Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/19668
DOI URL: http://dx.doi.org/10.21474/IJAR01/19668

RESEARCH ARTICLE

MECHANICAL PROPERTIES OF GLASS FIBER AND CARBON FIBER REINFORCED COMPOSITES

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Manuscript Info

Manuscript History
Received: 15 August 2024
Final Accepted: 18 September 2024
Published: October 2024

Key words:-
Glass Fiber, Types, Thermal Conductivity, Mechanical Properties, Polymer Composites, Manufacturing Methods, Glass Fiber Reinforced Polymers (GFRP)

Abstract

The significant potential of glass fiber-based composite materials in aerospace and aviation industries, automotive manufacturing, and medical equipment production is emphasized. It is concluded that glass fiber is much cheaper and less brittle compared to materials like carbon fiber or other plastic fibers, as glass fiber exhibits high resistance to tensile and compressive loads. The main stages of the technological process of composite manufacturing are described, and the key requirements for evaluating the mechanical parameters of glass fiber products are listed. An analysis of the scientific literature has established that the high strength of fiberglass ensures the stability of its thermal conductivity characteristics, making it resistant to environmental influences and aging. The thermal conductivity of fiberglass composites depends on several factors, the most important of which are the type of fiber and matrix, fiber volume fraction, fiber characteristics, control of heat flow, interaction between the matrix and fiber, and operating temperature. It is summarized that the mechanical properties of fiberglass structures depend on a number of factors, the most important of which are: the type of fiber and resin, fiber orientation (aligned, randomly oriented, woven, etc.), and the percentage content of each component.

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Introduction:-

Today, there are two of the most sought-after characteristics of any product – lightness and increased resistance to corrosion. Accordingly, these properties are expected from the materials from which these products are made. The demand for such materials is growing every year, especially in the fields of aerospace and aviation industry, automotive industry, medical equipment production, as well as in many areas of civil construction. Among the various types of composites, glass fiber and carbon fiber reinforced polymer composites have gained the most popularity due to their high specific strength and high corrosion resistance.

Fiberglass consists of extremely thin glass threads formed by extrusion from silica glass or glass of a different composition. Fiberglass is much cheaper and less brittle than materials such as carbon fiber or other plastic fibers.

The most common type of fiberglass is E-glass, which is an aluminum-borosilicate glass that is mainly used in the manufacture of fiberglass. In addition, other types of glass are used, such as a-glass, e-CR-glass, c-glass, d-glass, R-glass and S-glass. Fiberglass is characterized by high resistance to tensile and compressive loads. It is used for thermal insulation, electrical insulation, sound insulation, as well as in the production of corrosion-resistant and

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high-strength fabrics, etc. Fiberglass is widely used for the manufacture of tanks and containers made of fiberglass [1].

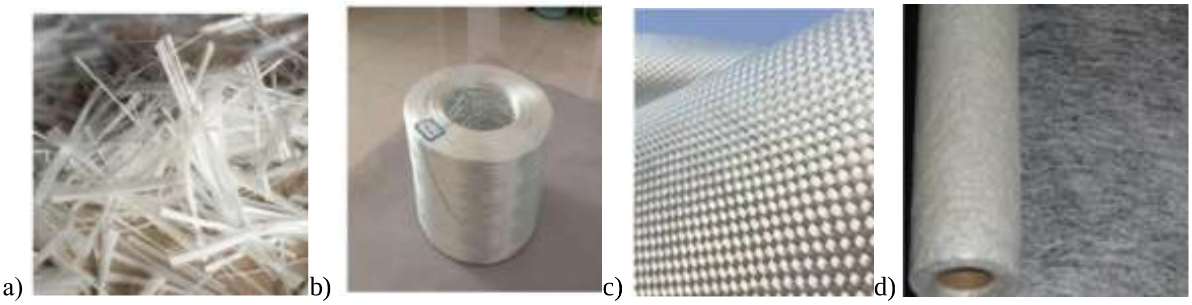

Fig. 1:- The main types of fiberglass
a) – chopped thread, b) – direct drawing roving, c) – woven mat, d) – mat made of chopped threads

