Comparative evaluation of approaches to determining biofibres characteristics: from mechanical tests to machine learning

Nikolay Tatus'l and Olga* Volkova[1]

[1] Blagonravov Mechanical Engineering Research Institute of Russian Academy of Science, 4 Maly Kharitonyevsky Pereulok, Moscow, 101000, Russia

Abstract. This article is devoted to a comparative analysis of methods for determining the characteristics of biofibers, a key component of modern environmentally friendly composites. The aim of the work is to systematize and compare approaches to the study of biofibers: from mechanical testing and microstructural analysis to digital image processing and machine learning methods. Particular attention is paid to the relationship between fiber characteristics and composite properties. As a result, a classification of methods has been developed, recommendations for their selection for different types of biofibers have been formulated, and promising areas of research have been identified. The analysis has made it possible to identify the optimal combinations of methods for effectively predicting the properties of composite materials.

1 Introduction

Reinforcing fibers are a key structural component of modern composite materials, directly determining their strength, deformation, and functional characteristics. The wide range of fibers used—from high-modulus carbon and glass to biopolymers and hybrids—requires accurate and reliable methods for evaluating their properties. The relevance of such an assessment is due to both the need to predict the behavior of composites in large-scale space-based structures and the development of new areas, such as biomedicine and smart materials, where not only mechanical but also physicochemical, morphological, and functional parameters of fibers are of critical importance.

Experimental studies of fibers are associated with significant methodological difficulties due to their small size, anisotropic properties, structural heterogeneity, and sensitivity to test conditions. Classic mechanical tests, microscopic and spectroscopic methods are well known. However, in recent years, the rapid development of digital technologies, in-situ diagnostic methods, and machine learning has opened up new opportunities for comprehensive analysis of fiber characteristics.

Global scientific practice shows a tendency toward integrating diverse methods—from nanoindentation and synchrotron tomography to artificial intelligence algorithms—to establish fundamental structure-property relationships. At the same time, domestic research continues to focus on traditional approaches regulated by GOST standards, which ensure reproducibility but often limit the depth of analysis.

The purpose of this article is to conduct a comparative analysis of modern methods for determining fiber characteristics used in international and Russian scientific practice. The paper systematizes approaches to assessing the mechanical, structural, and functional parameters of fibers, with a particular focus on comparing the capabilities of classical and innovative methods, as well as the prospects for introducing digital technologies and machine learning to improve the accuracy and predictive power of research.

2 Classification of biofibers characteristics

This section examines the classification of fiber characteristics according to key parameters: mechanical, structural, physicochemical, and functional characteristics. The significance of each of these groups is determined by the intended purpose of the material and varies depending on the area of application, whether it is the production of structural composites, the creation of biomedical materials, or the manufacture of technical textile products [1, 2]. This section discusses the classification of fiber characteristics according to key parameters: mechanical, structural, physicochemical, and functional characteristics. The significance of each of these groups is determined by the intended purpose of the material and varies depending on the area of application, whether it is the production of structural composites, the creation of biomedical materials, or the manufacture of technical textile products [1, 2].

1. Mechanical and strength characteristics for the most common fibers are given in Table 1.

Table 1. Mechanical and strength characteristics

Fiber Type	Modulus of elasticity (GPa)	Tensile strength (MPa)	Elongation to break (%)
Carbon	230–600	3000–6000	1.0–2.0
Glass	70–85	2000–3500	2.5–4.0
Aramid (Kevlar)	60–130	2500–4000	2.5–4.0
Polymer	2.5–4.0	500–1000	15–25
Collagen	~0.5	50–100	>10

2. The structural characteristics (Table 2) of the fiber are the main factor determining its physical and mechanical behavior at the micro- and nano-levels, as well as the nature and effectiveness of its interaction with the polymer or other matrix in the composite material. It is the structural features of the fiber that directly influence the following properties of the composite: strength, stiffness, impact toughness, and durability.

