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Research Article

Investigation of Mechanical, Tribological, and Electrical Properties of Silk Reinforced Polymeric Composite

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The continuous demand of today's scenario and ecological consciousness has made the researchers think about the utilization of alternate sources of materials without compromising the mechanical behavior and characteristics while focusing on the fulfillment of the desired requirements in the wide range of industrial applications. The present work is a noble attempt and a step towards the development of silk fibre composites (SFCs) reinforced with the vinyl ester matrix material. The processing and fabrication of SFRCs have been carried out using the traditional hand layup technique using untreated silk fibres (SFs) and silk cloths (SCs) in the form of single, double, and triple layers of SFs and SCs laminates oriented in uniaxial and biaxial directions. For the prepared composite samples, the density and void contents in the sample, mechanical characteristics in terms of their tensile and flexural strength, and tribological characteristics as well as the electrical impedance have been investigated. The percentage void content was found to be within the acceptance limit. The tensile and flexural test results show a considerable increment which indicates proper stress transfer from matrix phase to fibre with triple-layer cloths showing the highest tensile and flexural properties. In the tribological test, the coefficient of friction is higher in the case of cloth loading as fibre concentration increases significantly. In the impedance test, almost for all samples, the trend of change in conductivity with applied frequency is the same. From the economic perspective, the proposed composite is suitable for a wide range of applications in industries as well as this can be utilized as an alternate source of *traditionally used floor tiles currently using ceramic materials*. Also, the proposed composite has a biodegradable characteristic that is completely in accordance with the demand and consciousness involved in environmental and ecological perspectives.

1. Introduction

Over the last few years, the world has shifted its focus drastically towards alternative sources of new, advanced, and attractive materials apart from traditionally used materials. These advanced and attractive materials are nothing but natural fiber-based reinforced composite (NFRC) materials that possess immensely decent characteristics in terms of high efficacy, an unmatched strength-to-weight ratio, high fracture toughness, and higher corrosive resistance properties. Apart from the quest for alternative energy sources, the world has awakened its consciousness and continuously demanded to protect the environment from the rigorous utilization of hazardous materials. In this context, the record growth and developments in natural fibres and their capabilities of tremendous modifications have attracted immense attention and gained enormous popularity [1]. Nowadays, the NFRCs have been proven to be alternative material sources for synthetic fibres and are utilized as reinforcements of various resins that possess a wide application arena and carry appreciable properties such as high specific strength, lower density, and renewable and sustainable characteristics with eco-friendly nature [2, 3]. The unique characteristic of absorbing the carbon dioxide (CO_2) content helps in solving environmental issues. Also, their hydrophilic characteristics such as moisture absorbent, low matrix fibre interfacial adhesion, lower fibre dispersion, and inflammable characteristics, put some limitations in their utilization as polymer reinforcements but also pave the way towards industrial applications and characteristics enhancements [1]. According to the literature survey, many studies have been carried out on surface modifications or surface treatments in order to enhance the NFRCs characteristics as well as overcome such limitations [4, 5].

Over the centuries, natural fibres are being utilized in making various domestic items such as rope, clothing, baskets, etc., but in recent years, under the emergence of new trends, the natural fibres (i.e., jute, hemp, flax, and sisal etc.) have been utilized in developing the various automobile components in auto industries [6]. Worldwide, multinational companies (MNCs) are labeling the NFRCs as the standard materials for large-scale applications in aerospace, aircraft manufacturing (like Boeing and Airbus manufacturing), etc. Presently the new aircraft and airbus coming onto the market are fully focused on the utilization of composite materials during their manufacturing processes [7]. During the composite preparation, various types of matrix and reinforcement materials are adjusted to obtain the desired material characteristics in terms of their strength and stiffness in a particular direction [8]. These self-obtaining characteristics of NFRCs made them suitable to compensate with the material strength without getting compromised in their recyclability. Their lower cost, biodegradability, high specific properties, high stiffness and damage tolerance capabilities, fatigue resistance property, weight reduction, and pollution reduction capabilities made NFRCs one of the most suitable materials for utilization in high-end applications [9]. Such biodegradable NFRCs possess two main concerns related to the environment and engineering perspective [10]. Furthermore, natural fibres have several advantages, including a favorable "fibre aspect ratio, low density, and high tensile and flexural moduli" [11]. Hence, natural fibres are hair like continuous filament materials or the elongated pieces like thread that can be spun into thread or rope, filaments. These can be utilized as an essential component of natural fibres that can be matted into sheets for producing essential goods like paper or felt [6]. The natural fibres can be utilized in papers, textiles, and fabrics (uses as biofuels) as well as a reinforcement material for composites. As a reinforcement material, NFRCs have proven to be an alternative source of glass fibres and have extended their utilization in various industrial applications [12, 13].

Natural fibres can be classified according to the sources (like lignocellulosic materials, animals, and minerals) from which they are obtained. Lignocellulosic fibres are also known as cellulose-based materials that can be further subdivided into wood, nonwood, or plant fibres. Plant fibers consist of "cellulose, hemicellulose, lignin, and pectin compounds" [14]. The various characteristics of such fibres can be approximated by the relative contents present in the constituents. Furthermore, the lignocellulosic fibres are subdivided into "seed, leaf, bas or stem, fruit, and stalk fibres." The majority of industrial fibres obtained from "bast (e.g., hemp, flax, kenaf, and jute)." Similarly, the fibres obtained from leaves (i.e., sisal) are the commonly used fibres that suffer from low stiffness [12] and have wide utilization as a raw material.

