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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

SELECTION OF EFFECTIVE METHODS OF QUALITY CONTROL OF PRODUCTS MADE FROM POLYMER COMPOSITE MATERIALS

Speciality: 3328.01 - "Xüsusi əməliyyatlar texnologiyası"

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and the degree of elaboration: In modern scientific and technical development, increasing the quality and reliability of materials, including polymer materials and products made from them, is one of the most urgent problems of the day. This is of particular importance for products made of heterogeneous materials, which are not homogeneous in structure. Thus, although these materials have high operational properties, certain changes occur in their physical and mechanical properties when operating in certain environments. The main reason for this is the heterogeneity of their composition and structure and, as a result, the formation of various defects. Therefore, in addition to increasing the reserve coefficient of strength in the construction of such materials, there is a need to control their quality using modern methods and more accurately. However, increasing the reserve coefficient of strength, in turn, leads to an increase in material capacity, structure mass, and cost.

At the same time, it should be noted that in the current very rapid development of the world economy, metal-based materials, including metal ores, are sharply depleted and do not adequately support the economy. Therefore, today, in the production of machinery and other constructions, artificial materials, including polymer composite materials, are gradually replacing metals and their alloys in manufacturing. However, in our opinion, the solution to the quality and reliability problem of construction and products made from polymer composite materials (PCM) should develop in the following directions:

1) The creation of PCM with improved operational characteristics;

2) The effective design of products and constructions through the application of materials that maximize their positive properties under specified conditions;

3) The implementation of quality control in the design process;

4) Ensuring stable and effective technological regimes and technological characteristics for raw materials and semi-finished products in the production of products and constructions;

5) Conducting input control of the quality of raw materials and semi-finished products, as well as the recycling processes of the material into the final product;

6) Comprehensive control of the quality of finished products and constructions, and the prediction of their reliability;

7) Continuous monitoring of the operational process;

8) Maintenance and reinforcement of constructions in the detection of defects.

The implementation of such complex measures allows for the maximum utilization of the operational capabilities of products and structures. It should be noted that these measures are more effective for large-scale products and constructions, as the costs associated with ensuring high reliability are minimal or measurable in relation to the product's cost.

Effective methods and means of control are of particular importance in solving the problem of quality and reliability of products.

Therefore, the dissertation work considers the issues of selection quality control methods in the production process of products made of PCM, as well as in their operation after production.

Non-destructive physical methods and means of control for predicting the reliability and operability of products in various operating modes, as a stage of the technological process in the production process, can be considered a more scientific and technologically intensive problem.

The most important types of control in the production process are input and output control. It is at this stage that, due to the variability of the technological process, the formation of all the negative properties of the product (defects, variability of physical and mechanical properties, structural damage, shrinkage, residual stresses, etc.) occurs. Therefore, the main task of control is to detect these imperfections and actively influence the technological process in order to maintain the technological regime and parameters within the given stable costs.[1]

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1. Критерии разрушения полимерных композиционных материалов. Р.Дж.Баширов, Н.Э.Исмаилов.

The use of non-destructive methods and means of control allows to carry out express analysis of the most important technological characteristics of the material in the process of manufacturing the product without taking samples and stopping the production process. This ensures the stability of the values of technological parameters and contributes to a significant reduction in the number of defects in the finished product. With the comprehensive non-destructive control of finished products, it is possible not only to determine the physical and mechanical properties of the material, including strength, hardness and geometric characteristics of the product, but also to predict the reliability indicators of the product based on the results of the control, and only high-quality and reliable products are released into the sphere of operation.

Thus, we can note that the problem under consideration is very relevant and requires a wide range of scientific research in this direction.

The goals and objectives of the research are to ensure effective control over the quality of products made from polymer composite materials and to substantiate the selection of control methods.

To achieve this goal, the following research objectives were solved:

1. Analysis of the physical and technological basis of the quality of products made from PCM;
2. Characteristics and causes of rejections in PCM and products based on them;
3. Selection of methods and means of quality control of products made from PCM;
4. Control of physical and mechanical parameters of materials and products;
5. Development of recommendations for the role of research results in predicting the reliability of products and their application in production.

The main provisions of the defense. As a result of the conducted research, the following main provisions are proposed for defense.

1. Effective methods for quality control of PCM and prediction of product reliability;

2. Analysis of physical and mechanical parameters of materials and products and methods of their control;

3. Methods that provide more accurate detection of defects in products made of PCM;

4. New approaches to predicting the reliability of products manufactured from PCM.

Reliability of research methods and results. The issues addressed in the dissertation work were resolved through theoretical and experimental studies conducted under both laboratory and production conditions. The obtained results were achieved using reliable, modern equipment, devices, and measuring instruments, including the application of ultrasonic, infrared, and microwave defectoscopes. Structural analysis of materials, determination of density, etc. tests were carried out using an optical microscope.

Scientific novelty of the research: The relationship between the production parameters, physical and mechanical characteristics and microstructure of polymer composite materials has been established. For this purpose, the causes of rejection in composite products have been determined with the help of mathematical apparatus. It has been established that the adhesion characteristics of the fiber play an important role in the formation of the quality of the composite. The formation of fiber-binder adhesion to the composite depends on the structure of the fiber surface and its chemical composition. The criteria for the dispersion of the composite product largely depend on the method of obtaining the composite and the type of connection between the fiber and the binder.

Environmental models of composites based on polymers were built. In these structures, the regularities and types of refraction and reflection of rays passing through them were determined by non-destructive control of the product based on the principles of Huygens-Fermat. The existence of the possibility of assessing the statistical interaction between strength and physical parameters in composites indirectly using non-destructive control methods was confirmed.

In glass-plastics, the interaction between the packaging methods of the freezer and their pressing parameters was established. In non-destructive control, the distribution velocities of longitudinal waves directed at different angles to the base of the composite were determined, and a hodograph of velocities in the main directions in the product was constructed.

Theoretical and practical significance of the research. The theoretical basis of the study is the mathematical evaluation of environmental models for polymer composites of various compositions. These environmental models play a decisive role in the non-destructive testing of the composite and the finished product. These developed environmental models are used to construct the velocities and hodographs of the velocities of the rays passing through the product and the reflected waves in non-destructive testing and to develop the theoretical foundations of the selected control method.

The practical significance of the research conducted allows for the organization of industrial-scale control using mathematical apparatus and physical methods without compromising the quality of products manufactured from composites.