Carbon fiber consists mainly of carbon atoms. Its atomic structure is similar to the structure of graphite, which consists of layers of carbon atoms arranged in the form of regular hexagons, but these layers differ in the way of their mutual arrangement [4]. Carbon fiber has a number of advantages, such as high tensile strength, significant stiffness, light weight, resistance to high temperatures, and low coefficient of thermal expansion. However, the cost of carbon fiber is significantly higher compared to other fibers such as glass fiber, aramid fiber or other plastic fibers.

Therefore, the main way to increase the strength of modern composite materials is their reinforcement with glass fiber and carbon fiber. The most effective method of manufacturing composites is considered to be manual laying of fibers.

The following materials are used for the industrial production of composites: glass fiber, carbon fiber, epoxy resin, Teflon sheet for removing impurities, silicone aerosol of increased strength, hardener, and a weighing device.

The technological process of manufacturing composites consists of the following stages. Preparation of the required length and mass of fiber, epoxy resin and hardener. Preparation of Teflon separator sheet and spraying of silicone on it. Mixing epoxy resin with hardener. Applying a layer of epoxy resin on a Teflon sheet. Laying out the cut fibers and fixing them in the form. Repeated laying of fiberglass in the form and filling with another layer of epoxy resin. Placement of load on cast composite. Extraction of the finished product and testing it for mechanical stability.

Let us analyze the mechanical properties of glass fiber and carbon fiber reinforced composites.

Mechanical stability. Before designing composite structures using carbon (CFRP) and glass (GFRP) fibers, it is necessary to study in detail the basic mechanical properties of fiber-reinforced polymers (FRP). All fiberglass composites use fiberglass as the primary reinforcing material. As shown below, the mechanical properties of fiberglass structures depend on a number of factors, the most important of which are: fiber and resin type, fiber orientation (aligned, randomly arranged, braided, etc.) and the percentage content of each component. According to research data [3], the "rule of mixtures" is used to describe the influence of the relative properties of resin and fibers. This rule is determined by the following ratio:
$PFRP = PfVf+ PmV$

The main mechanical properties of new types of FRP are defined as PFRP. In this context, Pf denotes the fiber mechanical properties, Vf – the fiber volume fraction, Pm – the matrix mechanical properties, and Vm denotes the matrix volume fraction.

Sometimes, when applying the "rule of mixtures", due to the insignificant influence of some components (matrix material or type of fibers) on the mechanical characteristics of certain fiberglass composites, they can be neglected. For example, the tensile strength of fiberglass depends more on the properties of the fibers, while the shear strength is mainly determined by the properties of the polymer matrix. In comparison, the Young's modulus of an FRP composite is mainly determined by the fiber properties, while the effect of the matrix material is negligible and can be neglected. In this case, the role of the resin is to transfer the load between the different fibers. However, it cannot be said that the varieties of the matrix and its characteristics do not affect the Young's modulus of the FRP composite at all.

For example, Mohammad A Amin et al [6] used the "rule of mixtures" to estimate the Young's modulus and tensile strength of various hybrid fiberglass rods. They noted that their elastic property predictions were very close to the experimental results, while the strength values were significantly lower than the experimental values for most types of fiberglass rods. Such significant differences in elastic properties are due to the fact that different organizations use different resins and fibers in different amounts in the manufacture of their fiberglass products.

Vyas C.J. et al [10] conducted a study of the mechanical properties and dynamic mechanical analysis of hybrid composites made of carbon fiber and glass fiber. They found that the main mechanical properties are preserved (after drying) if the moisture absorption does not exceed the saturation point.

Gaurav Rathore and others [4] investigated the mechanical characteristics of polyamide / polyphenylene sulfide (PA66 / PPS) matrix with different proportions of glass fibers (5%, 10%, 20% and 30%). The highest tensile strength was observed at 30% Vf, and the maximum flexural strength was observed at 25% Vf. Compared to composites with fiber filler, the authors noted the maximum viscosity at 0% Vf. During wear tests, they found that the minimum friction coefficient was around 20% Vf, and the amount of wear was lowest at 30% Vf.

