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RESEARCH ARTICLE

Investigation of the Mechanical Properties of Hybrid E-Glass and Mohair Fiber Reinforced Epoxy Composites

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ABSTRACT - Natural fiber composites have significant potential to replace traditional materials used in industries due to their excellent tensile strength, stiffness, low specific weight, and superior thermal and insulating properties. Mohair fiber, also known as the Noble fiber and the Diamond fiber, is obtained from the Angora goat, an animal of Tibetan origin. Renowned for its brilliant luster and resilience, Mohair is a symbol of luxury and exclusivity. The primary objective of this study is to manufacture and test a new natural fiber composite that could potentially outperform existing materials in real-world applications. Specifically, the study aims to investigate the mechanical properties of this composite. Mohair has previously been identified as a fiber many times stronger than a strand of steel of similar dimensions. Incorporating these highly desirable properties of Mohair into an epoxy matrix is one of the novel aspects of this research. The testing procedure begins with the preparation of ASTM molds, concurrent treatment of the fibers, and the preparation of the binding material. Specimens are created both with and without the addition of electrical glass (E- glass) fibers. The next phase is curing, during which the epoxy is allowed to solidify, forming strong bonds. Once developed and cured, the composites are removed from their molds and undergo post-processing and finishing techniques. This study aims to understand the tensile and flexural characteristics of natural fiber composites reinforced with epoxy. Three fiber orientations—uniaxial, biaxial, and criss-cross—are employed to assess the changes in the mechanical properties of the composites. The results indicate that adding E-glass fibers in alternating layers of the composite significantly enhances both tensile and flexural strength. Statistically, the addition of the biaxial arrangement of fibers with E-glass fibers results in an 18.47% improvement in ultimate tensile strength, while the maximum flexural strength increases by 49.90%. Furthermore, the topography of the cracked surface is examined using field emission scanning electron microscopy, and the breaking of the fibers in all three directions is studied.

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1. INTRODUCTION

Fibers obtained by extracting and processing organic components from natural sources, such as plants and animals, are known as natural fibers. These fibers have gained tremendous importance in recent times, as clearly evident from their presence in the clothing industries, insulating materials and geotextiles [1]. It is because natural fibers are linked with a variety of positive attributes that make them a sought-after material in almost all domains of engineering. A few properties of natural fibers that make them so desirable are their low specific weight, cost-effective methods of production, excellent heat and insulating characteristics, self-lubricating features, and biodegradability. The trends in research have gradually started to incline towards developing composites made from natural fibers, a practice that had been established over a century ago. The aerospace, construction, and automobile industries have shown great interest in natural fiber composites, and their scope of utility only seems to be expanding. Synthetic fibers, which have a reputation for being chief contributors to greenhouse emissions, have been supplanted by natural fibers owing to their eco-friendly behavior [2]. Extensive studies have been performed on natural fibers to expand their areas of application.

Recent research has revealed that Natural Fiber Polymer Composites (NFPC) may replace automobile panels with utmost ease [3]. Natural fibers have, therefore, proven to be the perfect replacement for various metals and other materials used in certain industries [4]. Besides displaying a range of useful properties, such as low specific weight and biodegradability, the additional support provided by the covalent bond formation between the fibers and the matrix further enhances the composite’s properties [5]. However, natural fiber composites pose a few shortcomings that are hindering their opportunity to enlarge commercially. Micro-voids have been observed in their structure, ultimately compromising the strength of the composite. Natural fibers need to be meticulously prepared, leaving no avenues open for flaws in their manufacturing. This implies that the process, despite being user-friendly, is very tedious and time-consuming [6]. Being polar in nature, these fibers are not necessarily always compatible with the polymer resin matrix [7]. In order to facilitate greater adhesive strength and enhance bonding within the resin matrix, the fibers undergo an initial alkali treatment, whose concentration is such that it would not affect the properties of the natural fiber [8].