2. Background and Work Undertaken

In the present work, an experimental investigation has been carried out to suggest the silk-based reinforced fibre composites (SRFCs) as an alternative source of composite materials against the utilization of ceramic-based products. The ceramics-based products have been manufactured for many decades via different conventional manufacturing process and techniques such as "casting, extrusion, over-sintering" etc. However, all above said manufacturing techniques possess their own advantages and disadvantages [15]. The ceramic materials are inorganic and nonmetallic material that possess a mixed form of chemical bonding such as "ionic, covalent, and less commonly metallic" [16, 17]. The ceramic materials possess a high "range of crystallinities," i.e., their existence ranges from "fully amorphous structure (glasses) to a well-oriented" structure (like ZrC_2). Most of the ceramic materials exist in the form of oxides like alumina (Al_2O_3). Some of the groups existed in the form of "nitrides (e.g., boron nitride (BN)), silicide (e.g., tungsten disilicide (WSi_2)), carbides (e.g., silicon carbide (SiC)), and borides (e.g., titanium diboride (TiB_2))" [15]. The aforementioned examples categorized the ceramics in a general domain of industrial, technical, or engineering ceramics which provides a sophisticated utilization due to their unmatched characteristics such as "resistance to wear, corrosion, and temperature." The favorable utilization of such engineering ceramics is due to their capability of possessing "high/low temperature resistance, high wear, and corrosion resistance," and also it possess comparatively lower weight [18, 19]. The engineering ceramics also possessed various characteristics that made them unfavorable towards engineering utilization. Their exhibition of low tensile strength, low toughness, and high brittleness made them the cause of the brittle failure. This results in the catastrophic failure other than the gradual failure of such ceramics. Furthermore, the postprocessing stage of engineering ceramics usually involves an additional step of densification due to the presence of high porosity. The densification step helps in reducing the porous nature and improving the mechanical performance of such ceramic materials [20–22]. Hence, to avoid such limitations many engineering ceramics are nowadays being replaced by natural fibre composites.

The present study is based upon the investigations carried out considering the utilization of silk fibre reinforced composites (SFRCs) as the alternative material sources for ceramic materials and ceramic products. Over the last few decades, polymers have drastically replaced the traditional utilization of materials or metals in various high-end applications. The significant advantages possessed by these polymers have attracted notable attention due to their higher productivity, processing convenience, and reduced costs [23]. In the view of diverse application arenas, the changes in polymer properties occur according to the types of filler materials and their utilization in order to obtain the desired strength and higher modulus [24]. Hence, a fibre reinforced polymers (FRP) are the type of composite prepared by using the polymers as a matrix material embedded with high-strength fibres [25, 26].

In the current work, the preparation of composite samples has been proposed using the hand lay-up technique [27]. The experimentation has been performed for both silk fibres and silk cloths used as a reinforcement in the vinyl ester polymer matrix in both the unidirectional and in bidirectional manner. Furthermore, the prepared samples have been analyzed under various mechanical and electrical tests such as tensile, flexural, and tribological tests and impedance test has also been conducted for the same. The analysis of mechanical and electrical properties has been done in order to obtain the required strength and roughness and their behavior has been investigated at room temperature.

3. Materials Used

In the current proposed work, the vinyl-ester polymer resin as a matrix material, and silk fibres (SFs) as well as silk cloths (SCs) have been utilized. The test samples were prepared using the vinyl-ester polymer matrix embedded with SFs and SCs using the hand lay-up technique. A brief discussion of all these materials has been summarized in aforementioned sections. The utilization of natural fibres has gained much popularity in recent years and has attracted the attention of researchers and scientists in order to counter the issues that occurred during the utilization of synthetic fibres. The cost, mechanical qualities, material strength characteristics, ecology and environment considerations, and biodegradability properties are among the primary elements that lead conventional fibre replacement (i.e., glass, aramid, and carbon fibre) to natural fibres [12].

3.1. Vinyl Ester. Vinyl ester (VE) is one of the members of the most common families of thermoset resin systems that have a wide range of industrial applications mainly due to having a low cost, versatility, and easy availability. Such a resin system is easy to handle during the manufacturing process [28]. VERs are formulated from styrene and a condensation product of methacrylic acid with an epoxy. This condensation product acts as a crosslinking agent and helps to improve the adhesion property" [29]. Vinyl ester resins offer superior chemical resistance, less shrinkage, and are less prone to moisture absorption and thermal degradation [30]. "Vinyl esters are organic compounds of group R-COO-R$'$ with a vinyl functional group (R$'$). Therefore, VEs are considered as polyaddition products" [31]. Vinyl-ester resins may have a colored tint, ranging from green to blue to purple. They are also slightly more transparent than polyester resins and possess easy flowing characteristics.

Vinyl ester resins (VERs) exhibit mechanical toughness, better corrosion and temperature resistance, chemical resistance properties that are slightly better than those of unsaturated polyesters (UPs), better mechanical strength, water absorption resistance, good impact resistance properties, good flame retardant properties, and higher biodegradability than the polyester resins [31, 32].

