

Article

Mathematical Modeling of the Reliability of Polymer Composite Materials

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Abstract: An urgent task in creating and using composite materials is the assessment and prediction of their performance properties and reliability. Currently, when studying the reliability of the materials, there is little experimental data, mathematical descriptions, and models for both probabilistic and deterministic methods to assess reliability. Based on the obtained experimental data, this article discusses the development of a methodology for predicting reliability. The article also proposes a statistical model for assessing reliability by the criterion of the structural strength of products made of polymer composite materials. The characteristics of the reliability changes in the materials when in operation are presented. The calculation allowed obtaining graphs showing the dispersion and statistical variability of the characteristics of polypropylene-based polymeric materials at the design, production, and operation stages of the product life cycle. The computational experimental results for determining the influence of the shape of inclusions and mass on the mechanical properties of a polymer composite material aimed at improving the strength characteristics of the products are presented. Based on a computational experiment in the MSC Digimat MF nonlinear solver, equations are provided to demonstrate the regression dependence of the strength of a part made of a polymer composite material on technological factors.

Keywords: modeling; mathematical methods; reliability of materials and structures; statistical characteristics; composite materials; polymeric materials

MSC: 65C20



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1. Introduction

The main tasks of the reliability theory of products made of polymer composite materials are the establishment of regularities in the occurrence of failures, the determination of quantitative characteristics, and the development of methods for assessing and calculating reliability [1]. These problems are solved in two ways. The first way consists of the study of the statistical regularities of the occurrence of failures of the same type of materials under certain operating conditions. This way is the basis for establishing the laws of distribution of the studied parameters and obtaining numerical characteristics of the operational reliability of the materials and products made from them [2].

The characteristics found in this way are used to calculate the reliability of materials and products.

The second way is aimed at studying the physical nature and the mechanism of failures. It serves as the basis for developing measures to improve the reliability of existing and newly designed technological materials [3].

This way, due to the complexity of obtaining the required initial information, has not yet been widely used in reliability studies, since it is often difficult to take into account all the factors affecting the reliability of systems [4].

Nevertheless, such an approach seems to be more effective in terms of identifying the physical nature of material destruction and the reasons why parameters deviate from acceptable limits. This way is used, despite the operational specifics, when it is still possible to obtain the required initial data, for example, when studying the reliability of polymeric materials and the most critical products manufactured from them [5].

A mathematical model is a set of mathematical objects (numbers, symbols, sets, etc.) and relationships between them, reflecting the most important properties of a technical system. This means taking into account the possible states of the system, path, and intensity of transitions from one state to another, and implies containing tolerance limits to determine parameters and the dependence of these parameters on random disturbances and processes in the elements.

Traditionally, mathematical reliability models can be divided into two groups [1]:

1. Structural models are the models based on the logical interaction schemes of the elements included in the system from the point of view of maintaining the operability of the system as a whole [6]. At the same time, statistical information about the reliability of the elements is used without involving information about the physical properties of the material, parts and connections, external loads and influences, and the mechanisms of interaction between the elements. Structural models are presented in the form of block diagrams and graphs (for example, fault trees and event trees). And the initial information is presented in the form of the known probability values of the failure-free operation of the elements, failure rates, etc.
2. Mathematical models of the reliability theory are the models taking into account mechanical, physical, and other real processes that entail a change in the object properties and object components. These are the models of mechanics widely used in the calculations of machines and structures. Force and kinematic interactions of machine elements and structures are complex. The behavior of these objects essentially depends on their interaction with the environment, nature, and the intensity of the exploitation processes [7].

To predict the behavior of polymeric materials, parts, and structural elements made of them, it is necessary to consider the processes of loading, deformation, wear, damage accumulation, and destruction under variable loads, temperature, and other external influences. It is possible to evaluate the reliability indicators of the systems in a theoretical and computational way, based on the physical models and statistical data regarding the properties of materials, loads, and impacts [8].

In order to compile adequate source mathematical models of the reliability of polymer composite materials and products made from them, it is first necessary to get an idea of the types and groups of such materials and study their mechanical and operational characteristics [9].

