforced Composites

Samples	Compressive Strength $б_c$ (MPa)	Young Modulus (MPa)	Flexural Strength $б_f$ (MPa)	Modulus of Rupture (MPa)
CS	6.57	20.27	5.3	0.88
2.5 SBG	4.725	72.13	7.2	1.19
5 SBG	2.26	44.31	5.3	0.89
7.5 SBG	1.63	62.69	8.7	1.45
2.5 LBG	3.8	60.31	13.41	2.24
5 LBG	2.29	49.5	6.03	1.01
7.5 LBG	1.63	62.69	7.37	1.22

Banana fibers affected the stiffness of the various gypsum composites in addition to the noted rise in flexural stress. It was discovered that the flexural modulus of the composites (Table 4) was considerably lower. It is important to remember that the flexural modulus decreases with increasing fiber length and content, in contrast to flexural load. The reinforcing composite becomes less rigid as a result of the fibers' increased porosity. Consequently, compared to the reinforced gypsum, the reference gypsum is stiffer. Other research work [49] also indicate that the inclusion of plant fibers in the matrix decreases the elastic modulus.

IV. CONCLUSIONS

This research work thoroughly assesses the thermal, mechanical, and physical attributes of gypsum composites with the inclusion of banana fibers in varied lengths. Adding banana fibers to the gypsum matrix provides an environmentally friendly method of improving the boards' mechanical and thermal qualities. Banana fibers can reduce the total environmental effect of gypsum composites since they are renewable and biodegradable. This is particularly important in the context of sustainability. It also expands the potential applications of these composites in the construction sector. The experimental findings can be summarized in the following conclusions:

- The thermal performance of gypsum composites is always better than that of control samples. It is crucial to find that the integration rate of the fibers, not their length, determines the change in thermal conductivity. In other words, the composite's heat conductivity decreases with increasing fiber quantity. For instance, the thermal conductivity was reduced by around 87% when 7.5% fibers were added.
- While adding banana fibers up to 5% can still yield satisfactory mechanical performance results, they severely reduce the gypsum's compressive strength characteristics.
- Fiber addition, on the other hand, enhanced load-bearing capability and flexural strength. As seen in the reference gypsum, flexural testing showed that the natural fibers were excellent at bridging microcracks and preventing their spread, preventing abrupt collapse. The reinforcement of banana fibers in gypsum improves ductile behaviour, and eventually, composite flexural properties are enhanced with the length of fibers.

The addition of banana fibers to gypsum significantly reduces the workability of new composites. Additionally, when the rate of fiber integration increases and the fibers become longer, workability is further hindered. Variations in material qualities, especially mechanical properties, can result from an uneven distribution of fibers. Nonetheless, the pace at which plant fibers are incorporated into the gypsum matrix can be accelerated by enhancements made to the production process. In addition, as gypsum itself is a hydrophilic material, these composites have a limitation in practical application on the exterior of the building, though they can be well installed indoors; hydrophobic treatments can be experimented with to cater to this limitation.

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