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ORIGINAL ARTICLE

Carbon and natural fiber reinforced polymer hybrid composite: Processes, applications, and challenges

J. Shewale[1,*], C. Choudhari[1], A. Bankoti[2]

[1] Department of Mechanical Engineering, Terna Engineering College, Nerul, 400706, Navi Mumbai, India.
Phone: +919860542404
[2] CL Educate, Mohan Co-operative Estate, 110044, New Delhi, India.

ABSTRACT – Composites have recently emerged as the ideal material for weight reduction in a wide range of technical applications. Hybrid composites offer special properties that enable them to meet a wide range of design objectives more efficiently and affordably than conventional composites. Natural fiber-based hybrid composites are also less damaging to the environment and have a reduced carbon footprint. The hybridization of natural fibres with synthetic fibres can substantially minimise the problems associated with natural fibre composites, since the advantages of one kind of fibre can outweigh the disadvantages of another. Several research have been carried out to investigate the different characteristics of carbon-natural fibre reinforced hybrid composites and to evaluate their suitability for a variety of technological applications. The objective of this work is to provide an overview of the materials and manufacturing processes currently utilised to fabricate carbon-natural fibre reinforced hybrid composites. This paper also attempts to discuss the reported mechanical, damping, and other characteristics of the resultant hybrid composites. This article provides a factual overview of the development accomplished so far in the field of hybrid composites constructed from carbon-natural fibres.

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INTRODUCTION

The development of advanced materials has become the centre of the development of many advanced technologies. These materials have successfully replaced traditionally used materials in many applications, and this trend is still continuing. Composite materials are a kind of advanced material that replaces iron, steel, aluminium, etc. in many engineering domains. The concept of composite materials came from nature itself. Wood and bone are the finest composite materials provided by nature. The distinguishing properties of composite materials and their lightness make them an excellent material that has been found suitable for many technical applications. Currently, composite materials are being used extensively in the aerospace, automobile, electronics, and civil sectors. Apart from these, their effectiveness is also found in other engineering fields as well. Composite materials consist of two parts, one of which is the matrix and the other is the reinforcement [1, 2]. They are usually classified on the basis of matrix materials. Among many composites, polymer matrix composites have gained special acclaim. Polymer composites with synthetic fiber reinforcement have developed very rapidly because of their distinctive properties, such as high-strength, high stiffness, improved fatigue life and enhanced corrosion resistance. Synthetic fibers have long life spans and can be produced with the special types of functionalities required for the expected application. High cost, high density, poor recycling capacity and non-biodegradability are the major drawbacks of this material [3–5]. These are excellent materials from a technical point of view, but from an environmental point of view, they are becoming a serious ecological concern in terms of disposal [5].

In the last decades, there has been an increased awareness of environmental protection. To deal with it, particular attention is being paid to alternatives of synthetic fibers in polymer composites. Efforts are being made to use natural substances as reinforcement and, accordingly, the composites are called natural fiber composites. A composite made using natural fibers could be a better option from the economic, environmental and sustainability aspects. Additionally, natural fibers do not create any kind of harmful gases during processing and also do not degrade processing equipment [6]. Although natural fibers can be considered as an alternative to synthetic fibers, they also have some issues. These problems are flammability, poor compatibility with the matrix and high moisture absorption. Chemical treatments of natural fibers and the use of flame-retardants at the time of processing are usually done to overcome these problems [7], [8]. The properties of natural fibers also vary according to their growth conditions, harvesting methods, and maturity.

In the last few years, the trend of manufacturing composites using more than two reinforcements has increased tremendously. This newly developed concept is named as hybridization. In this arrangement, two different reinforcements are used in a common matrix and these two reinforcements are complementing the shortcomings of each other as a whole [9]. The hybridization approach is a good option for making cost-effective composites. Advanced hybrid composites have a variety of potential applications. Many types of hybrid composites are in use. The main ones are Synthetic-Synthetic, Synthetic-Natural, and Natural-Natural fiber reinforced polymer hybrid composites. Synthetic-Natural fiber hybrid

*CORRESPONDING AUTHOR | J. Shewale | jiteshshewale@ternaengg.ac.in

composites were developed with the aim of reducing the dependency on synthetic fibers. The most commonly used synthetic fibers in Synthetic-Natural fiber hybrid composites are carbon, Kevlar, and glass fibers [10], [11]. Hybrid composites which are made from carbon and natural fibers usually ensure good mechanical properties [12].

This article attempts to review the development, importance, and applications of hybrid composites. This study has been limited to those hybrid composites that have used carbon fiber and any natural fiber as reinforcements. The purpose of this study is to logically explain the physical, mechanical, and other properties of these hybrid composites.

BENEFITS OF HYBRID COMPOSITES

Hybrid composites consist of two or more fibers of the same or different types embedded in a matrix and the configuration of these fibers can be optimized based on the application [13]. Hybrid composites have the characteristics of traditional composites and, additionally, they offer flexibility in design, ease of fabrication, lower cost, and high strength to weight ratio [14, 15]. Hence, they are finding their application not only in the aerospace and automobile industries, but in medical and health materials as well.

There are two types of fibers used as reinforcement, viz., synthetic fibers and natural fibers. Synthetic fibers, namely carbon fibers, glass fibers, etc., are stronger as well as moisture resistant as compared to natural fibers [16]. But, disposing or recycling of synthetic fibers has become difficult [17]. In order to avoid the harmful effects of synthetic fibers, natural fibers have received the attention of many researchers. Natural fibers are biodegradable, abundantly available and low cost. Also, they exhibit low abrasion properties which makes them suitable for various processing and recycling [18]. Natural fibers, on the other hand, have high water affinity as well as inferior mechanical strength as compared to synthetic fibers [14]. Hence, to benefit from the advantages of both fibers, natural fibers combined with synthetic fibers could offer an alternative solution that will provide appropriate mechanical strength, tribological characteristics, and also cost benefit over synthetic composites.

In many applications, the requirement for strength, impact resistance, along with stiffness are important. Also, some other factors, such as low cost, sustainability, and noise reduction, are becoming important. To achieve this, some trade-off between performance and property is required [13]. The mechanical properties of a hybrid composite depend on the type and property of the matrix used, the orientation of fibers with respect to the matrix, the amount or volume of fibers used, the stacking sequence of fibers, etc. [18].

Flexibility, light weight and good formability of hybrid composites have also attracted many researchers for the use of hybrid composites in electromagnetic interference (EMI) shielding applications [19]. EMI shielding depends upon the type of material used as matrix, the type and architecture of the yarn in the fabric, the layer architecture in a multilayer composite, the type of fiber used for reinforcement, etc.

Both natural and synthetic materials have been used to replace some body parts of living beings. Metals and ceramics are known for their strength, ductility, resistance to wear, etc., but metals have poor biocompatibility and corrosion resistance. Whereas, ceramics, although they exhibit fairly good biocompatibility and corrosion resistance, are brittle in nature. Hence, polymer biocomposites provide a better alternative for the replacement of human body parts as they not only have good biocompatibility and corrosion resistance, but they are easy to fabricate [20]. Polymer composites also have superior toughness, which prevents the fabricated parts from crack propagation.

FABRICATION TECHNIQUES OF HYBRID COMPOSITES

Hand Lay-up Technique

Hand Lay-up is an easy to operate and cost-effective method used to fabricate hybrid composites. Initially, epoxy and hardener are merged in the ratio as suggested by the supplier and are stirred for 5 min so as to get a uniform mixture. Then, after applying mold releasing gel into the mold, a peel ply is kept in it [21]. Now, depending on the sequence, the desired synthetic fiber or natural fiber is placed, followed by the application of epoxy with the help of a brush. Next, the fiber is placed on it and the roller is rolled so that the mixture is distributed uniformly and excess mixture is removed. This process is repeated until stacking of the desired thickness is achieved. The top of the mold is covered with polyester sheet and the composite stacking, along with the mold, is placed under a hydraulic press at room temperature for 0.5 MPa [14] or some heavy weight is added at the top so as to compress the stacking to the desired size [22]. Fabricated hybrid laminates are cured at room temperature for 24 to 48 hours Also, they can be cured at 0.5 MPa pressure and room temperature (20°C) utilizing a vacuum molding process for a minimum of 7 hours [23]. A schematic diagram of a very basic hand layup method is shown in Figure 1.