3.2. Silk Fibres. Silk fibres are natural proteins that are usually obtained naturally. It could come from a moth or spider [33]. Keratin and collagen are two naturally occurring protein types that produce animal fibres are further subdivided into hairy and silk fibres [34]. Further, "*Bombyx mori moth silk*" (BMM silk) produces most of the silk fibres for commercial utilizations. Such BMM silks are the most famous silk types that possess the characteristic of higher strength. Various studies on silk fibres have already been carried out that can be found in [35–40]. BMM silk is mainly composed of fibroin and sericin binder and is most commonly extracted from cocoon. Silk fibroin possess a semicrystalline structure and provides high stiffness and unmatched strength characteristics. It is a type of naturally obtained fibroin protein. Sericin binder offers an adhesive property that is helpful in binding and holding the silk fibres in their proper positions. Silk fibres have been widely utilized as a biopolymer reinforcement, particularly, in the domain of tissue and bio-medical engineering [34, 41–46].

Further, another type of silk fibres is obtained from spiders. From a single spider, a total of six types of silk fibres can be obtained [47]. "*Wool and silk fibers differ in many perspectives. Wool fiber is formed by keratin protein and growth from an outer skin layer like from a sheep or goat. Silk fiber is a protein fiber obtained from silk glands of an insect.*" Various intensive studies have been carried out due to their outstanding strength characteristics. The final performance of the silk fibre can be influenced by different harvesting methods. Studies have revealed that the magnetic properties, strength, and thermal properties of natural silk can be influenced by feeding the silkworm mulberry leaves with nanomagnetic powder to obtain the desired performance [48]. Our investigation found the higher strength of silk based reinforced composites (SRCs), with relatively low wear.

4. Methods and Fabrication

There exists a number of traditional manufacturing processes that are capable of developing the composite components such as "Resin Transfer Molding" (RTM), "Vacuum Infusion Technique" "Compression Molding Technique" as well as the "traditional hand lay-up Technique." Over the decades, these different manufacturing methods are very well developed and have been successfully incorporated in developing the composite components along with maintaining the desired level of performance and quality benefits [49]. These different processing methods have been designed in order to meet the demand of a specific product, but it is also worth noting that the selection of these different processing techniques depend upon the various types of materials and types of products as well as the application requirements [50].

In the current proposed work, the composite sample preparation has been done through the hand lay-up technique. This is the simplest and oldest known processing technique [51] for composite fabrication. First of all, the mold is applied with the antiadhesive agent to avoid the adhesion of fibres in the mold. Furthermore, the top and bottom mold surface is covered with a thin layer of plastic sheet to get a smooth surface of composite component [52]. Then the fibres of required size are placed on the bottom plate of mold and the resins mixed with other ingredients are infused onto the layers of fibres and with the help brush and roller, the resins are uniformly spread on the fibre layer. After developing this one layer, the other layers of fibres or woven mats are oriented in a unidirectional or bidirectional manner on the preceding polymer layer, and pressure is applied using the roller in order to remove any voids or air bubbles and excess amount of polymer as well. At last, the mold is then closed and the pressure is released and is left for curing at room temperature. Finally, the mold is opened and the ready composite is removed from the mold [53]. The fabricated set up for the sample preparation utilizing hand lay-up technique has been delineated in Figure 1.

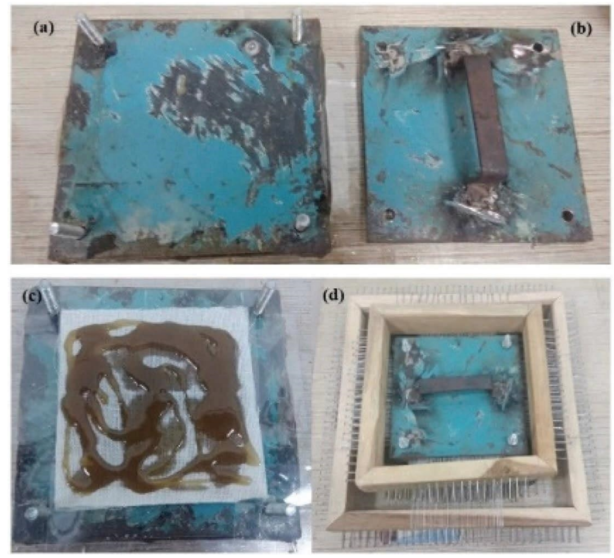


Figure 1: The fabricated set up for the hand lay-up technique used. (a) Lower plate; (b) upper plate; (c) lower plate with matrix material; and (d) arrangement for placement of bi-axial fibres.

5. Orientation of Fibers

For investigating the behavior and characteristics of SFRCs, the sample preparation has been carried out using different orientations and different layers of laminates made up of SFs and SCs reinforced vinyl ester matrix material. Various orientations and layer-wise arrangement of silk fibres have been summarized in the following sections.

5.1. Single-Layer Silk Composite. In the beginning of the experimentation, various composite samples have been prepared by incorporating a single layer of silk fibres and a single layer of silk cloth, oriented in biaxial directions as shown in Figure 2.

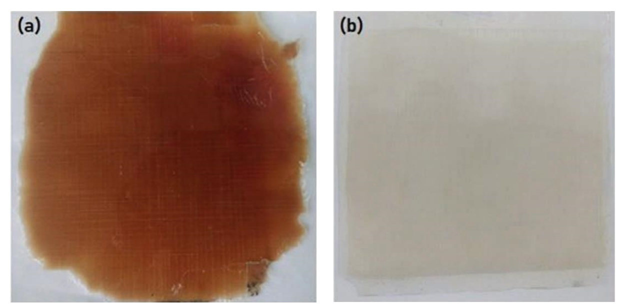


Figure 2: Composite samples prepared of a single layer oriented in biaxial direction: (a) silk fibres and (b) silk cloth.