The main structural characteristics of the fiber include:

• Fiber diameter: a decrease in diameter leads to a significant increase in the strength and flexibility of the fiber, reducing the likelihood of critical defects. Thinner fibers also provide a larger specific contact surface with the matrix.

• Cross-sectional shape: fibers come in round, oval, triangular, or hollow cross-sections. The shape affects the packing density of the fibers in the composite, mechanical bonding (interlocking) with the matrix (e.g., ribbed fibers create a stronger bond), and optical properties.

• Porosity: The presence and distribution of pores in the fiber volume reduce its density and can affect strength.

• Degree of crystallinity: A high degree of crystallinity usually correlates with increased strength and modulus of elasticity, but can reduce impact strength.

• Molecular orientation: The degree of orientation of macromolecules or crystals along the fiber axis, achieved during the drawing process, is a key parameter for achieving high strength and elastic modulus values.

• Anisotropy: Most fibers exhibit anisotropic properties, i.e., their characteristics (strength, thermal conductivity, thermal expansion coefficient) vary along and across the axis. This property is deliberately exploited in the design of composites to withstand specific loads.

Table 2. The structural characteristics

Parameter	Typical measurement scale	Assessment method
Fibre diameter	1-50 μm	SEM, optical microscopy
Degree of crystallinity	0–100 %	XRD, DSC, FTIR
Surface roughness	nm-μm	AFM, SEM
Molecular orientation	Relative values	Raman spectroscopy, XRD

3. Physicochemical characteristics determine the interaction of fibers with the environment, resistance to aging, chemicals and temperature (Table 3).

Table 3. Physicochemical characteristics

Characterization	Description	Method of evaluation
Hydrophilicity	Ability to absorb moisture	Wetting angle measurement
Thermal stability	Thermal degradation limits	TGA, DSC
Biocompatibility	Tissue response to material	In vitro/in vivo biotests

4. Functional characteristics of fibers:

• Electrical conductivity, characteristic of carbon fibers and fibers containing metal inclusions or coatings. This property allows the creation of composites capable of conducting electrical current, which is in demand for protection against electromagnetic interference, the creation of heating systems, or in electronics.

• Piezoelectric properties, which imply the ability of the fiber to generate an electric charge in response to mechanical stress (pressure, vibration). Such fibers are the basis for the development of "smart" materials used as strain sensors or energy sources.

• Surface functionalization is the targeted modification of the fiber surface to give it special properties. The most common example is the application of antibacterial coatings (based on silver or copper nanoparticles) for medical textiles. In addition, the surface can be modified to improve adhesion to a specific type of matrix.

3 Methods for analyzing biofibers characteristics in foreign studies

The wide range of existing fibers, from synthetic to biopolymer, necessitates the use of a variety of analytical techniques. In foreign practice, analysis is carried out in several key areas, including mechanical testing, microscopy, spectroscopy, X-ray structural and thermal analysis, often combined in comprehensive approaches.

3.1. Mechanical testing

One of the main tasks in analyzing fiber characteristics is to evaluate their mechanical properties, among which the determination of tensile strength and deformation

characteristics plays a central role. The most significant approach in this area is recognized as tensile testing of individual fibers, the methodology for which is regulated by international standards ASTM D3822 and ISO 11566. Conducting such tests requires the use of specialized equipment—universal testing machines (e.g., manufactured by Instron or Zwick/Roell), equipped with high-precision low-load sensors and special clamping devices. The latter are designed to securely fix micro-objects without damaging them and can be micro-clamps with controlled force.

The current level of development of experimental technology, as noted in [3], allows tests to be carried out on micromechanical test benches equipped with high-speed video recording systems. This comprehensive approach makes it possible not only to record standard strength parameters (strength limit, elastic modulus, relative deformation), but also to visually track the kinetics of deformation and destruction of the sample in real time. This paves the way for analyzing the initiation and development of microdefects, which is extremely important for understanding the mechanisms of fiber material failure.