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There are numerous sources available in nature from which natural fibers may be extracted, a few of them being Banyan, Banana, Hemp, Fern, Spider Silk, Sheep Wool and many others. Being low in cost and possessing high specific properties, natural fibers attract many industries in order to be made fit for multiple applications [9, 10]. They find utility in industries like aerospace, marine, sport, construction and electronics. Natural fibers like Sisal, Hemp and Bamboo are used in polymer composite fabrication as reinforcements [11]. Composites of natural fibers and glass fibers are often fabricated and collected to achieve significantly better results that enable them to identify potential applications in the production of components for the automotive industry, as observed in that of door panels, bumpers and under-floor protection. Mercedes-Benz was the first company, among other automobile giants, to incorporate natural fiber composites for their inner door panels in 1999 [4]. Following this, Toyota developed an eco-plastic made from sugarcane, which can be used in the interiors of cars [12]. Besides industrial applications, natural fibers, animal fibers, in particular, are widely used in the bioengineering sector [13]. Often, the characteristics of such natural fiber composites are further improved by reinforcing them with glass fibers [14]. Today's market has a variant of glass fibers for every application, with a few common ones being A-glass (used to make process equipment and window glass), C-glass (used in applications where chemical resistance is an important factor), E-glass (used in electrical applications due to its property of electrical insulation) and S-glass (which was developed specifically for military and ballistic operations. Due to its lightweight, inexpensiveness, and ease of availability, E-glass fibers are of primary concern when reinforcing natural fiber composites. Other valuable properties they showcase include excellent ductility, little brittleness, a high ratio of surface area to weight, effective thermal insulation and its amorphous nature.

Mohair fiber was selected for this work. Mohair is one of the oldest fibers used in fabric production, and for thousands of years, its production was confined to Turkey. It is obtained from Angora goats, which have Tibetan origins. The goats are shorn twice a year and yield about 1 to 1.5 kilograms of fiber [15]. Mohair fibers are the warmest of all natural fibers and have a natural shine, putting them into the list of the textile industry's most luxurious fibers. It keeps the wearer warm even when wet, a feature that sets it apart from fibers like wool and alpaca. Mohair exhibits great durability owing to its high tensile strength. Other properties include crease resistance, flame resistance and wicking of moisture [16]. An extensive literature review has revealed that no research has been conducted to examine the tensile and flexural behavior of Mohair fibers. For the various properties, Mohair boasts, such as high durability, mechanical strength, and luster, a comprehensive study must be performed in order to disseminate the advantageous nature of this fiber and compel industries to take Mohair into account for several applications. E-glass fibers, which are known to possess more tensile strength than steel, can be amalgamated with Mohair fiber composites so as to efficaciously lead to better mechanical properties. Two main mechanical properties that dictate the behavior of any material are the tensile and flexural strengths. These are measured using any universal testing system fitted with the right apparatus and clamps for testing. This data, like any other, will have variances, either due to the varying parameters or unaccounted inaccuracies.

To understand the macro properties of the specimens effectively, it is essential to observe them on a microscopic level. This can be achieved by incorporating surface analyzing techniques, such as field emission scanning electron microscope (FESEM). FESEM, with its wide range of magnification spectrum, enables the user to comprehensively study the surface topography as well as the micromechanical properties [17] and composition arrangement with nearly unlimited depth of field vision. FESEM utilizes a field-emission cathode in the electron gun, which produces narrower beams at multiple levels of electron energy, giving both high spatial resolution and minimal damage to the sample [18-20]. The aim of this paper is to understand the mechanical behavior of Mohair fibers and observe the variation in properties with incorporation of E-glass fibers as well as changes in the orientation, namely uniaxial, biaxial and criss-cross.

2. METHODOLOGY

The methodology can be split into three major and distinct processes, starting with the initial preparation, which deals with the arrangement of the essentials required to begin the preparation of the composites. At this stage, the different orientations, as well as the process of layering the fibers and epoxy, are discussed in detail. The third and final process discusses the curing of the composites, the extraction of the composite from the mold and the various post-production operations used to improve the surface finish of the composite. These stages have been elucidated below.

2.1 Initial Preparations

There are two main categories of natural fibers: those that come from plants and those acquired from animals. Fibers of one category have differing proteins and constituents from fibers of the other category due to their differing needs and the purposes they satisfy. Plant fibers are known to contain cellulose, hemicelluloses, lignin, pectin and various other waxy substances [21]. This help makes the fibers hydrophilic, which doesn't help with the bonding with the hydrophobic resin-matrix [22]. Thus, these substances and the waxy layers are broken down with various chemical treatments, the most commonly used of which is the Alkali treatment. On the other hand, animal fibers are mainly made up of keratin and silk fibroin, which are structural proteins with a large number of reactive functional groups that help with the cross-linking bonds with other polymers, which is quite advantageous in the production of natural fiber composites [23]. However, woolly fibers like Mohair are often greasy and covered with the perspiration of the animal, which may impact the bonding in the composite. To tackle this, Mohair fibers (as seen in Figure 1) are first washed thoroughly with a solution of Sodium Hydroxide (NaOH) diluted down to 0.5% weight/volume (w/v) using water. The soapy fibers are then washed lightly with water to rid them of the soap and the entrapped grease, dirt and impurities that have been mentioned above.