Kim C. U. et al analyzed the tensile properties of electron glass and plain weave polyester composites made at different curing pressures (35,8, 70,1, 104 and 138,2 kg/m²) [5]. To create fiberglass composites, they used two different stacking schemes: symmetric and asymmetric. The results showed that the modulus of elasticity of fiberglass composites decreased with increasing curing pressure both in proportional and non-proportional stacking. Proportional stacking was more limited by the stiffness of fiberglass composites.

In addition, the plasticity increased with increasing hardening pressure both with disproportionate and with proportional stacking of materials. Azira M. Y. and others [3] studied the main mechanical properties of various laminates under different loading conditions. Experimental studies were carried out at a constant traverse speed of 5 mm/min and temperature of25 °C.

Ahmad S. M. and others [2] investigated two different materials, one with glass fiber reinforced glass-plastic and the other with fiber metal laminate (FML), while Achukwu E. O. et al [1] chose six types of laminates for analysis. First, they observed that the integrity of FML samples with metal layers is better than that of plain fiberglass samples. Second, due to different densities, the specific strength of fiberglass composites is significantly higher than that of the corresponding FMLs.

In addition, the comparison of specific stiffness and stiffness indicators shows the improvement of the properties of FML compared to fiberglass composites. The authors note that these six composite laminates represent a wide range of FRP laminates used for various engineering applications.

Nagendran M. and others [7] created several hybrid composites using epoxy resin, glass fiber, and nanoclay, which were subjected to tensile and three-point bending tests. The main mechanical properties (such as tensile strength, flexural strength, Young's modulus, flexural modulus, interlaminar shear strength, and Vickers microhardness) of the new hybrid composites improved with increasing nanoclay content up to 5 wt%. Further loading of nanoclay was calculated, and the marked improvements in Young's modulus and tensile strength in the composites with 5 wt% nanoclay were attributed to the excellent combination of nanoclay and epoxy, as confirmed by SEM images of the crack surfaces in the samples. This phenomenon is explained by the improved interaction between the matrix material and the nanoparticles.

Yeon-Jae Jeong et al [13] investigated the fatigue properties of fiberglass composites under tension and low-velocity impact. They used two different GF fiber orientations: 0°/90° at a fiber mass fraction of 47% (Wf) and ±45° at 42% (Wf). The results showed that the stiffness and residual tensile strength decreased as the impact energy increased from 0 to 25J. High performance values were noted in tests up to 10J, but as the impact energy increased from 10 to

20J, there was a significant decrease in these properties. The authors also noted that the wear of the samples during impact tests was similar for both geometries.

In addition, low impact energy led to a decrease in basic properties and matrix damage in fiberglass composites. Tensile fatigue tests were performed at impact energies of 1.4, 5, and 10 J. On the curve of stress amplitude (S) versus the number of cycles to failure (N) (S-N fatigue curve or Weller curve), the fatigue strength gradually decreased, and it was higher at 1.4 J, as well as at a higher voltage for ±45° and 0°/90° orientations. The S-N fatigue curves decreased sharply, showing moderate stress values for the 0°/90° geometry.

Wu D. and others [11] produced and tested polyamide composites with carbon fiber (CFR) of different number of layers and thickness. They found weak interfacial adhesion between carbon fibers (CFs) and polyamide, which resulted in a change in transverse tensile strength. Polyamide 6 / 6 with a higher carbon fiber content demonstrated better shear compression performance; thus, in the case of PA6 thermoplastic composites with carbon fiber, the volume fraction of CF did not affect the interlaminar shear strength.

To obtain a homogeneous mixture of carbon nanofibers (CNF) and epoxy resin SC - 15, Yawen Wu et al [12] used a high-intensity ultrasonic liquid processor. The optimum CNF concentration was 2.0 wt%, which provided the greatest increase in tensile strength. The new carbon fiber composite showed an improvement in flexural strength of 22.3% and tensile strength of 11%. Increasing the amount of CNF in the matrix also increased the wear resistance of the FRP composite.