Special attention is paid to the methods of determining the mechanical characteristics of fibers, namely:

1. Static tensile tests. The most fundamental approach to assess the mechanical properties of fibers is uniaxial tensile testing, regulated by the international standards ASTM D3822 and ISO 11566. The technique involves the use of specialized micro-grips with a controlled clamping force (0.1-0.5 N) to minimize sample damage. The critical parameter is the length of the free fiber section, which is 10-50 mm depending on the fiber type. Modern systems (e.g., Instron MicroTester) provide loading speeds of 0.1-5 mm/min with load measurement accuracy of ±0.1 mN. To accurately determine strain, the following are used:

- Laser extensometers with 0.1% resolution;
- Digital Image Correlation (DIC) systems with acquisition rates up to 500 fps.

2. Nanoindentation studies. Characterization of local mechanical properties is carried out using the instrumented nanoindentation method (ISO 14577). In fiber studies, predominantly used are:

- Berkowitz indenters (angle at apex 65.3°);
- Spherical indenters with a diameter of 1-5 μm.

Typical test parameters include:

- Penetration depth: 50-500 nm;
- Maximum load: 0.1-10 mN;
- Loading rate: 0.05-0.5 mN/s.

Oliver-Farr load-displacement curve processing allows hardness and other mechanical characteristics of the material to be determined by measuring the load and tip displacement together during indentation.

3. Dynamic mechanical analysis. Investigation of rheological properties of fibers in a wide temperature range (-100...+400°C) is carried out on DMA instruments (e.g. TA Instruments Q800). Standard test parameters:

- Strain amplitude: 0.01-1%;
- Frequency range: 0.1-100 Hz;
- Heating rate: 2-5°C/min.

Key parameters to be determined:

- Accumulation modulus (E');
- Mechanical loss modulus (E'');
- $\tan \delta = E''/E'$ (mechanical loss coefficient).

4. Micromechanical methods for evaluating interfacial characteristics. To analyze the fiber-matrix interaction, the following are used:

- Pull-out test;

- Fragmentation test.

5. Cyclic fatigue tests. Durability assessment is carried out at:
- Frequency of loading: 1-50 Hz;
- Cycle asymmetry coefficient: R=0.1-0.5;
- Failure Criteria:
- Damage accumulation (10% stiffness reduction);
- Complete failure (10^6 cycles).

The high cycle fatigue test is used to determine the behaviour of a material under repeated cyclic loading. The purpose of this test is to determine how many cycles of loading a material can withstand before failure occurs, given a specified stress range and frequency of load application. The test is typically conducted using a standard fatigue testing machine, where the test specimen is pretested and then stressed to failure. Throughout the test, computer software records various necessary parameters such as the number of cycles travelled and the exact location of fracture. Based on the data obtained, an S-N curve (Wöhler curve) [4] is plotted to show the dependence of the stress amplitude (S) on the number of cycles to failure (N) (Fig.1). By constructing these curves for different materials, engineers can compare them and make an informed decision on the choice of the optimal material for specific engineering tasks.

The S-N dependence is usually expressed by Baskin's fatigue law, which is as follows: [5]:

$$s_a = s_f' \left(2N \right)^b,$$

where s_a - stress amplitude; s_f' - fatigue strength coefficient; N – number of cycles to failure; e_f' - fatigue plasticity coefficient; b – fatigue strength index. s_f' Equation.DSMT4 and b are material properties.