Approbation and application. The main provisions of the dissertation have been discussed and approved at the following conferences and seminars:

1. "Education and Research Activities in the New Era: Realities and Challenges" International Scientific Conference, Mingachevir State University, 2022.

2. Scientific-Practical Conference on "The Development of Azerbaijan's Water Economy Sector is Associated with the Name of National Leader Heydar Aliyev," Baku, State Agency for Water Resources of Azerbaijan, 2023.

3. VII Republican Scientific-Technical Conference of Students and Young Researchers on "Progressive Technologies and Innovations" dedicated to the 100th anniversary of Heydar Aliyev's birth, Baku, 2023.

4. VIII Scientific-Technical Conference on "Current Problems in Combating Emergencies," Academy of the Ministry of Emergency Situations, Baku, 2023.

5. IX Republican Scientific-Technical Conference of Students and Young Researchers on "Progressive Technologies and Innovations" dedicated to the 101st anniversary of Heydar Aliyev's birth, Baku, 2024.

6. IX Scientific-Technical Conference on "Current Problems in Combating Emergencies," Academy of the Ministry of Emergency Situations, Baku, 2024.

7. Scientific seminars held in 2022, 2023, and 2024 by the Department of "Safety of Life Activity" of the Academy of the Ministry of Emergency Situations.

8. Scientific seminars held in 2022–2024 by the Department of "Special Purpose Materials and Tools" of AzTU.

Total volume of the dissertation with characters and separate volume of it structural sections.

The dissertation consists of 5 chapters, 196 pages of computer text, 51 figures, 34 graphs, 8 tables, and a list of 116 references. Cover and table of contents (5218), introduction (9979), Chapter I (45085), Chapter II (56710), Chapter III (45351), Chapter IV (66097), Chapter V (33587), conclusions (4632), and a list of references (16727). The volume of the dissertation consists of 256,373 characters, excluding figures, tables, graphs, and a list of references.

Publication rate. The main content of the dissertation work is reflected in 10 scientific works. 1 of them is a high impact factor periodical publication indexed in the “Web of Science” database, 2 in the Scopus databases. Also, 1 patent (AzPatent No. a20230121) was obtained for the work. Others were published in international and republican conferences.

MAİN CONTENT OF THE WORK

The introduction formulates the relevance of the topic of the dissertation and the main provisions put forward for defense.

The first chapter examines the physical-technological foundations of the production of products from polymer composite materials (PCM). For this purpose, the viscosity of the binder in the PCM and its role in structural formation are emphasized. The formula for the binder's life cycle is given. The kinetics of wetting between the binder and the reinforcement are examined. In this case, the formula for determining the volume fraction of the binder in PCM based on the cross-section of the capillary is derived.

The physical and technological basis of the production of various products from polymer composite materials has been analyzed. The main parameters affecting the quality in their production have been determined. Among them, the following are predominant as the main parameters: the viscosity of the binder, the choice of reinforcing material, its drying, molding of the product, and the hardening of the semi-finished product. It has been established that the lifestyle of the binder (matrix) is of particular importance and can be determined by analytical expression.

Reliable and constant control over the correct dosage of the binder components - solvents, diluents, hardeners, initiators, inhibitors, plasticizers - is necessary. Maintaining a constant temperature is of paramount importance in the preparation of the binder.

In the impregnation of the reinforcing material with a binder, the type and material of the reinforcing and fiber (thread, fabric, jute, strip, glass, carbon, organic polymer, etc.) play an important role. The volumetric flow of the binder through the capillary cross section during impregnation, the pressure determining the capillary movement of the liquid, and the linear speed of movement of the binder can be estimated by mathematical expressions. The relative conductance of the binder during impregnation is accurately determined by a special formula.

It was determined that one of the most important operations in the preparation of products from PCM is the selection of one of the drying modes of the reinforcing agent. For this purpose, the importance of mathematical expressions for determining the temperature of the semi-finished product and the length of the piece during the drying of the reinforcing agent is emphasized. After the semi-finished product is dried, the main parameters that determine its quality are considered important-adhesion, the amount of volatiles, the composition of solubles, the density of the semi-finished product, the introduction of the binder, and the determination of tensile strength.

One of the main operations in the production of products from PCM is the molding of the semi-finished product. For this purpose, the most common molding methods were analyzed, their advantages and disadvantages were noted. The process of winding fibers onto the filament as the main operation was considered, and the mathematical expression of the tensile force was analyzed.

The properties of the solidification of the semi-finished product extended after molding were considered. It was noted that the solidification temperature depends on the type of binder (matrix). The effect of the technological parameters of PCM production on the solidification temperature of the semi-finished product was analyzed. The mathematical expressions that determine and control the rates of reactions occurring during solidification were considered. Graphs of the dependence of the initial, intermediate and final substance concentrations on time and the dependence of the reaction rate concentration on temperature were constructed.[2]

The requirements for the control methods of the PCM and products manufactured on its basis were discussed. These control methods are divided into statistical, destructive and non-destructive. If the first two methods cannot cover all products 100%, the latter method allows for 100% inspection of the product. Therefore, the application of non-destructive physical control methods (NDPC) in the modern pace of industry development creates the basis for ensuring high quality of manufactured products.

The advantages and disadvantages of NDPC are analyzed and the development of new approaches to increase their accuracy and sensitivity is emphasized. Among such approaches, ultrasound, radio waves, radiation, magnetic and electric fields, etc. are considered more effective. Therefore, the research conducted in the dissertation is devoted to substantiating the choice of NDPC and improving the quality of products manufactured from them.

In the second chapter, the characteristics of the rejection cases occurring in PCM and products based on them are analyzed, the reasons that cause rejections in PCM and products based on them, and the criteria for the breakdown of PCM are investigated. It is shown

2. Optimal fiziki-mexaniki xüsusiyyətlərə malik polimer əsaslı kompozitlərin əldə edilməsinin əsasları. N.E.İsmayılov.

that rejections in PCM mainly depend on the defects occurring in its structure and the reasons that cause them.

To clarify these reasons, a relationship between the tensile strength of PCM and the strength limit has been established. A similar relationship for oriented fiberglass based on various binders is given in Figure 1.