5.2. Double-Layer Silk Composite. Similarly, a composite sample has been prepared by incorporating two layers (one by one) of silk fibres and silk cloths reinforced with a vinyl ester resins-based matrix oriented in biaxial directions, as shown in Figure 3.

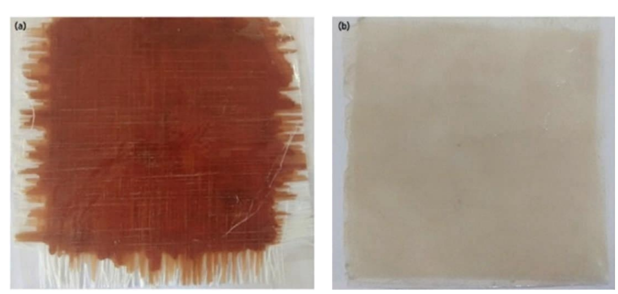


Figure 3: Composite samples prepared of double layers oriented in biaxial direction: (a) silk fibres and (b) silk cloths.

5.3. Triple-Layer Silk Composite. In the same manner, using the three layers (one by one) of silk fibres and silk cloths, the composite samples have been prepared by embedding these silk fibres and silk cloths as reinforcement with the vinyl ester resins-based matrix, as depicted in Figure 4.

6. Testing Details

6.1. Density and Void Content. Void formation during the composite manufacturing is an induced manufacturing defect which directly affects the mechanical properties and estimated performance of a material. It is a very critical issue that arose during manufacturing and must be investigated in order to maintain the desired level of accuracy and desired performance of the prepared composite materials. Furthermore, "*the density of polymer composites depends upon the composition of the composite material and is defined as the ratio of mass per unit substance volume*." However, theoretically, the density calculation of composites is estimated using the "Weight Additive Principal Equation," and the actual density of composites is estimated experimentally. Such an experimental investigation of density measurements is carried out by the simple "Water Immersion Method" using "Mettler Toledo Electronic Balance," as depicted in Figure 5. The difference between theoretical and experimental measurements gives the desired void content in a fabricated composite sample and the void assessment test is carried out according to ASTM D 2734 – 94.

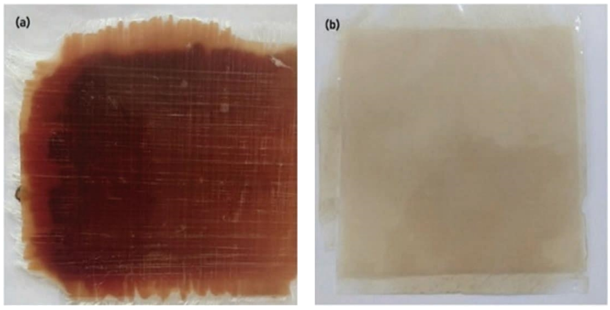


Figure 4: Composite samples prepared of triple layer oriented in biaxial direction: (a) silk fibres and (b) silk cloths.

Figure 5: Mettler Toledo electronic balance for density measurement.

6.2. Tensile and Flexural Test. In order to estimate the tensile behavior of a prepared composite sample, the tensile test was carried out using the Instron Universal Testing Machine (UTM), Instron Ltd, UK (Model 3366), as per the standards and guidance provided by ASTM D 638. Similarly, for estimating the flexural behavior, the 3-point bending or flexural test was carried out under the standards and guidance provided by ASTM D 790. In order to perform and analyze both the tests, the prepared composite samples of single, double, and triple layers of fibres oriented in unidirectional and bidirectional manners as well as the prepared composite samples of reinforced silk cloth of size 100 mm × 12 mm × 8 mm were considered under the maintained relative humidity of 55% at ambient temperature of 24°C. For carrying out both the tests, the strain rate (or crosshead speed) of UTM was maintained at 1 mm/min. The schematic of an Instron UTM have been depicted in Figure 6 and the samples for the same are shown in Figure 7.

6.3. Hardness Test. The hardness of the composite material depends upon the distribution of fibre contents into the sea of matrix [54]. Various hardness tester can be utilized to estimate the hardness of composite laminates. For relatively softer materials, the Shore D hardness tests are conducted to measure the hardness. This is a gauge-type hardness tester having a range of 0–100 shore with an accuracy of 1 shore for hardness measurement. In the present work, the Shore D hardness tests have been performed on the SFRC samples as per the standard of ASTM D2240 and ISO 868 where the hardness of composite is determined using the measurement of "*depth of penetration*" of a specific indenter. The hardness value is determined by the "penetration of the Durometer indenter foot into the sample." Shore hardness is a dimensionless quantity and the higher noted shore value represents the harder material. The penetration depth of the indenter depends upon material hardness, viscoelasticity property, indenter shape, and dwell time of the indentation.

6.4. Impedance Test. In the present work, the electrical impedance test has been carried out using the impedance analyzer (IA). This impedance analyzer is electronic equipment that are utilized to analyze the complexity of an electrical impedance as a "function of test frequency." Impedance is an essential parameter in materials investigation in order to characterize the materials that are prepared for the manufacturing of various components. Also, the impedance analyzer helps in investigating the materials characterization in terms of their complex dielectric behavior and conductivity. During the present investigation, an impedance analyzer manufactured by Novocontrol Tech., Germany (Model ALPHA ATB) was used. The equipment has the frequency range of 3 μhz to 20 MHz and has the impedance range of 10^{-2} to 10^{14}. The AC voltage supply ranges from 100 μV to 3 V. A schematic of an electrical impedance analyzer that was utilized for impedance test is depicted in Figure 8 and the impedance test samples can be seen in Figure 9.

