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TECHNOLOGIES FOR THE PRODUCTION OF GLASS FIBER REINFORCED POLYMERS (GFRP) AND CARBON FIBER REINFORCED POLYMERS (CFRP)

Summary. *The introduction highlights that composite materials made of polymers reinforced with carbon fiber (CFRP) or glass fiber reinforced polymers (GFRP) are frequently used for energy absorption in modern vehicles. The raw material base for the production of glass fiber and carbon fiber has been investigated. The advantages and disadvantages of the most common raw materials are outlined, along with the specific technological operations involved in the production of composite materials based on them. It is noted that glass fiber (GFs) is currently considered one of the most adaptable production materials due to its availability and the ease of manufacturing using abundant raw material resources.*

The essence of the main technological operations in the production of composite materials from glass fiber is described. A schematic representation of the industrial stages of fiberglass production is provided. The results of previous studies on the mechanical properties of fiberglass are presented, and methods for improving the properties of the finished composite material are suggested. The methods of production, properties (mechanical, vibrational, environmental, tribological, and thermal), advantages, limitations, and main areas of application of composites based on glass fiber and carbon fiber are thoroughly reviewed.

Key words: *Glass fiber, glass fiber reinforced polymers (GFRP), carbon fibers (CFs), polyacrylonitrile (PAN), compression molding, casting process, mold, resin transfer molding, Hand Lay-Up – HLU.*

Throughout human history, from the earliest civilizations to the innovations of the future, composite materials have played a key role in it. They are significantly different from steel or aluminum in several parameters: they have low weight, high strength and rigidity, absorb vibrations well, are flexible in design, and have resistance to corrosion and wear. These properties make them popular in many industries from household goods to high-tech applications such as medicine, sports, shipping, and construction [1–5].

Composite materials, which are made of polymers and reinforced with carbon fiber (CFRP) or glass fiber reinforced polymers (GFRP), are often used for energy absorption in modern cars. They have moderate density and higher mechanical characteristics than traditional metals [11].

There are many types of fibers (glass, carbon, aramid, etc.) for making modern fiberglass composites. Fiberglass and carbon fibers are the most common because of their unique properties. Glass fibers have proven themselves well under high tensile loads, while carbon fibers have high compressive strength [15]. Combining these materials makes it possible to create fiberglass composites, which are effectively used in the production of cars, the aerospace industry, sports goods, and many other industries [16–19].

The process of making fibers involves pushing raw materials through tight holes and curing them under various conditions, which promotes the formation of molecules along the axis of the fiber. The industry uses both natural (cellulose, animal, mineral) and artificial (organic, inorganic) fibers, in particular glass and carbon, which are the most popular for the production of high-performance fiberglass composites.

Glass fibers (GFs) are currently considered as one of the most adaptable manufacturing materials due to their availability and the possibility of easy fabrication using unlimited raw material resources.

Today, glass fibers (GFs) are actively used in the production of structural composites, in electronics, shipbuilding (boat hulls), printed circuit boards, aerospace, automotive (in particular, for rubber tires and light parts), as well as in special purpose products. Glass fibers have unique characteristics, such as low thermal conductivity, high strength, excellent electrical insulation, elasticity, non-flammability, rigidity and resistance to chemical influences. They can be in the form of individual strands, cut fibers, threads, fabrics and mats. Each type of fiberglass has its own characteristics and is used for different purposes in the manufacture of fiberglass composites. However, one of the significant disadvantages of fiberglass is its relatively low modulus of elasticity [9–10].

As for carbon fibers (CFs), they are made from polyacrylonitrile (PAN), viscose, mesophase pitch, or petroleum products (under protected atmosphere conditions). Carbon fibers are approximately 5–10 micrometers in diameter and are more than 90% carbonized. Their main characteristics include light weight, high stiffness, high tensile strength, fatigue resistance, effective vibration damping, heat resistance, high chemical and corrosion resistance, electrical conductivity, inertness to organic substances, X-ray permeability, self-lubricating properties and low coefficient of thermal expansion. Due to these properties, carbon fibers have become popular in various fields of engineering, such as the aerospace industry, automotive and marine transport, the military, the production of antennas, support structures, construction, the medical field (surgical and X-ray equipment, prostheses, implants), as well as in sports inventory.