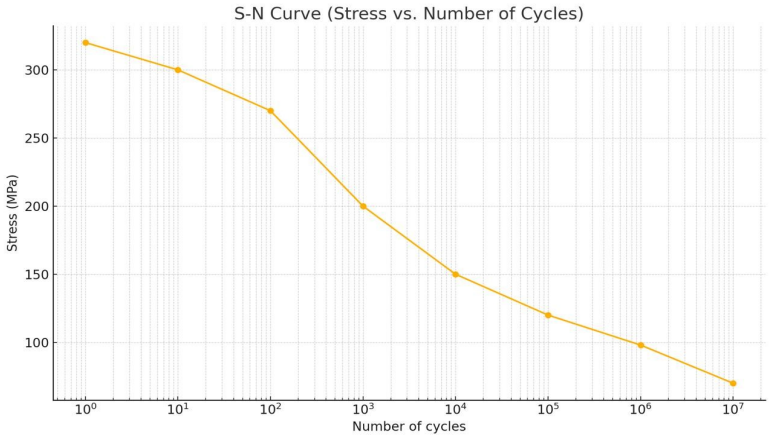

Fig. 1. Image of a typical S-N curve (using brittle aluminium with a tensile strength of 320 MPa as an example) [4].

6. Innovative approaches. Current trends include:
1. In-situ studies:
   - SEM/TEM with nanomanipulators;
   - Synchrotron X-ray diffraction.
2. Acoustic emission:

- Frequency analysis (20-1000 kHz);
- Classification of damage signals.

3. Computational methods:
   - Weibull model;
   - Multiscale modelling.

Each method is accompanied by a systematic error of 2-15%, which requires an integrated approach to characterisation. Particular attention is paid to accounting for dimensional effects and statistical data processing (at least 30 trials per fibre type).

3.2 Methods of microstructural analysis of the surface

For a comprehensive study of the fiber structure, high-resolution methods such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used. These technologies enable detailed analysis of cross-sectional geometry, pore distribution, and microdefects, as well as investigation of the formation of the interphase boundary between the fiber and the matrix in composites. In contrast, atomic force microscopy (AFM) allows quantitative data on the nanorelief of the surface to be obtained and its local mechanical properties, such as adhesion and elasticity, to be studied.

The study presented in [6] demonstrates the effectiveness of AFM for characterizing biopolymer fibers. The method made it possible to identify subtle differences in their supramolecular organization and quantitatively assess adhesion characteristics at the nanoscale, which is critical for predicting the behavior of such fibers in composite systems.

3.3 Analysis of molecular structure and chemical composition

Information about the internal structure of fibers at the molecular and supramolecular levels is provided by X-ray diffraction (XRD). It is used to determine the degree of crystallinity, the orientation of macromolecules along the fiber axis, and to record phase transitions occurring under thermal or mechanical stress.

The chemical nature and molecular structure of fibers are studied using spectroscopic methods. Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy are used to identify functional groups, assess the degree of polymer chain orientation, analyze the degree of cross-linking, and even measure internal stresses arising in the material, as shown in study [7]. The combination of these methods allows a direct link to be established between the chemical structure and macroscopic properties of fibrous materials.

3.4 Thermal analysis

Thermal methods, in particular differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), are key to analyzing the thermal stability of fibers. They are used to determine critical temperature points: glass transition temperature, melting point, and the onset of thermal decomposition. This data is particularly sought after in studies devoted to the use of natural and biodegradable fibers as reinforcing elements, where their low thermal stability is often a limiting factor.

3.5 Comprehensive approaches

The current trend in foreign research is a shift towards comprehensive approaches that involve combining several analytical techniques. This allows for a comprehensive characterization of the material. A striking example is provided by works [8, 9], in which a

combination of SEM, Raman spectroscopy, and digital image correlation (DIC) methods was used to correlate the structural and chemical characteristics of fibers with their mechanical behavior in a composite. Such studies significantly deepen our understanding of the structure-property relationship.

3.6 Digital analysis methods and machine learning

The current stage of development of fiber characteristic analysis methods is marked by the active introduction of advanced digital technologies. Techniques such as X-ray microtomography allow three-dimensional models of the internal structure of materials to be obtained, which opens up opportunities for non-destructive testing of the distribution and orientation of fibers in the composite volume [6]. Image processing procedures obtained using electronic and optical microscopy are increasingly being automated using computer vision algorithms.