6.5. Tribological Test. The friction and wear resistance properties of a material depends upon the experimental parameters and are not considered as intrinsic properties. The wear behavior of a material depends upon many other factors such as "surface energy, cohesive and adhesive strength, interaction and adhesion with the counterface, ultimate tensile strength, elongation to break, hardness, creep, hydrogen bonding," etc. However, there occurs no direct correlation between the wear behavior and mechanical properties of a composite materials. The wear characteristics of any material are essentially investigated by performing the tribological tests using different tribological test methods. In the current study, a multitribometer (TR25) manufactured by Ducom, India, have been utilized, as shown in Figure 10 and the tribological study was performed without using any lubrication as per ASTM G99 and ASTM G133 standard. A prepared sample of dimension

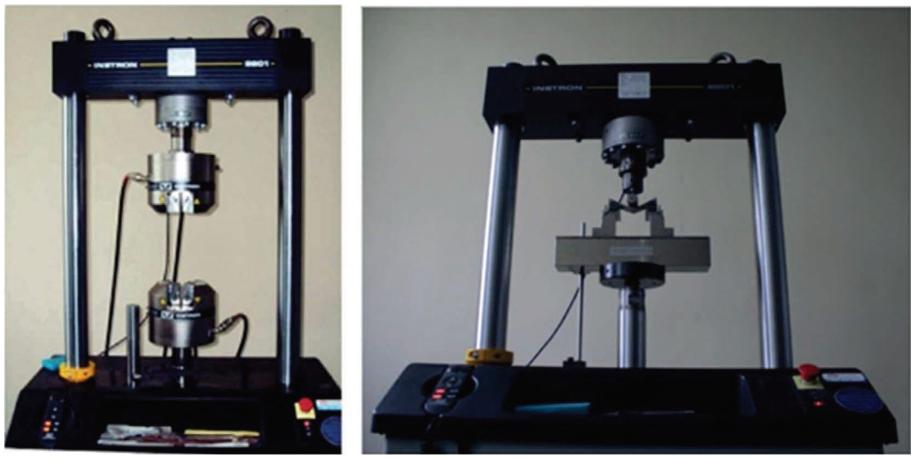
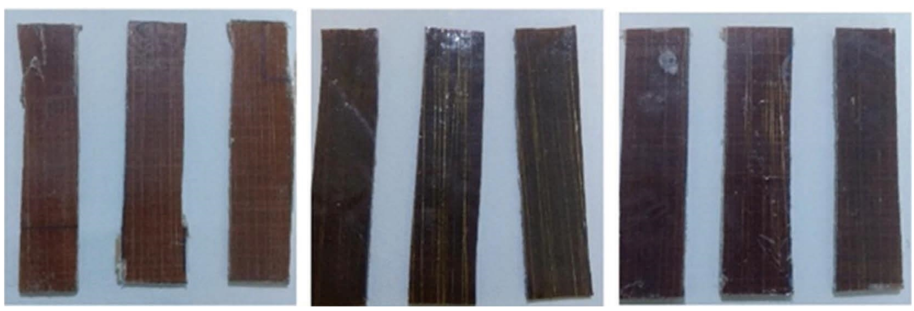
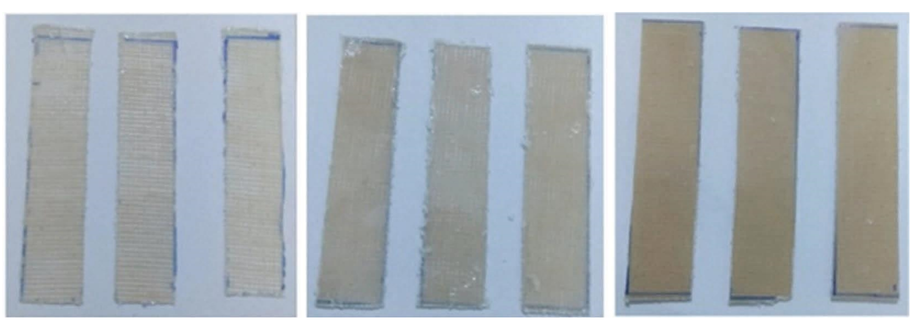


Figure 6: Instron universal testing machine.



(a)



(b)

Figure 7: Composite samples prepared for tensile and flexural test characteristics estimation of: (a) single, double, and triple layers of silk fibres oriented in the biaxial manner; (b) single, double, and triple layers of reinforced silk cloth composite samples.

Figure 8: Impedance analyzer.

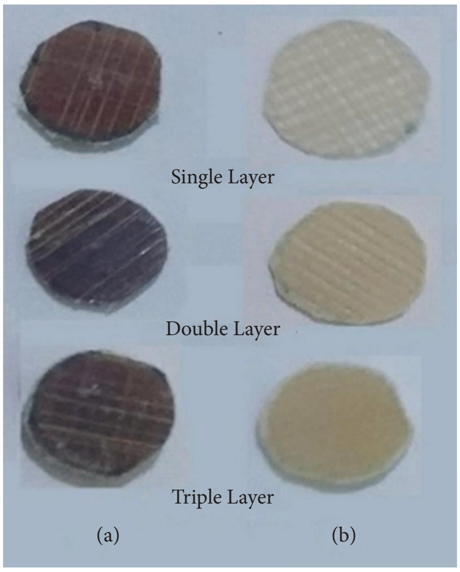


Figure 9: Prepared composite samples for impedance test characteristics estimation of: (a) single, double, and triple layers of silk fibres oriented in biaxial manner; (b) single, double, and triple layers of reinforced silk cloth composite samples.