Carbon fibers are classified by the type of fibrous precursor materials. These can be fibers based on pitch, PAN, mesophase, viscose, isotropic pitch or gas phase. According to their mechanical properties, they are divided into two main categories: general-purpose fibers and high-performance fibers, which have medium, high (>3.0 GPa) or ultra-high (>4.5 GPa) tensile strength, and low (<100 GPa), medium (200–350 GPa), high (350–450 GPa) or ultrahigh (>450 GPa) modulus of elasticity.

Carbon fibers can be classified based on their final heat treatment temperature (FHTT). Class I includes fibers that have undergone high-temperature treatment (over 2000°C) and are characterized by a high modulus of elasticity. Class II covers fibers after medium heat treatment (above 1500°C) and this class of fibers has high strength. Class III covers fibers with low heat treatment (less than 1000°C) and they have low modulus and low strength. Depending on the production methods, carbon fibers (800–1600°C), oxidized fibers (oxidation at 200–300°C), graphite fibers (2000–3000°C), activated CFs and fibers grown from steam are distinguished [6– 8].

According to the functional purpose, carbon fibers are classified into several categories: fire-resistant fibers, fibers for structural loads, activated fibers (for adsorption), lubricating fibers, conductive, corrosion-resistant and wear-resistant fibers.

Technologies for the production of composites based on fiberglass and carbon fiber also deserve a detailed study. According to Kumar V. [12], the perfect production technology can be defined by the following characteristics: minimum material costs (low material storage costs, low value-added materials and transportation costs) and finishing requirements (mesh mold production), high productivity (low labor intensity, short cycle time), maximum geometry (complexity of dimensions and shape of the part) and properties (variety of types of fittings/matrixes and the ability to control the main properties), flexibility, reliability and high manufacturing quality (low variability and percentage of defects). However, there is no production technology that would simultaneously meet all these requirements, which are in demand in all leading industries.

Analysis of the scientific literature [13–14] proved that the autoclaving and filament winding processes provide the best quality of the parts, while compression molding provides the lowest equipment costs and optimal dimensions. The best performance is achieved with injection molding. In the conditions of the rapidly changing market of composite structures, the industry is forced to constantly improve the methods of manufacturing fiberglass materials, developing new types of reinforcing materials, polymer systems and their combinations. At the same time, the main task is to reduce costs, reduce processing time, as well as reduce the weight and size of fiberglass parts.

In the development of FRP (reinforced plastic) composite materials, along with numerous material combinations, various modern technologies are used to manufacture fiberglass and carbon fiber components, such as contact molding and compression molding. The use of these methods allows you to optimize the properties of materials, the shape of products, their processing time and production costs.

Technologies for forming composites under pressure make it possible to create products with minimal labor costs that already have two or more finished surfaces [20–25]. These methods include injection molding, the use of silicone rubber, low pressure and temperature molding, transfer molding, resin transfer, and injection molding using structural molds.

The composite injection molding (IM) process, also known as "thermoplastic injection molding" or "thermoplastic molding", involves injecting a molten or softened thermoplastic material under high pressure into a pre-prepared mold. This is a reversible formation process. The press mold consists of several main parts: a nozzle, movable and fixed plates, a heating nozzle, a loading hopper, a vacuum system, a screw for spreading or laminating, a closing mechanism and a console (Fig. 1). The press mold consists of two parts: fixed and movable plates. It is usually made of aluminum alloys, which allows reducing production costs due to easier and faster processing compared to steel.

After the aluminum mold is made, the composite material, which can be in the form of granules, pellets, balls or powder, is loaded into the hopper. The material is then transported using an auger that rotates in a heated drum. Thanks to the rotation of the screw and temperature control (up to 200°C), the granules are gradually softened and transformed into a molten mass. This molten plastic is injected under high pressure through a nozzle into a mold using a hydraulic injection molding machine. After cooling, the product acquires the desired solid shape and is pulled out of the mold with the help of push-out mechanisms. At this stage, the process can be repeated again, starting a new cycle (Fig. 1).