A particular breakthrough is associated with the use of machine learning methods, in particular artificial neural networks. These technologies are used to solve a wide range of tasks: from automatic classification of morphological fiber types and identification of microdefects to the construction of predictive models linking structure to properties. Algorithms allow large arrays of experimental data (micrographs, spectra, mechanical test curves) to be processed, revealing hidden patterns that are not obvious in traditional analysis. This provides an unprecedented level of objectivity, speed, and reproducibility of research, taking the characterization of fibrous materials to a whole new level.

4 Methods for analyzing biofibers characteristics in Russian research

The methodological basis for determining fiber characteristics in Russian research practice has historically been formed within the framework of a strict regulatory framework represented by state standards (GOST), industry guidelines, and adapted methodologies. A key feature is the focus on methods that ensure reliable reproducibility of results in real industrial production conditions, which determines the dominance of mechanical and thermal approaches to analysis. The introduction of modern high-tech methods of microscopy and spectroscopy is hampered by the availability of expensive equipment and the development of the relevant laboratory infrastructure.

4.1 Approaches to mechanical testing

The assessment of the strength and deformation properties of reinforcing fibers (glass, carbon, basalt, organic) is regulated by a set of normative documents. These include GOST 1798-70 (tension), GOST 6611.2-73, GOST 57407-2017, GOST R 56561-2015, GOST 6611.2-73, GOST 32794-2014, GOST R 57407-2017, as well as departmental guidelines for testing reinforcing elements in composites. Tests are traditionally carried out on universal tensile testing machines. In recent years, there has been a trend towards modernizing measuring complexes through the introduction of digital strain gauge systems and high-speed video recording of the deformation process, which allows for greater accuracy in recording parameters [10].

4.2 Microscopic analysis in Russian research

Optical microscopy remains the most common tool for analyzing cross-sectional geometry, packing, and fiber breakage characteristics. For tasks requiring higher resolution, such as studying the surface morphology of natural fibers (flax, hemp), scanning electron microscopy (SEM) is used. Methods operating at the nanoscale, such as atomic force microscopy (AFM) and transmission electron microscopy (TEM), are used sporadically. Their application is concentrated mainly in scientific centers of the Russian Academy of Sciences specializing in nanomaterials.

4.3 Application of X-ray diffraction (XRD)

X-ray diffraction is used in domestic studies to determine the phase composition, degree of crystallinity, and texture of reinforcing fibers. Research is usually conducted on serial domestic diffractometers (e.g., DRON-3, DRON-7), as demonstrated in studies on the analysis of the structure of basalt and glass fibers [11]. At the same time, conducting a complex quantitative analysis of macromolecule orientation, widely represented in foreign literature, is difficult due to the insufficient development of specialized software for processing diffraction data.

4.4 Spectroscopic methods

Among spectroscopic methods, Fourier transform infrared spectroscopy (FTIR) is the most widely used in Russia. It is actively used to identify the chemical composition of polymer binders and modified fibers, in particular those of plant origin [12]. Unlike FTIR, Raman spectroscopy is used much less frequently, which is explained by the high cost and limited availability of high-precision equipment, as well as the complexity of its operation and interpretation of the data obtained.

4.5 Thermal analysis

Thermal analysis methods, including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), are standard tools in Russian laboratories. They are used to evaluate the thermal stability of fibers, phase transition temperatures, and quantitative analysis of composition. An example is the use of DSC and TGA to study composites based on glass fiber and a polyester matrix [13].

5 Analysis of foreign and domestic approaches

A study of foreign scientific literature reveals their predisposition to use integrated approaches and combine various methods of analysis. Such studies usually involve international standards (ASTM, ISO), in-situ visualization methods, automated information processing, and modeling techniques. In contrast, Russian scientific works tend to focus more on classical engineering methods based on GOST standards and other Russian regulatory documents. This methodology ensures their compliance with current requirements and the possibility of application in real production conditions, in particular in the machine-building and construction industries.