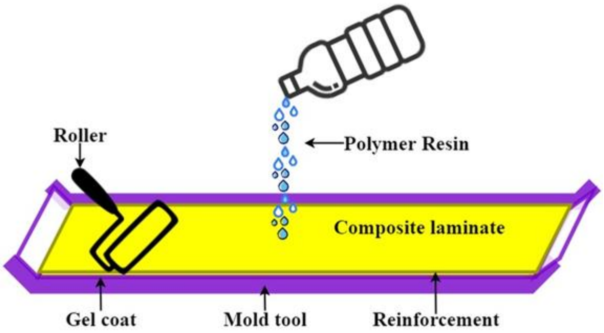

Figure 1. Block diagram of a basic hand layup method

Injection Molding

In the injection molding process, fibers that are being used as reinforcement are ground into small particles, screened to a size of 60 to 80 microns, [17, 24] and dried in an oven to remove moisture content. They are then fed into the hopper of a single screw extruder. The screw speed is usually kept at 100 rpm. For twin screw extruders, a speed of usually 250 rpm is set and the barrel temperature profile ranges from feed throat to nozzle of 149°C, 171°C, 177°C, 182°C and 188° [16, 25].

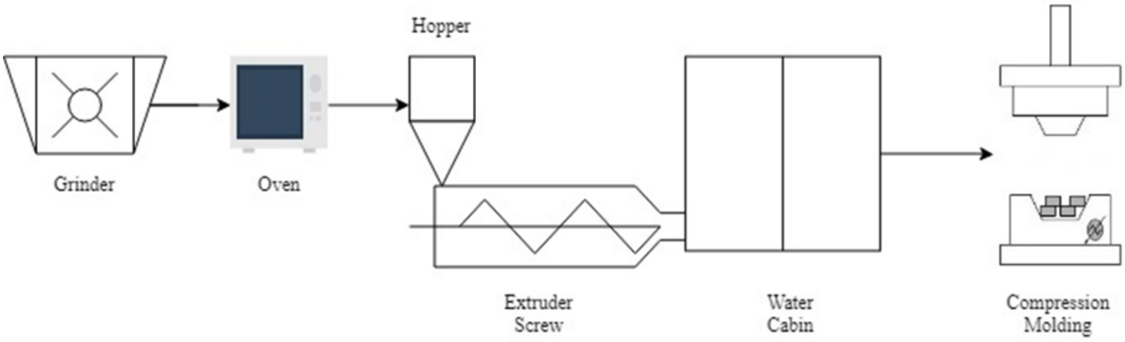

Figure 2.1. Injection molding process

The reciprocating screw pushes the material through the runner system. The polymer melts during its flow through the barrel due to heat conduction and forces the material into the relatively cold cavity of the mold until the mold is completely filled, taking care of the shrinkage due to cooling by supplying additional material through the screw under pressure. The mixture coming out of the barrel is passed to a water cabin where it gets cooled and pelletized. Pellets are then fed to a hot press where they get compression molded.

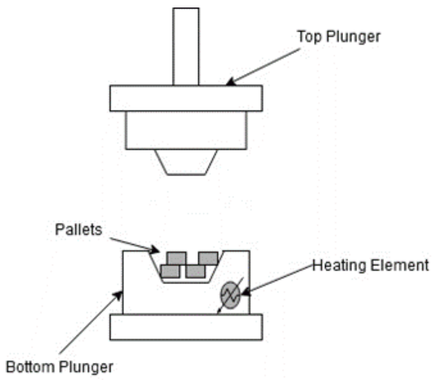

Figure 2.2. Block diagram of hot press compression molding

Compression molding basically involves a two-part mold. Pallets are fed to the lower mold and pressure is applied through the upper mold at about 45 MPa and cured at a temperature of 175°C for 3 min [17, 24].

High Performance Discontinuous Fiber (HiPerDiF)

In the HiPerDiF method, fibers are first immersed in water, which then passes through a nozzle into a gap formed by two parallel plates. Following this, they impact the plate held vertically following the passing of two parallel plates, where a change in momentum of water suspended fibres occurs, and they fall onto a conveyor belt where water is absorbed and aligned fibres are exposed to infrared radiation to dry.

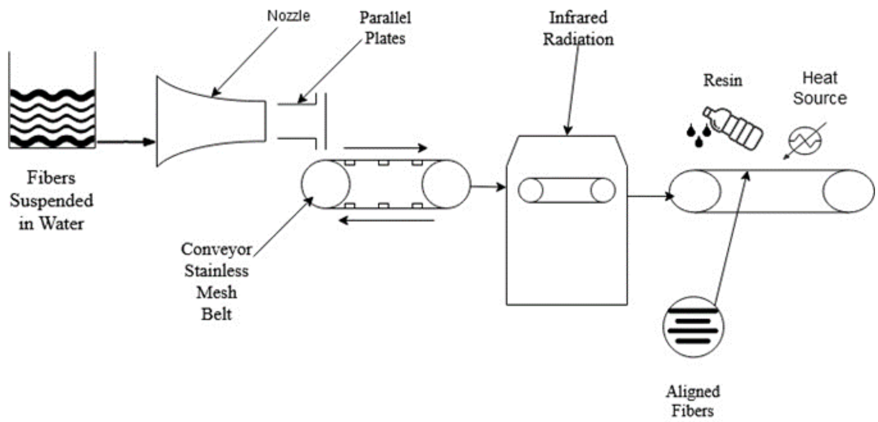

Figure 3. Block diagram of HiPerDiF process

Aligned fibres are now impregnated through a resin coating. All of these resin tapes are manually stacked to achieve the appropriate thickness, placed in a semi-closed mould, and the entire assembly is maintained in a vacuum bag to cure at 135 °C in an autoclave for 135 minutes at a pressure of 6 bar [26]. In an autoclave, the moulded component is placed in a plastic bag and vacuum pressure is applied to remove the trapped air, followed by heat and inert gas pressure, which cures the moulded parts.

Vacuum Assisted Resin Infusion (VARI)

VARI is a cost-effective technology for creating large-scale composite parts such as aeroplane structures, wind turbines, and so on. The fibres are dried in an oven at 70 ° C for three hours [27]. The fibres are then held between two metal plates on the Universal Testing Machine (UTM) at constant temperature and pressure during the hot compaction process.

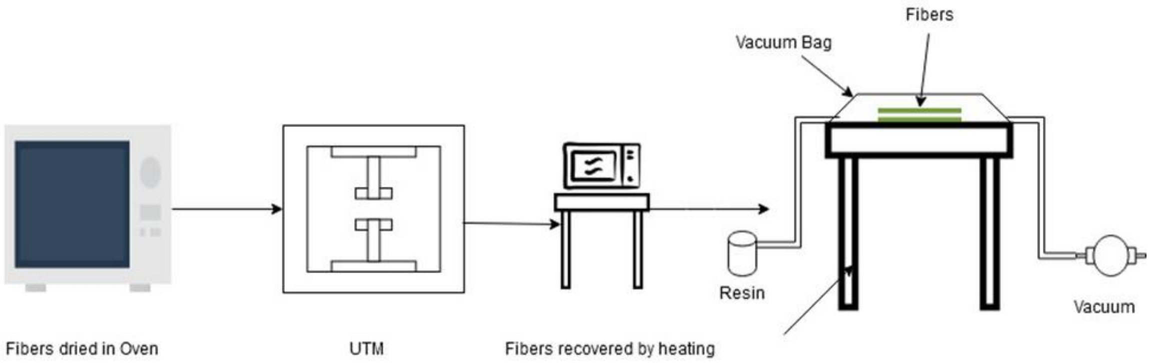

Figure 4. Block diagram of VARI process [27]

The UTM is equipped with a special compression clamp and a temperature-controlling unit. The pre-compacted fibers are recovered at 25 °C without any external pressure for about an hour and placed in a one-sided mold. The mold is sealed with a vacuum bag and resin is inserted into the fibers using vacuum pressure and then cured in an oven at 70 °C for a period of 6 hours.

Pultrusion Process

The Pultrusion process is used to produce parts having good dimensional tolerances [28]. It is a continuous process in which preheated fibers are carried through a liquid resin bath. These wetted fibers are now carried through the cooling die with the help of the puller to get the finished product.

