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Fabrication and Mechanical Characterization of Hybrid Natural Fiber Reinforced Composites using Ferromagnetic and Graphite Fillers

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Abstract

The past few years have seen a lot of interest in the creation of hybrid natural fiber composites because of their lightweight properties, environmental friendliness and their potential use in structures. The hybrid composite laminates in the current study were produced by the hand lay-up process by blending the natural fibers with the functional filler materials. Three types of composite structures were created and these are Natural Composite Material (NCM), Ferromagnetic Composite Material (FCM), and Graphite Composite Material (GCM). Jute, cotton, silk and glass fibers were reinforced to the composites and epoxy resin was employed as the matrix material. The functional fillers were ferromagnetic powder and graphite powder which were added to increase the mechanical performance of the composites. SEM was used to study the microstructural features of the fabricated composites to analyze the interaction of fibers with the matrix and the dispersion of the fillers. The mechanical properties were tested using the Brinell hardness tests, Rockwell hardness tests, and Izod impact tests. The findings showed that the Ferromagnetic Composite Material (FCM) had better mechanical performance with higher hardness and impact strength than the other composites. This was because the Graphite Composite Material (GCM) exhibited moderate mechanical performance and the Natural Composite Material (NCM) exhibited a relatively low strength as there was no filler reinforcement. Comprehensively, the paper has shown that mechanical performance of hybrid natural fiber composites is greatly enhanced with the inclusion of functional filler particles rendering them useful in engineering and structural applications that need lightweight.

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Keywords: Hybrid natural fiber composites, Ferromagnetic filler, Graphite reinforcement, Mechanical properties, Scanning Electron Microscopy, Hand lay-up technique.

INTRODUCTION

In the vision of a Natural Composite of JCGGFS Materials, the concept is to incorporate Jute and Cotton and Glass Fibre and Graphite Powder and Ferro magnetic Powder and Silk (JCGGFS) within a polymerous structure to attain a multi-component reinforcement approach with JCGGFS blended in a homogenous structure to provide a high level of mechanical performance, thermal control, and possible functional (electrical/magnetic) behaviour. It is reported in the literature on hybrid natural-fibre systems that the combination of various reinforcements could enhance tensile flexibility and impact property and allow the enhancement of energy absorption, stiffness, and processability on condition that interfacial bonding and moisture sensitivity are controlled adequately by the use of surface treatment and optimizing the selection of the matrix [1,5,6,7,9,13,15,23].Though the specifics of a JCGGFS-companion are not reported directly yet in the described sources, the overlap of evidence created by similar natural-hybrid systems, as well as by fillers that are known to impact thermal and electrical characteristics, e.g. graphite and graphene-like fillers, offer a plausible roadmap on how to realize a multi-functionality within a friendly-to-the-environment format [2,4,8,10,12,19,20,24,27].The development of JCGGFS composites must be done with a lot of consideration of compatibility between matrices, fiber architecture, and processing pathways. Epoxy or polyester matrices are typically used together with natural reinforcement and may be bonded to either type of reinforcement through surface treatment or a coupling agent in order to ensure the highest possible transfer of loads and the least amount of degradation of the composite through moisture [3,11,12,14,21,25]. The stiffness, strength, and damage tolerance will depend on the spatial control of the various fibers-layered laminates, selective location of high-stiffness components, and orientational control, and one direction to desired thermal/functional performance is the introduction of conductive or magnetic fillers (graphite powder, ferro-magnetic powder). Processing techniques (hand lay-up, vacuum infusion, resin transfer molding) have to be selected in order to reduce the number of pores and to achieve even distribution of fillers, and interfacial engineering is an essential component towards achieving the desired level of properties improvement.An effective research roadmap that JCGGFS may use would involve: (i) determining the baseline mechanical performance of a well-selected matrix and a specified group of fiber loadings, (ii) systematic interfacial engineering and surface modification approaches towards each constituent, (iii) dispersion optimization and processing parameter, (iv) simultaneous measurement of thermal conductivity, possible electrical/magnetic responsiveness, and environmental impact measures, and (v) life-cycle considerations to make sure that it has sustainability benefits over present composites. Seeing that there is no direct data on JCGGFS, such a program would be based on a proven multi-component natural-fibre literature and on the fact that multifunctional performance in functional fillers is achievable and natural-reinforced matrices are becoming increasingly more popular and able to be combined with natural fillers [16,17,18,22,26]. The current research is concerned with the creation and the definition of hybrid natural fiber reinforced composite with the use of functional filler materials. In this study, three various composite structuresNatural Composite Material (NCM), Ferromagnetic Composite Material (FCM), and Graphite Composite Material (GCM) were developed by use of the hand lay-up method. The newness of this study is the combination of natural fiber like jute, cotton, and silk with the glass fiber reinforcement and functional fillers like ferromagnetic and graphite particles to improve mechanical and structural integrity of the composite laminates. It is believed that the addition of these fillers will affect the interfacial bonding, compactness of the structure, and energy absorption properties of the hybrid composites.The area of the current research is the study of the microstructural and mechanical behavior of the composites developed. Microstructural features were analyzed in terms of the Scanning Electron Microscopy (SEM) as a means of studying the fiber-matrix interaction and filler dispersion of the composite structure. Brinell hardness, Rockwell hardness and Izod impact tests were used to characterize the mechanical properties of the composites to determine their resistance to indentation and abrupt loading conditions. The findings of the given research give valuable information regarding the effect of filler particles on the hybrid natural fibre composites performance and point at their possible usage in lightweight structural elements, automobile interior components, protective panels, and materials engineering elements that have to face enhanced mechanical strength and life.