The monolithic properties and high shear strength of PCM are primarily ensured through the binder, specifically the polymer matrix. Consequently, special requirements are imposed on the binder, not only in terms of adhesion properties but also in terms of deformation characteristics. To fully utilize the strength of the molded fibers, a specific ratio is required between the relative deformations of the fiber's ultimate tensile strain E_B and the matrix's ultimate tensile strain E_M. The dependence of stress σ on deformation is shown in Figure 2. In the figure, σ_{ba} and σ_{bm} represent the ultimate stresses in the reinforcement (fibers) and the matrix (resin), respectively.[3]

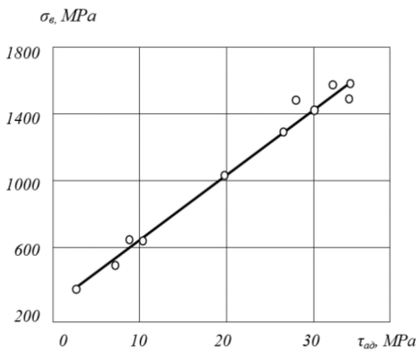

Figure 1. Dependence of adhesion strength τ_{ad} on the tensile strength σ_b of PCM

The monolithicity and high shear strength of PCM are provided mainly by the binder, that is, the polymer matrix, therefore special requirements are imposed on it not only in terms of adhesion

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3. The influence of defects on the physico-mechanical properties of polymer composite materials and products. N. Ismailov, R. Bashirov, F. Rasulov, I. Hamdullayeva

properties, but also in terms of deformation. In order to fully utilize the strength of the molded fibers, a certain ratio between the ultimate relative deformations of both the fiber E_B and the matrix E_M is required. The dependence of stress σ on deformation is given in Fig.2.

In the figure, σ_{ba} and σ_{bm} are the destructive stresses in the reinforcement (fibers) and matrix (resin), respectively.

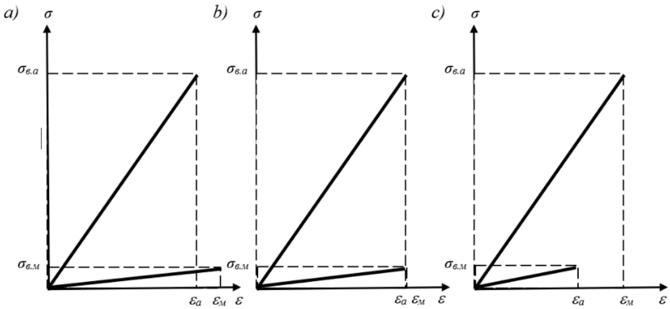

Figure 2. Strain dependence of stress in resin (matrix) ε_m and fiber (reinforcement) ε_a: ε_a: *a* - $\varepsilon_a < \varepsilon_m$; *b* - $\varepsilon_a = \varepsilon_m$; *c* - $\varepsilon_a > \varepsilon_m$

It can be seen from Figure 2 that in case $\varepsilon_a > \varepsilon_m$ the strength of the fibers is fully utilized. Therefore, the ultimate elongation of the matrix must be greater than the ultimate elongation of the fibers, i.e. $\varepsilon_m > \varepsilon_a$.

An important role in ensuring the work of the molded fibers with the matrix is also played by the ratio of the elastic moduli of the matrix and the reinforcement (E_m/E_a). In this case, the composite material is more sensitive to deformations in the width of the fibers. In this case, for a square (hexagonal) arrangement of the fibers, the following expression can be derived, which establishes the relationship between the optimal ratios of the relative deformations ($\varepsilon_{y.m}/\varepsilon_{y.k}$) of the matrix and the PCM and the elastic moduli of the matrix and the reinforcement (fiber's E_m/E_a).

$$\frac{\varepsilon_{y.m}}{\varepsilon_{y.k}} = \frac{1}{\left(\frac{D}{S} \cdot \frac{E_m}{E_a} + \frac{S-D}{S}\right)} \qquad (1)$$

where D – the diameter of the fiber, S – the distance between the fibers.

With a decrease in *S-D/S*, that is, with an increase in the content of molded fibers in the PCM, the ratio $\varepsilon_{y.m}/\varepsilon_{y.k}$ should increase, and at S=0 the value E_a/E_m should be accepted.

A more precise expression for determining the values of the relative deformation of the matrix along the width of the fibers will be as follows.

$$\varepsilon_{y.m} = \left[\frac{1}{\frac{DE_m(1-\mu^2)}{SE_a(1-\mu_m^2)}+\frac{S-D}{S}}\right] \cdot \left\{\varepsilon_{y.a} + \varepsilon_x \frac{D}{S}\left[\mu_a - \frac{E_m(1-\mu_a^2)}{E_a(1-\mu_m^2)}\right]\right\}, \qquad (2)$$

where "A" and "B" are Poisson's coefficients for the reinforcing fiber and matrix. Shear deformation in the "x" and "y" planes

$$\gamma_{xy.m.} = \frac{1}{\frac{DG_m}{S\,G_b}+\frac{S-D\gamma_{xy.k.}}{S}}, \qquad (3)$$

elongation along the fibers

$$\varepsilon_{x.m.} = \varepsilon_{x.k.}, \qquad (4)$$

where G_m, G_a – are the shear modulus of the matrix and reinforcing fiber; $\gamma_{xy.k}$ – is the shear deformation in the x, y plane of the composite.

For an optimally fiber-filled (50–75 %) PCM, the matrix elongation relative to the fiber should be 6–15 times greater. We recommend that the binder be in the range of 5–28% of the optimal elongation to eliminate surface cracking and increase load-bearing capacity for oriented fiberglass composites containing 30–70% fiber by volume.

It has been shown that the strength of the fiber in PCM depends on its diameter, that is, the greater the fiber diameter, the lower the strength of the PCM, the greater the dependence between strength and ultimate relative deformation. Higher values of these parameters are achieved at smaller fiber diameters.

The strength of fiberglass reinforcement depends on the nature of the defects on its surface. It has been established that surface defects are most dangerous for long fibers. However, the behavior of a fiber bundle under load differs from the behavior of a monolith. The stresses corresponding to the maximum load acting on the bundle depend on the dispersion of the strength of the monofibers.

The main processes of interaction between the matrix and the fiber depend on the adhesion characteristics of the fibers, their surface structure and chemical composition. It has been established that the weakening of the matrix strength in PCM is caused by the inhibitory effect of the fibers on the hardening process of the binder. In addition, there is a mutual relationship between the adhesion strength and the tensile strength limit in PCM.

In accordance with the conducted research and the obtained results, an analysis was carried out, on the basis of which the main characteristics of polymer composite materials and materials based on fiberglass were determined. On this basis, the main criteria for strength and breakdown, which depend on several technical and technological parameters of production, were revealed. These obtained values allowed us to draw the following relevant conclusions.