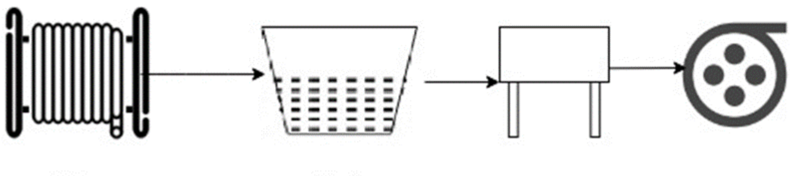

Figure 5. Pultrusion process [28]

The shape and size of the die decides the final shape of the composite, which is usually in the form of rods or bars. The puller also controls the finishing of the product by controlling the speed of the fiber pulled through the die. A palletizing system can be used to cut the end product as per requirement. The composites made using the pultrusion method usually have high strength due to high fiber content [29].

Sheet Molding Compound (SMC)

The SMC process incorporates two resin sides, namely side-A and side-B. Side-A contains unsaturated polymers, additives, diluents, mold release agents, fillers, etc. Whereas, side-B contains monomer, alkaline thickener material, carrier resin, etc. [30]. Mixtures on both side-A and side-B are carried through a thin plastic film. The thickness of the film is controlled by using a blade of adjustable height and is held above the thin plastic support film carrying the resin mixture. Fibers are chopped and laid on the resin paste in a downstream direction after passing through side-A. The speed of the support film controls the percentage of fiber. For this purpose, synchronization between the translation speed of support film and fiber chopping can be set up [31]. Resin paste from side-B is laid above chopped fiber in the downstream direction, which creates a sandwich pattern of resin and fiber which is further passed through a roller set, thereby compressing the resin and fibers, hence wetting the chopped fibers with resin. Grooves are provided on the rollers so that the air entrapped within the layers is removed by compression and this compressed sheet of resin and fibers is then collected onto a roller and stored.

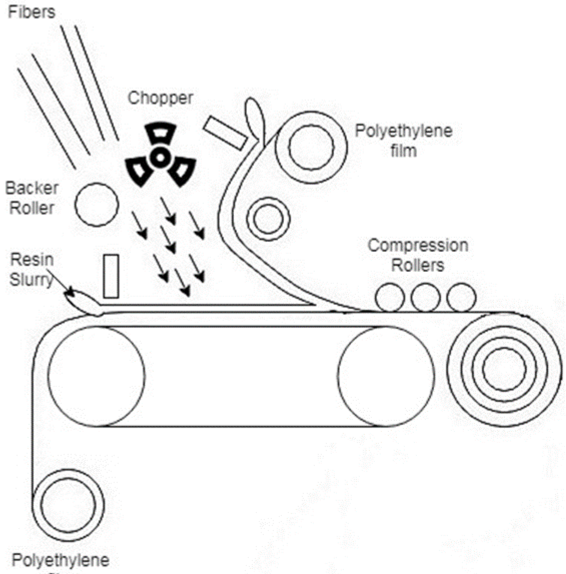

Figure 6. Sheet molding compound [30]

CHALLENGES OF HYBRID COMPOSITES MANUFACTURING TECHNIQUES

The hand lay-up technique, although simple, involves low initial cost, but as performed manually, it is labour intensive and requires more cycle time, which results in a decreasing production rate. Inconsistent fiber orientation results in poor surface finish of layers, which in turn results in weak bonding between the layers, giving poor dimensional tolerance [32]. Skilled labour is required for proper mixing of resins, amount of resin required for each laminate, quality of laminate, etc. But still, the laminate is usually fabricated with excessive void content, limiting the mechanical strength and other properties [33].

Injection molding reduces material wastage to a great extent, but some problems occur when it comes to dimensional accuracy or mechanical properties of the material due to residual stresses. Residual stresses could be due to flow induced or thermally induced. Also, due to inhomogeneous cooling, defects such as shrinkage and stress cracks occur. These problems are usually observed in thin walls and can be minimized by using proper design parameters and molding [34].

The vacuum assisted resin infusion process involves non-reusable parts such as vacuum bags, peel ply, flow distribution medium, resin tubing, seal tape, etc. There is a chance of air leakage caused by unskilled workers or the quality of consumables used, which may lead to dry spots and incomplete resin infusion [35]. Due to the limitation of pressure used between atmospheric pressure and vacuum, the fiber volume fraction is limited. Other drawbacks include the process requires many tools as well as infusion pressure is inefficiently controlled, leading to decreased flow of resin, which further leads to accumulation of resin at the centre [36].

The pultrusion process can be used for composites with constant cross section, but twisted and tapered cross sections are very difficult. Also, although the 'I' section and other solid cross sections are possible, hollow parts are difficult to fabricate [32]. This inability to fabricate intricate shapes limits the volume output of fabricated parts. Also, the necessity of large, automated equipment increases the initial investment required, while the cost of heating of drawing die may also add to production costs [37].

Sheet Molding Compound is cost-effective and can fabricate complex shapes, but low fiber volume fraction and short fiber length lead to low stiffness and strength of fabricated parts [38]. Also, variations in rheological properties and continuous thickening of the paste impact the effectiveness of the curing reaction. Variations in cooling of molding parts, if not controlled properly, may lead to some geometric distortions [39].

MECHANICAL BEHAVIOUR OF HYBRID COMPOSITES

Tensile Strength

Tensile strength is one of the measures of mechanical properties of the material which provides the value of the resistance offered by the material when loaded in tension. In the case of fiber reinforced composite materials, the value of tensile strength is governed by the stiffness of the fibers. Amongst the natural fibers, flax fibers are known to be among the strongest and stiffest natural fibers, possessing acceptable mechanical properties and having the capacity to replace synthetic fibers such as glass. The properties of hybrid composites where flax fibers are used along with carbon fibers were studied by Kureemun et al. [13]. A tensile strength of 232.5 MPa was obtained in a hybrid composite with a carbon fibre content of 14%. Nisini et al. [40] investigated ternary hybrid composites reinforced with carbon, flax, and basalt fibres. Sandwich and intercalated sequences were employed as stacking sequences. Carbon fibres are utilised as outer layers in both kinds. The tensile test indicated that the strength of both composites was almost identical, with values of 189.23 MPa and 185.24 MPa, respectively.

Jute fibers are also among the high-performing natural fibers, having a high value of specific strength as well as modulus. Ramana et al. [14] carried out an investigation, comparing the properties of the carbon/jute fiber epoxy composite with the epoxy composites made of carbon and jute fibers separately. The tensile strength of the carbon/jute epoxy composite was found to be 213.02 MPa, i.e. 16 times greater as compared to the jute/epoxy composite. Wang et al. [15] used carbon and jute fiber reinforcements in the vinyl resin matrix. On comparing tensile and bending properties of Jute fiber vinyl composites (JVC) and Jute-carbon fiber vinyl composites (JCVC), it was found that JCVC absorb more energy under tensile test. Also, tensile modulus of JCVC is enhanced due to addition of carbon fiber. Carbon nano fillers and Jute fibers have been used by Saiteja et al. [22] to prepare hybrid composite. It was found that a hybrid composite consists of fixed volume % of jute and 6 volume % of CNT exhibited tensile strength of 36 MPa. Beyond this value of CNT, the tensile strength seems to be decreasing. The effect of sequencing of carbon fiber layers and jute fiber layers on the tensile behaviour of Polyvinyl Butyral (PVB) hybrid composite was studied by Salman et al. [41]. They observed the best tensile strength (469.95 MPa) when carbon fiber layers are placed at the outer layers of the hybrid composite. On the other hand, a slight reduction in tensile strength (455.38) was observed when one side outer layer is carbon and another side outer layer is jute. A similar study was also conducted by Khalid et al. [21] on Epotecyd 128 epoxy hybrid composite. They found maximum tensile strength of 257.6 MPa when carbon layers reside at the apex edges of the hybrid composite. The exact studied sequencing of the reinforcements are Carbon-Carbon-Jute-Carbon-Carbon. The pressure used in the curing process during composite manufacturing has also been seen to have an impact on its mechanical properties. Ashworth et al. [42] studied the effect of curing pressure on the tensile strength of Carbon-Jute hybrid composite. They varied the curing pressure from 4 to 8 bar of the hybrid composite specimens, the specimens prepared at 4 bar curing pressure showed maximum tensile strength (98.2 MPa) whereas those at 8 bar pressure were found to have lower tensile strength (92.4 MPa). The possible reason for this difference could be increase of void content or probable damage of natural fiber at high pressure [42].