Table 4 presents a comparative analysis of methods for determining fiber characteristics used by foreign and Russian researchers.

Table 4. A comparative analysis of methods

Method	Foreign approaches	Russian approaches
Mechanical testing	Stretching of single fibers ASTM D3822, ISO 11566; use of micro-clamps, DIC, automatic measuring systems	GOST 11262, tensile and bending tests, manual fiber clamping, standard testing machines
Electron microscopy (SEM)	High resolution, fracture and interface analysis, EDS coupling, automatic segmentation	SEM analysis of morphology, without spectral analysis or with limited use of local chemical analysis
AFM and STM	Use for nano-adhesion and surface defect analysis synchrotron studies	Practically not used, limited access to equipment
X-ray diffraction analysis	Determination of the degree of crystallinity, chain orientation, phase transitions; synchrotron studies	XRD in standard configuration, focused on large structures; analysis limited by resolution
Spectroscopy (FTIR, Raman)	FTIR, Raman spectroscopy to assess molecular orientation, functional groups, residual stress, sometimes in-situ under stress	FTIR in IR to assess composition, no in-situ approach; Raman is rarely used
Thermal analysis (DSC, TGA)	Highly accurate DSC/TGA analysis of fiber thermal stability; often used in biocomposites and new materials	Used mainly in certification; lower accuracy; focused on determining thermal stability ranges
Integrated analysis methods	SEM + DIC + Raman + mechanics + modeling; in-situ tests for micromechanically	Separate application of methods; lack of coordinated analysis, integrated studies are rare

Foreign practice is characterized by the integration of methods (SEM, Raman spectroscopy, DIC) for comprehensive analysis of fiber mechanics and structure, including in situ process monitoring. Domestic research is focused on ensuring the reproducibility of results within the regulatory framework, but the depth of analysis is limited by the availability of high-tech equipment.

In this regard, the urgent task is to introduce digital methods (DIC, machine learning) into Russian laboratory practice, which is necessary to achieve the international level of research on reinforcing fibers.

6 Analysis of biofibers characteristics in composite materials

Determining the properties of reinforcing fibers integrated into the composite structure is a separate complex task in materials science. Its solution requires an interdisciplinary approach combining mechanical testing, microstructural analysis, diffraction, and spectroscopy methods. The key difficulty of such studies lies in the need to study the properties of the fiber as a separate structural element located inside a heterogeneous matrix. This necessitates the use of either non-destructive testing methods that allow the volume of the material to be examined, or requires labor-intensive procedures for preparing samples (grinding, cutting) for subsequent local analysis. Modern techniques are aimed at overcoming this barrier, ensuring the transition from averaged characteristics to establishing direct correlations between the microstructure of the fiber and the macroscopic

behavior of the composite material. Such analysis is critical for verifying micromechanical models and predicting the operational properties of structures.

Comprehensive techniques, including mechanical testing, microscopy, and diffraction and spectroscopy methods, are used to evaluate the quality of fiber properties in composites. The complexity of the analysis is due to the need to locate fibers within the material, which requires the use of non-destructive technologies or precise preparation of polished sections.

6.1. The use of experimental data to evaluate the strength of composite materials

The mechanical properties of reinforcing fibers are a determining factor for the strength and deformation characteristics of composites, especially in the longitudinal direction. The experimental data obtained on the fibers serve as the basis for predicting the mechanical response of composites during design. Parameters such as elastic modulus, tensile strength, and Poisson's ratio are critical inputs for micromechanical models. The most common of these are the Halpin-Tsai model, the mixture rule approach, and numerical simulation methods such as the finite element method (FEM).

The properties of fibres in composite materials are of crucial importance. Complex techniques including mechanical testing, microscopy, as well as diffraction and spectroscopic methods are used to assess their quality before and after integration into the matrix. Increasing the complexity of the analysis is the need to localise the fibres within the material, which requires the use of non-destructive techniques or the precise preparation of slits.