SeshaiahTuraka and others [9] proposed a new method of processing and production of hybrid (micro/nano) composites. They used cellulose nanocrystals to integrate pure carbon nanotubes into carbon-plastic composites without the need for surfactants or chemical functionalization. It was noted that the addition of 0.2 wt% cellulose nanocrystals and 0.2 wt% pure carbon nanotubes to carbon fiber composites increased interlaminar shear strength by 35% and flexural strength by 33% compared to pure carbon fiber composites.

In addition, the research results indicate that the use of cellulose nanocrystals together with pure carbon nanotubes increases the thermal stability of CFs compared to the use of pure carbon nanotubes alone. This is of great importance for FRP composites used in structures.

Sharma P. et al [8] evaluated the physical and chemical changes of the CF composite surface after exposure to low-pressure oxygen plasma, depending on the power of the plasma and the duration of the treatment. They noted that O2 plasma treatment increased the shear strength of FRP composites from 24 to 27 MPa. There were also changes in both the chemical composition of the surface and its roughness after processing.

In addition, several researchers have studied the characteristics of carbon fiber and fiberglass composites in high and low speed impact tests, as well as in static indentation [5–8]. They found that the main properties of fiberglass composites (as determined by impact force, damage size and energy absorption) depend significantly on the speed of testing.

One of the urgent tasks of recent years is the development of nano-sized reinforcing materials that can be used to create carbon-plastic composites for various purposes. In this regard, Karakassis and colleagues support the idea of using radially aligned graphene nanosheets grown directly on carbon fibers (CFs) as a novel nanostructured interface. Their results showed that the hybrid CFs not only increased the shear strength at the interface between graphene nanosheets and epoxy by 101.5%, but also increased the tensile strength of the fibers by 28%.

In addition to improved mechanical properties (tensile and shear strength), the authors also noted that the electrochemical capacity and electrical conductivity of the fibers increased by 157% and 60.5%, respectively. Consequently, these improvements in mechanical, physical, and chemical properties demonstrate the potential of graphene nanosheets as a reinforcing material for the cost-effective production of stronger multifunctional carbon-plastic composites.

Aluminum alloys are widely used in the aerospace industry for various structural elements. However, depending on the type of fibers used, fiber-reinforced polymer (FRP) composites can have a stiffness-to-weight ratio 5 times higher, and their damping properties can exceed similar characteristics of aluminum alloys by 100 times. Therefore, it is not surprising that fiberglass constructions are gradually replacing traditional metal materials, especially where vibrations may occur. In such designs, damping capacity and dynamic modulus are two key properties that become attractive to the material under vibration conditions.

The high level of damping achieved through energy dissipation can reduce unwanted effects such as noise, vibration, and their long-term negative impact on structural integrity. At the same time, the high dynamic modulus provides sufficient rigidity of the structure with almost minimum weight, which is especially important for various types of transport, in particular in the aerospace industry. Due to the ability to dissipate energy, damping significantly increases the impact resistance of the material.

In addition, structural defects in modern FRP composites, such as cracks, voids, and delamination, lead to significant increases in damping. In contrast, in the case of all-metal structures, the damping properties are very low and can only be improved by increasing the weight of the product. In hybrid FRP composites, the main characteristics of vibration (damping capacity and dynamic modulus) additionally depend on the sequence of layering and fiber orientation.

Sharma S. and co-authors [2] studied the vibration properties of cylindrical shells made of crystallized fiberglass composite, conducting analytical, empirical and statistical studies. For the production of continuous samples reinforced with glass fiber, specially developed equipment for winding the thread was used. The results of three different studies showed a wide range of data. The authors presented several new results on the study of natural vibration frequencies and modeling of new reinforced composite cylindrical shells.