MATERIALS AND METHODS

A combination of natural and synthetic reinforcement materials was used to prepare the hybrid composite materials. The most common reinforcement material employed in this experiment was the jute fiber, cotton fiber, glass fiber and silk fiber whereas the functional fillers were the graphite powder and ferromagnetic powder. The matrix material was an epoxy resin system comprised of an epoxy hardener to bond the layers of reinforcement to create a composite laminate. Jute fiber has been chosen because of its good tensile strength, low density and biodegradable properties. The core material was cotton fiber due to its flexibility and the ability to be compatible with polymer matrices. Glass fiber was used to make the composite structure stronger and stiffer. The laminate structure was then enhanced

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with silk fiber that helps in enhancing interfacial bonding and flexibility. As a filler material, graphite powder was added to increase electrical conductivity and thermal resistance, and ferromagnetic powder was added to increase magnetic and thermal properties. The epoxy resin adopted as the matrix material is an epoxy material that is highly adhesive and has a strong resistance to chemicals as well as good mechanical properties. The hand lay-up technique was used to manufacture the composite laminates. The arrangement of reinforcement materials in this process was done in series within a wooden mould and saturated with epoxy resin. To start with, epoxy resin and hardener were combined in the ratio of 3:1 to achieve a balanced resin mixture. Polyvinyl alcohol (PVA) solution was applied to the surface of the mould to avoid sticking of the composite laminate to the mould in the course of curing. Once the mould had been coated, the reinforcement materials were arranged in layers with each layer laid on epoxy resin so that they would bond properly. The order in which reinforcement layers were stacked was in the following order: glass fiber, jute fiber, silk fiber and cotton fiber which were arranged in a stacked form. At the center of the laminate structure, there was the cotton layer. Graphite powder or ferromagnetic powder was added to the cotton core layer depending on the type of composite. Table 1 shows the compositions of the fabricated composites. This study had three composite laminates that were manufactured:

- Natural Composite Material (NCM),
- Ferromagnetic Composite Material (FCM) and
- Graphite Composite Material (GCM)

Figure 1. Fabrication procedure of JCGGFS hybrid composite step by step using the hand lay-up method. 1(a) Starting with the raw reinforcement materials, 1(b) mixing of epoxy resin and epoxy hardener, 1(c) preparation of the mould with PVA release agent,(d) inserting a layer of glass fiber reinforcement, (e) wrapping up the mould with wooden plate, (f) primary compressing of laminate, (g) adding ferromagnetic powder, (h) PVA applied on mould cover plate, (i) stacking reinforcement layer inside mould, (j) adding graphite powder, (k) adding graphite filler by dispersion, (l) compression in curing, (m) pressure curing of the laminate, and (n) completed artificial plate of composite.

Table 1. Composition of JCGGFS composite laminates

Material	NCM (wt%)	FCM (wt%)	GCM (wt%)
Jute fiber	14	14	14
Glass fiber	25.8	13.5	13.5
Cotton fiber	16	18.3	18.3
Silk fiber	14.2	14.2	14.2
Ferromagnetic powder	–	10	–
Graphite powder	–	–	10
Epoxy + Hardener	30	30	30

COMPOSITE FABRICATION

The hybrid JCGGFS composite laminates were produced in the hand lay-up method which is commonly employed to prepare the fiber-reinforced polymer composite as it is an easy and economical method. The general process through which the fabrication is done is shown in Figure 1(a-n). The natural reinforcement materials, such as jute fiber, cotton fiber, graphite powder, silk fabric, graphite powder and ferromagnetic powder, had to be gathered initially and made ready to fabricate laminate as depicted in Figure1 (a). These are materials that can be used both as natural and synthetic reinforcements and functional fillers in the composite structure that is a hybrid.This was followed by the addition of resin and hardener in proportions of 3: 1 to form the polymer matrix on which the reinforcement layers will be bonded Figure1(b). Preparation of the mould surface was then done by brushing the surface using polyvinyl alcohol (PVA) solution to serve as a release agent and ensure that the mould did not stick to the composite laminate whilst it was curing Figure1 (c). When the mould was ready the initial reinforcement layer in the form of the glass fiber mat was put inside the mould Figure1(d), and the next reinforcement material was put in, and on until the hybrid laminate structure was achieved. After placing the reinforcement layers in position, a wooden plate was used to cover the mould in order to keep the laminate setup Figure1 (e). Concrete blocks were then used to compress it to make sure that the layers of reinforcements bonded together as well as to squeeze off the excess resin of the laminate Figure1 (f). In order to manufacture the ferromagnetic composite laminate, ferromagnetic powder was placed in the cotton core layer to improve the magnetic and thermal properties of the composite Figure1(g). To prevent sticking of the mould cover plate, PVA solution was applied on the cover plate Figure1(h). Then the reinforcement layers were positioned within the mould in a hybrid form of glass fiber, jute fiber, silk fiber, and cotton layers Figure1(i). The graphite laminate was made into a composite of graphite powder and cotton to enhance electrical conduction and thermal retardation in the instance of the graphite composite laminate Figure1(j). The graphite filler was homogeneously dispersed in the reinforcement layer to make the dispersion even Figure1 (k). Once the laminate stacking was done, extra compression with the help of concrete blocks was done to compact the laminate structure Figure1(l). The composite was then left to dry under pressure to ascertain that epoxy matrix is properly polymerized and the bond is properly formed between the epoxy matrix and the reinforcement fibers Figure1(m). The laminate was then finally taken out of the mould thus producing the fabricated JCGGFS hybrid composite plate, as depicted in Figure1 (n).