Figure 1. Mohair fibers before washing with 0.5% (w/v) diluted NaOH solution

The molds used to prepare the composite specimen are then prepared. They are shaped in accordance with the ASTM Standards for Tensile Testing (ASTM D638) and Flexural Testing (ASTM D790), illustrated in Figure 2 (a) and (b). The molds are hand-crafted by a carpenter out of Particle wood, as seen in Figure 2 (c). This material, coupled with the preference for manual wood-working, gives the molds the dimensional accuracy sufficient to ensure that no large variations arise in the testing results of the different specimens. It also ensures that the mold is easily breakable for the swift and clean extraction of the specimen from the mold.

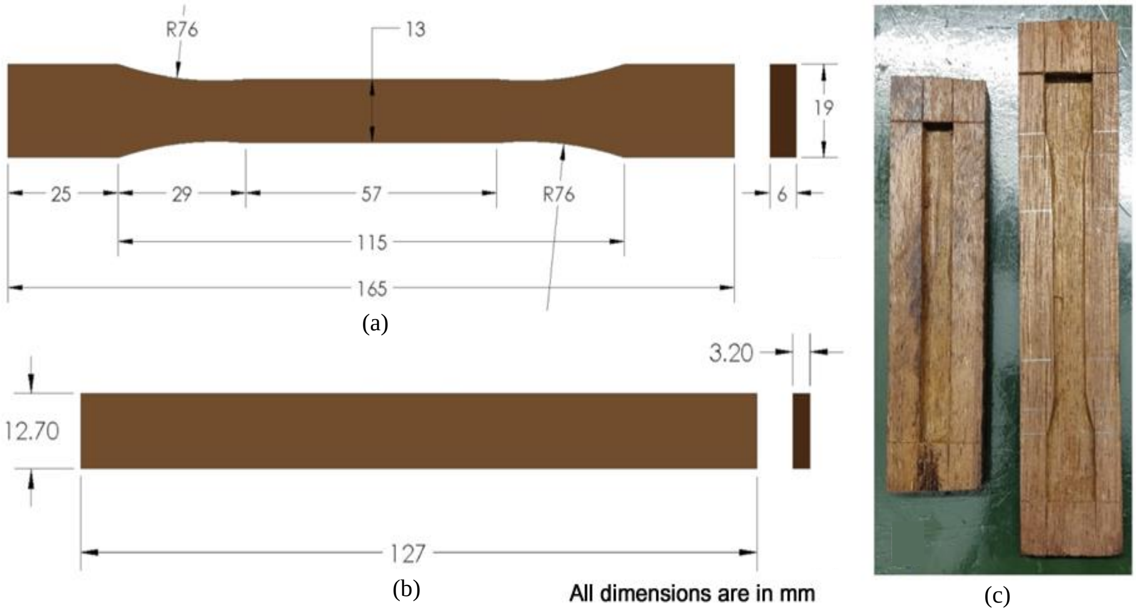


Figure 2. (a) Tensile specimen Dimensions as specified by the ASTM D638 standard; (b) Flexural specimen Dimensions as specified by the ASTM D790 standard; (c) Molds made of Particle wood

2.2 Preparation of Specimen

First, the resin, which is used as the bonding matrix, is prepared. The bonding matrix is the principal component of any composite, as it helps by holding the other constituents of the composite and provides sufficient bonding to hold these constituents together. Here, an epoxy-based resin is the matrix, while the Mohair fibers and the E-glass fibers act as the constituents. The Mohair and E-glass fibers exhibit superior tensile strength but are prone to damage caused by cyclic loading [27-30]. On the other hand, epoxy-based resins, by themselves, possess substandard tensile strength but have been found to be tough and capable of handling damage. Thus, when combined, the fibers and the resin function together, eliminating their weaknesses and bringing their strengths to the fore. Here, epoxy LY-556 and Araldite hardener HY-951 are used to prepare the resin. They are mixed in the volume/volume (*v/v*) ratio of 10:1, and the resin is simultaneously stirred continually to ensure that no air bubbles are trapped in the resin.

The resin is prepared by combining the epoxy and hardener in a volume/volume (*v/v*) ratio of 10:1, and continuous stirring is carried out to achieve a homogeneous mixture and prevent early solidification. Also, excess hardener can speed up the curing process of the epoxy resin, causing it to become solid much faster than intended. Next, the washed and dried fibers are cut to specific lengths according to the orientation followed. While the uniaxial orientation requires fibers to be cut along the length of the longer side of the mold, the biaxial orientation demands that the fibers be cut along the lengths of both sides of the rectangular mold. In the criss-cross preparation, however, the fibers need to be cut such that they fit perfectly in the mold when placed at an angle of 45° with respect to the longer side of the mold. Each of these orientations and the order of the layers placed have been illustrated in Figure 3. For each orientation, the hand lay-up technique is followed by laying the fiber layers in the mold, followed by soft compression, which packs the specimen more tightly, thus removing any voids present in the epoxy [31-33].