A modern technology trend is to increase the share of polymer composite materials. Polymer composite materials (PCMs) are widely used because of their properties. At present, almost no industry can function without PCMs due to their unique properties [10]. Works in the PCM field make it possible to improve material operational properties. Even today, PCMs are resistant to corrosion and oxidation, have good thermal stability, and can be used for thermal, acoustic, and electrical insulation. In addition, due to their manufacturability, PCMs allow the shortening of production processes. They also allow the reduction of material waste during processing [11]. All the processes described above gradually decrease the use of ferrous metals (such as steel alloys, carbon steel, cast iron, and forged iron) and non-ferrous metal alloys (primarily aluminum) when constructing machines and units. This is most evident in the aviation industry. The process of replacing metallic materials has been proceeding for many years [11].

When creating PCM, a bunch of the polymer matrix and fiber is often used to enhance the strength properties of the material in modern technology. Having different matrices and reinforcement mechanisms, composites can be of different types. The most commonly used composite materials are either glass fiber (GF) or reinforced carbon fiber (CF). The share of the studies of such composites is more than 90% of the total number of studies of composites [12]. Composite matrices are most often made from thermoplastic [13] or thermosetting [14] polymers.

The application scope of PCMs in mechanical engineering is quite large. However, the most complete manifestation of the advantages and strengths of PCMs is impossible in a large number of cases. Such cases include impellers, propellers, and impellers for electric centrifugal pumps. In [15], composites from a polymer matrix reinforced with glass fiber were used to manufacture impellers [15]. In general, fiberglass is an inorganic non-metallic material. Heat resistance, high tensile strength, and excellent chemical stability are among the properties of these fibers. Differences in fiber composition vary the properties, making them different. Different Young's moduli can be obtained in the range from 51.7 to 86.9 of the mean score [16].

The main incentive for increasing the economic efficiency of using PCM parts is to reduce the high cost of equipment and increase its reliability. The development and application of the PCM reuse technology by equipment manufacturers will allow companies to reduce the life cycle cost of the equipment operation by increasing its reliability. Increased reliability reduces the number of equipment failures and eliminates the risks of environmental problems [17].

Expanding the application scope of polymeric materials in industry is constrained by the lack of a scientifically-based approach to the choice of performance criteria, methods for assessing the reliability of products, and insufficient experience in their operation under various conditions. Currently, there are very few experimental data and developed methods for assessing the reliability that take into account the behavior of polymeric materials [18]. The review results show that the majority of works are devoted to the study of the PCM mechanical characteristics. A peculiar feature of polymer composite materials is a significant dispersion of strength and deformation characteristics at the initial state, as well as their change and dispersion when in operation. In addition, there are almost no methods for assessing the reliability of the products made of polymeric materials at the stages of design, production, and operation, taking into account the statistical variability of their characteristics. At the same time, the assessment of the reliability and overall mechanical properties of PCMs without mechanical testing is extremely important in the design and manufacture of products made of these materials. The designer must know and consider the material behavior under various loads, changes in material properties over time, and changes in the properties accompanied by scale variations of parts [19].

As to the reliability of polymer composite materials, researchers traditionally try to conduct a series of experiments, process the obtained statistical information, and derive from it the distribution functions of degradation and changes in the reliability of material samples, attributing to them the existing classical distribution functions of a random variable. They are Normal (Gaussian), Lognormal, Gamma distribution, Exponential, Laplace, Rayleigh, Weibull, Wigner, and Pareto. This is convenient from the point of view of the mathematical apparatus that already exists for such distributions. However, as the mathematical apparatus develops, including numerical methods for processing mathematical data, it is much more important to obtain native graphs of the functions of changing the source materials depending on the factors of time, temperature, and other performance indicators. There is no need to attribute these functions (sometimes with large errors) to the existing distribution laws of a random variable. This provides a certain flexibility in research work and allows for results that are more accurate for practical engineers conducting studies on changes occurring in the reliability and degradation of materials depending on changing operational factors in real conditions, as well as on predicting changes in their reliability in the future.

Based on this, it is possible to conclude that there is a lack of experimental data and deterministic methods for assessing reliability, taking into account the behavior of polymer composite materials. There are also no adequate methods for assessing the reliability of products made of polymer composite materials when designing, producing, and operating them, considering the statistical variability of the materials' characteristics. These factors make this topic relevant to the study [20].