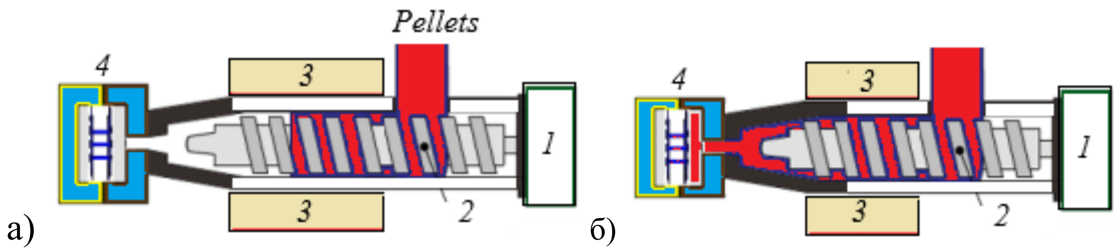

Fig. 1. The main technological operations of casting composite material under pressure:

injection – a) and forming – b)

1 – motor, 2 – screw, 3 – heater, 4 – mold

This technology makes it possible to produce a large number of identical parts from high-quality fiberglass with minimal production cycles. The manufactured components have the same mechanical properties that meet mass production standards and range from very small elements weighing only a few grams (e.g. electronic components) to large parts weighing several kilograms (e.g. car body panels).

Silicone Rubber Molding (SRM) technology is widely used to create models in a variety of leading industries, including automotive and electronics.

Xiao Y. and others [26] created a fiberglass composite structure using glass fibers (GFs) and silicone rubber (SRM). In order for the SRM to serve as a release material for the molds, the researchers polished its surface and applied hard wax to it. After that, to ensure uniform distribution of the pure resin, a gel coating of unsaturated polyester resin was applied to the surface of the mold. After the gel coating hardened, layers of fiberglass and resin began to be applied. With the help of rollers, fiberglass was soaked with resin and evenly wetted. Then, for final sealing of the structure, a polymer film was applied.

Compression molding (CM) is a method of manufacturing fiberglass products, in which a preheated (or cold) reinforcing package is placed in an open and heated mold cavity [27]. The form is fixed in a mechanical or hydraulic press. The two metal halves of the mold are heated, after which they are closed and high pressure is applied. Under the influence of pressure, the FRP material adapts to the shape, giving the product the required shape. External pressure and temperature are maintained until the material solidifies. The forming time, which depends on the thickness and dimensions of the product, can vary from a few seconds to a few minutes. In the CM process, various thermosetting resins are used, which are used in a partially hardened state in the form of pastes, granules or blanks.

As such, CM is the simplest form of SRM process, which was originally developed to produce fiberglass parts as replacements for metal components, especially in the automotive industry (e.g. spoilers, fenders, hoods, and buckets). This method provides short production cycles, easy automation, high productivity and dimensional stability. Pressed parts made of fiberglass have two perfectly finished surfaces and are characterized by high repeatability of parameters.

In practice, high-temperature CM technology is often used to produce strong fiberglass components and complex large-size parts (both flat and moderately curved) in various sizes. In addition, compared to other fiberglass manufacturing methods (IM, RTM, TCM), CM is one of the most economical molding processes. Another advantage of this method is a significant reduction of material waste, which is a significant advantage when working with expensive compositions. In addition, costs for further processing are minimal [28].

However, in order to improve the quality of products made with CM, there are several important challenges that need to be addressed in future research. In particular, it is necessary to determine the exact amount of material that is required to manufacture the product, the minimum amount of energy and time required to heat the material, the optimal heating method, and the optimal pressing force. In addition, it is important to design a mold that will ensure rapid cooling after the process is completed.

Resin transfer molding (RTM), also known as fluidic molding, is a manufacturing technology for fiberglass composites. It is a method that uses closed molds and is suitable for the production of high-quality composite parts in small quantities. With relatively short production cycles, low equipment costs, and minimal labor costs, this method is used to produce automotive truck panels, boat hulls, aerospace components, and wind turbine blades. RTM is a low-temperature, low-pressure (typically 3.5–7 bar) process in which a low-viscosity liquid thermosetting resin is applied to pre-laid reinforcing materials. This method is suitable for a variety of fiber types, including woven materials, mats, and harnesses. In addition, the use of glass fibers (GFs) and carbon fibers (CFs) in the RTM process has been reported to increase the strength and stiffness of FRP composites.