Dixit A. and his colleagues [8] investigated the vibrational characteristics of composites based on shape memory alloys (SMA) and piezoelectric materials (PZT). They found that the SMA-based actuator is relatively more efficient than the PZT-based actuator because the charge required to power the SMA is insufficient.

In addition, the use of an SMA-based drive has been found to reduce the need for powerful amplification circuits.

Xiaowei Mao et al [12] developed a new fiberglass composite panel to replace traditional wood panels. The authors studied the vibration characteristics of single-layer, two-layer and sandwich panels made of fiberglass. The 0°/90° fiber orientation provides higher frequency in single-layer panels, while the ±45° orientation provides higher frequency in double-layer transverse panels. Fiberglass panels with simple fixing have the lowest frequency, while sandwich panels with adhesive floor fixing have the highest frequency.

Jeong-Dae Kim et al [13] investigated the elastic performance of unidirectional fiberglass laminates using plate vibration experiment. The authors used two different methods of coating the fibers. One group of fibers was coated with an epoxy dispersion with the addition of aminosilane (to improve the adhesion of the fiber to the matrix), while the other group was coated with polyethylene (to limit adhesion). They found that the elastic properties were better for the first group of composites and worse for the second.

Vignesh Moorthy Pandian and co-authors [7] experimentally investigated vibration damping in bonded multi-layer beams reinforced with multiple layers of fiberglass-reinforced polymer (GRP) composite beams. The use of half-band power detection technology has increased the accuracy of vibration damping analysis of composite materials, providing a relatively high level of damping. Empirical results also showed that increasing the amount of fiberglass reinforcement significantly improves the stiffness and strength properties of composite beams made of glulam.

Farjana Islam et al [6] investigated the vibration properties of carbon fiber composite pipes by integrating them with different types of active fluids (shear thickening fluids, STFs). During the vibration tests, the STF/CFRP systems were actuated by hammer impact, and the displacement of the CFRP composites was measured using an accelerometer to determine the dynamics parameters in the modal analysis. The results showed that the integration of shear-thickening fluids in composite pipes significantly increases the natural frequency of oscillations of CFRP structures and provides a higher damping ratio in STF / CFRP systems.

In addition, the damping ratio correlates well with the rheological characteristics, with the damping properties improving with increasing STF characteristics in the suspensions.

Shuib S. B et al [1] investigated the natural frequency and specific damping range of carbon and glass-ceramic composite plates using several finite element (FE)-based vibration analysis methods. Their results, obtained on the basis of different modes, shapes and orientations of the fibers, revealed significant torsion of the material. This torsion was more obvious in cases where the bulk of the strain energy was stored in tension/compression in the fiber rather than in tension or shear in the matrix. The obtained results indicate that the FE method using the component damping model is an excellent tool for the general investigation of composite structures.

Vibration characteristics, such as structure, frequency and amplitude, must be studied during the manufacturing or machining of fiberglass and carbon fiber plates to determine the effect of wear on parts used in shipbuilding and other related industries.

Environmental characteristics. The integrity and durability of fiber-reinforced polymer composites (FRP) in various environments can depend on certain properties of their constituents (for example, the polymer matrix or fibers), as well as on the state of the matrix-fiber interface. All components and structures made of fiberglass are exposed to a certain environment during their long-term operation, but their response to destruction depends on the characteristics of this environment. Major environmental factors may include cold or high temperatures, immersion in water, humidity, UV radiation, alkaline environments, salt water, etc. The harsher operating conditions of modern fiberglass composites may be due to cyclic exposure (freeze-thaw cycles, high humidity cycles, etc.) or to a combination of various factors.

The energy associated with UV exposure can promote the breaking of molecular chains in the matrix, which can lead to material degradation. An important part of FRP composites is the fiber-matrix interface, which is formed when the FRP components are combined and has its own chemical composition and morphology. This boundary plays a key role in the properties of FRP composites. Low temperatures can cause fiberglass to change from a plastic state to a brittle state, which can cause microcracks to form. Regardless of the method of use, when microcracks appear in the fiberglass, the strength of the composite structure is automatically reduced. On the other hand, high operating temperatures can lead to softening of the material and deterioration of its main properties.