Disintegration criteria of solid media are characterized by the principle of application and summation of disintegrations, that is, individual local disintegrations are completely concentrated up to the limit, in which case the cracks reach a critical value and disintegration occurs.

The processes of PCM disintegration occur in the gradual growth of deformations, the growth of existing defects in it, and the "emergence-growth" of cracks due to the gradual accumulation of residual local stresses caused by the irreversible nature of successive single faults.

The main criterion for the breakdown of the PCM is the time-dependent change in the effect of residual stress and the formation of directed successive compression stresses that cause compression. The duration of the effect on each of these and the time of effect of each is related to the time of effect of the externally applied force.

Based on the conducted analyses, more precisely, on the basis of mathematical modeling of the long-term strength of polymer composite materials, a piezoelectric device for detecting defects was proposed. As a result of the research conducted in this area, the main advantage and distinctive feature of the proposed device is that it provides an accurate indication of the location of defects in the composite material based on coordinates, as a result of comparing the amplitude of the electrical signals transmitted to the layers of the composite material from the transmitting piezoelectric elements divided into matrices based on the coordinates, with the small-amplitude electrical signals received from the receiving piezoelectric elements divided into matrices corresponding to the signals reflected from the layers of the composite, and the reference signal table in the comparison scheme.[4, 5]

The essence of the device is explained by the diagram shown in Figure 3.

A piezoelectric device for detecting defects in polymer composite materials consists of (1) a voltage generator, (2) a transmitter connected to it, (3) a matrix-divided piezoelement transmitter connected to the transmitter and (4) a matrix-divided piezoelement receiver, (5) a summator, (6) a voltage converter, (7) a comparison circuit consisting of two parts, which compares the signals input in the reference and real measurement modes, and (8) two-color light-emitting diodes connected in parallel to this circuit, indicating normal (green) and alarm (red) states, and (9) a digital display screen for presenting data.

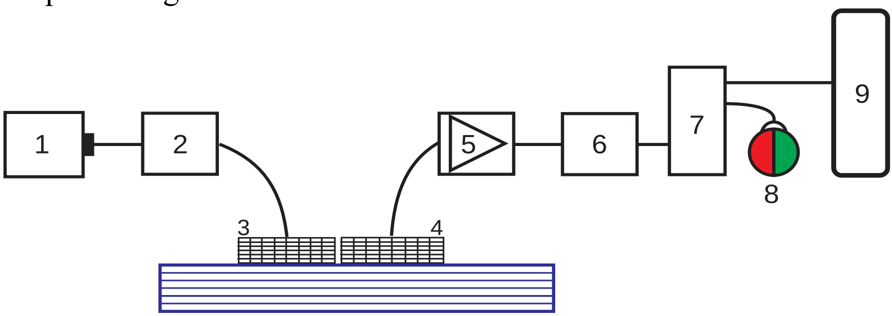

Figure 3. Block diagram of a piezoelectric device designed for detecting defects in polymer composite materials

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4. Polimer kompozit materiallarda daxili qüsurların aşkarlanmasında piezoelektrik sensorların tətbiqi effektivliyinin araşdırılması. N.E.İsmayılov

5. Dağıtmadan nəzarət metodları ilə qüsurların aşkarlanmasında piezoelektrik materialların tətbiqi imkanlarının təhlili. N.E.İsmayılov

The working principle of the proposed piezoelectric device for detecting defects in polymer composite materials is as follows:

To establish the required signal transmission parameters, the voltage generator – 1, sends signals through the matrix-shaped piezo-element transmitter – 3, into the composite material. Signals initially generated by the transmitter – 2, are conveyed to specific sections of the matrix-divided piezo-element transmitter - 3. The transmitter piezo-element plays a crucial role in determining the presence or absence of defects within the polymer material. The device operates by capturing signal waves reflected from the material, identifying differences in the inner layer of the polymer part (homogeneous or defective) and relaying the data through the matrix-divided piezo-element receiver - 4. Subsequently, input signals received from various matrices are amalgamated into a signal with overall amplitude via the summator – 5 and are then transmitted to the voltage converter - 6. The output signal from the voltage converter is directed to the comparator circuit - 7, which consists of two segments for comparing signals under standard and actual measurement conditions. The comparison circuit integrates two-color LEDs – 8, to indicate the device's status. If no defects are detected in the composite material, the green LED is illuminated; however, the red LED activates if there are differences in the incoming signal amplitudes, signifying the presence of defects. The results are displayed on the digital screen - 9. As a result, it is determined in real time whether there are defects in the composite material and the parts made from it throughout the complex volume.[6]

The third chapter examines the issues of ensuring control over the physical and mechanical parameters of materials and PCM products. The prediction of effective methods of quality control and their reliability is analyzed, models of the controlled environment for PCM are selected, and the theoretical foundations of the control method are developed.

An analysis of the effectiveness and reliability of quality control methods for PCM and products obtained from them was carried out. For this purpose, 8 factors were identified for the selection of the

6. Polimer kompozit materiallarda qüsurları aşkarlayan pyezoelektrik qurğu. AzPatent – No. a20230121. N.E.İsmayılov, M.H.Həsənov, R.C.Bəşirov.

method and prediction of reliability, taking into account its complexity, for the purpose of controlling PCM. Also, low-frequency ultrasound, radio wave, infrared, optical, thermometric, electrical methods were recommended for non-destructive control of PCM and products made from them.

Models were selected for control of PCM and products based on it, and based on them, the effectiveness of the application of low-frequency ultrasound equipment at the boundaries of the controlled environments was determined. With this method, the physical-mechanical, technological and structural parameters of the composition can be determined non-destructively. At the same time, the echo-impulse method is also very effective for such control.

The following models were selected for the controlled environment for PCM: 1) a homogeneous isotropic medium; 2) a homogeneous transverse-isotropic medium; 3) a homogeneous orthotropic medium; 4) a combined two-layer medium; 5) a three-layer medium; 6) a multilayer medium. The characteristics of each of these mediums were analyzed separately and their adequacy was checked using mathematical approaches and experimental methods. The most common types of controlled models are given in Table 1.[7]

1. Homogeneous isotropic medium. This model most fully reflects the structure of products made of unfilled polymeric materials (organic glass, polystyrene, block polyethylene, nylon, etc.) or materials filled with finely dispersed filler (RPP-170 fiberglass, premixes, carbolite, etc.). In some cases, for products with different thicknesses, there may be a violation of parallelism between the medium with reflecting and emitting surfaces. In this case, it is considered that the application area of the low-frequency echo-impulse method is limited to the medium, the thickness of which should not be less than one wavelength (λ). At the boundaries of parallel separation, the radius of curvature should be (R≥5λ). These conditions are necessary to ensure the opening of the products obtained in experimental studies.

