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Research Article

Thermal and Mechanical Performance of 3-Phase Polymer Composite Panels for Structural Applications

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The objective of this study is to establish a conceptual framework for fiber-reinforced polymer composite (FRPC) panels designed for structural purposes through the incorporation of a third phase (fillers). The present investigation was aimed to design and fabricate 3-phase polymer composite panels that offer enhanced thermal insulation and strength while maintaining low material and labor expenses. Two types of fibrous reinforcements (jute fabric and glass fabric) of different origins were used as reinforcement; polypropylene (PP) was used as the matrix, and microcrystalline cellulose (MCC) was used as particle reinforcement material. The composite materials were fabricated with different MCC concentrations (0, 2 wt%, and 4 wt%), using a hot compression molding technique. It was found that MCC helped to enhance the mechanical performance of the composite panels, while the thermal conductivity showed a slight reduction due to lower concentrations of MCC used. For polypropylene/glass (PPG) composites, thermal conductivity was reduced from 0.214 to 0.193 W/m·K by the addition of 4% MCC fillers. Similarly, for polypropylene/jute (PPJ) composites, it was reduced from 0.14 to 0.126 W/m·K by 4% MCC fillers. The Charpy impact strength of both PPG and PPJ composites was enhanced by the addition of fillers, and the effect was more significant in the case of PPG (increased from 24.83 to 43.98 kJ/m^2 for 4% fillers). Cost analysis of the composite panels was also done, showing PPJ panels to be slightly cheaper as compared to PPG. The findings indicate that the developed composite panels have the potential to serve as partitioning as well as the outer shield of the building due to their effective thermal and mechanical properties.

1. Introduction

Fiber-reinforced polymer composites (FRPCs) have enabled the development of construction industry solutions with light weight, durability, high strength-to-weight ratio, and corrosion resistance. Due to their advantages, these materials were widely used in construction, including strengthening and rehabilitation of structures, bridge construction, and precast profiles and panels. These features and industrialized processes make FRP materials suitable for modular housing and other efficient building systems. The traditional system of housing, from materials, such as masonry, timber, steel, and concrete, is expensive, slow, and less energy efficient. A lot of energy wastage in the temperature management of buildings has given birth to the concept of thermal insulation of civil structures [1]. Considering a conventional house without insulation, the thermal energy is transferred through its walls, causing the overall temperature of a building to rise or fall. Hence, an extra amount of electricity is consumed to maintain the inside temperature of the building [2]. The existing insulation solutions include wall cavity insulation, spray insulation, padding, and painting. These are costly and require a lot of insulation time.

Moreover, there are some other problems like the conventional structure being too heavy, nonresistant to weather and corrosion, and needing frequent maintenance.

Therefore, there is a strong need to design and develop lightweight, quickly constructed, and high-quality houses at an affordable price. The exponential increase in the global population, coupled with the scarcity of power resources and the emission of harmful gases from air conditioning systems, has further fostered research in this domain.

It has resulted in a growing interest recently in the development of advanced composite materials for structural applications. The need for lightweight, durable, and high-performance materials has been the driving force for these developments. Fiber-reinforced polymer composites (FRPCs) have emerged as a promising alternative to conventional materials owing to their excellent mechanical properties, corrosion resistance, and flexibility of design. Owing to these advantages, Setyowati and Pandelaki [3] demonstrated the use of natural fiber-reinforced composite panels for modular housing. The properties of FRPC depend upon the properties of its constituents, i.e., reinforcement and matrix material [4, 5]. The relative proportion of constituents, reinforcement geometry, and stacking sequence are some of the key parameters that govern the performance of FRPC [6, 7]. The filler-dispersed resin is a two-phase composite, and fibrous laminate impregnated using filler-dispersed resin is a 3-phase composite. The development of a 3-phase hybrid composite, using fibers and particles, is also a widely practiced approach for tailoring the properties of FRPC. The addition of particles allows for the synergistic enhancement of the functional, thermal, and mechanical properties [8, 9].

The response of FRPC material to thermal exposure depends on the thermal properties of all the constituents [10, 11]. The polymer matrix is considered a poor conductor of heat and contributes to the enhanced thermal insulation of resulting FRPC panels for enhanced energy efficiency [12]. However, a highly ordered matrix structure causes the movement of phonons resulting in high thermal conductivity, while the random or amorphous structures hinder the movement of phonons and provide an irregular structure through which the thermal passage is difficult [13]. Fibers, being the load-bearing component of FRPC, also play an effective role in determining its thermomechanical performance. Cellulosic fibers are one of the oldest materials used to fabricate composite materials, along with different matrix materials [14, 15]. The amorphous cellulose is reported to have better thermal insulation, as compared to crystalline one [16]. Similarly, mineral wool is used in the form of mats, boards, and crushed filling material [17].

The addition of particles controls the thermal and mechanical properties of FRPC; e.g., addition of silica microparticles reduces the thermal expansion coefficients (CTE) and increases the modulus of the resulting composite material [18]. Sun et al. [19] fabricated glass/polyurethane composites by the addition of hollow glass microspheres, to investigate the effect on the thermal insulation performance. They reported a significant increase in thermal insulation performance of FRPC, with a 42.5% reduction in thermal conductivity. Nanofoams are also used as an effective source of tailoring the thermal insulation of composite materials [20]. Xu et al. [21] reported an increase in the thermal insulation of PP composite materials by the addition of graphene nanoplatelets and boron nitride fibers. Xu et al. [22] designed a composite material for infrared stealth and thermal insulation using a carbon nanotube-doped aerogel sandwich structure on polyimide fabric and coated with a low emissivity Al-doped ZnO.