Some researchers observed that adding glass fiber to carbon/jute epoxy hybrid composite further improves material properties such as tensile, flexural, impact, etc. El-baky et al. [43] performed experimentation on the stacking sequences of jute/carbon/glass fibers into epoxy hybrid composites. They discovered that adding high-strength fibres to the composite's outer layers increases flexural resistance, but the sequence of the layers had no effect on tensile characteristics. Patel et al. [18] investigated the characteristics of a hybrid composite reinforced with alkali-treated and acrylated jute fibres and carbon fibres. They discovered that this combination had better mechanical and electrical characteristics. This might be because acrylation drastically reduces the water absorption capacity of jute fibres.

Sisal fiber also represents one of the promising alternatives for reinforcement for hybrid composites along with carbon fibers. Aslan et al. [17] looked at the possibility of utilising natural fibres in tribo-composites as a viable alternative to synthetic fibres. They found that sisal and carbon fibre hybrid polypropylene (PP) composites had inferior mechanical characteristics and a higher coefficient of friction. The sisal and glass hybrid PP composite, on the other hand, demonstrated superior tribological characteristics and comparable mechanical characteristics. The best characteristics were obtained in both scenarios when 25 wt% sisal and 75 wt% carbon or glass were used as reinforcements. Tufan et al.

[24] investigated the tensile, flexural, and thermal characteristics of sisal-carbon hybrid composites. Their findings revealed that raising the weight ratios of carbon fibre in hybrid composites enhanced biological durability, mechanical, and thermal characteristics. In their investigation, the hybrid composite composition of 12% sisal fibre, 28% carbon fibre and 60% recycled polypropylene yielded the best mechanical performance. The mechanical characteristics of untreated and 18% NaOH boiled sisal/carbon hybrid composites were investigated by Khanam et al. [44]. According to their findings, the increased carbon fibre content in hybrid composites improved tensile and flexural characteristics. In addition, they observed that 18% NaOH boiled sisal/carbon fibre reinforced hybrid composites outperformed untreated sisal/carbon fibre reinforced hybrid composites in terms of tensile and flexural properties. This is because alkali treatment enhances the adhesive properties of fibre surfaces.

Kenaf fibre is a well-known natural fibre that is utilised as a reinforcement in polymer matrix composites. Hibiscus cannabimus L., often known as kenaf, is a herbaceous annual plant that thrives in a variety of climates. Sapiai et al. [45] examined the tensile and compressive characteristics of hybrid composites reinforced with kenaf and carbon fibre. Kenaf fibres were oriented in either the longitudinal (0°) or transverse (90°) orientations in these composites. Good results were obtained when 0° unidirectional kenaf fibres were used for hybridization.

Hemp (Cannabis sativa L.) fibres are a strong member of the natural fibre family that are generated from the hemp plant, which belongs to the Cannabis species. Because of their biodegradability and low density compared to artificial fibres, these fibres are now widely used as reinforcements in composite materials. Shah et al. [25] investigated the mechanical characteristics of a hybrid composite made up of hemp fibre and recycled carbon fibre. The use of recycled carbon fibre reduced mechanical variability, while maleic anhydride treatment of hemp fibre boosted interfacial adhesion, resulting in improved mechanical characteristics. The mechanical behaviour of Wood-Carbon Fiber Polypropylene Hybrid Composites was studied by Kada et al. [16]. Tensile strength, flexural strength, and modulus of elasticity all improved. However, there was little effect on impact strength and break elongation.

The melt of basalt stones can be used to make basalt fibres. Basalt fibres are classified into two types: staple fibres and filaments. Basalt fibres offer a lot of promise for application in fiber reinforced polymer hybrid composites (FRPC) because they have strong mechanical characteristics, minimal water absorption, and good chemical resistance. Bozkurt and Gokdemir [46] discovered that incorporating basalt fibre into carbon fiber/epoxy composites resulted in a significant change in tensile characteristics. With an increase in the basalt fibre volume percent, tensile strength and modulus dropped, but tensile strain increased.

Table 1. A comparative study of tensile properties of various hybrid composites

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Tensile Strength (max) MPa
[13]	Epolam 5051	Carbon	Flax	Vacuum Assisted Resin Infusion	232.5
[40]	CR83 epoxy and CH83-2 hardener	Carbon	Flax	Hand Lay-up + Vacuum Bagging Technique	189.23
[14]	Araldite LY-5560 epoxy and K-5200 hardener	Carbon	Jute	Hand Lay-up Technique	213.02
[15]	Vinyl ester resin	Carbon	Jute	Vacuum Assisted Resin Transfer Molding	95.63
[22]	LY-556 epoxy and HY-951 hardener	Carbon	Jute	Hand Lay-up Technique	36
[41]	Polyvinyl Butyral	Carbon	Jute	Hot Press Technique	464.95
[21]	Epotecyd 128 epoxy and K-5200 hardener	Carbon	Jute	Hand Lay-up Technique	257.6
[42]	DR2188 epoxy and HY2188 hardener	Carbon	Jute	Resin Transfer Molding	98.2
[43]	Kemapoxy 150 RGL	Carbon	Jute	Hand Lay-up Technique	111.37
[18]	Bisphenol-C and Bisphenol-C formaldehyde	Carbon	Jute	Hand Lay-up Technique	14.65

Table 1. A comparative study of tensile properties of various hybrid composites (cont.)

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Tensile Strength (max) MPa
[17]	Polypropylene	Carbon	Sisal	Screw Extrusion Process + Compression Molding	17.1
[24]	Polypropylene	Carbon	Sisal	Screw Extrusion Process + Compression Molding	17.25
[44]	Polyester resin and Methyl ethyl ketone peroxide	Carbon	Sisal	Hand Lay-up Technique	107.51
[45]	Morcrete	Carbon	Kenaf	Vacuum Bagging	110.2
[25]	Polypropylene	Carbon	Hemp	Screw Extrusion Process + Injection molding	47.5
[16]	Polypropylene	Carbon	wood (poplar)	Screw Extrusion Process	52
[46]	MOMENTIVE-MGS L160 Epoxy and MOMENTIVE-MGS H160 hardener	Carbon	Basalt	Vacuum Assisted Resin Transfer Molding	585.08

Table 1 presents a comparative study of the tensile properties of hybrid composites based on variations in reinforcements, matrices used, and fabrication techniques. Table 1 illustrates that when the same reinforcements are employed in different matrices, they exhibit varied tensile characteristics. This is also true for the use of diverse manufacturing processes. Apart from all this, the layers of reinforcement, their kind, configuration, and arrangement, etc., play a crucial influence in determining tensile characteristics as well.

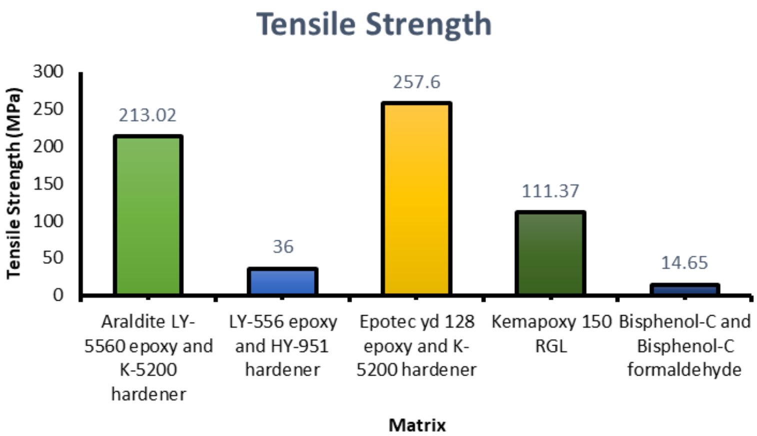

Figure 7. Tensile properties of carbon-jute epoxy hybrid composites fabricated using hand lay-up technique

On the basis of the polymer matrix employed, Figure 7 compares the tensile characteristics of hybrid composites that use carbon and jute fibres as reinforcement. The polymer matrix utilised has an impact on tensile characteristics, as indicated in the diagram. In the comparison, the composite using the polymer Epotecyd 128 epoxy and K-5200 hardener had the maximum tensile strength. The appropriate percentage of carbon fibre and natural fibres utilised also influences tensile strength. Ramana et al. [14] used 22 wt% of carbon and 23 wt% jute fiber, whereas, Khalid et al. [21] used 33.8 wt% of carbon and 8.2 wt% jute fiber for which they obtained tensile strengths of 213.02 MPa and 257.6 MPa respectively. Because carbon fibre has a higher tensile strength than jute fibre, the percentage of carbon fibres utilised determines the composite's tensile strength. Furthermore, the void content of manufactured FRPC affects its tensile characteristics significantly. The development of voids is caused by incomplete wetting of fibres with epoxy resin. This might be owing to natural fibres' hydrophilic nature, which renders them epoxy incompatible. As a result, the void content rises with the amount of natural fibre used [43]. Air entrapment during fabrication and curing owing to relative movement of fibre and resin might potentially result in an increase in void content [21].