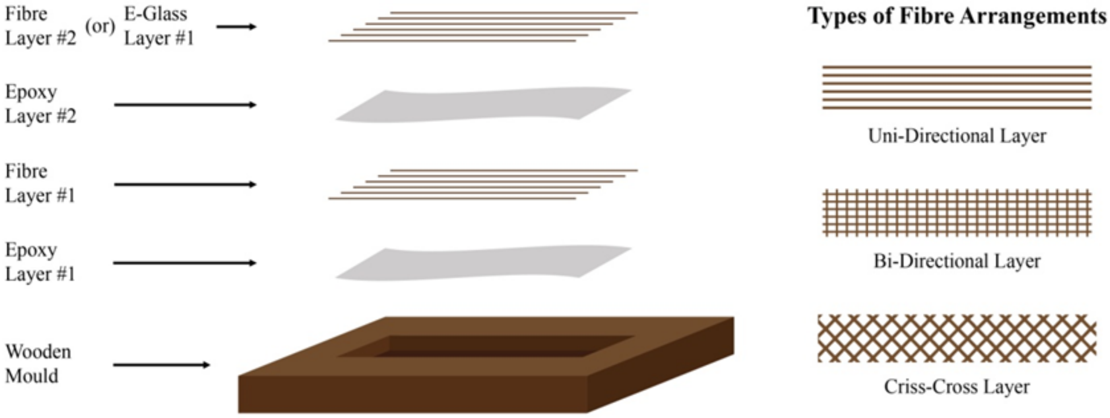


Figure 3. Process of preparing Mohair fiber composites, along with the different types of fiber arrangements

Once the fibers are cut to size and the epoxy resin is ready, the specimen preparation begins. The mold is first coated with a thin layer of oil, which helps in the easier removal of the specimen from the mold. Afterward, a layer of the epoxy resin is coated as the first layer, which is then followed by a layer of the Mohair fibers. Before being placed in the molds, the fibers are smeared with a few blobs of the resin, as this seems to improve the bonding that the resin has with the fiber strands. From here, the addition of alternative layers of the resin and fibers is followed till the mold is filled to the brim. Upon careful measurement, it is observed that each specimen is made up of, on average, 55% of the Mohair fibers and 45% of the epoxy resin. Enhancing the strength of Mohair fiber composites can be achieved by increasing the fiber volume fraction and extending the post-curing time. In addition, the Mohair fibers with a higher weight ratio have a reputation for offering excellent adhesive strength for composites. To observe how the addition of E-glass may alter the mechanical behavior of the composite, a set of specimens is prepared where alternate layers of fibers are substituted with layers of biaxial E-glass fiber sheets with a density of 270 grams per square meter (GSM). These E-glass fibers were procured from the Vibrations Lab at Vellore Institute of Technology (VIT), Vellore. As done before, upon careful measurement, it is observed that the specimens made with the inclusion of the E-glass fibers are made up of, on an average, 45% of the Mohair fibers, 45% of the epoxy resin, and 10% of the biaxial E-glass fibers.

2.3 Curing and Finishing Operations

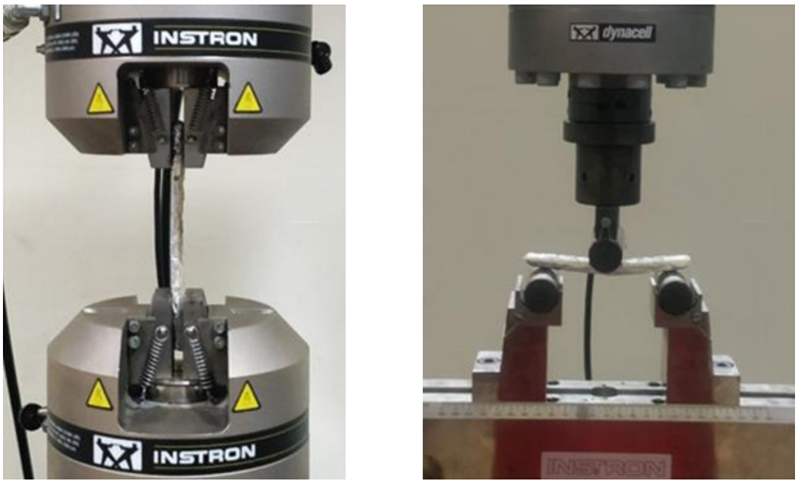
During the process of curing, the epoxy is made to react with the suitable hardener so that it forms a three-dimensional cross-linking resin. There is a significant difference in the mechanical performance of a properly cured epoxy resin and a resin that has not been cured properly or one that has been disturbed or damaged in the midst of curing. This makes curing a process of utmost significance, which is also the reason why the Mohair fiber composites are left untouched for a span of 10 days at room temperature to get cured. Once cured, the specimens are then extracted carefully from the molds using a chisel and a hammer while ensuring that no structural damage is caused due to excessive or vigorous chiseling. Since extraction is done by chiseling, it is apparent that the surfaces of the specimens would have burrs and rough surfaces, which could affect the grip that the testing machines have on the specimens while testing. To solve this, the gripping surfaces of the samples are ground using a fixed grinding machine, with the finer operations done by sanding using sandpaper of suitable grit. Burrs are removed either using the chisel, by hand, or using sandpaper. Once the surfaces are smoothened, the specimens are washed in water to rid them of the dust.