The continuous growth of the use of fiber-reinforced materials for various architectural purposes requires a deeper understanding of the basic thermal properties (thermal conductivity, specific heat capacity, mass or density, etc.) of fiberglass composites. The high strength of fiberglass ensures the stability of its heat-conducting characteristics, making it resistant to environmental influences and aging. Thermal conductivity, as is known, is a characteristic of a material that determines its ability to conduct heat. Polymeric materials have low thermal conductivity, so fiberglass are effective heat insulators.

The thermal conductivity of fiberglass composites depends on several factors, the most important of which are fiber and matrix type, fiber volume fraction, fiber characteristics, heat flow control, matrix-fiber interaction, and operating temperature. The distribution of temperature fields in fiberglass structures can only be determined if there is data on the thermal conductivity of the material surrounding the structure, and any engineering material must have low thermal expansion. Determining the thermal characteristics of fiberglass is critical to their appearance, so optimal thermal properties of fiberglass composites are crucial.

In the specialized literature, there is not much information about the thermal characteristics of fiberglass. Yang Q. [14] investigated the thermal conductivity of carbon-plastic composite in both transverse and axial directions, and found that the thermal conductivity increases non-linearly as the fiber volume fraction increases. He concluded that none of the existing theoretical models could accurately predict such behavior.

Recently, Zhou Y. et al [15] created epoxy composites filled with hollow glass microspheres (HGM), with filler content from 0 to 51.3% by volume, to control the dielectric properties of epoxy resin. As the HGM content increases, the dielectric constant and the degree of dielectric breakdown in composites decrease, which is important for the quality of high-frequency devices.

In addition, an increase in the glass transition temperature and coefficient of thermal expansion was recorded. To improve heat resistance, epoxy composites modified with reinforced E-GF glass fibers with different fiber content (10%, 20%, 30%, 40%, 50%, 60%) were developed. Chen S. et al [15] used poly(styrene-coacrylonitrile) to modify the diglycidyl ester of bisphenol-A-based epoxy mixed with diaminodiphenylsulfone. A nitrogen environment with a temperature range from 30 to 900°C was used for the tests. Thermogravimetric analysis (TGA) showed that at a fiber content of 60% by volume there was greater thermal stability and an increase in the decomposition temperature from 357 to 390°C.

Wang D. [14] investigated the reusability of E-GF polyester composite waste using TGA data. It was found that the decomposition temperature varied from 209.8 to 448.7°C, and the mass loss varied from 1.8 to 4.4%. They developed new carbon-plastic composites consisting of a highly effective nanocomposite based on clay and epoxy resin, as well as a woven carbon cloth. A nitrogen medium with a temperature from 25 to 800°C was used to measure the temperature of the samples. To evaluate the heat resistance of clay-epoxy carbon-plastic, the heating rate was set at 2, 5, 10, and 20°C/min. Thermogravimetric analysis (TGA) performed on a Q500 analyzer showed that both the neat epoxy resin and the epoxy resin with 0.6 vol% clay exhibited high thermal stability with a decomposition temperature of 370°C. Therefore, the decomposition temperature increased in the range from 350 to 400°C at a heating rate of 2 and 20°C/min.

Conclusions:-

A literature search has shown that fiberglass is significantly cheaper and less brittle compared to materials such as carbon fiber or other plastic fibers due to its high resistance to tensile and compressive loads. The text describes the main stages of the manufacturing process of composites and provides key requirements for assessing the mechanical characteristics of fiberglass products. It is emphasized that the high strength of fiberglass ensures the stability of its thermal conductivity, making it resistant to external influences and aging. Analysis of the results of previous studies allows us to formulate the opinion that the mechanical properties of fiberglass structures depend on a number of factors, in particular: the type of fiber and resin, the orientation of the fibers (aligned, randomly arranged, braided, etc.) and the percentage content of each of the components.

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