Flexural Strength

Flexural strength is one of the parameters used to determine the mechanical strength of composites. It refers to the greatest bending stress that a material can withstand. Ramana et al. [14] discovered that by substituting half of the fibre content in a jute-epoxy composite with carbon, the flexural strength improved fourfold. The flexural modulus of jute/carbon FRPC is somewhat lower than that of carbon-epoxy composite. Jute fibre and carbon nanotube reinforced hybrid composites were investigated by Saiteja et al. [22]. At 8 volume % CNT, flexural strength was observed to improve to 22 MPa. Wang et al. [15] also discovered that the addition of carbon fibre improves the flexural toughness of hybrid reinforced composites. El-baky [43] observed that adding high-strength fibres onto the composite's outer layers improves flexural resistance. According to Patel et al. [18], alkali treatment and the acrylation technique enhanced the flexural strength of a Jute-Carbon reinforced epoxy composite. Changes in the chemical composition, crystallinity, strength, and surface modification of the fibres provide an increase in flexural strength after alkali treatment and acrylation. When comparing Jute-Carbon laminates to Jute-Glass and Plain Jute laminates Murdani et al. [47] discovered that Jute-Carbon laminates have the highest flexural strength.

Sisal fibres are produced from the leaves of the sisal plant (Agave sisalana) and have a high strength. Aslan et al. [17] discovered that a hybrid ratio of 25/75 in total mixed fibre by weight yields a flexural strength of 36.9 MPa for Sisal and Carbon fibre reinforced composites. The flexural characteristics of sisal carbon hybrid composites were investigated by Tufan et al. [24]. Their findings revealed that when the weight ratios of carbon fibre in hybrid composites increased, flexural strength improved. The mechanical testing revealed that the best hybrid composite composition was 12% sisal fibre + 28% carbon fibre + 60% rPP. Khanam et al. [44] reported that 18% NaOH boiled sisal/carbon fibre reinforced hybrid composites had better flexural characteristics than sisal/carbon hybrid composites that had not been treated.

Shah et al. [25] investigated the mechanical characteristics of a hybrid composite composed of a polypropylene (PP) matrix with recycled-carbon fibre and hemp reinforcements. They observed a 30-35 % improvement in flexural strength when hemp was employed as a reinforcement in hybrid composites with recycled carbon fibre.

Polypropylene-Wood-Carbon Fiber Hybrid Composites were investigated by Kada et al. [16] for their mechanical characteristics. They discovered that a hybrid composite composed of 40% poplar wood fibre, 9% carbon fibre, 48% PP, and 3% Maleic anhydride grafted Polypropylene (MAPP) had the highest flexural strength of all the compositions tested. Borukati et al. [48] investigated polymer hybrid composites reinforced with Sansevieria Trifasciata and carbon fibre and discovered that hybrid composites produced with 40% Sansevieria Trifasciata and 60% carbon fibre had up to 25% higher flexural strength than other analysed compositions.

In their work, Bachmann et al. [49] discovered that combining flax fibres with a small amount of recycled carbon fibre (rCF) resulted in a substantial boost in the flexural mechanical characteristics of epoxy hybrid composites when compared to composites reinforced simply with flax fibres. It has also been observed by them that when rCF is placed in the outer layers of the laminate, the flexural mechanical properties are further enhanced. Dhakal et al. [50] discovered that carbon prepegs hybridised with flex had higher flexural strength. The elongation at break was also shown to be significantly improved in this composition. Nisini et al. [40] investigated ternary hybrid composites composed of carbon, basalt, and flax fibres in an epoxy matrix. They found better flexural strength in a configuration with carbon fibers on the outside and basalt and flax fibers in an intercalated sequence on the inside.

Table 2. A comparative study of flexural properties of various hybrid composites

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Flexural Strength (max) MPa
[14]	Araldite LY-5560 epoxy and K-5200 hardener	Carbon	Jute	Hand Lay-up Technique	380
[22]	LY-556 epoxy and HY-951 hardener	Carbon	Jute	Hand Lay-up Technique	22
[15]	Vinyl ester resin	Carbon	Jute	Vacuum Assisted Resin Transfer Molding	80.33
[43]	Kemapoxy 150 RGL	Carbon	Jute	Hand Lay-up Technique	94.58
[18]	Bisphenol-C&Bisphenol-C formaldehyde	Carbon	Jute	Hand Lay-up Technique	19.33
[17]	Polypropylene	Carbon	Sisal	Screw Extrusion Process	36.9
[24]	Polypropylene	Carbon	Sisal	Screw Extrusion Process	36.92

Table 2. A comparative study of flexural properties of various hybrid composites (cont.)

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Flexural Strength (max) MPa
[44]	Polyester resin and Methyl ethyl ketone peroxide	Carbon	Sisal	Hand Lay-up Technique	169.14
[25]	Polypropylene	Carbon	Hemp	Screw Extrusion Process	47.5
[16]	Polypropylene	Carbon	wood (poplar)	Screw Extrusion Process	70
[49]	Epikote RIMR135 epoxy and RIMH 1366 curing agent	Carbon	Flax	Single Line Infusion Method	286.7
[50]	--	Carbon	Flax	compression molding	319
[40]	CR83 epoxy and CH83-2 hardener	Carbon	Flax	Hand Lay-up + Vacuum Bagging Technique	286.67

Table 2 compares the flexural characteristics of hybrid composites depending on reinforcements, matrix types, and manufacturing procedures. Table 2 shows how the same reinforcements display various flexural properties when used in different matrices. This is also true when it comes to the usage of various processing techniques. Aside from that, the reinforcing layers, their kind, design, and arrangement, and so on, all have a significant impact on flexural properties.

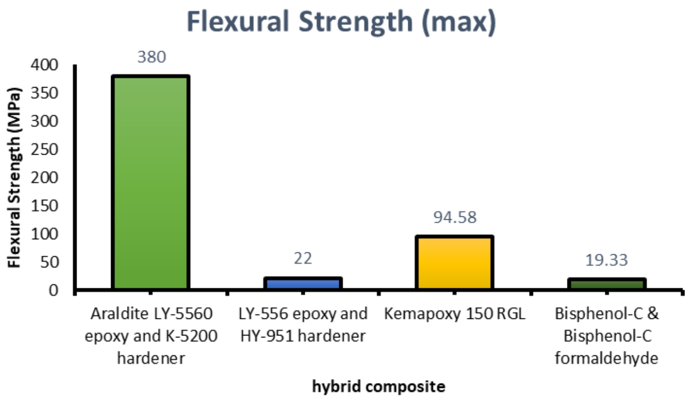

Figure 8. Flexural properties of carbon-jute FRPC fabricated using hand lay-up technique

Figure 8 depicts a comparison of the flexural strengths of hybrid composites composed of identical reinforcements but different matrices. Carbon and jute were employed as common reinforcement in all hybrid composites. It is clearly seen from the analysis of Figure 8 that using Araldite LY-556 epoxy as a matrix has been found to have better flexural strength. The amount of carbon content used in hybrid composites also plays an important role in defining flexural strength. A simple example of this can be taken from the studies done by Ramana et al. [14] and El-Baky et al. [43]. Ramana et al. [14] obtained a flexural strength of 380 MPa from a hybrid composite composed of 22 wt% carbon fiber, 23 wt% jute fiber and 55 wt% polymer matrix, whereas El-Baky et al. [43] obtained a 94.58 MPa flexural strength from a hybrid composite composed of 7.76 wt% carbon fiber, 15.52 wt% jute fiber and 76.72 wt% polymer matrix. Here, the flexural strength of the hybrid composite is found to be enhanced due to an increase in carbon fibre content. Apart from this, the value of flexural strength also depends upon the stacking sequences of reinforcement layers and, in the majority of cases, the flexural strength is reported to be high when carbon fiber layers are arranged on the outer layers of the hybrid composite configurations [43].