MICROSTRUCTURAL ANALYSIS

The fabricated composite materials have been analyzed using the Scanning Electron Microscopy (SEM) to determine the microstructure and fiber-matrix interaction. The SEM was conducted to examine bonding behavior of the reinforcement fibers and epoxy matrix and also the filler materials distribution in the composite body.

Brinell Hardness Test

The Brinnel hardness test was conducted to establish the hardness of the fabricated composite laminates according to ASTM E10 - Standard Test Method on Brinnel Hardness of Metallic Materials. A test was conducted with Brinell hardness testing machine with 5 mm, 10 mm diameter spherical indenters. During the testing, loads of 1000 kg and 2000 kg were added to the composite specimens. To assess the hardness properties of the composite materials the indentation diameter created on the paper surface of the specimen was measured.

Rockwell Hardness Test

Rockwell hardness test was performed to measure the hardness of the composite materials to resistant indentation and deformation as stated in ASTM E18 -Standard Test Methods of Rockwell Hardness of Metallic Materials. A Rockwell hardness testing machine was used to carry out the test in which the test was done using a 0.25 inch ball indenter and a 60 kg load. The values of hardness found with the help of this test identify the structural stiffness and resistance of the composite laminate to permanent deformation.

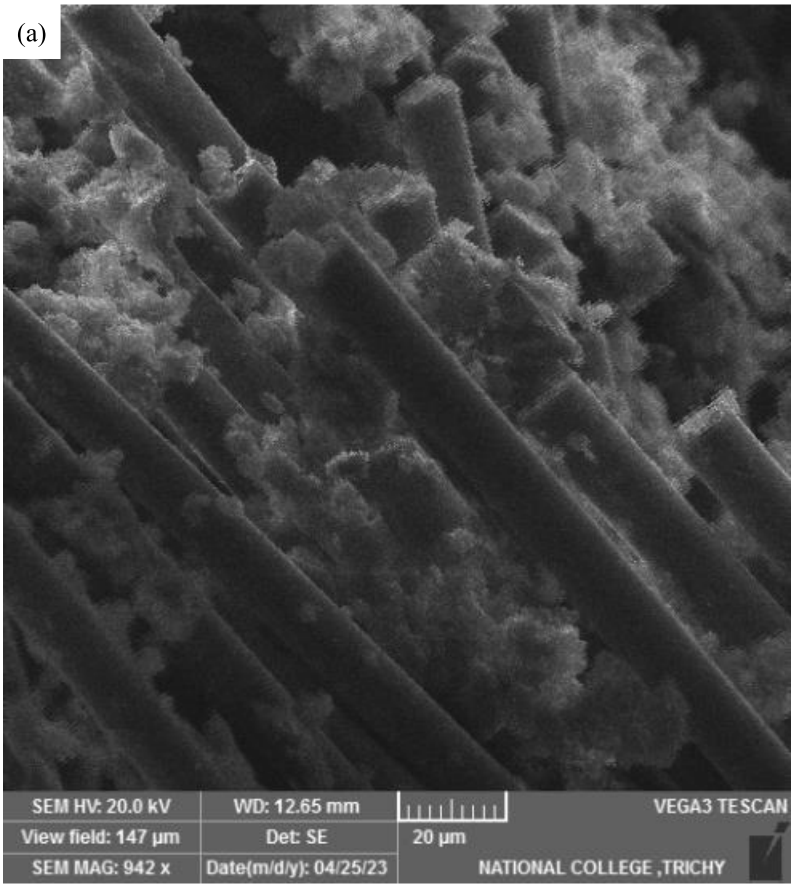
Impact Test

The Izod impact resistance of the composite laminates manufactured was tested by using the Izod impact test based on the ASTM D256 - Standard Test Methods of determining the Izod Pendulum Impact Resistance of Plastics. The experiment in this test used a notched specimen, which was hit by a hammer of a pendulum, and the quantity of energy captured in the fracture was measured. The absorbed energy can give the indicator of toughness and impact resistance of the composite materials.

RESULT AND DISCUSSION

Microstructural Analysis

To determine the interaction between fibers and the matrix and the structural properties of the composite laminate, the surface morphology of the fabricated Natural Composite Material (NCM) was studied on SEM. The SEM micrographs obtained at different magnifications are shown in Figure 2(a–b).



(b)