Figure 4. The Mohair uniaxial composite specimen after post-processing

3. RESULTS AND DISCUSSION

The results attained from the various analyses done are discussed below. These include mechanical testing, various chemical and microscopic analyses, the analysis of variances (ANOVA), and the trained neural networks used to check the correlation between significant factors involved in mechanical testing. Mechanical testing is conducted using the Instron 8801 Servohydraulic Fatigue Testing System. With appropriate modifications to the setup, this system is capable of performing several tests to analyze and understand specimens of varying shapes, sizes and properties (as seen in Figure 5). For the purpose of this study, the system is adapted to test the tensile and flexural strengths of the Mohair fiber composites. 6 specimens are chosen as subjects for each of the tests, with exactly half of them comprising the biaxial layers of E-glass in them. The tests were conducted, and the data obtained is tabulated below.

3.1 Mechanical Testing



(a) (b)

Figure 5. Showcases the Instron 8801 Servohydraulic Fatigue Testing system, (a) the system is equipped with the tensile testing apparatus and is conducting a tensile test; (b) the system is fitted with the flexural testing apparatus and is performing a flexural test

Table 1. Tensile testing on the Mohair fiber composites

S. No	Maximum Load (N)	UTS (GPa)	Young's Modulus (MPa)	Tensile strain at Break (%)	Specimen Label
1	1961.76767	0.016	462.804	5.138	Mohair (Uniaxial)
2	2121.65117	0.019	1742.865	4.435	Mohair + E-Glass (Uniaxial)
3	1872.81370	0.015	742.869	10.917	Mohair (Biaxial)
4	2125.62084	0.016	1314.094	1.440	Mohair + E-Glass (Biaxial)
5	1456.88057	0.010	541.348	2.644	Mohair (Criss-cross)
6	1777.82774	0.013	604.017	5.528	Mohair + E-Glass (Criss-cross)
Maximum	2125.62084	0.019	1742.865	10.917	
Mean	1886.09362	0.015	901.333	5.017	
Minimum	1456.88057	0.010	462.804	1.440	

Table 2. Flexural testing on the Mohair fiber composites

S. No	Maximum Load (N)	UTS (GPa)	Tensile strain at Break (%)	Young's Modulus (MPa)	Specimen Label
1	301.420	37.21243	4.918	2513.99470	Mohair (Uniaxial)
2	276.580	43.21616	2.971	5467.54881	Mohair + E-Glass (Uniaxial)
3	202.050	26.72590	2.824	2085.34418	Mohair (Biaxial)
4	301.860	31.05512	4.305	2738.57200	Mohair + E-Glass (Biaxial)
5	126.960	13.60327	4.150	1474.82568	Mohair (Criss-cross)
6	207.580	29.56968	1.751	3907.62562	Mohair + E-Glass (Criss-cross)
Maximum	301.860	43.21616	4.918	5467.54881	
Mean	236.075	30.23000	3.487	3031.31800	
Minimum	126.960	13.60327	1.751	1474.82568	

Upon keen observation of the values obtained post-testing, two trends are inferred. The first is based on the orientations of the specimen within the composite. As it may be seen, the uniaxial type of arrangement depicts higher toughness for both the tensile and the flexural tests, achieving the maximum value of strength in either scenario. Following this is the biaxial type of arrangement, which reveals mediocre results in terms of strength. Finally, the criss-cross type of arrangement accounts for extremely meager values of strength and thus falls last in the category. This trend can be justified by the following argument: In the case of the tensile test, the specimen comprised of fibers is arranged in the direction that applies external force, providing more resistance than those fibers that are aligned in any other position. The contribution of the uniaxial fibers towards resisting is, therefore, the highest as compared to its counterparts. The flexural test follows in a similar fashion, with the uniaxial arrangement of fibers having the highest strength, while the biaxial and criss-cross arrangement provides relatively lesser reluctance to breakage.