Although particle-loaded FRPC has been studied extensively, the particles used are not of a bio-based origin. The 3-phase polymer composite panels developed by a combination of jute/glass fabric with polypropylene resin and bio-origin microcrystalline cellulose (MCC) particles need to be investigated. To the best of the authors' knowledge, comprehensive studies on the mechanical and thermal performance of such composite panels are lacking in the literature. Natural fibers like jute are a sustainable source of reinforcement material for polymeric composites and help to provide a sustainable substitute for existing materials [23–25]. Hence, this study is aimed at bridging the research gap and providing useful insights into the performance properties of such panels. The outcome of this study can help solve the need for environmentally friendly substitutes in the manufacturing and construction sectors by advancing the development of high-performance, sustainable composite materials for structural applications.

2. Materials and Methods

The nonwoven polypropylene sheets prepared from SABIC® PP were used as matrix material. This PP had a melting point of 165°C, with very low water absorption (0.06% approx.). Two different fabrics were explored as reinforcement materials. Jute fabric having an areal density of 200 grams/sq. meter was obtained from Sargodha Jute Mills, Pakistan, and the glass fabric (areal density = 350 grams/sq. meter) was obtained from local suppliers. Both fabrics were in pristine condition, and no pretreatment was applied on these reinforcements. MCC particles PH-101 were procured from Huzhou City Linghu Xinwang Chemical Co., Ltd., China. The MCC particles used for the current study had a z-average size of 1325 d·nm, while the polydispersity index (PDI) was 0.601. These MCC particles had a rod or needle-like structure with 14.28-181.31 μm length and 2.19-63.73 μm width. The crystallinity index of these MCC particles was 82.3% [26].

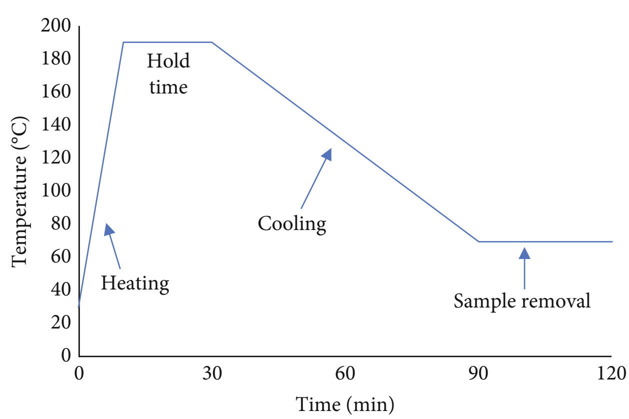
2.1. Methodology

2.1.1. Design Parameters. As the study was focused on the development material and investigation of its properties, FRPC plates of 300 mm × 300 mm having an average thickness of 1.1 mm were produced. Table 1 shows that six different FRPC plates were fabricated, by varying the reinforcement materials and MCC filler concentrations. Four plies of reinforcement were used for each FRPC, and the ply stacking sequence was 0/90/0/90. The composite fabrication was done in two steps, namely, stack formation and consolidation by hot compression. In the stack formation step (for PPG0 and PPJ0), alternate plies of reinforcement (glass and jute fabric) and matrix material (PP sheet) were stacked over each other, to get a uniform matrix distribution

Table 1: List of unique FRPC plates produced for the study.

S. #	Sample ID	Reinforcement	Matrix (resin)	MCC (wt%)
1	PPG 0	Glass fabric	Polypropylene	0
2	PPG 2	Glass fabric	Polypropylene	2
3	PPG 4	Glass fabric	Polypropylene	4
4	PPJ 0	Jute fabric	Polypropylene	0
5	PPJ 2	Jute fabric	Polypropylene	2
6	PPJ 4	Jute fabric	Polypropylene	4

(a)



(b)

Figure 1: (a) Compression molding machine. (b) Fabrication cycle for thermoplastic composites.

in the resulting composite material. For filler-loaded composites (PPG2, PPG4, PPJ2, and PPJ4), the known quantity of MCC particles was poured onto the surface of PP sheets and dispersed uniformly with the help of a knife. This filler-dispersed PP sheet was then alternatively stacked between the reinforcement layers.

2.1.2. Process Parameters. After stack formation, the stack was placed between the platens of a hot compression machine, as shown in Figure 1(a). Teflon sheets were placed at the top and bottom contact surfaces between platen and stack, for ease of removal after consolidation. The stack was consolidated with a pressure of 0.5 ton, and a temperature of 180°C was provided to melt the PP matrix and impregnate the reinforcement material. The processing cycle adopted for the fabrication of thermoplastic composites is given in Figure 1(b).