6.1.1. Micromechanical models

Mechanical and strength characteristics of fibers (elastic modulus, tensile strength, Poisson's ratio) are used in micromechanical models such as:

- Rule of Mixtures (ROM) - determines the effective elastic modulus of the composite:

$$E_c = V_f E_f + V_m E_m,$$

where E_c - is the modulus of the composite, V_f, V_m - the volume fractions of fibers and matrix, and E_f, E_m - the elastic moduli of the components.

- Hirsch model, Halpin-Tsai model - take into account the peculiarities of distribution and orientation of fibers, interaction between phases [14, 15].

Figure 2 [14, 15] shows a visualisation of the use of fibre characteristics in the calculations.

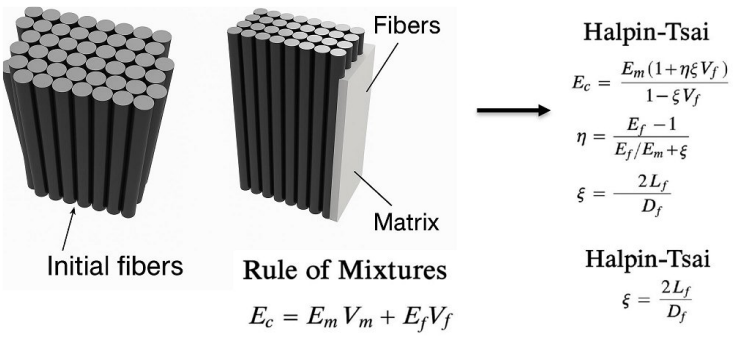

Fig. 2. Simplified scheme of Rule of Mixtures and Halpin-Tsai model.

Such models require precise knowledge of fiber characteristics, including interfacial interaction parameters and degree of alignment (orientation) of fibers, which can be obtained from SEM, XRD and Raman spectroscopy.

6.1.2. Macro-level modeling and finite element analysis (FEA)

Finite element methods (FEM) are widely used in engineering calculations for composite structures. When constructing FEA models, fibers are approximated as orthotropic or anisotropic structural inclusions, whose mechanical properties are specified based on experimental data obtained, for example, in accordance with ASTM D3822.

The modeling process includes several stages:

• Development of mesoscopic and macroscopic models designed to analyze stress and strain distribution, as well as to predict the occurrence and development of damage.

• Integration of microstructure data obtained using AFM and SEM, which allows the influence of initial defects and structural features on the mechanical behavior of the material to be taken into account.

• Use of specialized engineering analysis software such as ANSYS, ABAQUS, and COMSOL Multiphysics.

6.1.3. Prediction of composite material failure

Experimentally determined fiber characteristics serve as key input parameters for composite failure prediction models. This data is used in the following approaches:

• Application of strength criteria, such as the maximum stress criterion, Hashin and Tsai-Wu criteria, to assess the limit state of the material.

• Development of models that take into account the process of damage accumulation, including the failure of the fibers themselves and delamination at the interface with the matrix.

This data is used in the following approaches:

• Application of strength criteria, such as the maximum stress criterion, Hashin and Tsai-Wu criteria, to assess the limit state of the material.

• Developing models that take into account the process of damage accumulation, including the destruction of the fibers themselves and delamination at the interface with the matrix.

• Building stochastic models that take into account the statistical distribution of fiber strength (e.g., Weibull distribution) for more accurate prediction of structural reliability.

Thus, the combination of modern computational methods with experimental data allows us to create models that predict the behavior of composites under load up to the moment of failure.

7 Influence of morphological and structural parameters of reinforcing fibers on the functional properties of composites.

The morphological and structural characteristics of reinforcing fibers have a decisive influence on the formation of the complex functional properties of composite materials. These parameters determine not only mechanical behavior (strength, stiffness, impact toughness), but also thermophysical characteristics, as well as adhesive interaction at the interface with the matrix, which ultimately determines the service life of the entire material.