The RTM process includes five main stages: preparing the workpiece, placing it in the mold, filling the mold by injecting resin, the curing process, and dismantling the finished part. Initially, a release gel is usually applied to the surface of the mold to facilitate removal of the fabricated FRP composite. Then, oven-dried reinforcing fibers (usually a blank or roll material cut according to a certain pattern) are placed in the cavity of the mold, which is covered with a molding coating. Two heated mold plates are tightly compressed to prevent resin leakage [29].

Next, the resin together with the catalyst is mixed in special dosing equipment, after which this mixture is injected under low or medium pressure through one or more injection holes (depending on the complexity of the shape of the part) into the fibrous blank. After cooling the mixture of the matrix and the reinforcing material, various tools are used to remove the finished fiberglass part from the ventilated mold. Moreover, an additional curing process is necessary to achieve full curing of the resin.

In addition, due to the surface treatment of the composites, a uniform distribution of fibers in the matrix is achieved and their compatibility with the matrix material is improved. High manufacturing speed and relatively low cost make this method more attractive compared to other rapid prototyping technologies. This makes it a cost-effective and efficient way of manufacturing plastics.

The injection molding process allows recycled or colored plastic to be added to the base material, with the parts typically requiring little additional processing, and in some cases none at all. The pressure contact molding method helps reduce cost when only one quality surface is required and speeds up product development by simplifying mold making.

The Hand Lay-Up (HLU) method is the simplest and one of the oldest in the production of fiberglass composite materials. This method is actively used in the small-scale production of large structures in such industries as marine (boat hulls and related parts), automotive (body panels), energy (wind turbine blades), transport (large containers) and household (swimming pools, bathtubs, garden ponds and architectural elements) [10].

HLU technology includes creating a high-quality product surface and protecting the mold from moisture by applying a thin layer of pigmented gel coating to the mold. This gel also acts as an anti-adhesive, making it easier to remove the finished product from the mold. After the gel layer has hardened, a reinforcing material is applied to the form. Next, a thermosetting liquid resin (usually epoxy or catalyzed polyester) is poured over the reinforcing layer, which can consist of continuous or chopped fibers, fabrics, mats or canvases.

Manual rolling is also performed to remove air trapped between the reinforcing fibers, which helps to improve the bond between the matrix and the reinforcing material. In addition, rolling helps to compact the FRP composite material and thoroughly impregnate the reinforcing fibers with resin. To achieve the desired thickness of the fiberglass composite material, additional layers of resin and reinforcing material are gradually added. To harden the composite, instead of using external heating, you can use catalysts or accelerators.

The HLU method uses inexpensive equipment and is primarily used to produce fiberglass parts with a large area-to-thickness ratio. Simplicity of component processing, high flexibility in creating complex shapes and the possibility of easy design changes make it possible to manufacture parts of various sizes. This method is ideal for prototyping and manufacturing small batches or individual large parts. However, parts made by the HLU method in open molds have only one well-finished surface, which may require further processing. Thus, parts can have a smooth surface on the mold side, but a rough surface on the exposed side. It is worth noting that increasing the volume content of the resin can significantly increase shrinkage, and the formation of gases and air entrainment can weaken the polymer matrix, which will lead to a decrease in the strength of the components. Accurate dosing of catalyst and resin and their proper mixing are critical to achieving the required curing time. All these aspects create challenges for the development of new approaches in the HLU process. Since HLU is a highly manual process, special attention must be paid to fire safety and resin toxicity.

Among the main difficulties, it is worth noting the confusion of fibers, their short length and the possibility of reuse in other fiberglass composites. The most environmentally acceptable solution to these problems may be the use of recycled carbon fiber (CFs) as an alternative product with high added value.

Characterizing the main mechanical characteristics of fiber-reinforced polymers (FRP), including composites with carbon (CFRP) and glass (GFRP) fibers, the following properties should be noted. The tensile strength of fiberglass depends to a greater extent on the characteristics of the fibers themselves, while the shear strength is much more determined by the properties of the polymer matrix. In comparison, the Young's modulus of an FRP composite structure is mostly determined by the properties of the fibers, and the effect of the matrix material is so small that it is often neglected. However, it is important to note that matrix varieties and their characteristics can still have some effect on the Young's modulus of an FRP composite. In this context, the main task of resin is to transfer loads between fibers.