Impact Strength

Impact strength refers to a material's ability to withstand the energy generated or transferred when a load is suddenly applied to it. The impact strength of hybrid composites comprised of synthetic and natural fibres is typically higher than that of composites composed largely of natural fibres. In comparison to composites produced solely of flax fibre, a hybrid composite comprised of flax and carbon fibre has greater impact strengths. Al-Hajaj et al. [51] investigated the impact properties of carbon fibre with flax (unidirectional or crossply) FRPC. These hybrid composite designs outperformed the flax reinforced composite in terms of impact properties. However, the crossply flex fibre hybrid composite outperformed the unidirectional flex fibre hybrid composite in terms of impact strength. Prakash et al. [52] used a cooling reaction on carbon-flax FRPC to identify damage in impact and post-impact fatigue cycled components. The specimen is heated in transmission and reflection mode using an infrared thermography method. When comparing the transmission and reflection modes, it was discovered that the transmission mode gives better defect detection. The impact characteristics of a ternary hybrid composite comprised of carbon, flax, and basalt fibre were investigated by Nisini et al. [40]. They discovered that composite samples with varied stacking sequences had almost equal impact strengths.

Ramana and Ramprasad [14] observed that the jute-carbon-epoxy hybrid composite exhibited 46% better impact strength than the carbon-epoxy composite. Saiteja et al. [22] investigated the impact strength of jute fiber-CNT reinforced hybrid polymer composites. They discovered that a hybrid composite with 6% CNT had the highest impact strength. According to Lenda and Mridha [53], the impact strength of the Jute-Carbon-Epoxy Composite was reduced in all specimens as moisture absorption increased. Furthermore, the higher fiber-content composites had lower impact strength in almost all test conditions.

When compared to recycled carbon fibre composites, hemp fibre composites have better impact properties. As a result, it is evident that the impact strength of hybrid composites decreased as the percentage of carbon fibre increased. Shah et al. [25] found that a hybrid composite consisting of 10% carbon fiber, 20% hemp fiber, 68% PP, and 2% MAPP showed a 30–35% increase in impact properties. Kada et al. [16] discovered that adding carbon fibres to wood plastic composites improves poplar fibre dispersion in the PP matrix, resulting in increased impact strength. The incorporation of 6% carbon fibres resulted in the highest impact strength.

Anuar et al. [54] conducted experiments to investigate the impact properties of kenaf and carbon FRPC. Although surface treatment of carbon fibres increased tensile, bending, and interlaminar shear strength, impact strength decreased. Carbon fibre surface treatment not only roughens the fibre surface but also makes it brittle and easily fractured. As a result, treated carbon fibres containing composites were found to have low impact strength.

Table 3. A comparative study of impact strength of various hybrid composites

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Impact Strength (max) KJ/m^2
[51]	Araldite LY 1564 resin &Aradur 22962 hardener	Carbon	Flax	Hand Lay-up Technique	507.15
[40]	CR83 epoxy and CH83-2 hardener	Carbon	Flax	Hand Lay-up + Vacuum Bagging Technique	73.62
[14]	Araldite LY-5560 epoxy and K-5200 hardener	Carbon	Jute	Hand Lay-up Technique	157.02
[22]	LY-556 epoxy and HY-951 hardener	Carbon nano fillers	Jute	Hand Lay-up Technique	1.2
[25]	Polypropylene	Carbon	Hemp	Screw Extrusion Process	7
[16]	Polypropylene	Carbon	wood (poplar)	Screw Extrusion Process	0.3

As shown in table 3, the value of impact strength is affected not only by the type of matrix used, but also by the percentage combination of natural and carbon fibres used in the composite. Because natural fibres have a higher impact property than carbon fibres, the greater the quantity of natural fibres, the higher the value of impact strength. Furthermore, the cross-ply arrangement of fibres in the composite improves the value of impact strength significantly when compared to the unidirectional arrangement of fibres [51].

Damping Property

Damping refers to a material's ability to absorb vibration and is one of the most important parameters to consider when designing hybrid composites for use in automobiles, aerospace, and other applications. Guen et al. [55] found that the flex-carbon hybrid composite had a damping coefficient four times higher than the carbon fiber composite. But despite having a better damping coefficient, it had weak elastic modulus and strength. Longana et al. [26] found that intermingled flax-recycled Carbon Fiber hybrid composites exhibited reduced levels of noise, vibration, and harshness (NVH). This type of hybrid composite is useful for applications where low primary mechanical properties are acceptable but high functional properties and cost reduction are required. Ameur et al. [23] conducted a damping investigation on the UD carbon/flax fibre hybrid composite. Both experimental and computational approaches revealed that the damping factor rises with frequency. Furthermore, the damping factor is affected by fibre orientation and flax fibre content. The vibration behaviour is also affected by the arrangement in which the carbon and flax fibres are stacked. Assarar et al. [56] investigated the influence of stacking sequence on the damping characteristics of flax and carbon FRPC. The study revealed that the bending modulus increases as the carbon fibre content increases, particularly when carbon fibres are utilised in the exterior layers of hybrid composites. The damping coefficient increases significantly with frequency when carbon fibres are placed as outer layers. When flax fibres are placed as outer layers, the damping coefficient decreases with frequency. Li et al. [57] studied the damping characteristics of carbon and flax FRPC utilising Bisphenol-A epoxy as the matrix material. It was discovered that using flax fibres in the outermost layers enhances the damping quality of the hybrid composite, making it equivalent to a flax fibre reinforced composite. Furthermore, when outer layers made of flax fibre are modified further by adding CNTs, damping qualities increase by 6% when compared to the outer layer composed of just flax fibre. Longana et al. [58] conducted a free vibration damping test on hybrid FRPC made of intermingled flax fibres and recycled carbon fibres. The damping coefficient was found to be dependent on flax fibre content, with the greatest damping coefficient being 1.43 % for a flax/reclaimed carbon fibre ratio of 75/25 %.

Murdani et al. [47] created hybrid composites with reinforcements made of jute, glass, and carbon fibre. The hybrid laminates were created by stacking jute clothes covered by one ply glass cloth and jute clothes covered by one ply carbon cloth. They discovered that increasing the amount of jute plies and hybridization have a detrimental impact on the damping ratio. Ashworth et al. [42] discovered that jute fibre reinforced polymers and hybrid jute-carbon fibre reinforced polymers had much higher damping than CFRP. Higher fabrication pressures appear to lower the damping ratio but also modify the strain dependency. This might be related to changes in the fiber-matrix bond. Sezgin et al. [59] examined the influence of varied jute and carbon fabric stacking sequences on the dynamic mechanical characteristics of composite laminates. According to their findings, the composite sample with carbon fabric on the outer layers had the maximum storage and loss modulus.

Bozkurt and Gökdemir [46] examined the impact of basalt fibre hybridization on the vibration damping of carbon fibre epoxy composites experimentally. Their findings revealed that incorporating basalt fibre into carbon fibre epoxy composites greatly improved damping characteristics. Damping characteristics were improved further by increasing the volume percentage of basalt fibre content.