2.2. Characterization. As this study was conducted to investigate the properties of composites for construction

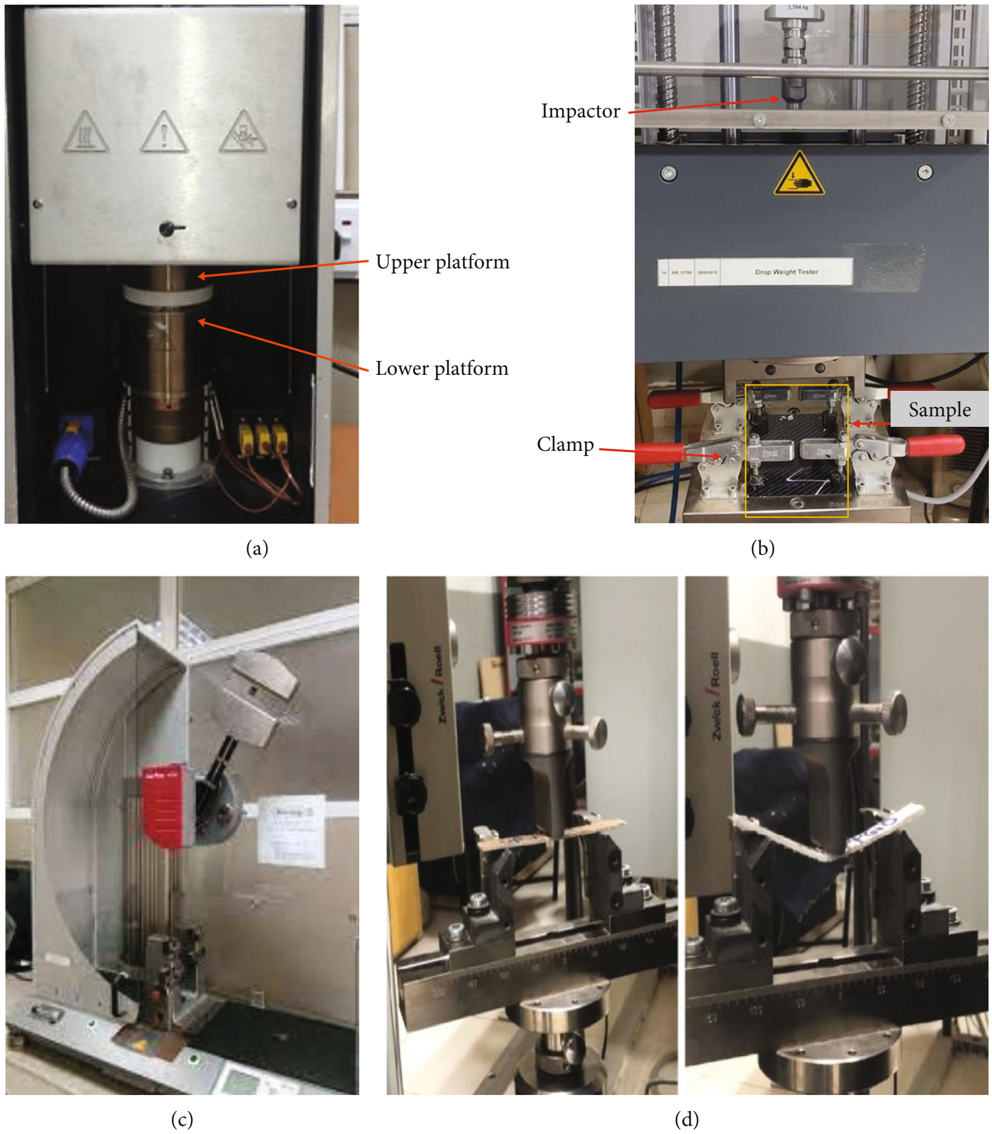


Figure 2: Equipment used for characterization: (a) DTC 300 for thermal conductivity, (b) HIT 230F, (c) HIT 5.5P for impact test, and (d) UTM Z100 for flexural test.

applications, the thermal and mechanical properties are of the most importance. The mechanical properties include pendulum impact, drop weight impact, and flexural properties.

2.2.1. Thermal Testing. For thermal testing of composites, the samples were cut to the diameter size of 50 mm with the help of an overhead hole saw cutter. After cutting the samples, thermal paste was applied for better contact of the sample with the upper and lower platform of guarded hot plate equipment (DTC 300) by TA instruments as per ASTM E1530 (Figure 2(a)).

2.2.2. Impact Testing. The mechanical testing of composite panels was conducted using a drop weight impact tester (HIT 230F, ZwickRoell) as per ASTM D7136 and a pendulum impact tester (HIT 5.5P, ZwickRoell) according to ISO 179 [27], as shown in Figures 2(b) and 2(c), respectively. The drop weight test was performed with a falling weight of 3.28 kg. The size of the specimen was kept at 100 mm by 150 mm. The sample was placed inside the sample holder and indenter holding.

2.2.3. Flexural Testing. The flexural properties were investigated according to a three-point bending test, following the standard method ASTM D7264 [28]. The span length and width of the test specimen were 80 mm and 13 mm, respectively. All the samples were tested for bending strength and modulus on a universal testing machine (Z100 ZwickRoell, Germany) as shown in Figure 2(c).

3. Results and Discussion

The cross-sectional images of the composite samples are given in Figure 3. Different plies of reinforcement can be easily identified in the cross-section. It can be observed that