In terms of vibration performance, fiber-reinforced composites (FRP) can achieve a stiffness per unit weight that is 5 times that of aluminum alloys, and their damping properties can be 100 times better. The property of energy absorption significantly increases the impact resistance of fiberglass. Moreover, structural defects such as cracks, voids, and delamination contribute to a significant increase in damping in modern FRP composites. In the case of solid metal structures, the damping properties are significantly lower and can be improved only by increasing the weight of the material. In hybrid FRP composites, vibration characteristics such as damping capacity and dynamic modulus additionally depend on the order of stacking layers and fiber orientation.

The durability and integrity of glass fiber reinforced FRP composites can change under various environmental conditions, such as temperature, humidity, UV radiation, or chemical exposures, including salt water or alkaline environments. All elements of fiberglass structures are exposed to these factors during operation, but their destruction is determined by specific conditions of use. More extreme operating conditions, such as freeze-thaw cycles or high humidity cycles, can significantly affect material properties.

At low temperatures, fiberglass can change its properties from plastic to brittle, which leads to the appearance of microcracks. As soon as these cracks form, the strength of the composite structure decreases. At the same time, high temperatures can cause softening of the material and deterioration of its main characteristics.

Sanchez Q. and other researchers [18] studied the effect of external factors, such as UV radiation, hygrothermal conditions, aging due to thermal shocks and exposure to salt solution, on the thermal performance of glass fiber (GF)-reinforced polyetherimide (PEI) composites. The experiment was carried out in different temperature conditions with a humidity of 90% for 60 days in sea water. It has been found that the moisture absorption of a PEI/glass fiber laminate is often dependent on temperature and humidity. The moisture absorption curve showed a linear increase in the weight of the material as a function of time, with a maximum moisture absorption of approximately 0.18% observed on day 25. In addition, Mohamed M. and colleagues [14] investigated the effect of temperature on the mechanical properties of epoxy-based fiberglass composite tubular specimens, focusing on the effects of moisture penetration and sensitivity to this factor. They immersed the GF composite tubes in distilled water at 20°C and 50°C. The tests lasted for 4 months and it was found that at 20°C there was a mass accumulation of 0.23%, while at 50°C it was 0.29%.

The thermal conductivity of glass fiber composites depends on several factors, among which the most important are the type of fiber and matrix, the volume ratio of the fiber, the properties of the fiber itself, the control of heat flow, the interaction between the matrix and fibers, and the ambient temperature. In order to accurately determine the temperature distribution in fiberglass structures, it is necessary to know the thermal conductivity of the medium, since minimal thermal expansion is important for any engineering material. The study of the thermal characteristics of fiberglass composites plays a crucial role in ensuring their functionality, therefore, ideal thermal properties are necessary for the optimal operation of fiberglass.

Conclusions. The raw material base for obtaining fiberglass and carbon fiber was analyzed. The advantages and disadvantages of the most common raw materials are indicated, and the features of technological operations for obtaining composite materials based on them are indicated. The essence of the main technological operations in the production of composite materials from fiberglass is described. A schematic representation of the industrial stages of production of fiberglass is given. The results of previous scientists in the study of the mechanical properties of fiberglass are presented, and ways to improve the properties of the finished composite material are indicated. Production methods, properties (mechanical, vibrational, environmental, tribological and thermal), advantages, limitations and main areas of application of composites based on glass fiber and carbon fiber are considered in detail. The main issues that require resolution involve controlling the uniform distribution of resin and reinforcing material in the mold, preventing defects such as air bubbles or uneven compaction, and minimizing shrinkage during cooling. To enhance the quality of the final products, special vacuum forming methods and additional drying of composites before final polymerization are applied. Additionally, an important aspect remains the investigation of the compatibility of polymer matrices with different types of reinforcing fibers, which will allow for further improvement of the mechanical and operational characteristics of the finished products. Furthermore, ongoing research is focused on optimizing the curing process to ensure better adhesion between the polymer matrix and reinforcement fibers, which can significantly enhance the structural integrity of the composite materials. Innovations in resin formulations, as well as the development of advanced reinforcement techniques, are also being explored to improve the thermal stability and durability of the products under extreme conditions. The integration of nanomaterials into composite structures is another promising area, offering potential improvements in strength-to-weight ratios, corrosion resistance, and overall longevity of the components. These advancements aim to meet the growing demands of industries such as aerospace, automotive, and construction, where high-performance materials are critical for efficiency and safety.