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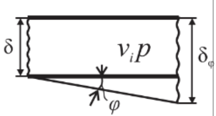
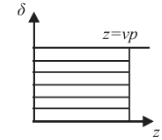
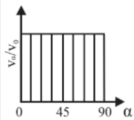
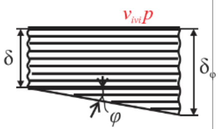
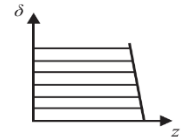
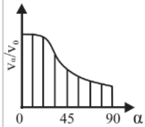
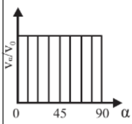
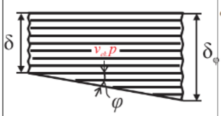
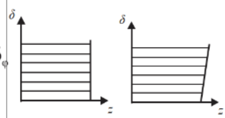
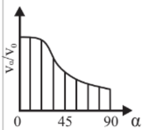
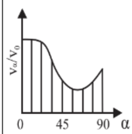
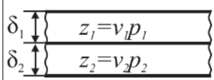
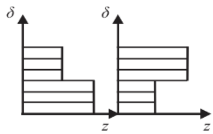
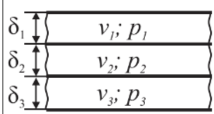
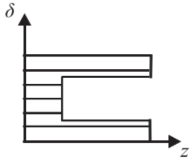
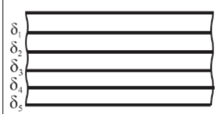
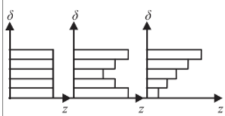
7. Polimer kompozit materiallara nəzarət üsullarının təhlili. R.C.Bəşirov, N.E.İsmayılov.

Table 1.

The most common types of controlled environment models

Model	Sketch	Dependence of acoustic resistance *z* on the thickness (depth) of the product *δ*.	Anisotropy of the velocity	
			on the depth	on the plane
Homogeneous isotropic medium				—
Homogeneous transversely-isotropic medium				
Homogeneous orthotropic medium				
Combined dual medium			—	—
Three-layer medium			—	—
Multilayer medium			—	—

Note: The following notations are adopted in the table: δ, δ_φ – product thickness; δ_1, δ_2, δ_3 ... δ_n – medium layer thickness; v, v_{ik} – ultrasonic velocity; α – angle between the direction of the tests and the axis of elastic symmetry; v_α/v_0 – indicator of the velocity anisotropy of the USN; φ – angle creating non-parallelism of the product surface.

2. Homogeneous transversely isotropic medium. The conditions for the propagation of elastic waves in this medium are characterized

by the fact that their propagation velocity in the plane of the medium is constant and does not depend on the direction of propagation. In the transverse direction (in the plane) of the waves, the velocity is a dependent parameter (it depends on the angle between the propagation direction and the interface of the medium), while in the perpendicular direction (through the thickness) the velocity is constant.

3. Homogeneous orthotropic medium. Among anisotropic polymer composite materials, the orthotropic medium has the widest distribution. It is characterized by three mutually perpendicular axes of elastic symmetry of the material. For such a medium (for each structural direction) the speed of propagation of elastic waves has a different value. Given that the controlled medium consists of a minimum of two different materials in the form of finely dispersed or fibrous fillers, the geometric dimensions of which are significantly less than the wavelength, it is assumed that such a compositional medium is homogeneous and anisotropic in relation to elastic waves. In this case, the degree of anisotropy is determined by the ratio of elastic waves in structural directions that coincide with the direction of elastic symmetry. For such a medium, the values of the speeds of elastic waves that do not coincide with the directions of the axes of elastic symmetry are a function of the angle between the direction of propagation and the axis of elastic symmetry.[8]

4. Combined dual medium. Consideration of the issues of the manifestation of elastic waves in the model of this medium allows us to solve the problems of quality control both in the production process of products and in finished products. The manufacture of large-sized products, as a rule, is associated with the casting of a composite material into a mold that repeats the configuration of the product. For products of the rotating body type, the most widespread application is winding, which consists in the fact that a reinforcing material in the form of a fabric, strip or thread, initially impregnated with a binder, is wound onto a coil having a shape identical to the shape of the product. According to the entire structure of the cross section, this medium corresponds to the model we are considering, that is, it is double, in

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8. Quality control methods and models of polymer composite materials. R.J. Bashirov, N.E. Ismayilov, R.E. Huseynov, N.M. Muradov.

which the lower layer is the material of the coil, and the upper layer is the material of the product (semi-finished product). Solving problems related to determining the distribution of elastic wave parameters in such an environment allows us to qualitatively and quantitatively assess the technological parameters of the latter during the winding process (in semi-finished products), thermal processing (hardening) and the finished product. This allows us to control the technological process in order to obtain flawless products.

5. Three-layer medium. This model has received the greatest popularity in three-layered structures, in which the first and third layers are made of strong materials, and the inner layer is made of lightweight filler (foam plastic, sotplast, etc.). In this case, the thickness of the outer layers is much smaller than the inner. The acoustic resistance of the outer layers is significantly greater than that of the inner layer. The outer layers are very thin in relation to the length of elastic waves.

In lightweight three-layered structures, as a rule, the acoustic resistance of the outer layers is smaller than that of the inner layer. The type of medium (isotropic or orthotropic) in each layer depends on the type and purpose of the product, but, as a rule, it is always known in advance. Sometimes, for constructive reasons, in order to increase the load-bearing capacity of the structure, its cross-sectional scheme may have a package structure, in which case each package (layer) is made of materials with different anisotropic properties. In this case, the exact solution to the problem of determining acoustic parameters poses insurmountable difficulties. In this case, experimental methods for determining acoustic parameters are considered more appropriate.

6. Multilayered environment. The model of such an environment is more typical for glued large-sized structures. In this case, the following combinations of layers can be observed in such structures: 1) all layers are isotropic, and the glued layers are also homogeneous (the acoustic and physical-mechanical properties of the layers are the same); 2) all layers are anisotropic (the acoustic and physical-mechanical properties of the layers are the same); 3) a combination of isotropic and anisotropic layers (distribution of acoustic and physico-mechanical properties is known on layers and obeys a certain law.).