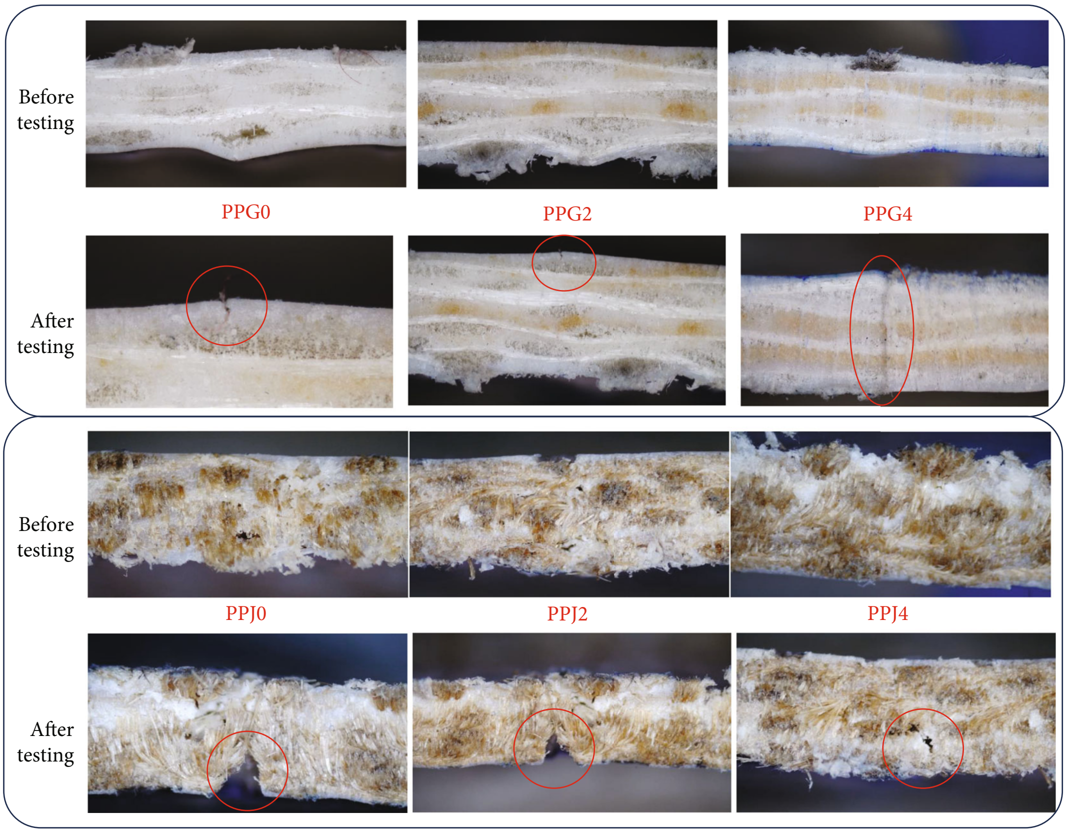


FIGURE 3: Cross-sectional images of PPG and PPJ composites, before and after mechanical test.

the PP matrix melted properly during composite fabrication and impregnated the reinforcement material. A perfect bonding can be observed between reinforcement and matrix with no voids or delamination in the composite material.

3.1. Thermal Conductivity. The thermal conductivity values obtained using DTC 300 are graphically represented in Figure 4. A glance reveals that the addition of MCC particles has reduced the thermal conductivity of composite panels, and the trend is linear. For PPG composites, thermal conductivity was reduced from 0.214 to 0.193 W/m·K by the addition of 4% MCC fillers. Similarly, for PPJ, it reduced from 0.14 to 0.126 W/m·K by 4% MCC fillers.

The addition of particles to a composite material causes some discontinuity in the resulting FRPC. When heat is transferred through composite by conduction, the thermal energy is diffused theoretically to the other side of crystalline fillers. It is partially in contact with the polymer chain, and this incomplete contact at the interface leads to large phonon scattering and higher thermal resistance of the 3-phase composite material [29]. This phenomenon has resulted in the reduction of the k-value of the FRPC, by the addition of MCC particles. The schematic of this phenomenon at the filler-matrix interface is shown in Figure 5. Furthermore, more time is required for heat to diffuse through the polymer chain than through the crystalline filler.

The heat transfer through the polymer chain is less efficient due to the vibrations of the chain and phonon scattering. The polypropylene and microcrystalline cellulose particles do not establish a strong interface, causing hindrance to the passage of heat. As a result, heat diffuses slowly and briefly accelerated along MCC and is considerably slowed by the matrix. Hence, the overall thermal conductivity of the composite is reduced. The lower thermal conductivity is exhibited by jute-reinforced composites as compared to glass composites. The thermal conductivity of jute and glass fiber is 0.038-0.042 and 0.05 W/m·K, respectively. This has been translated into the composite panels, as the fiber volume fraction was the same for all panels, i.e., 35% ± 0.7.

3.2. Drop Weight Impact. The drop weight test determines the damage resistance of a composite panel when a known weight is allowed to fall from a certain height. A hemispherical impactor is connected to the specimen that strikes the specimen. The variation in force during this impact event is recorded as a function of the distance traveled by the impactor [30]. The schematic and actual image showing the placement of the test specimen is shown in Figure 6.

The 3-phase composite panels were subjected to an impact event of 10 J. The load-displacement curves obtained after the drop weight impact test on HIT 230F (ZwickRoell) are shown in Figure 7. Two distinct behaviors can be observed from load-displacement curves, a rebound behavior exhibited by the PP/glass (PPG) composites, while puncture behavior was shown by the PP/jute (PPJ) composites. These behaviors can be attributed to the ductile and brittle

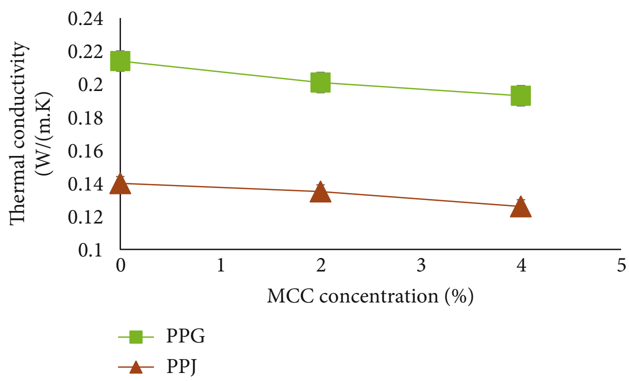


FIGURE 4: Thermal conductivity results of different composite materials.