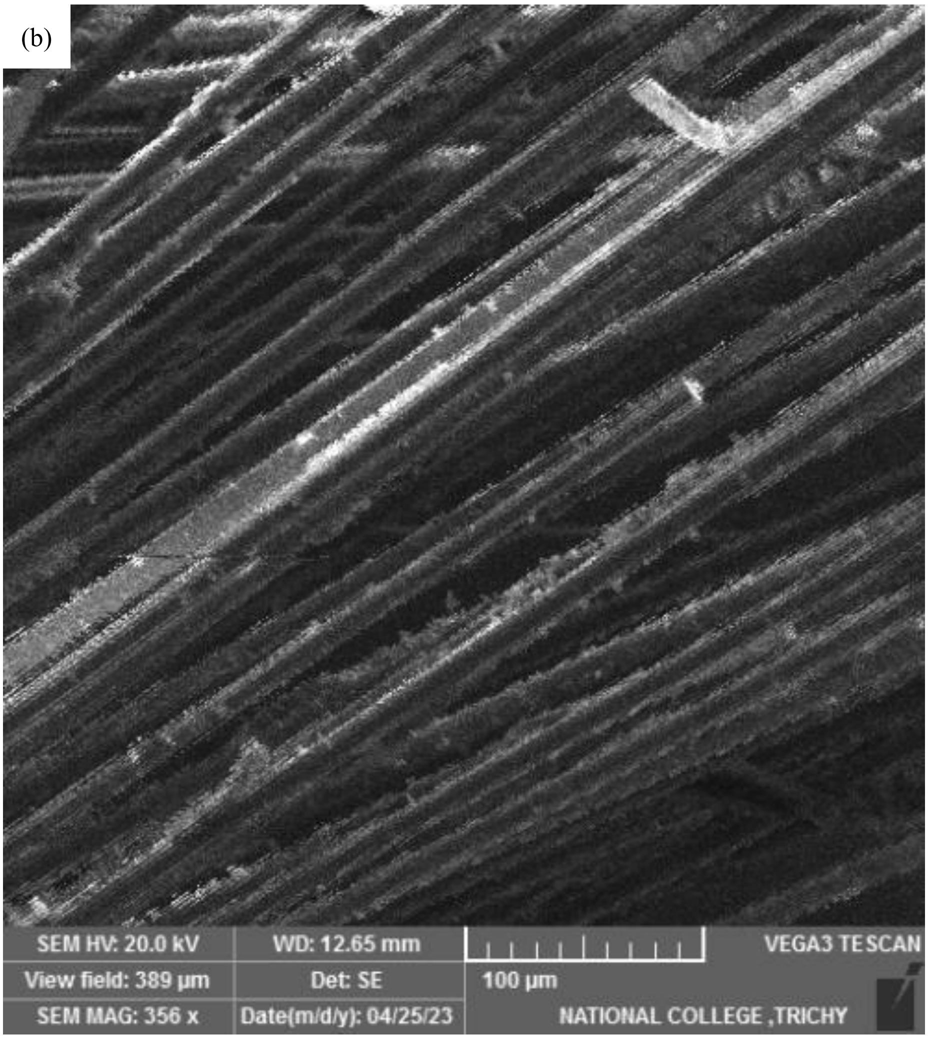


Figure 2. SEM micrographs of Natural Composite Material (NCM): (a) high-magnification image showing fiber–matrix interfacial bonding and matrix distribution, and (b) low-magnification image showing fiber alignment and overall composite morphology

Figure 2(a) represents the SEM image of the microstructure of the composite with higher magnification. The picture unveils the existence of the cylindrical reinforcement fibers in the epoxy framework. The fibers are also seen to be properly enclosed in the matrix material, which means that the resin has impregnated it well when the hand lay-up fabrication process was done. The interfacial bond between the fibre and the matrix displays a fairly good adhesion that is necessary in the transfer of stress in the composite material. The fact that the fibers are encircled by clusters of mattresses indicates that the epoxy resin has infiltrated the reinforcement layers during the fabrication process. The micrograph in Figure2(b) of the SEM depicts the composite structure at a relatively lower level of magnification, where the orientation and layout of the fibers in the composite laminate is seen in totality. These fibers seem to be positioned in a relatively consistent direction that creates a continuous reinforcement structure of the matrix. This alignment is useful in enhancing mechanical performance through the increase of load transfer capability between the fibers and the surrounding matrix. Several micro structural flaws like the small voids and matrix agglomerations can however be seen in some parts of the composite. Such flaws are widely known in relation to the hand lay-up fabrication method and can affect the mechanical characteristics of the material to some slight degree. Nevertheless, in spite of these small flaws, the general arrangement of the microstructure suggests high-quality fiber distribution and acceptable fiber-matrix bonding which are significant aspects of the mechanical stability of the hybrid composite.