The purpose of this work is the development and creation of probabilistic, stochastic source models of both PCMs and products made from them at each stage of the technological processes when treating these materials and products. That would allow revealing the peculiarities of changes in the reliability of materials and products depending on the main parameter (time t). To achieve this goal in the course of research and experimental work, the authors have completed the following tasks:

1. Development of a methodological approach and methodology for predicting the reliability for solving the problem of predicting the reliability of materials for products made of polymer composite materials according to various criteria.
2. Use of the probability theory to process the stochastic information of physical experiments: the information on the statistical variability of deformation–strength, elastic, dilatometric, and shrinkage characteristics.
3. Development of a model for calculating reliability according to the strength criterion.
4. Determination of the statistical characteristics of composite materials and the effective stress concentration factor of the materials.
5. Determination of the mathematical dependence of the failure-free operation probability of the samples on their cross-sectional area.
6. Construction of the dependence of the failure-free operation probability on the holding time at different pressures and temperatures of casting and molding the products from composite materials at different operating temperatures of the products.
7. Experimental studies on the products made of polymer composite materials to improve the strength characteristics of the products and their reliability.
8. Numerical modeling of the strength function of the materials and molded products depending on the cross-sectional area of the samples and the yield strength of thermoplastics based on polypropylene.

2. Materials and Methods

The experimental research in this article was carried out in two main stages. In the first stage, we calculated the reliability parameters of polymeric materials. Since reliability is a complex property of an object, including parameters that largely depend on the mechanical characteristics of the material [21], it is necessary to evaluate it. Therefore, we simulated the mathematical expectation of material degradation, the scattering dispersion of material degradation, the standard deviation of material degradation or scattering, and the coefficient of variation.

First of all, the dependencies were determined and built between the average value of the yield strength and the standard deviation of the yield strength from the logarithm of the cross-sectional area of the samples. Then, based on the obtained statistical model of reliability, the no-failure operation probability was calculated for the samples, and the dependencies of the no-failure operation probability on the cross-sectional area of the samples were plotted [22]. Next, the dependence of the failure-free operation probability on the technological parameters of production, namely, the exposure time under the pressure of the sample and the dependence of the average value, and the standard deviation of the yield strength on the aging time at low temperatures were obtained and plotted [23].

In the second stage of the research, we carried out experimental work to determine the properties of the real samples to compare the calculated parameters for the developed models with the experimental results. The comparison was carried out for one of the materials since this kind of work is extremely laborious and requires a lot of time and resources [24].

2.1. Selection of Research Materials

Polymeric materials of various grades were chosen as the research material. Basically, the choice of materials for the research was based on their wide applicability in modern industries, in particular in the aviation and automotive industries. For the numerical and natural experiments, we chose several groups of common polymeric materials. These were polystyrene, polyamide, polypropylene, and polycarbonate. In general, these materials belonged to the same group of polymeric materials, but their properties differed. This allowed for a more complete construction and testing of the models. In addition, the choice of these materials was also due to the fact that it was quite simple to obtain data on their properties and structure. This sometimes allows for avoiding the need for a large number of full-scale experiments.

One of the promising and topical areas for improving the structure of polymeric materials is the use of fillers. This allows changing their operational properties quite strongly. In the work, we also tested our models on a polymer material with a filler. We took a composite material based on a polycarbonate matrix filled with fiberglass as an experimental material. The choice of this material was due to the fact that it was promising for the purpose of significant improvement of the polymer strength properties. Such composite usage required additional full-scale experiments to confirm the constructed theoretical dependencies.

PP-based thermoplastics were chosen as objects of the study. They were polypropylene homopolymer PP 21060-16; block copolymer of propylene with ethylene BSPE 22007-16; frost-resistant grades of polypropylene MPP 15-04; MPP 15-04-901, asbestos-filled polypropylene PP 21060-A20; glass-filled polypropylene SNP 21060-16-S30; and polycarbonate with short glass fiber, made by injecting 30 pcs of molding for each size. The samples were tensile tested on an Instron 3400 testing machine (Instron Engineering, Norwood, MA, USA) at a tensile rate of 50 mm/min.

2.2. Mechanical Testing

Mechanical tests were carried out in two stages: the first stage was to obtain experimental data for probabilistic modeling of the properties and reliability of CPT, and the second stage was to verify the obtained results and test the developed mathematical models [25]. For this purpose, the calculated properties were compared with the results of mechanical tests. For comparison, the experimental results of testing the samples of PCM (polycarbonate matrix and glass fiber as a reinforcing element) for tension according to the standard method [26] were obtained. The initial data for determining the design properties of the material samples obtained as a result of the full-scale experiments are not given in the article due to the large amount of statistical information. The article presents the results of processing these data in the form of graphs.