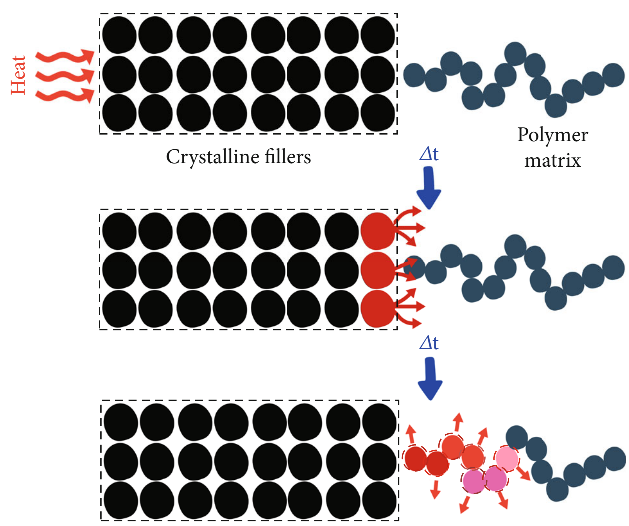


FIGURE 5: Schematic of conduction at particle-matrix interface [29].

behaviors of these composites, respectively. In the case of PPG0 composites, the impactor displaced the composite under the impact point, and the load increased with displacement. Upon reaching a maximum load of 1788 N and 10 mm displacement, the force and displacement decreased, showing a rebound of the impactor. It can be observed from Figure 7 that the load-bearing capacity of the composite is decreasing with the addition of MCC particles in the 3-phase composite panel. Additionally, the samples undergo more displacement with the addition of fillers. It shows that the behavior of composite is changing from ductile to brittle.

In the case of PPJ composites, no rebound is observed, showing matrix failure or fiber cracking. The impact under high energy may result in perforation in such cases. All the composites showed a similar behavior with very slight variation. The highest load was borne by the PPJ0 and subsequently reduced for PPJ2 and PPJ4. As discussed earlier, the addition of MCC particles causes a discontinuity in the composite material. When a load is applied, there are losses in load transfer from one phase to the other, leading to a reduced load-bearing performance of MCC-reinforced FRPC.

The drop weight-tested samples are shown in Figure 8, and the impact area has been circled. A similar behavior can be seen in tested samples, as discussed earlier. The indentation is visible in the PPJ specimen, while no indentation is observed in the PPG specimen. The PPG4 specimen has shown some indentation in the specimen.

3.3. Charpy Impact. The Charpy impact test was performed on the developed composite materials, and the energy absorbed by these specimens was determined. The impact strength of the tested specimen is given in Figure 9. It can be observed that the impact strength is increasing with the addition of fillers and the trend is increasing with an increase in the filler concentration. The trend is the same for both glass and jute reinforcements; however, it is not very significant in the case of jute composites.

The increase in the Charpy impact strength of composite materials with increasing concentrations of microcrystalline cellulose fillers can be attributed to the toughening mechanism, crack arrest, damping, and enhanced interfacial adhesion. MCC fillers, when incorporated into the matrix, can absorb and dissipate impact energy by undergoing localized deformation. It prevents crack propagation and enhances the impact resistance of the composite material. Similarly, the presence of MCC fillers acts as a physical barrier to arrest and deflect/prevent the propagation of cracks that are initiated during impact loading, thus effectively increasing the energy absorbed.

It has been widely reported in the literature that MCC has reinforcing properties and helps to enhance the mechanical properties of the resulting material. The addition of MCC produces a localized particle-loaded composite material. This local composite material reinforces the matrix at a microscale, thereby contributing to the enhanced mechanical performance of the composite material [31]. Additionally, the MCC fillers also provide a damping effect by reducing the stress wave propagation and dissipating impact energy.

3.4. Three-Point Bending. The three-point bending test results are graphically represented in Figure 10. The graph shows the effect of microcrystalline cellulose filler on the strength of composite samples. The strength of composites with glass fabric reinforcement can be seen increasing with the addition of filler, while jute composites show a decrease in strength due to the low strength of jute and the high strength of glass fabric. The MCCs are not increasing the bending strength of jute here as they increase the thermal properties. Besides good strength, jute has other benefits like its biodegradability and porosity and is also annually renewable.

Stress applied on the specimen causes a bending deflection in the specimen, and this deformation could be of an elastic or plastic nature. The deformation of composite samples along with stress applied shows that stress decreases or remains almost the same with the addition of MCC in all samples, while the amount of deformation in the samples varies with filler insertion. The deformation produced in the sample with PPJ is less as compared to PPG composites due to the brittle nature of jute. This brittle behavior of the

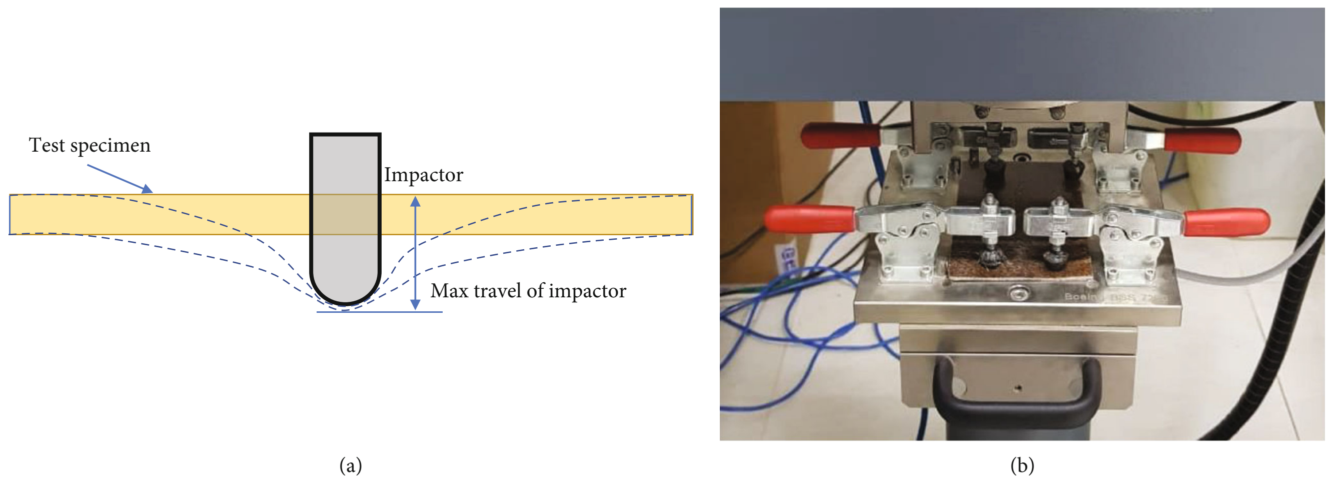


Figure 6: (a) Schematic of drop weight test. (b) Sample placement for test.