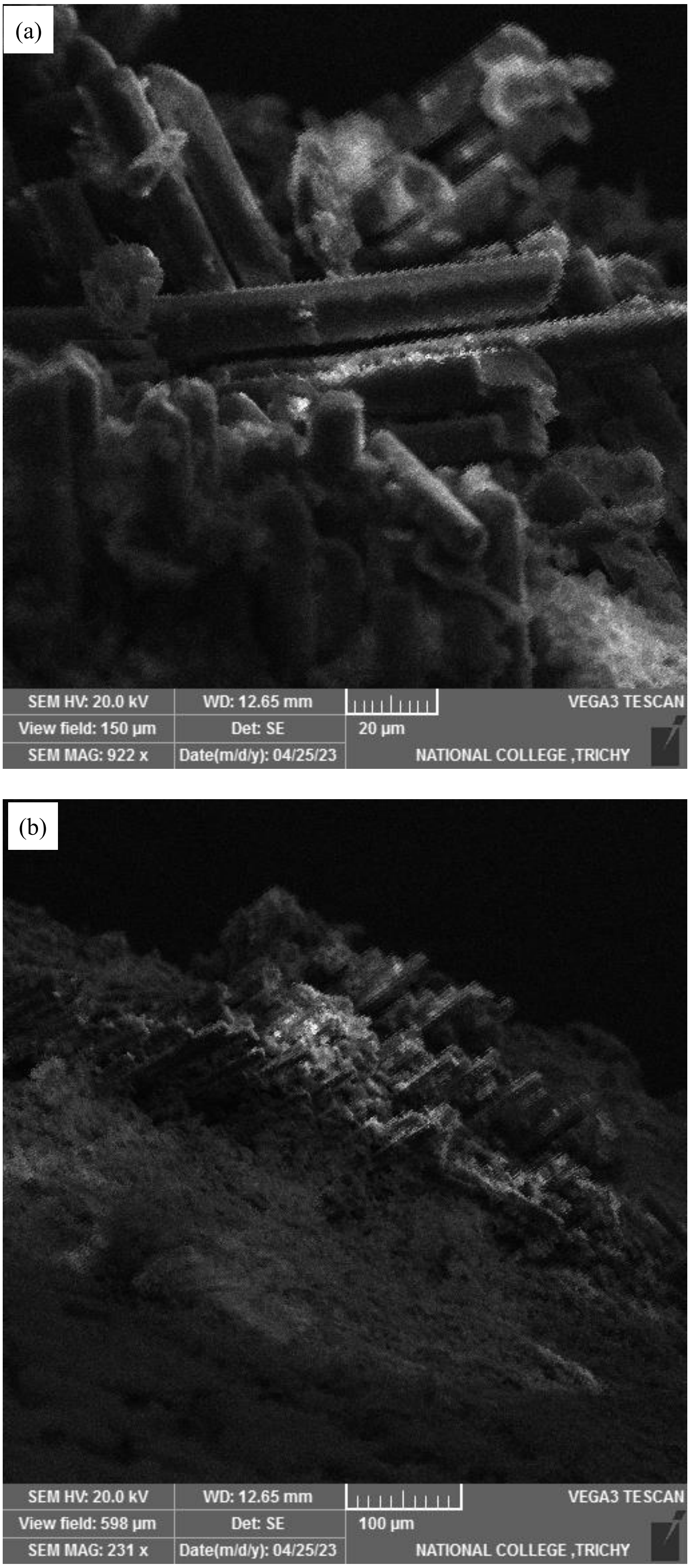


Figure 3. (a-b) shows the SEM micrographs of varying magnifications for NCM

The microstructure of the composite at a higher magnification is depicted in the SEM image in Figure3(a). It is found that there are reinforcement fibers entrenched into the epoxy matrix besides scattered particles of ferromagnet. The cylindrical fiber structures are well exposed and seem to be surrounded by the matrix material which is an indication that resin impregnation is effective in the fabrication process. The particles of the ferromagnetic material may be seen as irregularly shaped clusters which are attached to the surfaces of the fibers and are dispersed among the matrix phase. These particles lead to better interfacial bonding and they also increase the ability of the reinforcement fibers to transfer loads with the matrix. Figure3(b) is a SEM micrograph which is an enlarged version of the composite micrograph in Figure3(a), revealing the overall pattern and distribution of ferromagnetic filler in the composite laminate. The pictures mean that the ferromagnetic particles are rather well distributed throughout the matrix area. The reaction between the filler particles and the matrix seems to create a tight structure that can help in the improvement of other mechanical characteristics of hardness and impact resistance. Also, the process of ferromagnetic filler in the matrix provides a more exaggerated microstructure than that of the natural composite material, which enhances the stiffness and structural stability of the laminate. In spite of the fact that some agglomeration of filler particles may be observed in some areas, the distribution is comparatively even.

Figure 4. (a) and (b) show the micrographs of GCM is at various magnifications, obtained through the SEM using a low power microscope. SEM image in Figure4(a) represents the microstructure of the composite under a low magnification that indicates that the composite contains reinforcement fibers in the epoxy matrix with graphite filler particles. The fibers seem to be in a layered form and comprise a continuous reinforcement network in the composite laminate. The graphite particles may be seen as irregular clusters that are located on the surfaces of the fibers and in the matrix phase. The incorporation of graphite filler helps to provide the creation of a relatively compact microstructure and improves the functional properties of the composite. The increased magnification of SEM image in Figure4(b) gives a clear picture of the interface of the graphite particles and the matrix. The graphite filler can have the form of a flakelike structure which is part of the epoxy matrix, which means that the filler is effectively incorporated in the composite during the fabrication of the composite. The particles of the graphite as well as the reinforcement fibres are enclosed by the matrix material and it is presumed that the reinforcement layers are well wet by the process of hand lay-up. Slightly agglomerating particles of graphite and small micro-voids however, can be seen in some areas of the composite structure. These microstructures are normally related to the particle-reinforced composites that are manufactured through the hand lay-up method. These small flaws notwithstanding, the graphite particles seem to be fairly dispersed in the matrix, which adds to better structural compactness and increased functional characteristics of thermal conductivity and electrical conduct.

Brinell Hardness

Brinell hardness test was done to assess the resistance of the fabricated hybrid composites to surface indentation. The test was conducted under ASTM E10; with the assistance of a spherical indenter with a definite load. The values of hardness that were obtained in the three composite combinations NCM, FCM, and GCM are shown in Figure5.The comparison of the hardness value presented in graph shows that the hardness value of NCM composite is the highest with a hardness value of about 8 and the hardness value of both FCM and GCM composites is a value of about 7. This comparatively increased hardness of the NCM composite could be explained by the fact that the interfacial bonding between the natural reinforcement fibers and the epoxy matrix is high enough to increase the ability of the material to localized plastic deformation.FCM composite has slightly less hardness than NCM, which can be explained by the presence of ferromagnetic particles in the matrix. Even though these particles do add to the structural compactness, agglomeration of filler particles, though to a small degree, can lead to reduced uniformity of the matrix and affect the indentation resistance.On the same note, the GCM composite displays similar hardness values as FCM which is attributed to the presence of filler particles of graphite in the composite structure. Particles of graphite are more likely to have lubricating properties that can decrease the resistance of the material to indentation even though it enhances other functional properties like thermal conductivity.