Figure 10: Universal tribometer with heat chamber.

$20 \times 20 \times 8$ mm^3 was utilized and for the study, the sample was kept firmly on the sample holder in such a way that it was made to slide against the steel roller that acted as a counterface. Using the loading lever, a normal load was applied at the top face of the sample, and corresponding to this test, the data for the coefficient of friction were recorded and finally the weight loss of the composite sample was used to determine the specific wear rate.

7. Results and Discussion

7.1. Density and Void Content. The density and void content (in %age) for virgin material and the different orientation of silk fibres and silk cloth have been tabulated in Table 1. The percentage void content were found to be within acceptance limit. Moreover, the void content for composite reinforced with cloth was found to be lower than that of biaxial fibre which can be due to the woven nature of the cloth and the smaller pore size when compared to the biaxial fibre.

Table 1 shows the void content with a difference in fibre concentration observed between the three composite samples with loading and cloth loading. Lower void content with biaxial fibre loading compared with cloth loading is seen as the air bubbles get entrapped more in case of cloth due to the denser and more intermingled placement of the fibres. Void content is observed to increase with increasing fibre content. This can be attributed to the fact that a higher concentration of fibre provides more surface for adhesion of air droplets and a higher vacuum pressure is required for their removal.

Table 1: Density and void content of prepared composite.

Designations	Density (gm/cm^3)	Void content (%)
Virgin material	1.140 ± 0.001	N/A
Single layer biaxial fibre	1.196 ± 0.001	0.43
Double layer biaxial fibre	1.203 ± 0.001	0.54
Triple layer biaxial fibre	1.211 ± 0.002	0.68
Single-layer cloth	1.223 ± 0.001	1.35
Double-layer cloth	1.226 ± 0.002	1.42
Triple-layer cloth	1.228 ± 0.002	1.77

7.2. Tensile Tests. The tensile testing was carried out for both biaxial fibre reinforced and woven cloth-reinforced silk to optimize the suitable concentration fibre contents, and the effect of the fibre loading on each composite types whether it was fibre loaded or cloth was documented (Figures 11 and 12). The results show a considerable increment of tensile stress in both the cases which indicates proper stress transfer from the matrix phase to fibre. Here the fibres have promoted the diffusion of polymer resin through the fibre network before curing, the interactions at an interface are intensified, and a material probably with greater possibility of matrix to fibre load transfer is obtained. But the increment of properties is not significant in the case of a bilayer in comparison with single or triple layer that may be due to improper distribution of fibre in the matrix which may result in stress concentration in the matrix phase and subsequently failure at an early stage. Another reason may be the lack of adequate impregnation of polymer resin into fibres limits interfacial bonding between fibre surface and matrix, which could reduce the transmission of stress to the bulk of material through the interface. Similar observations are reflected in the case of silk cloth reinforced composite. Triple layer cloths show highest tensile properties for better stress distribution from a weaker matrix phase.

7.3. Flexural Tests. The changes in flexural strength with fibre concentration are shown in Figures 13 and 14 for all compositions. In the case where there was no fibre present, the flexural strength remained unchanged, but after introducing fibre and increasing the fibre loading, the values

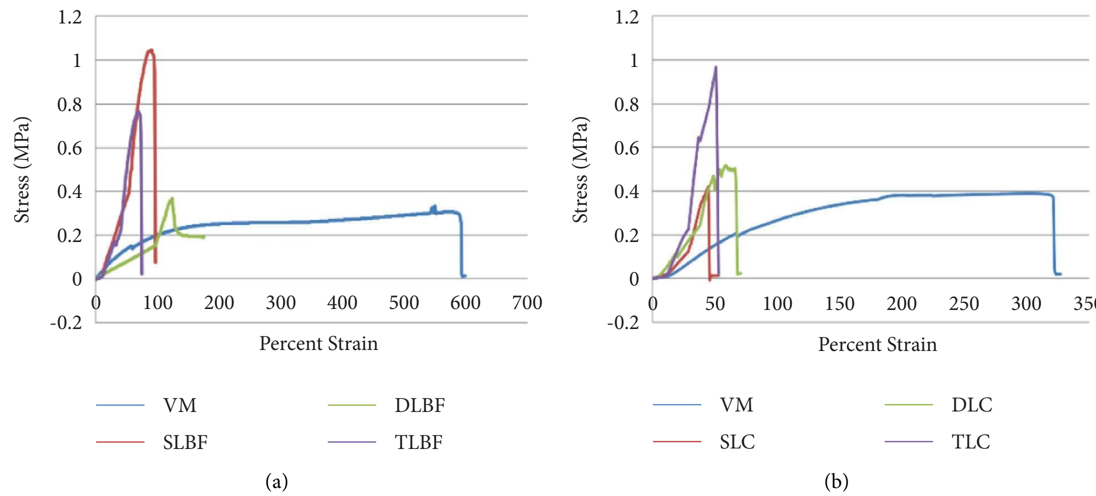


Figure 11: Comparative study of tensile properties (a) with different layers of silk fibre (b) with different layer of silk cloth.