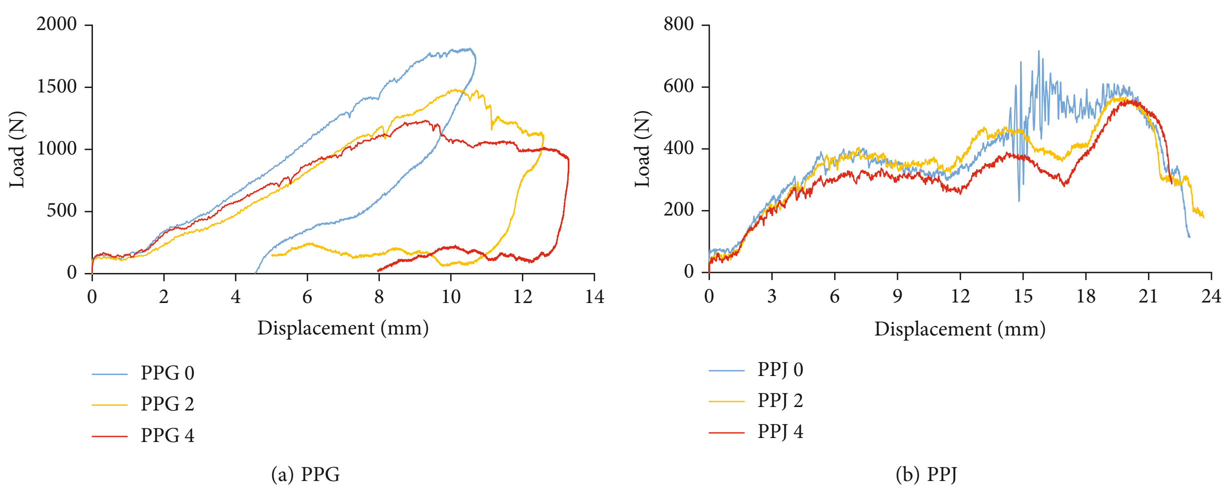


Figure 7: The load-displacement curve of drop weight-tested samples.

composite material can be explained in terms of different phenomena including reinforcement effect, enhanced interfacial bonding, increased filler concentration, and improved matrix reinforcement dispersion.

The MCC fillers have a high aspect ratio and act as reinforcing agents, distributing and transferring the applied load more efficiently. This reinforcing effect leads to increased stiffness and in some cases increased strength of the composite. An extensively strong interfacial bonding can restrict the movement of the reinforcing phase, limiting the energy dissipation mechanisms and causing a more brittle behavior. Lastly, the uniform dispersion of MCC enhances the reinforcement efficiency and load transfer between the matrix and the reinforcing phase.

The flexural modulus of all composite panels is compared in Figure 11. The modulus of jute fiber and glass fiber is 25 and 78.5 GPa, respectively. It can be observed that the composite materials reinforced with these fibers have shown similar behavior, i.e., higher modulus for PPG and lower for PPJ. The addition of fillers has not affected the modulus significantly. There is a slight increase in the modulus, but the effect is not very significant, due to the lower concentration of fillers.

3.5. Cost Analysis. The cost of the developed 3-phase composite panels is compared in Table 2. The cost has been broken down into four components as shown in the following equation [32]:

$$C_{\text{Total}} = C_{\text{Material}} + C_{\text{Equipment}} + C_{\text{Labor}} + C_{\text{Tooling}}. \quad (1)$$

3.5.1. Material Cost. There are three materials used for the fabrication of composite panels including matrix, reinforcement, and fillers. Therefore, material cost is determined using

$$C_{\text{Material}} = C_{\text{Matrix}} + C_{\text{Reinforcement}} + C_{\text{Filler}}. \quad (2)$$

The cost of the matrix, reinforcement, and fillers used for the fabrication of the panel is calculated from primary parameters like the volume fraction of each component, number of plies, and area of the panel.