References

1. Karzad A. S., Leblouba M., Al-Sadoon Z.A., Maalej M., Altoubat S. Modeling the flexural strength of steel fibre reinforced concrete. *AIMS Materials Science*. 2023. 10 (1). P. 86–111. doi: 10.3934/matersci.2023006.

2. Sandá A., Ruiz R., Mafé M. Á.l, Sarasua J. A., González-Jiménez A. Scrapping of PEKK-based thermoplastic composites retaining long fibers and their use for compression molded recycled parts. *AIMS Materials Science.* 2023. 10 (5). P. 819–834. doi: 10.3934/matersci.2023044.

3. Shiverskii A. V., Kukharskii A. V. Recycling glass fiber-reinforced plastic in asphalt concrete production [J]. *AIMS Materials Science*. 2024. 11 (2). P. 231–242. doi: 10.3934/matersci.2024013.

4. Alkhatib F., Mahdi E., Dean A. Crushing response of CFRP and KFRP composite corrugated tubes to quasi-static slipping axial loading: experimental investigation and numerical simulation. *Compos. Struct.* 2020. 246. Article 112379. https://doi.org/10.1016/j.compstruct.2020.112370.

5. Dehrooyeh S., Vaseghi M., Sohrabian M., Sameezadeh M. Glass fiber / Carbon nanotube / Epoxy hybrid composites: Achieving superior mechanical properties. *Mech. Mater.* 2021. 161. 104025. doi: 10.1016/j.mechmat.2021.104025.

6. Fajrin J., Akmaluddin A., Gapsari F. Utilization of kenaf fiber waste as reinforced polymer composites. *Results Eng.* 2022. 13. P. 100380. https://doi.org/10.1016/j.rineng.2022.100380.

7. Gao X., Cheng L., Tan J., Yang W. Conductive Nanocarbon-Coated Glass Fibers. *J. Phys. Chem. C.* 2020. 124. P. 17806–17810. doi: 10.1021/acs.jpcc.0c03948.

8. Guo R., Jiang S., Hu M., Zhan Y., Cheng K., Duan G. Adsorption of volatile benzene series compounds by surface-modified glass fibers: Kinetics, thermodynamic adsorption efficiencies, and mechanisms. *Environ. Sci. Pollut. Res. Int.* 2021. 28. P. 30898–30907. doi: 10.1007/s11356–020–12227–4.

9. Heudorfer K., Bauer J., Caydamli Y., Gompf B., Take J., Buchmeiser M. R., Middendorf P. Method of Manufacturing Structural, Optically Transparent Glass Fiber-Reinforced Polymers (tGFRP) Using Infusion Techniques with Epoxy Resin Systems and E-Glass Fabrics. *Polymers.* 2023. 15. 2183. https://doi.org/10.3390/polym15092183.

10. Huyan C., Dong Liu, Pan C. Thermally recyclable and reprocessable glass fiber reinforced high performance thermosetting polyurethane vitrimer composites. *Chemical Engineering Journal*. 2023. Vol. 471. P. 144478. https://doi.org/10.1016/j.cej.2023.144478.

11. Kalusuraman G. et al. Vibration studies on fiber reinforced composites – a review. *J. Nat. Fibers.* 2023. 20 (1). P. 2157361. https://doi.org/10.1080/15440478.2022.2157361.

12. Kumar V. et al. Factors affecting direct lightning strike damage to fiber reinforced composites: a review. *Compos. B Eng.* 2020. 183. P. 1–15. https://doi.org/10.1016/j.compositesb.2019.107688.

13. Karim M. A., Abdullah M. Z., Deifalla A. F., Azab M., Waqar A. An assessment of the processing parameters and application of fibre-reinforced polymers (FRPs) in the petroleum and natural gas industries: A review. *Results in Engineering*. 2023. Vol. 18. P. 101091. https://doi.org/10.1016/j.rineng.2023.101091.

14. Mohamed M., Selim M., Ning H., Pillay S. Effect of fiber prestressing on mechanical properties of glass fiber epoxy composites manufactured by vacuum-assisted resin transfer molding. *J. Reinforc. Plast. Compos.* 2020. 39 (1–2). P. 21–30. https://doi.org/10.1177/0731684419868841.