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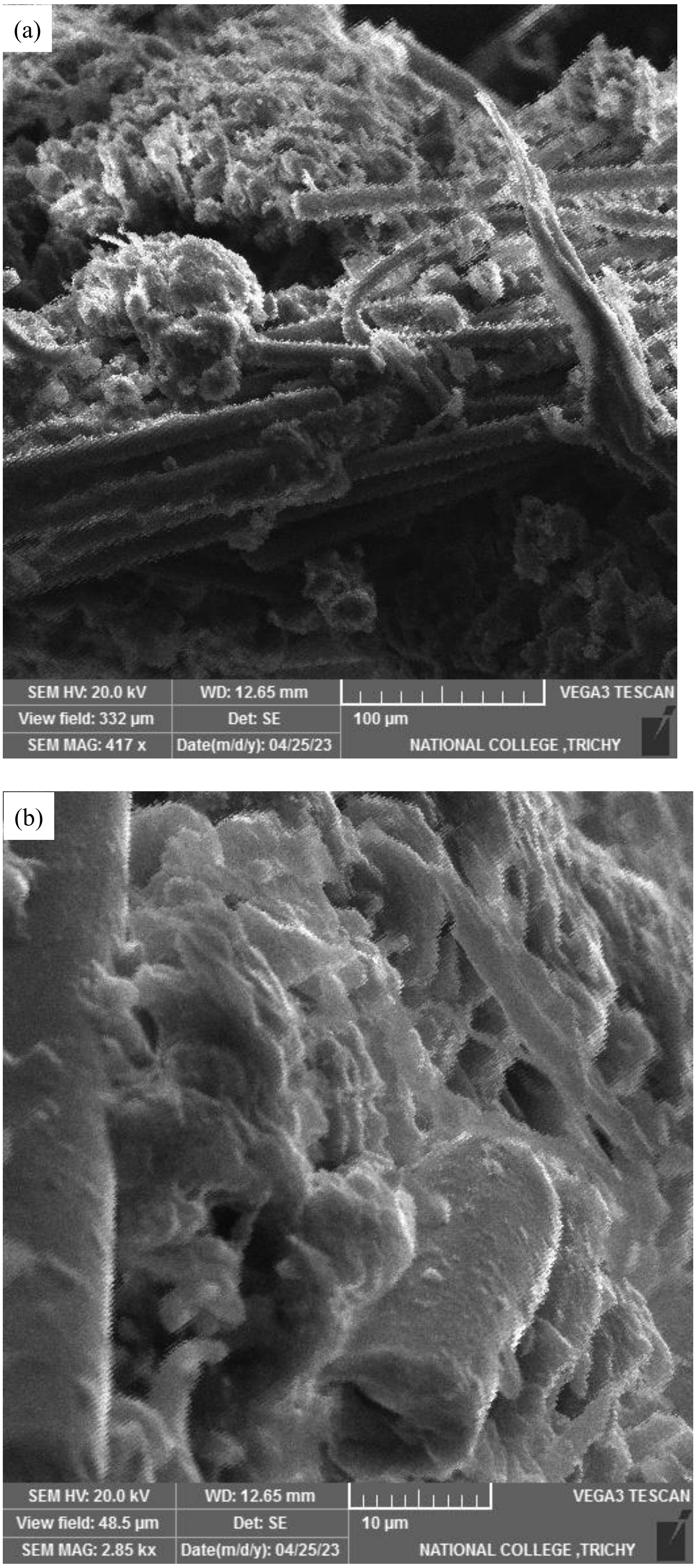

Figure 4. SEM microstructure of Graphite Composite Material (GCM): (a) low-magnification image showing fiber distribution and graphite filler dispersion, and (b) high-magnification image showing graphite particle–matrix interaction.