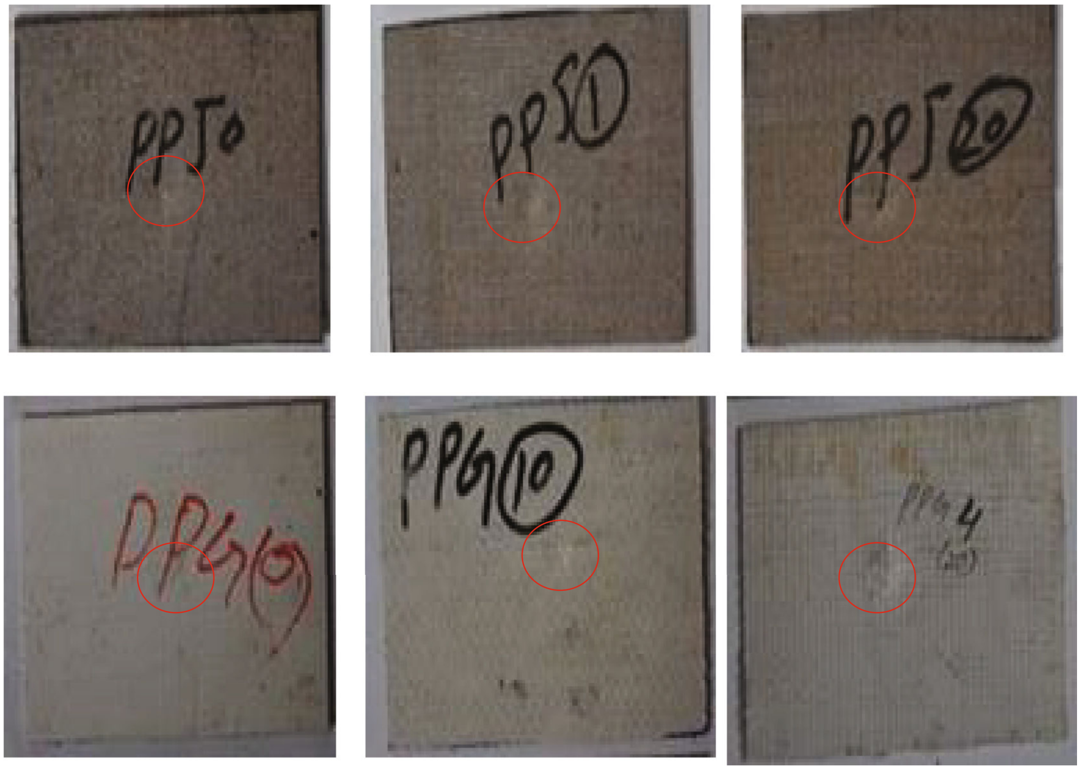


Figure 8: Drop weight impact-tested specimen, showing indentation.

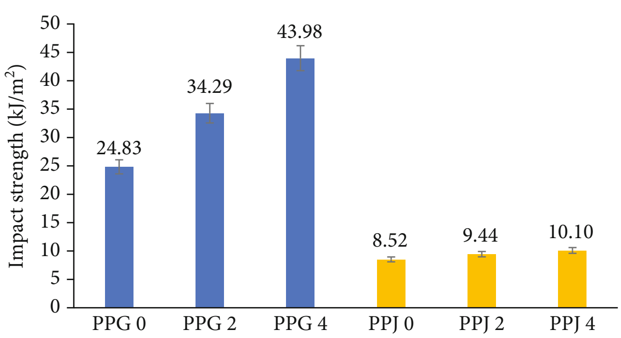


Figure 9: Impact strength of composites determined by the Charpy impact test.

3.5.2. Equipment Cost. To determine the contribution of equipment cost for composite panel cost, the hourly cost of a machine is determined. It is done by distributing the total capital cost of the equipment into equivalent annual payments along with an interest rate. The amount of annual payment is then divided by the annual hours of operation to determine the hourly cost of a machine. The detailed methodology has been discussed by Joshi [32].

3.5.3. Labor Cost. For calculating labor cost, process time is determined by estimating the time for all the operations of the composite manufacturing technique. As discussed earlier in Section 2.1.1, the composite fabrication was done in two steps, namely, stack formation and consolidation by hot compression. The following operations were identified for labor cost calculation.

(1) Preparation of materials

(2) Cut reinforcement plies according to part size

(3) Cut matrix (PP) plies according to part size

(4) Clean mold

(5) Arrange the matrix layer in the mold

(6) Pour MCC particles on matrix layer

(7) Arrange reinforcement ply in the mold

(8) Repeat steps 5, 6, and 7 till all plies are stacked

(9) Place the stack in a hot compression press

(10) Consolidation of the stack by lowering the upper platen

(11) Cut-off temperature when the curing cycle is completed

(12) Open platens and remove the panel

$$C_{\text{Labor}} = \sum T_i . R_{\text{Labor}\,i}, \quad (3)$$

where T_i is the time for step i (hours) and $R_{\text{Labor}\,i}$ is the labor rate for step i ($/hr). The idle time is also multiplied by the labor rate to determine the utilization overhead cost.

3.5.4. Tooling Cost. The cost of mold and other accessories (Teflon sheets) required to manufacture a composite panel has been included in the tooling cost. The cost of the mold

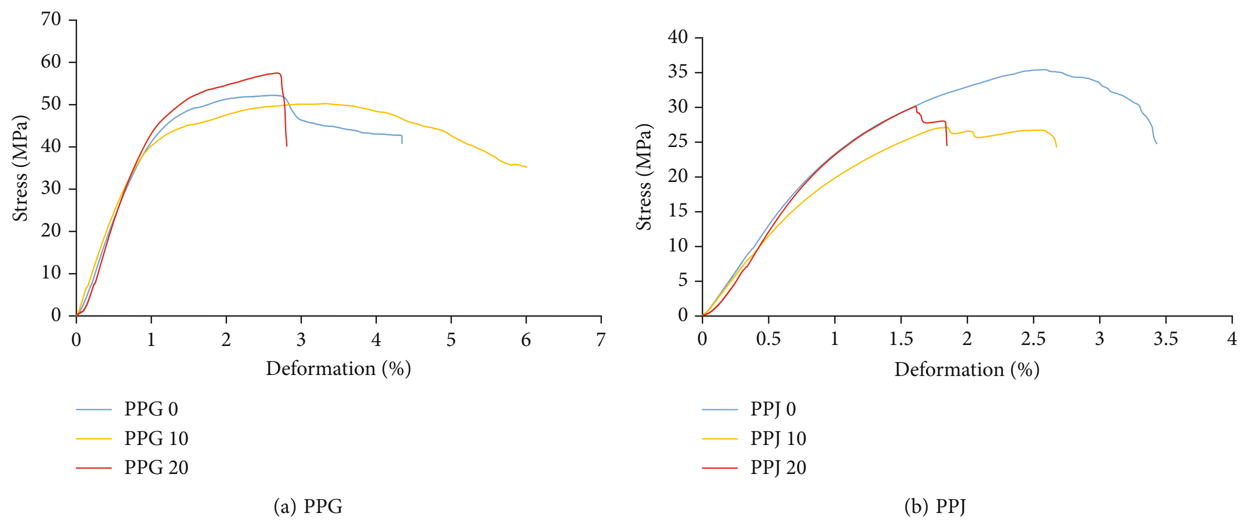


FIGURE 10: Stress-strain curve obtained in three-point bending.