Table 4. A comparative study of the damping behavior and strength of various hybrid composites

Reference	Matrix	Reinforcement 1	Reinforcement 2	Fabrication Technique	Elastic Modulus (max) GPa	Loss Modulus (max) GPa	Loss Factor %
[55]	diglycidyl ether of bisphenol A	Carbon	Flax	Compression Molding + Vacuum Bagging	14.9	0.0101	--
[26]	diglycidyl ether of bisphenol A & tetraglycidyl-4,4'-diaminodiphenylmethane (TGDDM)	Reclaimed Carbon	Flax	High Performance Discontinuous Fiber HiPerDiF	--	--	0.65
[23]	SR 1500 epoxy and SD 2505 hardener	Carbon	Flax	Hand Lay-up Technique	--	--	2.1
[56]	SR 1500 epoxy and SD 2503 hardener	Carbon	Flax	Platen Press Process	50	--	18
[57]	Bisphenol-A epoxy	Carbon	Flax	--	38.64	--	2.05
[58]	MTM49-3 epoxy	Carbon	Flax	High Performance Discontinuous Fiber	--	--	1.43
[47]	Polyester	Carbon	Jute	Vacuum Infusion Technique	31	--	6.5
[42]	DR2188 epoxy and HY2188 hardener	Carbon	Jute	Resin Transfer Molding	33.7	--	0.87
[59]	Polyester and Methyl ethyl ketone Peroxide hardner	Carbon	Jute	Vacuum Bagging	14	2	0.45
[46]	MOMENTIVE-MGS L160 Epoxy and MOMENTIVE-MGS H160 hardener	Carbon	Basalt	Vacuum Assisted Resin Transfer Molding	27.78	3.27	8.33

As shown in table 4, damping characteristics are affected by the volume proportion of carbon and natural fibres utilised, as well as the stacking order of fibre layers. Assarar et al. [56] used a volume fraction ratio of 40/12 for carbon and flax fibre to obtain a maximum bending modulus of 50 MPa using carbon fibres in the outer layer, whereas Li et al. [57] used a volume fraction ratio of 35/25 for carbon and flax fibre to obtain a maximum bending modulus of 38.64 MPa using flax fibres in the outer layer modified by the addition of CNTs. The values of the loss factor depend largely on the types of natural fibers used and the stacking sequence of fibers used in the composite. Assarar et al. [56] utilised three outer layers of flax fibre while Bozkurt et al. [46] used five outer layers of basalt fibre to achieve loss factors of 18% and 8.33%, respectively. On the other hand, Murdani et al. [47] utilised alternate layers of Jute and Carbon fibres to achieve a loss factor of 6.5%.

OTHER PROPERTIES OF HYBRID COMPOSITES

Thermal Stability

Thermal gradients are unavoidable in situations where composite materials are generally employed. The influence of temperature gradients on composite performance in such an environment is critical. Under these service conditions, the layers of composite material tend to expand or contract but are constrained by neighbouring reinforcement layers. As a result, it causes thermal strains. Apart from that, during polymer matrix composite manufacturing, thermal cycles for matrix curing are frequently used. A typical cycle comprises increasing the temperature to a particular level, maintaining it there for a set amount of time, and then lowering it to the ambient temperature. It is widely known that the coefficients of thermal expansion of reinforcements and matrix materials differ. Owing to this mismatch in coefficients of thermal expansion, residual thermal stresses were generated. These thermal stresses may cause issues during the application stage. Therefore, the thermal stability of the composites must be investigated. Tufan et al. [24] investigated the heat deterioration of sisal carbon hybrid composites. They discovered that hybrid composites outperformed sisal fibre composites in terms of biological performance. The thermal stability of the hybrid composite has increased substantially with the inclusion of carbon fibre. Increased carbon fibre content improved the thermal decomposition values of the hybrid composites.

Dhakal et al. [50] studied the thermal degradation behaviour of carbon-flax hybrid composites. They discovered that adding carbon fibre to the hybrid composite enhanced its thermal stability. Lower weight loss rates were achieved when carbon fibre hybridization was used on flax prepreg composites. Carbon fibre hybridised composites also produced more residual char than flax prepreg composites.

Chemical Resistance

The ability of a material to withstand a chemical attack for a particular period of time can be characterised as chemical resistance. Thus, chemically resistant materials are less prone to corrode. In the case of plastics, chemicals can attack the polymer chain by oxidising functional groups on the chain or depolymerizing it. Chemicals might cause the polymer to expand or soften. Stress cracking can also be caused by certain chemicals. Therefore, it is necessary to study the chemical resistance of the polymer composite. Khanam et al. [44] revealed that untreated and alkali-treated sisal-carbon fibre hybrid composites are resistant to all chemicals except carbon tetrachloride. Jawaid et al. [60] investigated the chemical resistance of jute and oil palm empty fruit bunches reinforced FRPC to chemicals such as benzene, H2O, NaOH, and others. The manufactured composite did not lose weight in any of the cases, suggesting that no erosion had occurred. Jute fibre was also shown to greatly enhance the chemical resistance of the hybrid composite. Kumar et al. [61] studied the chemical resistance characteristics of sisal and glass FRPC. The effects of different acids and solvents on both untreated and alkali-treated fibres were studied. Weight growth in the majority of the samples revealed that the hybrid composites are resistant to different chemical reagents, with toluene and sodium carbonate being the exceptions. Reddy et al. [62] examine the influence of solvents, alkalis, and acids on kapok and sisal FRPC. When soaked in carbon tetrachloride, both untreated and alkali-treated hybrid composite samples lost weight. Weight increase was observed when those hybrid composites were submerged in acids and alkalis, suggesting chemical resilience. As a result, with a few exceptions, such as carbon tetrachloride, toluene, sodium carbonate, and so on, carbon and natural FRPC may provide high resistance to a wide range of chemical reagents.

Electrical Properties

Hybrid reinforcement can increase the electrical characteristics of polymers as well. Patel et al. [18] fabricated Jute Carbon FRPC using bisphenol-C as the matrix. They discovered that using alkali-treated jute fibres as reinforcements rather than untreated jute fibres enhanced the electrical strength of hybrid composites.

DEGRADATION OF HYBRID COMPOSITES

As natural fibers are susceptible to biodegradation, their effect on hybrid composites when subjected to different applications needs to be considered. The following points illustrate the effect of various factors on hybrid composites.

Moisture effect

The absorption of water in hybrid composites depends upon temperature, orientation of reinforcement in the matrix, area of the surfaces exposed, diffusivity, fiber volume fraction, permeability of fibers, etc. [63]. Moisture absorbed in the interfacial region is the reason for the decrease in interfacial strength of the epoxy matrix and fiber that is affecting performance. The interlocking between fiber and matrix is affected during cooling of the specimen due to moisture induced swelling as well as a difference in thermal expansion of fibers and matrix. [64]. Although carbon fibers show impermeability to moisture, the epoxy matrix is permeable. This leads to changes in the glass transition temperature of the epoxy matrix due to plasticization on exposure to moisture, affecting the performance of the composite. In the case of natural fiber, the hemicelluloses in the plant cell wall absorb moisture. This hydrophilic nature of natural composites decreases the tensile and flexural strength of the composites with an increase in fiber content. Venkateshwaran et al. [65]

investigated moisture absorption in sisal and banana fibre composites. It was discovered that adding sisal fibres to the banana-epoxy composite by 50% resulted in a reduction in moisture absorption. Amiri et al. [66] investigated the influence of rapid weathering on the mechanical characteristics of flax FRPC. The mechanical characteristics of all composite samples were found to be decreasing. Tensile characteristics of untreated flax fibre reinforced composites were reduced by 63% owing to moisture absorption. When alkaline treated flax fibres were employed as reinforcement, the tensile strength was reduced by 46% owing to moisture. Bajuri et al. [67] conducted experiments for water absorption tests on silica/ kenaf hybrid composites by using two fabrication methods namely, Hot Press Method & Impregnation method. The components fabricated using impregnation method were found to absorb less water with composites made using 5% silica & 60% kenaf having lowest water absorptivity. Except for flexural strength, other characteristics such as flexural modulus, tensile modulus, and interlaminar shear strength indicated a favourable effect of alkaline treatment. Hence, an appropriate alkaline treatment on fibres is necessary while constructing the hybrid composite in order to decrease the moisture impact.

Hygrothermal Effect

Composite structures are exposed to a wide range of temperature and moisture conditions, which can have a significant influence on their performance. These hygrothermal effects are caused by changes in temperature and moisture content, and they are connected to differences in the thermal and hygroscopic characteristics of the components. Almeida et al. [68] investigated the influence of hygrothermal conditioning on the mechanical characteristics of carbon fiber-reinforced composites. In this situation, they discovered considerably reduced tensile and compressive strength, as well as modulus. Interfacial debonding and matrix plasticization are to blame for the poor characteristics. This occurred as a result of moisture penetrating the carbon/epoxy interface.