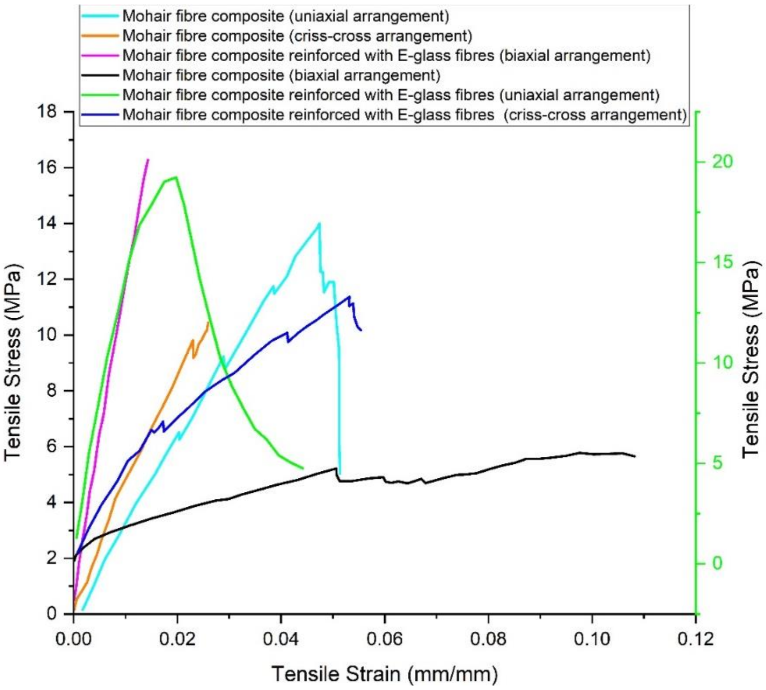


Figure 6. Tensile testing results

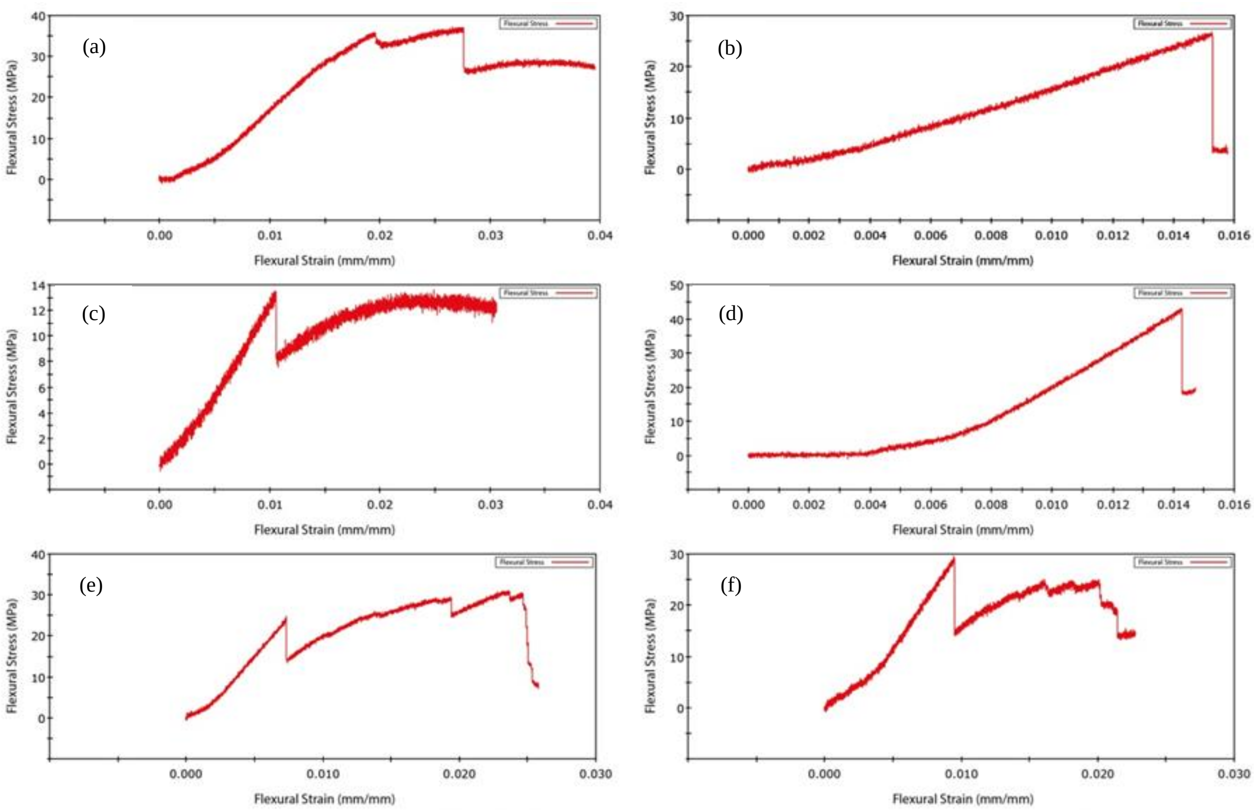


Figure 7. Results of flexural testing for different arrangements of (a) Uniaxial arrangement of Mohair fiber composite; (b) biaxial arrangement of Mohair fiber composite; (c) criss-cross arrangement of Mohair fiber composite; (d) uniaxial arrangement of Mohair fiber composite reinforced with E-Glass fibers; (e) biaxial arrangement of Mohair fiber composite reinforced with E-Glass fibers; (f) criss-cross arrangement of Mohair fiber composite reinforced with E-Glass fibers

The second inference takes into account the presence of E-glass fibers within the specimen. It is clear from the tabulated data that in the tensile as well as the flexural tests, the specimens that housed E-glass fibers in their composition demonstrated higher values of strengths, while those that did not incorporate E-glass fibers showed significantly lesser values. This claim can be supported by the fact that E-glass fibers are considered to be among the strongest available fibers in the industries, displaying strength even more than that of steel. When added to Mohair fiber composites, the overall specimen shows intermediate properties between a complete Mohair based composite and a complete E-glass based composite. All in all, the values of tensile and flexural strengths of the fiber composites are enhanced by the addition of E-glass. Combining E-glass fibers with natural fibers has resulted in a significant improvement in the mechanical properties of the fiber composites. In addition, the inclusion of glass fiber allows for a more advantageous distribution of stress, leading to improved strength. The glass fibers possess exceptional chemical resistance to acids and solvents, minimal moisture absorption, and a high strength-to-weight ratio. They are affordable and simple to trim even after they have fully cured. Due to its excellent properties, the mechanical behavior of E-glass composites is increased [34-36].