The samples were in the form of blades with a cross-sectional area of 2.5, 10, 39, and 200 mm², made by injection molding of 30 pcs for each size. The shape of the samples is shown in Figure 1. The length of the symmetrical broadenings at the ends was 34 mm; the length of the inner part between the broadenings was 82 mm. The samples were obtained by casting. Short fiberglass was used as a filler. The short form was chosen based on the technological requirements of foundry technology. The polymer mixtures were prepared on a single-screw extruder with a diameter of 45 mm, L:D = 25 mm, manufactured by Esmos. Electric heating was implemented as follows: The temperature is controlled by thermocouples and a thermostat. The extrusion temperature regime is as follows: Zone I—260 °C; Zone II—265 °C; Zone III—270 °C; and Zone IV—260 °C. The sample testing and stress-strain plotting were performed on an Instron 3400 testing machine (Instron Engineering, Norwood, MA, USA) at a tensile rate of 50 mm/min. The tests were carried out in accordance with “ISO 1268-10:2005 Polymer composites”. The production of samples tests the injection molding of long-fiber press materials. The same path geometry of the composite material and the symmetrical arrangement of the cavities ensures the same properties of the test specimens made from the same material batch.

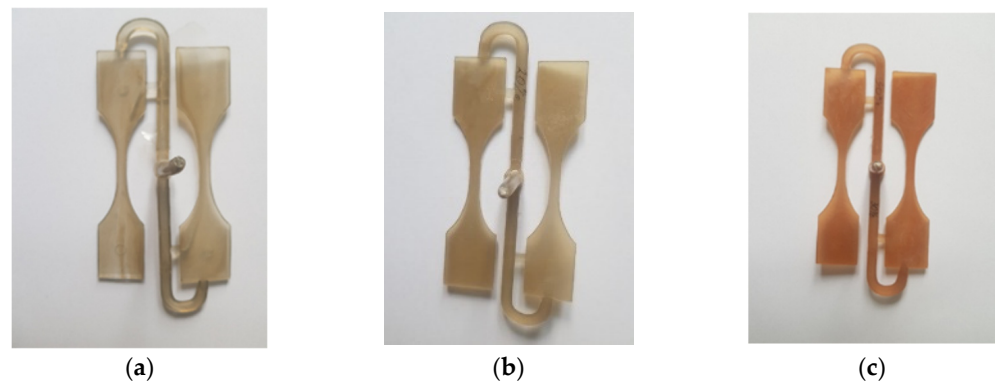


Figure 1. Test samples of composites: (a) unfilled; (b) filled with 20% short glass fibers; (c) filled with 30% short glass fibers.

2.3. Methods for Modeling and Calculating Deviations

For the polymeric materials based on PP, the yield point is chosen as the ultimate strength characteristic [17]. It is known that the distribution of random values of stress and strength for structural elements made of polymeric materials can be described by the normal distribution law [27].

The normal distribution of a random variable (Gaussian distribution) is a probability distribution, which in the one-dimensional case is given by a probability density function coinciding with the Gaussian function [28]:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (1)$$

where parameter μ is the mathematical expectation (mean), median, and the distribution mode; σ is the standard deviation; σ^2 is the variance of the distribution.

1. Mathematical expectation of the degradation of materials is as follows:

$$L_0 = \frac{\sum_{i=1}^k L_i \cdot m_i}{\sum_{i=1}^k m_i} \quad (2)$$

where L_i is the degradation time in the i -th digit, h; m_i is the number of sample breaks in the i -th digit; k is the number of digits.

2. The dispersion scattering degradation of materials is:

$$D = \sigma^2 = \frac{\sum_{i=1}^k (L_i - L_0)^2 \cdot m_i}{\sum_{i=1}^k m_i} \quad (3)$$

3. The material degradation standard deviation or scattering:

$$\sigma = \sqrt{D} = \sqrt{\frac{\sum_{i=1}^k (L_i - L_0)^2 \cdot m_i}{\sum_{i=1}^k m_i}} \quad (4)$$

4. The variation coefficient is:

$$V = \frac{\sigma}{L_o} \quad (5)$$

By processing the statistical information using Formulas (1)–(4), and calculations of the numerical characteristics of the degradation of materials for the obtained samples, it is possible to determine an important characteristic of the degradation of materials when the maximum number of their failures is observed [29].