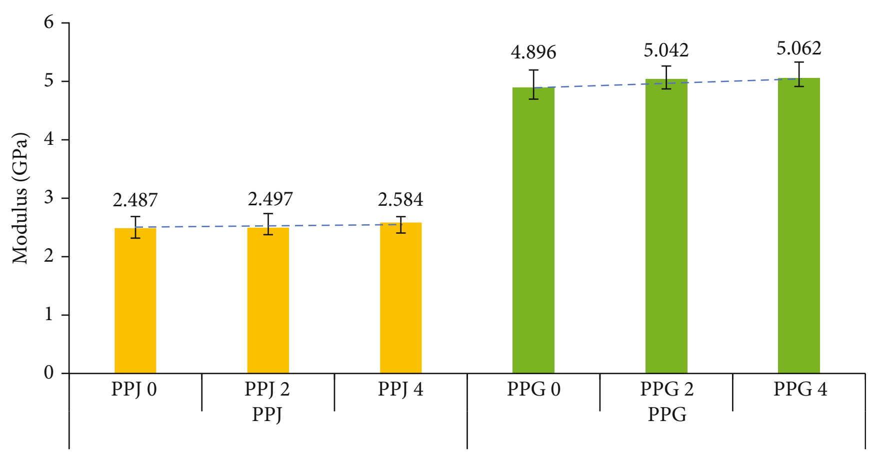


FIGURE 11: Flexural modulus of jute and glass fiber composites.

TABLE 2: Cost analysis of 3-phase composite panels.

	Jute/PP*	Glass/PP*
Material cost ($)	0.25	0.28
Equipment cost ($)	0.39	0.39
Labor cost ($)	0.30	0.30
Tooling cost ($)	0.07	0.07
Total cost ($)	1.02	1.04

*MCC fillers due to the very small quantity had no significant effect on the cost of composite panels.

has been distributed over the number of panels expected to be fabricated to estimate the tooling cost per part.

3.6. Potential Applications. Structural integrity and insulation are the key properties required in a panel for structural/housing applications. The structural integrity was determined in terms of three-point bending, drop weight impact, and pendulum impact, while insulation was measured in terms of the thermal conductivity of the panel. The experimental results of developed composite materials are compared with those of the commercial plywood in Table 3.

Plywood is used for floors, walls, and roofing in construction applications. It is also used for packaging boxes, fencing, and other similar applications. It can be observed that the thermal conductivity of PPJ composites is less than plywood, while PPG has a higher value of thermal conductivity. The density of PPJ is comparable to plywood, and PPG is a heavier material. The mechanical properties of both are comparable to conventional plywood, without any significant failure during the drop weight test. Additionally, the PP-based FPRC offers the advantages of recyclability, and jute reinforcement is an annually renewable fiber. Owing to these advantages, it can be considered a potential replacement for conventional plywood material.

Table 3: Comparison of the structural integrity and insulation of FRP panels and plywood.

	Plywood results (literature) Value	Ref.	Experimental results PPG	PPJ	Remarks
Thermal conductivity (W/m·K)	0.15	[33]	0.193–0.214	0.126–0.14	PPJ has lower thermal conductivity and can offer more resistance to heat
Density (kg/m^3)	325–1050	[33]	1475	1095	The density of PPJ is comparable to plywood; therefore, weight will be the same
Flexural modulus (GPa)	8.2	Matweb	4.89–5.06	2.48–2.58	The flexural modulus of PPJ is poor and needs improvement, before use for structural application
Drop weight impact (J/g)	0.45–0.86	[34]	0.70–1.22	—	PPG offers more resistance to falling weight and can result in enhanced life
Impact strength (kJ/m^2)	10.1	[35]	24.83–43.98	8.52–10.10	PPJ and plywood offer comparable resistance to a low-velocity impact

4. Conclusions

This study investigated the effect of MCC particle addition on the thermal and mechanical properties of FRPC, for construction applications. The FRPC showed a decrease in thermal conductivity upon the addition of MCC fillers. The PPG and PPJ composites showed a reduction of 9.81% (from 0.214 to 0.193 W/m·K) and 10.0% (0.14 to 0.126 W/m·K), respectively, by the addition of 4 wt% MCC fillers. However, no significant improvement was observed in terms of mechanical properties (impact and flexural). Drop weight impact testing of PPJ and PPG composites showed a reduction in the load-bearing capacity with the addition of MCC fillers. However, in case of pendulum impact, where pendulum strikes the FRPC sideways, impact strength was increased by 77.12% (from 24.83 to 43.98 kJ/m^2) and 18.54% (from 8.52 to 10.10 kJ/m^2) for PPG and PPJ composites, respectively, by the addition of 4 wt% MCC fillers. No significant difference was observed in the flexural properties by the addition of MCC fillers. Cost analysis of the composite panels was also done, showing PPJ panels to be slightly cheaper as compared to PPG. The outcomes of the study are quite promising, showing the potential of MCC-reinforced FRPC plates as structural elements in construction applications.

Data Availability

Data will be made available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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