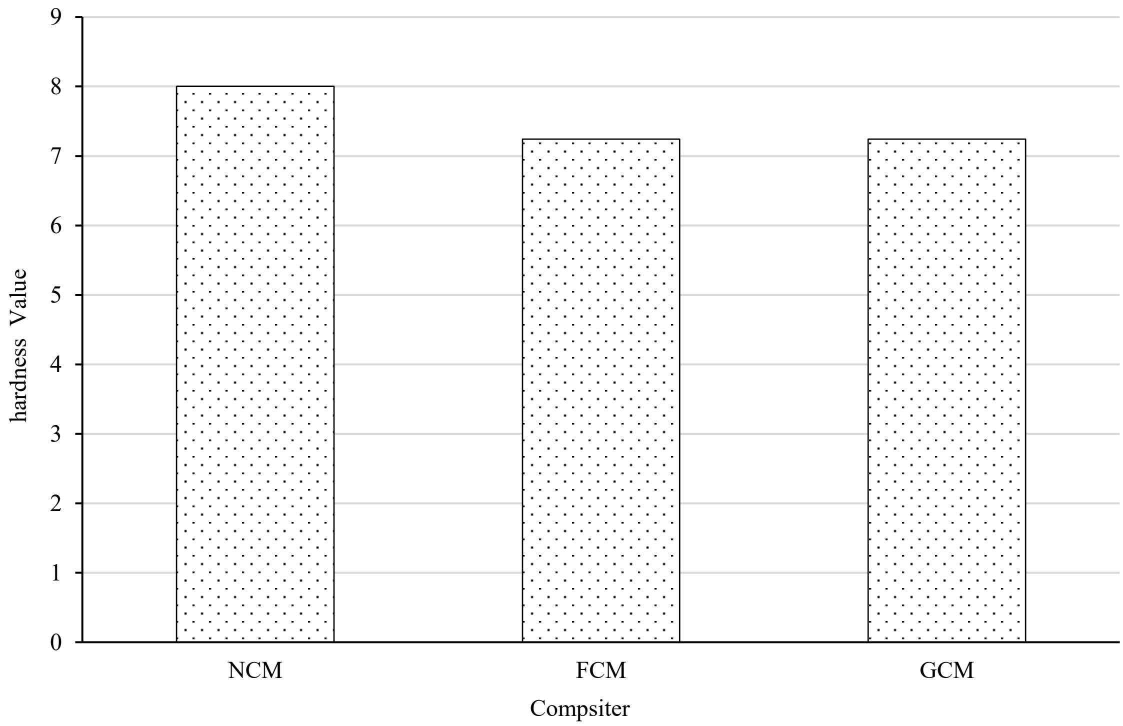

Figure 5. Brinell hardness comparison of fabricated composites (NCM, FCM, and GCM)

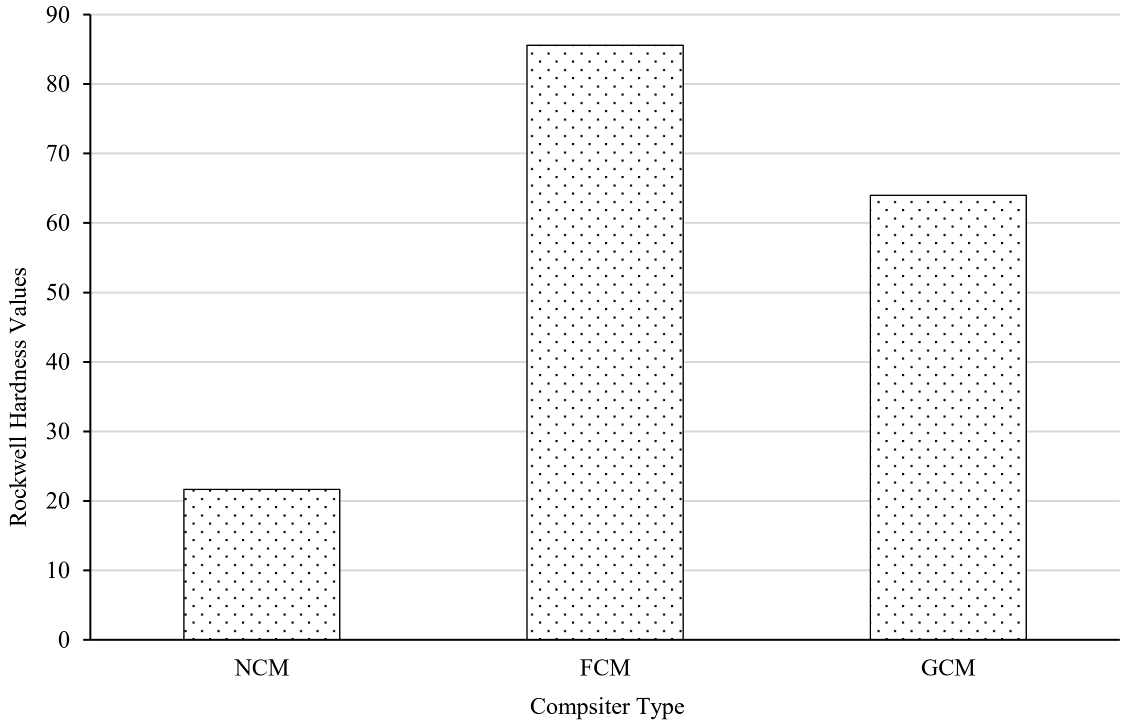

Figure 6. Rockwell Hardness Values comparison of fabricated composites (NCM, FCM, and GCM)

Results of Rockwell hardness of the fabricated hybrid composites are represented in Figure6 that demonstrates the relative hardness behavior of NCM, FCM and GCM. The findings are a clear indication that there is a great difference in hardness of the three composite arrangements. As can be seen in Figure6, FCM has the highest hardness of around 87 which is why it has better resistance to permanent deformation than the other composites. This is through the addition of the filler particles that

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are ferromagnetic in the composite matrix which has improved its hardness. The heterogeneity of these particles makes the composite laminate more compact structurally and has the effect of increasing the load-bearing potential of the matrix-fiber interface. Moreover, the contact between the particles of the ferromagnetic part and the epoxy matrix also helps in enhancing the stress transfer in the composite structure. GCM exhibits a medium hardness range of about 65 and this is less than FCM composite but much higher compared to the natural composite. Graphite filler enhances the structural stability of the composite; though the lubricating effect of the graphite particles can cause slight decrease in material to indentation and deformation resistance. However, when present, graphite also adds value to better functional qualities of thermal and electrical conductivity. The NCM, on the contrary, has the least value of hardness around 22. This comparative lower hardness can be explained by the fact that there is no further filler reinforcement in the structure of composites. The behavior of hardness of the NCM composite primarily relies on the bondage between the fibers and the matrix and also the in-trinsic mechanical compassion of natural fibers that have been employed in the laminate.