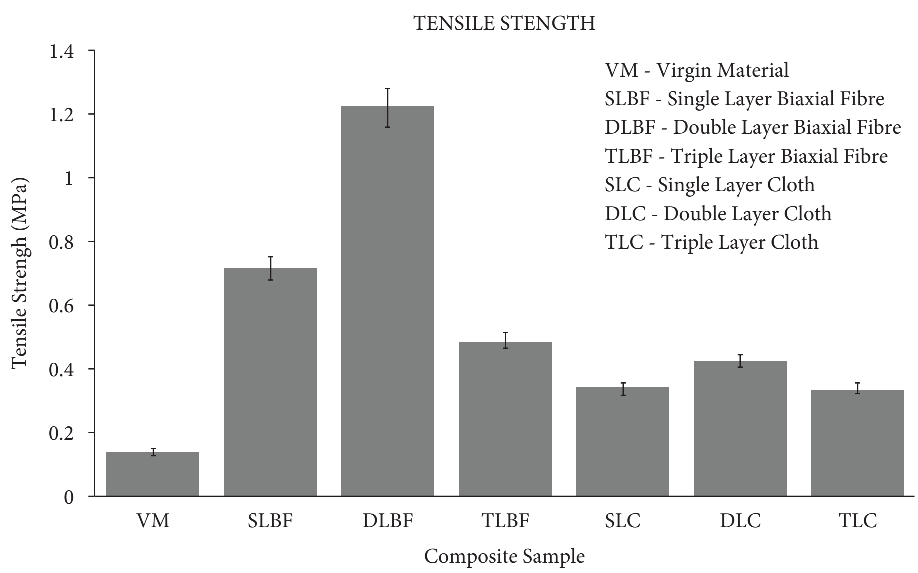


Figure 12: Comparative study of tensile strength of SFs and SCs reinforced vinyl ester composites.

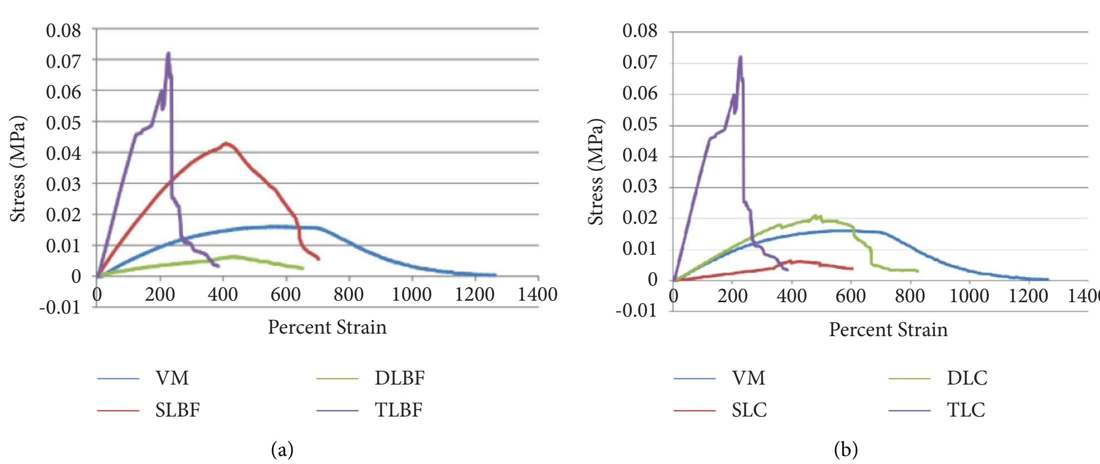


Figure 13: Comparative study of flexural properties (a) with different layers of silk fibre (b) with different layer of silk cloth.

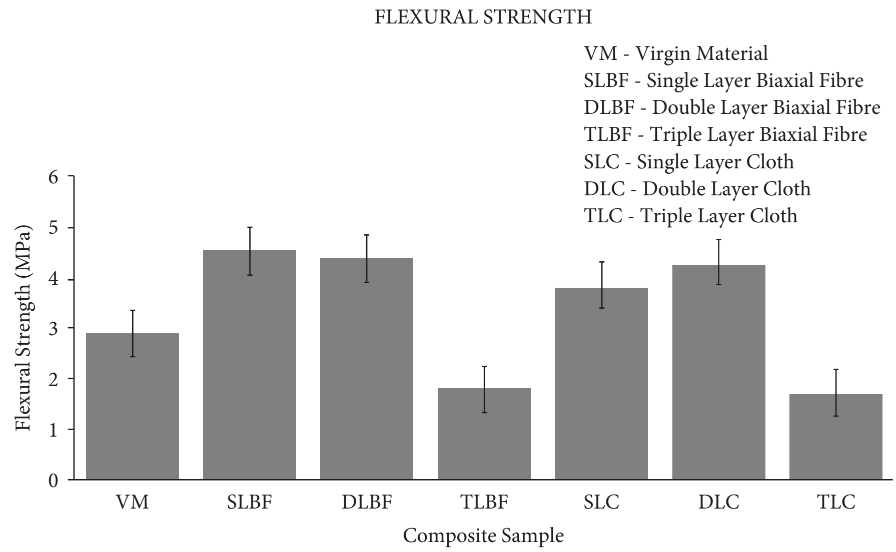


Figure 14: Comparative study of the flexural strength of SFs and SCs reinforced vinyl ester composites.