The mathematical expectation of the degradation L_o characterizes the condition when the number of equipment failures is maximum. Scattering σ and the variation coefficient V show the possible spread of degradations in contrast to their expectation.

It is proposed to evaluate the relative characteristic of the reliability (lack of degradation) of the materials as the main component of their reliability and to determine it through an indicator that characterizes the number of material failures over a certain time, that is, through the failure rate [30]. The failure rate is understood as the ratio of the number of failed samples per unit of time to the average number of objects that are working properly in a given period, provided that the failed objects are not restored and are not replaced by serviceable ones [31]. In other words, the failure rate is numerically equal to the number of failures per unit of time, divided by the number of samples that have worked without fail up to this time. The mathematical description of the failure rate is presented below:

$$\lambda(t) = \frac{n(t)}{N_{av}\Delta t} = \frac{n(t)}{[N - n(t)]\Delta t} = \frac{f(t)}{P(t)} \quad (6)$$

where N is the total number of the samples under consideration;

$f(t)$ is the failure rate or the number of the samples that have failed by the time t per unit time;

$P(t)$ is the number of the samples that have not failed by the time t ;

$n(t)$ is the number of the failed samples in the time interval from $t - (\Delta t/2)$ to $t + (\Delta t/2)$;

Δt is the time interval;

N_{av} is the average number of the properly working samples in the interval of Δt : $N_{av} = \frac{N_i + N_{i+1}}{2}$;

where N_i is the number of the properly working samples at the end of the interval Δt .

The failure rate dimension is the inverse of time, usually measured in 1/hour.

Based on the proposed structure of material processing, using the statistical reliability model, it is possible to determine the probability of the failure-free operation of the element according to the strength criterion [32].

As the sampling results show, the probability of the failure-free operation of the materials and samples made from them obeys the normal distribution law [33]. Expressing the probability of the failure-free operation R in terms of the normalized normal distribution function, we have:

$$R = 1 - \Phi \left[-\frac{\bar{\sigma}_t - \bar{\sigma}_{eq}}{\sqrt{S_{\sigma_t}^2 + S_{\sigma_{eq}}^2}} \right], \quad (7)$$

where R is the failure probability; Φ is the normalized (standardized) normal distribution function; $\bar{\sigma}_t$, $\bar{\sigma}_{eq}$ are the average tensile yield strength of equivalent voltage; S_{σ_t} , $S_{\sigma_{eq}}$ are the standard deviation of the tensile yield strength of equivalent voltage.

The probabilistic mathematical apparatus presented above is used to determine the reliability parameters of materials.

To assess the reliability of the products made of polymeric materials according to the main criteria (strength, rigidity, climatic resistance, and dimensional accuracy), one must have information on the statistical variability of deformation–strength, elastic, dilatometric, and shrinkage characteristics [34].

The model for calculating the reliability by the strength criterion is based on the analysis of the distributions of acting and ultimate stresses. To assess the strength reliability,

it is necessary to know the distribution of random variables, i.e., the maximum equivalent stress and ultimate strength characteristics [35].

At the design stage, factors that affect the variability of equivalent stresses for a complex stress state of a loaded product and the variability of ultimate strength characteristics are taken into account. Factors affecting the variability of equivalent stresses include the dispersion of characteristics, the stress state type, and temperature. The components of the model for calculating the reliability according to the strength criterion in the general case are the characteristics of the polymer material: elastic modulus E , Poisson's ratio μ , coefficients of linear thermal expansion in the glassy α_{st} and highly elastic states, and glass transition temperature T_{st} .

An analysis of the factors affecting the strength shows its dependence on the state or cleanliness of the surface, the scale factor or the influence of the absolute dimensions of the sample, the influence of stress concentrators, and temperature [35].

Reliability was assessed according to the strength criterion for the products made of polymer structural materials operating under load, polymer coatings of the materials with different coefficients of linear thermal expansion, polymer parts reinforced with metal inserts, and metal–polymer products [32].

3. Results and Discussion

Figure 2 shows the mean value and standard deviation of the yield strength as a function of the logarithm of the sample cross-sectional area for PP-based thermoplastics. An increase in the cross-sectional area of the samples causes a decrease in the average value and a change in the standard deviation of the yield strength of the investigated thermoplastics. This is due to the layered structure that is formed in the process of processing the material into a product. In addition, the scale factor has a significant effect on other deformation–strength properties of the materials based on polypropylene [3,4].