Distribution parameters of elastic waves in such an environment depend to a great extent on the adhesion quality of all layers, physical-mechanical and acoustic characteristics of each layer, the ratio of the length of elastic waves and the thickness of the layer.

The theoretical basis of the selected dispersion control method was developed. For this, the main conditions for the distribution of ultrasonic waves were determined. To evaluate these conditions, mathematical expressions were obtained based on the basic principles of geometric acoustics. In accordance with the Fermat principle, a mathematical expression for the distribution time of elastic waves in the composition along the beam was obtained.

Based on the Huygens-Fermat principles, the general laws of refraction and reflection of rays in a medium have been considered. The passage of these rays through a medium can take the following forms: 1) longitudinal and shear waves, their angles of incidence α, refraction β and reflection γ have been determined; 2) reflected and refracted rays, they pass through a plane that falls on the plane normal to the boundary of the separation of the medium.

Models of various compositional environments have been proposed and their mathematical evaluation has been carried out. The following mediums are the most widespread in PCM: 1) homogeneous isotropic single-layer medium; 2) isotropic double medium; 3) multilayer isotropic medium; 4) transverse-isotropic medium; 5) orthotropic medium.

When considering PCM, each of the considered environments is encountered, and this constitutes the basis of theoretical and scientific approaches for the application of non-destructive control methods to materials and products. In each such environment, the longitudinal and transverse selection of the filler packing forms leads to the coincidence of the elastic symmetry axes of the composites with the fiber orientation.

The fourth chapter substantiates the organization of control over the physical and mechanical parameters of materials and products. The influence of structure and anisotropy on the structure and properties of PCM products is studied, and the basics of non-destructive control of the hardness of products and structures are developed.

Table 2

Structural parameters of fiberglass with longitudinal and transverse packing of reinforcing filler

The ratio of longitudinal and transverse fibers	Density, g/cm^3	Test direction φ … ^{0}	Speed of sound				Elastic modulus $E \cdot 10^{-4}$, MPa				Poisson's coefficient	
			for board		for stick		static		dynamic			
			experi-mental	calculated	experi-mental	calculated	experi-mental	calculated	experi-mental	calculated	static	dynamic
1 : 1	1,94	0	4220	4190	4190	4150	2,95	3,04	3,43	3,46	0,15	0,10
		45	3760	3710	3610	3580	1,82	1,80	2,57	2,54	0,46	0,27
		90	4250	4190	4220	4150	3,06	3,04	3,52	3,46	0,15	0,13
1 : 2	1,95	0	4510	4500	4470	4440	3,44	3,51	3,98	3,94	0,17	0,14
		45	3740	3710	3590	3580	1,79	1,80	2,56	2,54	0,44	0,28
		90	3900	3900	3870	3860	2,45	2,56	3,02	3,03	0,11	0,10
1 : 3	1,94	0	4630	4620	4590	4580	3,65	3,74	4,18	4,17	0,19	0,14
		45	3740	3710	3600	3580	1,81	1,80	2,56	2,54	0,45	0,27
		90	3760	3760	3730	3720	2,30	2,32	2,75	2,80	0,11	0,10
1 : 4	1,97	0	4680	4710	4630	4660	3,99	3,90	4,31	4,31	0,19	0,17
		45	3700	3710	3540	3580	1,72	1,80	2,52	2,54	0,39	0,29
		90	3700	3670	3660	3640	2,15	2,17	2,69	2,66	0,11	0,12
1 : 5	1,95	0	4700	4770	4650	4720	3,93	3,95	4,31	4,39	0,20	0,19
		45	3700	3710	3620	3580	1,86	1,80	2,61	2,54	0,43	0,21
		90	3640	3610	3600	3580	2,10	2,11	2,58	2,58	0,13	0,11
1 : 10	1,94	0	4920	4900	4860	4860	4,23	4,19	4,67	4,60	0,22	0,22
		45	3680	3710	3580	3580	1,87	1,80	2,54	2,54	0,29	0,24
		90	3500	3480	3450	3440	2,00	1,87	2,36	2,37	0,11	0,11
1 : 15	1,94	0	4980	4960	4920	4890	4,35	4,28	4,79	4,69	0,23	0,23
		45	3670	3710	3540	3580	1,78	1,80	2,44	2,54	–	0,26
		90	3370	3440	3340	3410	1,81	1,78	2,21	2,28	0,07	0,09
1 : 0	1,90	0	5000	5060	4930	5000	4,26	4,46	4,72	4,85	0,26	0,26
		45	3540	3710	3430	3580	1,72	1,80	2,26	2,54	0,37	0,25
		90	3200	3320	3160	3300	1,59	1,61	1,94	2,12	0,10	0,02

The influence of structure and anisotropy on the elastic strength characteristics of products made of PCM was studied. It was established that modern methods of non-destructive testing of the strength of materials are associated with the indirect statistical correlation of the measured strength and physical parameters in samples. Environmental models of various packings of fillers are given (Table 2) and the mathematical dependences of the interaction of these environmental models with the elastic moduli and strength were determined. It was established that the most important parameter for determining the strength of fiberglass in an arbitrary packing of the elementary layer is the structural coefficient.[9]

With the help of the obtained structural coefficient of PCM with various structures, its properties are known in mathematical expressions, and based on these properties, it is possible to determine the properties of the elementary layer in the composite. It was found that in the most commonly used products in industry, the directions of the extreme values of the stresses in the case of complex stresses coincide with the constructive direction of the product.

The mathematical analysis conducted between the structural coefficient and the properties of PCM determined the existence of the following relationships:

1) The semi-sum of the structural coefficients does not depend on the ratios of the layers and has a maximum value, i.e. a ratio of 1:1, for a composite with equal strength;

2) The value of the structural coefficient (strength) at an angle of 450 to the direction of the fibers is the same for any ratio of longitudinal and transverse fibers, does not depend on the thickness of the layers and has a minimum value for PCM with equal strength (q_{min});

3) The angle at which the minimum value of the structure coefficient is observed varies from 45^0 to 90^0 and depends on the thickness of the layers.

A table of final expressions of the structural parameters of fiberglass with longitudinal and transverse packing of the reinforcing

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9. Polimer əsaslı kompozit boruların dağılma göstəricilərinə suyun təsirinin təhlili. N.E.İsmayılov.

filler has been compiled (Table 3). Dependence relationships have been established between the tensile strength of CBAM fiberglass with butvar-phenolic binders and the longitudinal and transverse values of the fibers, and these data have been compared both experimentally and in reports. The closeness of the data has been confirmed.[10]

Table 3.