15. Morampudi P., Namala K. Review on glass fiber reinforced polymer composites. *Materials Today: Proceedings*. 2021. Vol. 43, Part 1. P. 314–319. https://doi.org/10.1016/j.matpr.2020.11.669.

16. Folhento P., Braz-César M. Cyclic response of a reinforced concrete frame: Comparison of experimental results with different hysteretic models. *AIMS Materials Science.* 2021, 8 (6). P. 917–931. doi: 10.3934/matersci.2021056.

17. Raju K., Balakrishnan M. Evaluation of mechanical properties of palm fiber / glass fiber and epoxy combined hybrid composite laminates. *Mater. Today Proc.* 2020. 21. P. 52–55. https://doi.org/10.1016/j.matpr.2019.05.359.

18. Sanchez Q., Jones M., Monir S., Vagapov Y. Evaluation of methodology for the carbon fibre recycling. *Proc. 2020 IEEE Conf. Young Res. Electr. Electron. Eng. EICon*. 2020. P. 2178–2183. https://doi.org/10.1109/EICon49466.2020.9039382.

19. Sarr M. M., Inoue H., Kosaka T. Study on the improvement of interfacial strength between glass fiber and matrix resin by grafting cellulose nanofibers. *Compos. Sci. Technol.* 2021. 211. 108853. doi: 10.1016/j.compscitech.2021.108853.

20. Shakiba M., Ahmadi H., Mortazavi S. M.R., Bazli M. A case study on the feasibility of using static-cast fibre-reinforced concrete electric poles fully reinforced with glass fibre reinforced polymer bars and stirrups. *Results Eng.* 2023. 17. P. 100746. https://doi.org/10.1016/j.rineng.2022.100746.

21. Srivatsava M., Sreekanth P. S.R. Experimental characterization of dynamic mechanical properties of hybrid carbon-Kevlar reinforced composite with sandwich configuration. *Mater. Today Proc.* 2020. 261 (1). P. 1–5. https://doi.org/10.1016/j.matpr.2020.01.261.

22. Wang F., Chen Z., Wu C., Yang Y., Zhang D., Li S. Analysis of acoustic performance of glass fiber felts after water absorption and their estimation results by artificial neural network. *J. Text. Inst.* 2020. 111. P. 1008–1016. doi: 10.1080/00405000.2019.1678559.

23. Wang F., Yu J., Ge A., Liang X., Lu S., Zhao C., Liu L. Comparison of the physical properties of heat-treated and hydrophobic modified glass fiber felt. *J. Ind. Text.* 2021. 51. P. 1422S–1440S. doi: 10.1177/1528083720988479.

24. Wu Y., Song Y., Wu D., Mao X., Yang X., Jiang S., Zhang C., Guo R. Recent Progress in Modifications, Properties, and Practical Applications of Glass Fiber. *Molecules*. 2023 Mar 8. 28 (6). P. 2466. doi: 10.3390/molecules28062466.

25. Vidya L. Mandal B. Verma P. K. Patel. Review on polymer nanocomposite for ballistic & aerospace applications. *Mater. Today Proc.* 2020. https://doi.org/10.1016/j.matpr.2020.02.652.

26. Xiao Y., Li J., Wu J. Glass fiber reinforced PET modified by few-layer black phosphorus. *Polym. Adv. Technol*. 2021. 32. P. 3515–3522. doi: 10.1002/pat.5362.

27. Ziari H., Aliha M. R.M., Moniri A., Saghafi Y. Crack resistance of hot mix asphalt containing different percentages of reclaimed asphalt pavement and glass fiber. *Construct. Build. Mater*. 2020. 230. 117015. https://doi.org/10.1016/j.conbuildmat.2019.117015.

28. Zhou Y., Jiang L., Jiang Z., Chen S., Ma J. Surface hydrophilizing modification of polytetrafluoroethylene / glass fiber fabric through oxidant-induced polydopamine deposition. *J. Ind. Text.* 2020. 50. P. 364–379. doi: 10.1177/1528083719830148.

29. Yang Q., Hong B., Lin J., Wang D., Zhong J., Oeser M. Study on the Reinforcement Effect and the Underlying Mechanisms of a Bitumen Reinforced with Recycled Glass Fiber Chips, vol. 251, Elsevier B. V. 2020. https://doi.org/10.1016/j.jclepro.2019.119768.