The result shows that the uniaxial orientation demonstrated superior tensile strength compared to the biaxial and criss-cross arrangements. We anticipated the observed behavior due to the augmenting properties of E-glass. Also, the researchers proved that the Young’s modulus of glass fiber ranges from 52 GPa to 87 GPa. Hence, the higher Young's modulus of Mohair + E-Glass (Uniaxial) compared to Mohair fiber (Uniaxial) was obtained.

3.2 Field-Emission Scanning Electron Microscopy

FESEM is a powerful analytical technique practiced in the field of material science to generate high-resolution images with a magnification varying from 10x to 300,000x. FESEM is commonly used to study surface topography and gather elemental information. It is different from other microscopic analyses as it works on the principle of field electron emission and uses an electron source to generate the images instead of the commonly used light source. A field emission cathode provides narrower electron beams at a wide spectrum of electron energy, resulting in enhanced spatial resolution. FESEM also has the benefit of obtaining nanometre-resolution surface images at voltages as low as 5kV. The samples also require low charging, meaning that the sample (especially when made of non-conducting materials) imparted a small amount of electric charge. This helps the electron beam detect the sample’s surface and strike it properly, resulting in microstructural images of higher clarity and higher resolution. A small sample is inserted into the system to perform the analysis. Next, the probing beam is bombarded towards the target and “backscattered” electrons are collected by a detector. The information gathered is sent to an image processing system. Thus, an image with high spatial resolution and reduced noise is formed, which helps to provide a highly accurate view of the surface topography.