Dependence of the tensile strength of CBAM fiberglass with a butyl-phenolic binder on the ratio of MPA fibers in the longitudinal and transverse directions

Fiber ratio	Test direction				The sum of the values of the longitudinal and transverse strength of the fibers		discrepancy %	$a-\sigma_{90}/\sigma_b$	
	lengthwise		widthwise					actual	report
	actual	report	actual	report	actual	report			
1:1	400	408,5	400	408	800	815	–2,0	1	1
1:2	545	528	325	289	850	815	+6,0	0,61	0,54
1:3	–	587	–	230	–	815	–	–	0,38
1:5	640	647	180	170	810	816	+0,36	0,27	0,25
1:10	690	702	105	115	790	815	–2,7	0,17	0,162
1:15	720	717	80	100	800	816	–2,0	0,10	0,13
Unidirectional	–	766	–	51	–	815	–	–	0,065

The values of the propagation velocity of elastic waves in fiberglass with different degrees of anisotropy in the structure and the relationship between the elastic characteristics of the composite have been determined. A summary table (Table 4) has been compiled relating the elastic moduli and the propagation velocity of elastic waves (sound) in fiberglass with different degrees of anisotropy.[11]

In addition, the values of the propagation speed of elastic waves and the elastic characteristics of fiberglass with different degrees of anisotropy were tested. The experimental and calculated values of the speed of sound and the modulus of elasticity are given in Table 4.

10. Kompozit materialların yoxlanılmasında tətbiq edilən dağıtmadan nəzarət metodlarının effektivliyinin araşdırılması. N.E.İsmayılov.

11. Kompozit materiallarda ultrasəslə dağıtmadan nəzarət metodunun tətbiqinin təhlili. R.C.Bəşirov, N.E.İsmayılov.

Table 4

Moduli of elasticity and speed of propagation of elastic waves (sound) in fiberglass with different degrees of anisotropy

Ratio of lengthwise to widthwise fibers	δ_1	δ_2	Structure coefficient at $q=\sigma_{UE}/\sigma_0$ in the test direction.		q_{min}	φ_{min} … ^{0}
			0	90		
1:0	δ	0	1	a	a	90
1:1	$1/2\delta$	$1/2\delta$	$1/2\ (1+a)$	$1/2\ (1+a)$	$\frac{2a}{1+a}$	45
1:2	$2/3\delta$	$1/3\delta$	$1/3\ (2+a)$	$1/3\ (2a+1)$	$\frac{1{,}94a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{2}-a}{1-a\sqrt{2}}\right)^{\frac{1}{2}}$
1:3	$3/4\delta$	$1/4\delta$	$1/4\ (3+a)$	$1/4\ (3a+1)$	$\frac{1{,}87a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{3}-a}{1-a\sqrt{3}}\right)^{\frac{1}{2}}$
1:5	$5/6\delta$	$1/6\delta$	$1/6\ (5+a)$	$1/6\ (5a+1)$	$\frac{1{,}75a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{5}-a}{1+a\sqrt{5}}\right)^{\frac{1}{2}}$
1:10	$10/11\delta$	$1/11\delta$	$1/11\ (10+a)$	$1/11\ (10a+1)$	$\frac{1{,}6a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{10}-a}{1+a\sqrt{10}}\right)^{\frac{1}{2}}$
3:2	$3/5\delta$	$2/5\delta$	$1/5\ (3+2a)$	$1/5\ (3a+2)$	$\frac{1{,}98a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{1{,}5}-a}{1+a\sqrt{1{,}5}}\right)^{\frac{1}{2}}$
$n:m$	$\frac{n}{n+m}\delta$	$\frac{m}{n+m}\delta$	$\frac{1}{n+m}(n+ma)$	$\frac{1}{n+m}(na+m)$	$\frac{n+m+2\sqrt{nm}}{n+m}\ \frac{a}{1+a}$	$\mathrm{arctg}\left(\frac{\sqrt{\frac{n}{m}}-a}{1-a\sqrt{\frac{n}{m}}}\right)^{\frac{1}{2}}$

The criteria for non-destructive control of the stiffness of products and structures based on polymer composites have been determined. For this purpose, mathematical expressions for the moment of inertia and stiffness modulus for various shapes, including circles, ellipses, rectangles, isosceles triangles, and equilateral triangles, have been obtained. It has been established that the main role in non-destructive control is played by bending stiffness.

The determination of bending stiffness has been considered in the case of the influence of various loads: uniformly distributed static load, accumulated load. It was determined that non-destructive control of PCM is dominated by approaches based on evanescent or non-evanescent waves and the frequency of the parameters of the oscillating process: frequency, decrement, efficiency, amplitude.

In the fifth chapter, the effect of pressing pressure on the elastic properties of fiberglass PCM was studied, technological problems of pressing composite plates made of fiberglass were determined, and the dependence of the physical and mechanical characteristics and structure of fiberglass on its pressing pressure was studied.

The compositions and technological parameters of composite materials produced on the basis of fiberglass were determined. A table reflecting the technological parameters of pressing plate-shaped products made of fiberglass was compiled. At low pressing pressures of such plates, even by visual inspection, the presence of a large number of pores was determined in them. The thickness of such plates is much greater than the calculated thickness.

The distribution velocities of longitudinal waves were determined by acoustic control of the plates obtained at different pressing pressures in directions oriented to the base of the material at angles equal to 0, 15, 30, 45, 60, 75 and 90^0, and a hodograph of velocities in the main directions was constructed on the plate.

The interaction between the physical and mechanical characteristics and microstructure of fiberglass with different bases was studied. It was found that changing the ratio between the base and the loop in different packaging options of the filler has a serious impact on the physical and mechanical characteristics of fiberglass. Therefore, technological errors in the packaging of the filler are unacceptable.