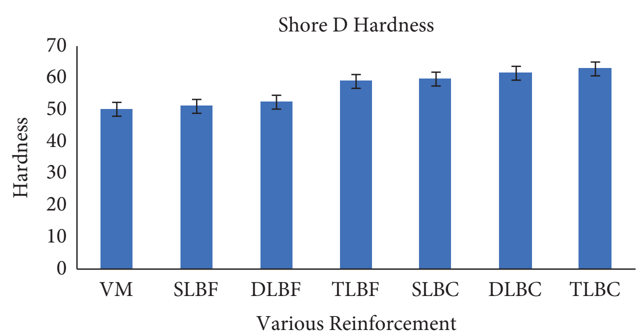


Figure 15: Comparative study of shore D hardness (with standard deviation) with different layers of silk fibre and silk cloth and the virgin material.

changed significantly. Flexural strength largely depends on the reinforcing capability of the fibre. There was improvement in flexural strength with increasing fibre loading. This indicates that there was sufficient interfacial bonding for the transfer of the load from matrix to fibre.

7.4. Hardness Test. The investigation of shore D hardness of the SFRCs has been carried out as per the mentioned standard of hardness test. Figure 15 provides the test results.

The Shore D hardness results follow the mechanical strength for the SFRCs and this is quite expected because with an increase in mechanical strength, resistance to deformation, i.e., hardness also increases.

7.5. Tribological Test. When a composite material is subjected to tribological test, the coefficient of friction changes significantly with change in fibre content in comparison with neat resin (as shown in Figure 16). It was observed that the coefficient of friction is higher in case of cloth loading as fibre concentration increases significantly. When the polymer adheres to the counter surface, the sliding interface is

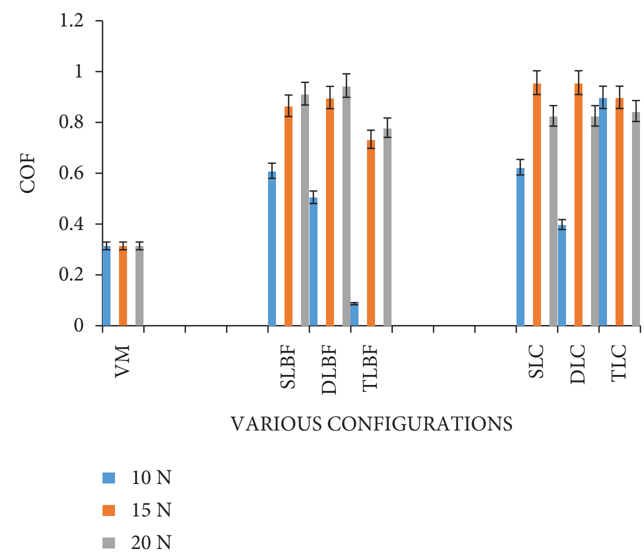


Figure 16: Comparative study of the coefficient of friction (with standard deviation) with different layers of silk fibre and silk cloth and the virgin material.

more for polymer-polymer than polymer-metal if the counter surface is, e.g., steel. This also means that the friction is mostly dependent on the polymer's resistance to shear. It is observed that the coefficient of friction decreases with an increase in fibre layer as the sliding of interface in more prominent. So, reinforcement improves the tribological properties of a polymer composite, but a multilayer composite might result in lower values for interlayer sliding.

7.6. Impedance Test. Figure 17 shows the variation of AC conductivity as a function of applied frequency. Almost for all samples the trend of change in conductivity with applied frequency are the same. The value becomes constant up to 0.1 MHz (low frequency), and this is mainly due to the DC

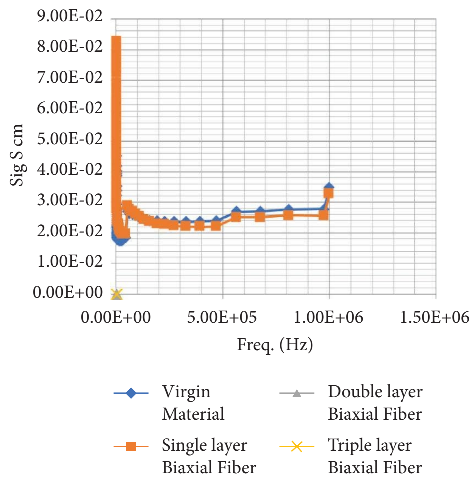


FIGURE 17: Comparative study of electrical impedance.

conductivity. This is followed by a slight bump that corresponds to the relaxation processes such as relaxation from the polar side chains of the matrix and also the contributions from space charge polarization. The AC conductivity increase in the composite films is marginal and occurs only at the high-frequency end of the applied field. This could be due to the lower contribution from polar groups of vinyl ester resin because relaxation times are short at high frequency.

8. Conclusion

The exploitation of natural fibre composites has opened up new opportunities for both researchers and industries for their sustainable manufacturing and utilization in the near future. Such new avenues have also suggested the utilization of SFRCs as an alternative source of materials as a green product for ecological, environmental, and economic benefits. The present study on SFRCs has proven to be a potential replacement for ceramic-based products in terms of their mechanical properties and behavior. The present work is a modest attempt to enlighten the readers about the new proposed silk fibres and silk cloth based reinforced composite materials. The work discusses the various aspects of silk fibres on the basis of different mechanical testing such as tensile and flexural test in order to analyze the mechanical behavior. Further, the tribological test as well as the electrical impedance test have been carried out to analyze the coefficient of friction, wear behavior, and material characteristics of such SFRCs, respectively. The paramount motivation of proposing such attractive silk fibre-based composites is to develop a new generation's smart composites with potential applications in the wide arena of industrial perspective. However, the potential of such silk fibres and silk cloth-based composites still needs much investigation for future processing and development.

Data Availability

All the data or models analyzed during the study are included in this published article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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