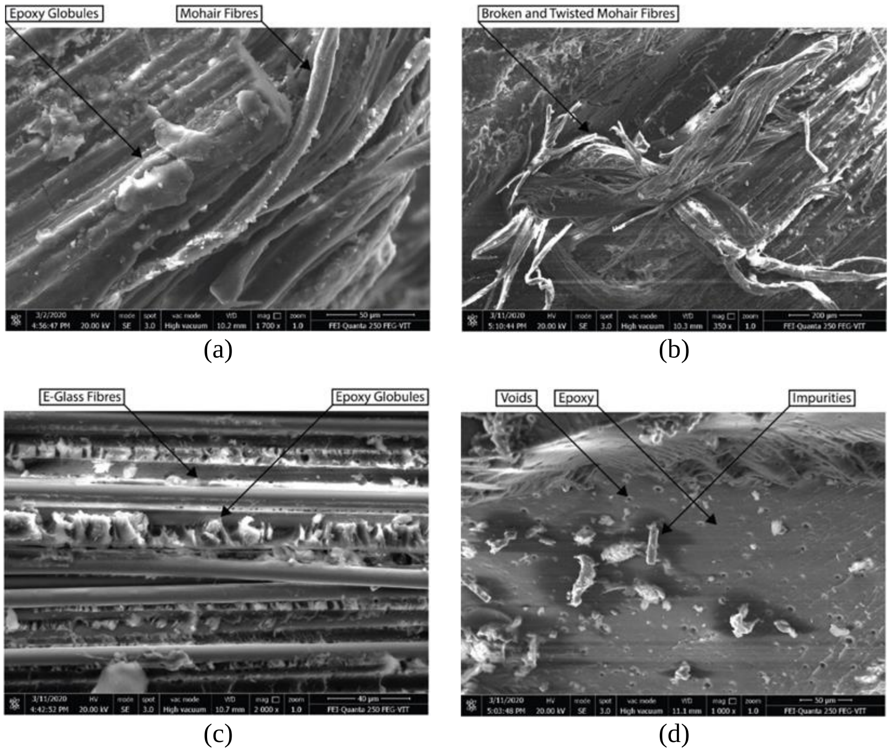


Figure 8. Microstructures of (a) uniaxial arrangement of Mohair fiber composite before fracture; (b) uniaxial arrangement of Mohair fiber composite after fracture; (c) Mohair uniaxial arrangement of fiber composite reinforced with biaxial arrangement of E-Glass fibers; (d) epoxy resin with embedded micro impurities

For this research, FESEM is done on the Mohair uniaxial fiber composites before and after mechanical testing on the samples. The Thermo Fisher FEI QUANTA 250 FEG is used to perform FESEM analysis. Electrons are shot from the Schottky Field Emission Electron Gun, while the backscattered electrons are detected with several detectors, namely the

Large Field Detector (LFD), Backscattered Electron Detector (BSED), Everhart-Thornley Detector and Gaseous Secondary Electron Detector (GSED). Figure 8 shows the images of the sample generated by the aforementioned system. In Figure 8 (a), Mohair can be observed as long, continuous fibers held in place by the epoxy-hardener resin. This resin can be observed in the form of epoxy globules, which can be seen in each of the four images. Another feature that can be easily sighted is the white dots, which are the heterogeneous micro-particles, also known as impurities. These creep into the composite while manufacturing the specimen and can be minimized to an extent by maintaining a cleaner manufacturing environment. Figure 8 (b) shows the microstructure of the same sample after mechanical failure. Due to the stress, the fibers have been displaced from their position and frayed out, while some of them have broken and twisted at various locations. The same can be observed in Figure 8 (c), where the straight E-glass fibers have sections colored in white, which is an indicator of stretched and/or damaged fibers. In Figure 8 (d), few micro-voids can be noticed, which is a consequence of air bubbles getting trapped inside the resin during preparation. Using a vacuum-based technique for the manufacturing of the specimen is a potential solution to avoid such defects.

4. CONCLUSIONS

The mechanical behavior of Mohair fiber composites, which are reinforced with epoxy and E-glass fibers and prepared according to ASTM Standards, has been investigated. The testing was done using an Instron 8801 Servohydraulic Fatigue Testing System, and Young’s moduli, as well as the maximum permissible strengths of the composites, were contrasted. From the tests and analyses performed, it is inferred that the addition of E-glass fibers in alternative layers of the composite enhanced the tensile as well as flexural strength of composites. Statistically, upon the addition of the biaxial E-glass fibers, an improvement of 18.472% is noted in the Ultimate Tensile Strength, while the Maximum Flexural Strength increased by 49.901%. The varying orders indicate that the different orientations of the Mohair fibers impart differing tensile and flexural strengths to the composite. The uniaxial orientation of fibers enhanced with E-glass fibers was found to be strongest for both tensile and flexural tests.

Having obtained data pertaining to the mechanical properties of the Mohair fiber composites, it is thereby possible to suggest suitable applications for the same. Aeronautical and automobile are the major industries that incorporate natural fiber composites for various accessories. Bearing lining, bushes, door panels, dashboards and bumpers are a few fields that promote the usage of such composites. Besides these, Mohair fiber composites may be applicable in the packaging, sports, and medical industries. The properties Mohair brings along with it, such as thermal insulation, durability, and resilience, promise a bright scope and a wider spectrum of applications for the fiber in the years to come.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

T. Narendiranath Babu – Research idea and Analysis of results

Suraj Shyam, Shivam Kaul, and Nirav Kalsara – Collection of literature and experimental data

D. Rama Prabha – Design and calculations

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