The relationship between the pressing pressure and the formation of the microstructure of the composite shows that as the pressing pressure increases, the pores in the structure of the material decrease, and the difference between the calculated and actual thicknesses of the plates decreases significantly. An expression has been derived to determine the amount of pores at a known density of fiberglass.[12]

Figure 4. Microstructure of fiberglass based on TC 8/3-250 glass fiber obtained at a pressing pressure of 0.15 MPa (x500)

Figure 5. Microstructure of fiberglass based on TC 8/3-250 glass fiber obtained at a pressing pressure of 0.34 MPa (x250)

Figure 6. Microstructure of fiberglass based on TC 8/3-250 glass fiber obtained at a pressing pressure of 0.75 MPa (x250)

Figure 7. Microstructure of fiberglass based on TC 8/3-250 glass fiber obtained at a pressing pressure of 70 MPa (x250)

Figure 8. Microstructure of fiberglass based on TC 8/3-250 glass fiber obtained at a pressing pressure of 3.7 MPa

12. The development of a pıezoelectrıc defect detectıon device through mathematical modeling applied to polymer composıte materıals. M.Hasanov, N.Akhmedov. R.Bashirov, S.Piriev, O.Boiprav, N.Ismailov.

Figures 4 – 8 show the microstructures of fiberglass based on TC8/3-250 glass fiber obtained at different pressing pressures. It can be seen from the figures that as the pressing pressure increases, the number and size of pores noticeably decrease. Moreover, in this case, the thickness of the sheets approaches the calculated size.

The amount of pores in a known density of fiberglass can be determined by the following formula:

$$p = \frac{\gamma_{əl.}\left(\gamma_{şüşə} - p_{ş.p.}f\right) - p_{ş.p.}\gamma_{əl.}(1-f)}{\gamma_{şüşə}\gamma_{əl}} \quad ,$$

where f – mass fraction of glass, %; $p_{ş.p.}$, $\gamma_{şüşə}$ $və$ $\gamma_{əl}$ – density of fiberglass, glass and binder, respectively.

Based on this formula, the amount of pores in all fiberglass was calculated. It was found that the porosity of fiberglass depends significantly on both the pressing pressure and the type of reinforcing material. For example, fiberglass based on the $T_{elast.}$ fabric has the largest amount of pores at low pressing pressures (0.15 - 0.34 MPa); in fiberglass based on the ТЖСК and TC8/3-250T fabrics, the amount of pores is significantly less at the same pressing pressures.

Graphs were constructed expressing the dependence of the longitudinal wave propagation velocity on the density in the same fiberglass. It can be seen from the graphs that the relationship between density and wave propagation velocity is determined by the test direction and the type of glass filler. The correlation coefficient between the longitudinal wave propagation velocity and the static elastic modulus was determined and the correlation equation was obtained.

GENERAL RESULTS

1. Theoretical and technological foundations for the selection of effective methods of quality control of products made of polymer composite materials have been developed. The physical and technological foundations of the production of products from polymer composite materials have been analyzed, the stages of preparation of

the reinforcing material for production have been determined. At the same time, the requirements for polymer composite materials were analyzed, the advantages of non-destructive physical control methods in the production of composites on an industrial scale were shown.

2. The characteristics of rejections in polymer composite materials and products based on them were investigated, and the criteria for rejection in these materials were determined. It was found that the larger the diameter of the fibers in polymer composite materials, the more dangerous the defects on their surface are, as a result, the strength properties of large-fiber materials are lower than those of small-fiber materials. At the same time, the strength of fiberglass reinforcements in particular also depends on the nature of the defects on their surface, and surface defects are more dangerous for long fibers.

3. It was determined that the criteria for the collapse of solid media are determined by the accumulation of local collapses to their full limit state, the formation of cracks, their reaching a critical value and the occurrence of collapse. In this case, the successive uniform violations occurring in the material become irreversible, as a result of which local residual stresses gradually accumulate, and their "emergence-growth" process occurs. It was noted that the main criterion for the collapse occurring in the material depends on the effect of its operating period. Depending on the type of impact, this can be long-term or short-term.

4. Effective methods of quality control of polymer composite materials and products based on them were selected and their reliability was predicted. The prediction of the reliability of the material and the product was considered on the example of 8 factors. Low-frequency ultrasound, radio wave, infrared, optical, thermometric, electrical methods were considered more effective for non-destructive control of the material and the product obtained from it.

5. Control for polymer composites was carried out for the following medium-models: 1) homogeneous isotropic medium; 2) homogeneous transverse-isotropic medium; 3) homogeneous orthotropic medium; 4) combined two-layer medium; 5) three-layer medium; 6) multilayer medium. Theoretical foundations of non-

destructive control for these medium were developed. For this, the main conditions for the distribution of ultrasonic waves in the medium were determined. Mathematical expressions were obtained based on the basic principles of geometric acoustics to evaluate these conditions.

6. For the considered medium-models, the general laws of refraction and reflection of rays in them were determined on the basis of the Huygens-Fermat principles. These rays can pass through the medium in the form of longitudinal and shear waves, reflected and refracted rays. The angles of incidence α, refraction β, and reflection γ of these waves were determined. It was noted that the reflected and refracted rays pass through a plane that falls on the plane normal to the boundary of the separation of the medium.

7. The basics of organizing control over the physical and mechanical properties of polymer composite materials and products manufactured from them have been developed. It has been established that modern methods of non-destructive control of the strength of materials allow for the indirect statistical evaluation of the relationship between the strength and physical parameters formed in samples.

8. Structural models for different packing of the filler in the composite are given and mathematical expressions of their interaction between the modulus of elasticity and strength of the material are obtained. The most important parameter in determining the strength of fiberglass in the case of arbitrary packing of the elementary layer in the composite is the structural coefficient. With the help of the structural coefficient of various composites, their physical and mechanical properties can be determined without destroying the sample using mathematical apparatus.

9. A table of final expressions of structural parameters of fiberglass in the longitudinal-transverse packing of the filler in the composite has been developed. The relationship between the values of the propagation speed of elastic waves in composites at different degrees of anisotropy in the structure and their elasticity characteristics has been established. At the same time, the criteria for non-destructive control of the stiffness of composite products and structures have been determined.

10. The effect of pressing pressure on the elastic properties of fiberglass has been studied. A table of technological parameters of pressing plate-shaped products from fiberglass has been compiled. The distribution velocities of longitudinal waves directed along the base of the material at different angles have been determined, and a hodograph of velocities in the main directions in the plate-shaped product has been constructed. The interaction between the physical and mechanical characteristics and microstructures of fiberglass with different bases has been established.

The conducted studies create a basis for organizing the production of products from polymer composite materials on an industrial scale, and confirm the effectiveness of non-destructive testing methods for determining their properties and structure.

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2. İsmayılov N.E. Optimal fiziki-mexaniki xüsusiyyətlərə malik polimer əsaslı kompozitlərin əldə edilməsinin əsasları. // – Bakı: FHN Akademiyasının Elmi xəbərləri jurnalı, – 2022. – № 3, – s. 48.
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