Scida et al. [69] on the other hand, investigated the effect of hygrothermal effect on flax fibre reinforced composites. Due to hygrothermal ageing, they observed inferior mechanical behaviour of the composite. The lack of stiffness and strength can be attributed to a plasticiser impact of water on the matrix.

The matrix appears to have a larger influence in the hygrothermal deterioration of composites. According to the findings of the preceding two studies, moisture absorption causes plasticization in the matrix, which is accountable for the composite's poor strength. Interfacial debonding caused by moisture absorption is another cause of poor strength.

Ultraviolet (UV) Radiation

The effect of ultraviolet radiation on the performance of hybrid composites must be explored because composites are usually subjected to harsh atmospheric conditions. Kumar et al. [70] experimented to investigate the performance deterioration of carbon FRPC due to UV exposure. They observed the weight loss of specimens exposed to UV light. Short exposure to UV light may cause the remaining moisture and volatiles in the composite to be removed, resulting in weight loss. On the other hand, cyclic exposure to UV light impaired the transverse characteristics of composites. The matrix material has the greatest influence on the transverse characteristics of a composite. For a short exposure time, the longitudinal characteristics of the composite remain unaffected. However, extended exposure may degrade the material's longitudinal characteristics as well. Prolonged UV exposure may degrade the matrix, causing the structure to collapse catastrophically. Yan et al. [71] investigated the endurance of flax FRPC when subjected to UV radiation and water spraying. The hybrid composites' flexural and tensile strength were found to be decreased under these testing circumstances. In addition, matrix erosion, microcracking, discoloration, and other consequences are seen. When compared to synthetic and hybrid fiber-reinforced composites, flax fiber-reinforced composites were significantly harmed by accelerated weathering.

APPLICATIONS

Hybrid materials are ideally suited for aviation applications requiring high specific strength and moderate specific stiffness. Recently developed hybrid materials, notably carbon and its many forms, have broadened the usage of aircraft designers. In comparison to woven fibres, untwisted or unwoven fibres can give strength and stiffness in filament directions [72]. Prepregs are the primary raw material utilised in the majority of aviation composites. Carbon fibre is used as a main structural component in high-performance fighter aircraft, control surfaces, satellites, antenna dishes, and other similar applications [73]. In their study, Mansor et al. [74] addressed the usage of natural fibre polymer composite (NFPC) material as a replacement for glass fibre, phenolic resins, and other materials for interior components of aircraft requiring low load bearing capability. The report also discusses the usage of NFPC in other aircraft components, such as radomes.

The wind turbine blade is a key component in wind power generation. Recently, there has been an increase in demand for bigger turbine blades in order to improve the efficiency of the wind power system. Many researchers have tried with natural and synthetic fibre hybrid composites to achieve this. The usage of carbon fibre in conjunction with basalt fibre is one of the greatest choices since basalt fibres are stronger than S2 glass fibres and less expensive than carbon fibres [75]. Superior characteristics of basalt fibre and carbon fibres are used in long turbine blades without significant change in overall fibre content, boosting energy production and hence performance. Subagia et al. [76] conducted experiments on carbon and basalt FRPC to examine the flexural characteristics of the composite. It was discovered that composites with carbon fibres at the outer part had the highest flexural strength among the various stacking sequences utilised for composite manufacturing.

For marine applications, maintaining the mechanical properties of the component due to sea water immersion is a big challenge. Jesthi et al. [77] carried out experiments by replacing some parts of a glass fiber reinforced composite with carbon fibers. It was observed that water absorption tendency is reduced compared to only glass fiber reinforced composite. It was also found that the flexural strength of the hybrid composite decreased by 10.1% after aging in sea water for 90 days, whereas the impact strength decreased by 2.9%. This decrease in values is less than for only glass fiber reinforced composites, indicating that replacing some glass fibers with carbon fibers has reduced the decrement in mechanical properties. Calabrese et al. [78] investigated the maritime environments of flax and glass FRPC. The hybrid composite samples were aged for 60 days in salt-fog environmental conditions. In comparison to just flax FRPC or glass FRPC, the hybrid composite exhibits a reduction in flexural strength and modulus.

In the case of structural applications, the corrosive resistance of hybrid composite may provide an extra benefit when life cycle cost is considered [72]. Alam et al. [79] demonstrated that the kenaf FRPC with 10% carbon fibre is a good composite material for ensuring shear strength in reinforced concrete structures. It was discovered that the hybrid composite with this structure had the maximum tensile strength of 301 MPa, which was 83% greater than steel plate. In their review study, Pakravan et al. [80] stated that micro-steel fibres reinforced in the cement matrix can be partially replaced by micro-cellulose fibres and palm fibres, respectively. In each of these situations, the resultant hybrid composite improved in toughness. Carbonation of cement can lessen the difficulties in utilising natural fibres as they mineralize owing to the alkaline nature of the cement matrix.

CONCLUSIONS

Hybrid composites offer unique properties that may be used to satisfy a wide range of design needs while being more cost-effective than traditional composites. Natural and synthetic reinforced hybrid composites provide a number of benefits over typical synthetic composites. It has been proven to be far superior to traditional composites in a variety of ways. This article aims to summarise recent advancements in polymer hybrid composites produced from diverse natural fibres and carbon fibre reinforcements. Hybrid composites made with carbon and natural fibre reinforcements have the potential to be a viable substitute for traditional composites since they blend the characteristics of synthetic and natural fibres. Various modern methods of making hybrid composites are also described in it. The Hand Layup process is one of the most cost-effective and easy hybrid composite manufacturing procedures known. However, because of the incorporation of high fibre content, the pultrusion process produces a high strength composite. HiPerDiF, on the other hand, employs aligned fibres, resulting in composites with strong directional characteristics.

The optimal volume fraction ratio of fibres is critical in determining the mechanical characteristics of hybrid composites. Mechanical characteristics can be enhanced further by using an appropriate fibre layer stacking sequence. Hybrid composites with carbon fibres organised in outer layers, in particular, have shown enhanced mechanical characteristics. The application of coupling agents and alkaline treatment of natural fibres strengthen the bonding between fibre and matrix, resulting in better mechanical characteristics of hybrid composites. It has also been shown that fibres placed in the loading direction enhance tensile and flexural characteristics, but fibres positioned in a cross-ply manner improve composite impact strength. The addition of carbon fibre to natural fibre in hybrid composites raises the decomposition temperature, resulting in enhanced thermal stability. It has been found that carbon and natural fiber reinforced hybrid composites resist erosion from many chemical reagents, except for a few chemicals such as carbon tetrachloride. Furthermore, alkaline-treated natural fibres can decrease moisture-induced deterioration of hybrid composites. Aside from all the benefits, hygrothermal ageing accelerates the degradation of hybrid composites, especially when compared to natural composites. Moreover, prolonged UV exposure of hybrid composites affects both transverse and longitudinal characteristics owing to matrix degradation, micro-cracking, discoloration, and other effects.

Hybrid composites are widely used in aviation applications, wind turbine blades, maritime applications, structural applications, and other areas because of their balanced characteristics. Ultimately, it can be said that hybrid composites are the need of the hour and there is a lot of scope for research work in this area. Following paragraph will give a brief idea about future work that can be done in this area.

The susceptibility of carbon and natural fiber hybrid composites to moisture needs to be taken into account while fabricating the composite. In particular, natural fibers should be used considering the optimality of the fiber/matrix ratio. Also, surface treatment of the hybrid composite will increase resistance to moisture. If the adhesion between the fibres and the matrix is increased, the mechanical characteristics of hybrid composites can be considerably improved. More strategies for increasing bonding between the matrix and reinforcements must be investigated. The endurance of carbon and natural fibre hybrid composites must also be evaluated in the face of harsh environmental circumstances such as lighting, rain, temperature fluctuation, and so on. As limited literature is available on fatigue testing, it could be an area of future research as many parts, such as in aircraft, wind turbines, marine applications, etc., are subjected to cyclical loading. Overall life span of the hybrid composites as compared conventional composites also needs to be studied.

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