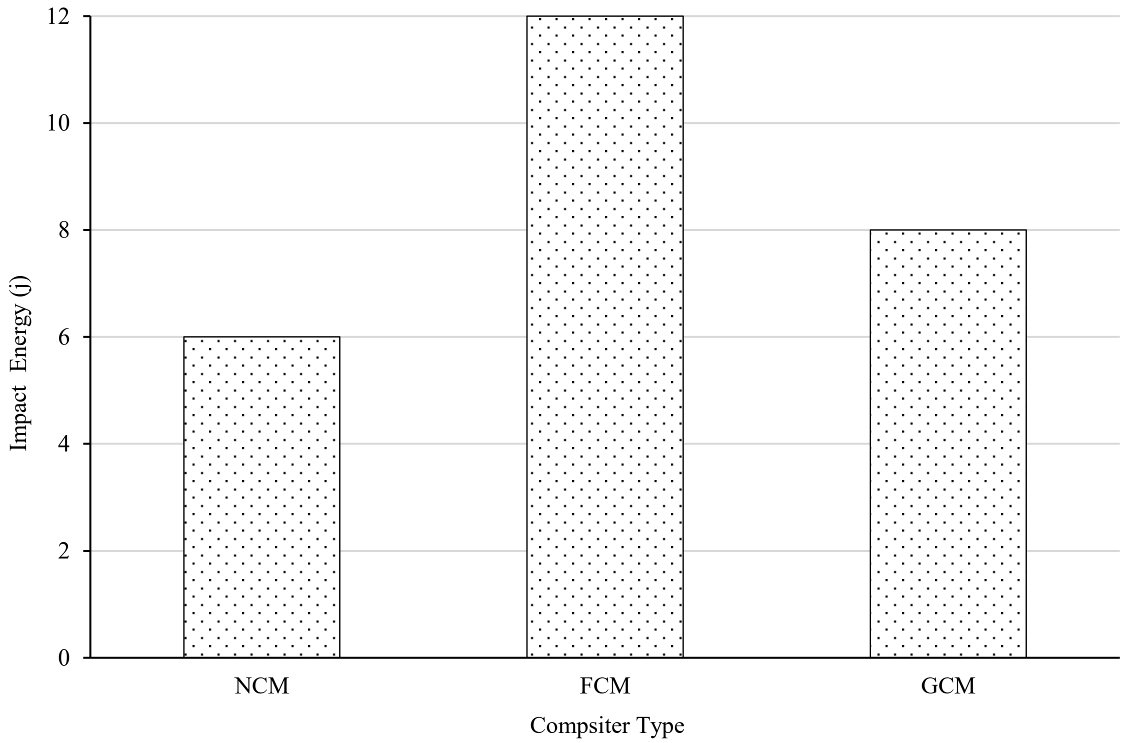

Figure 7. Impact strength comparison of fabricated composites (NCM, FCM, and GCM)

As presented in Figure7, the FCM is the material with the largest impact energy of 12 J, which means that the material is tougher and resists sudden fracture than the other composites. It can be explained by the fact that ferromagnetic filler particles are incorporated into the composite matrix in order to increase impact performance. These particles enhance the structural compactness of the laminate and the ability of the material to absorb energy since it allows the material to absorb better stress distribution between reinforcement fibres and epoxy matrix. The enhanced particle-matrix interaction is also useful in retarding the crack initiation and propagation of the impact load. GCM exhibits medium strength of impact with an energy absorption of 8 J. Graphite particles in the composite help in enhancing the flexibility and strength of the laminate. But the effect resistance is lower than the FCM composite because of the variations in filler properties and in combination with the matrix phase. Conversely, the NCM has the least impact energy of 6 J. Such relatively low toughness may be explained by the lack of extra filler reinforcement in the composite make-up. The mechanical properties of the natural fibers and the quality of the fiber matrix interfacial bonding are the major factors that influence the effect of performance in the NCM composite.

CONCLUSION

This research was able to produce hand lay-up hybrid natural fiber reinforced composite laminates by combining natural fibers with functional filler materials. Three composite set ups, NCM, FCM and GCM were fabricated and their microstructural and mechanical characteristics were studied in a systematic manner. Jute, cotton, silk, and glass fibers were taken as the reinforcement system and epoxy resin was the matrix material. The functional fillers that were added to the composite laminates to improve structural performance of the composite laminates are ferromagnetic and graphite powders. The microstructural examination conducted with the help of SEM has demonstrated that there are strong bonding values at the interfaces of fibers and the matrix, and the filler particles are distributed in the composite structure rather evenly. The SEM observations proved that the addition of filler particles had helped to enhance structural compactness and interaction of the reinforcement fibers with the matrix. Brinell hardness, Rockwell hardness and Izod impact were also used to provide mechanical characterization tests in order to determine how the composites resist indentation and sudden loading situations. The findings showed that the FCM was better in mechanical performance in the fabricated composites. The laminate contained ferromagnetic particles to a great extent and this greatly increased the hardness and impact resistance of the laminate due to load transfer capacity and structural density. The GCM exhibited a moderate mechanical behavior whereas the NCM was relatively less hard and impact strength as it had no filler reinforcement. The findings prove that, functional filler particles may be effectively incorporated in the hybrid natural fiber composites to improve the mechanical performance. The composites demonstrate a good potential on lightweight structural elements, automotive interior elements, protective panels, and engineering which demand enhanced strength, energy absorption and durability.

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Conflict of Competing Interest

The authors declare that there was no competing interest in conducting this study.

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