At the micro and nano levels, a number of key characteristics can be identified that require strict control:

- Cross-sectional geometry (round, oval, complex shape) determines the density of fiber packing and the mechanism of their adhesion to the matrix;
- Porosity and structural defects affect the density of the material and can act as stress concentrators;
- The degree of crystallinity directly correlates with strength characteristics and thermal stability;
- The orientation of macromolecules along the fiber axis determines the degree of anisotropy of mechanical properties;
- The chemical nature of surface functional groups regulates adhesion properties and compatibility with the polymer matrix.

Each of these parameters contributes to the final properties of the composite, creating a complex system of interrelated factors that determine the characteristics of the material under operating conditions.

The graph in Figure 3 shows that with increasing crystallinity due to a more structured structure, the elasticity of the modulus increases.

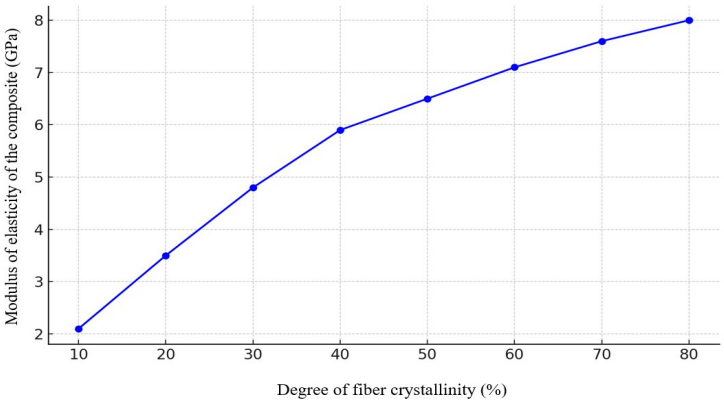

Fig. 3. Evaluation of the crystallinity of the elastic modulus of the composite.

8 Promising and innovative methods for studying biofibers characteristics

Modern fiber research methodology is characterized by a shift toward interdisciplinary approaches that integrate advances in nanomechanics, computer modeling, and artificial intelligence. The nanoindentation method shows significant potential, allowing for accurate assessment of the local mechanical properties of fiber surfaces, which is particularly important in the analysis of biological and modified natural materials.

A promising direction is the combination of high-resolution X-ray tomography methods, including in situ synchrotron studies, with machine learning algorithms for predicting mechanical characteristics based on spectral data from FTIR spectroscopy. This approach opens up new opportunities for studying biodegradable and modified fibers, where the chemical composition directly determines the operational properties.

To analyze the behavior of materials under cyclic loads, methods for creating digital twins based on microstructural models are being actively developed, as well as in situ

Raman spectroscopy, which allows tracking the distribution of internal stresses at the level of individual fibers.

Additional capabilities are provided by scanning thermal microscopy (SThM), which enables nanoscale analysis of the thermal conductivity and thermal stability of fibers.

These methods form a new tool for comprehensive research into the structure and properties of fibrous materials, enabling a transition from traditional testing to predictive modeling of their behavior.

9 Conclusion

The analysis of approaches to determining biofibers characteristics revealed key differences in methodological approaches in foreign and Russian practice. Foreign studies are focused on the comprehensive use of modern methods (in situ microscopy, spectroscopy, machine learning) for in-depth study of the structure-property relationship. Domestic research has significant potential in the field of standardized mechanical and thermal testing, ensuring data reliability for industry.

The main vector of development for Russian science is the active introduction of digital technologies (DIC, micromechanical modeling) in combination with traditional approaches. This will not only increase the accuracy and depth of analysis, but also create a scientific basis for the development of a new generation of reinforcing fibers and competitive composite materials with specified properties and bring Russian research to the international level.

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