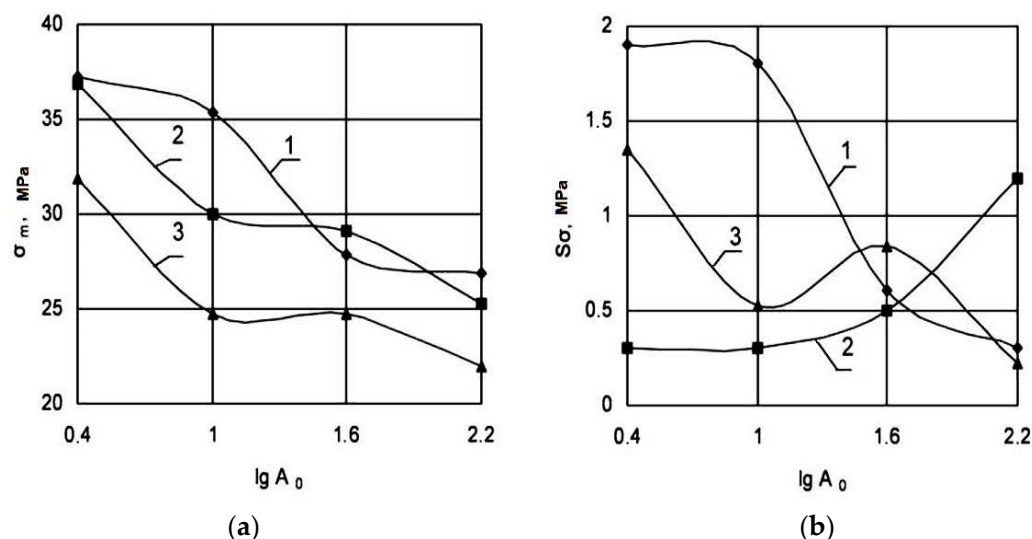


Figure 2. Dependence of (a) the average value of the yield strength and (b) the standard deviation of the yield strength on the logarithm of the cross-sectional area of the samples A_0 . Thermoplastics are based on polypropylene: (1) PP 21060-16, colorless; (2) PP 21060-A20; (3) MPP 15-04 colorless.

The dispersion of the values of equivalent stresses is affected by the dispersion of elastic, deformation, and thermophysical characteristics (Table 1).

Table 1. Statistical characteristics of polypropylene compositions.

Material	Description	E, MPa	μ	$A_{str}, 10^{-6},$ 1/grad	$A_{ver}, 10^{-6},$ 1/grad	T_{str}, K
BSPE 22007-16	Compositions of the frost-resistant propylene–ethylene copolymer with increased impact resistance BSPE 22007-16 are used to produce battery monoblocks, technical products, and car bumpers. They have increased impact resistance and can be made on the basis of the propylene–ethylene copolymer with the introduction of special additives that increase the impact strength. Compositions are produced colored and unpainted.	1170/95	0.37/0.020	-	98/12	-
MPP 15-04, colorless	Melt flow index: 1.0 g/10 min. Tensile yield strength: not less than 22.0 MPa. Elongation at break: not less than 130%. Charpy impact strength without notch at minus 50 °C: not less than 25 kJ/m ² . Softening temperature: according to Vicat, at a load of 10 N: not less than 135 °C. Frost resistance: not higher than −50 °C. Frost resistance for painted grades: not higher than −40 °C. Granules of the same color, 2–5 mm in size.	1110/77	0.36/0.018	-	104/14	-
MPP 15-04-901	It is frost-resistant polypropylene. Frost-resistant polypropylene compositions are intended for injection molding of automotive components, battery monoblocks, and technical products.	1100/76	0.36/0.017	-	101/13	-
SNP 21060-16-S30	Melt flow index: 4.1–8.0 g/10 min. Spread of PFR: no more than ±8%. Number of inclusions: no more than 3 pcs. Mass fraction of ash: no more than 0.035%. Mass fraction of volatile substances: no more than 0.09%. Resistance to thermal-oxidative aging: not less than 360 h. Tensile yield strength: not less than 30 MPa. Elongation at break: not less than 500%. Granules of the same color, 2–5 mm in size.	1500/114	0.26/0.016	15/2,7	30/3,2	272/2

Note: the numerator is the average value of the indicator; the denominator is the standard deviation of the indicator.

The experiments showed that there were stress concentration places in products made of polymeric materials at the site of a sharp change in shape, in parts reinforced with metal inserts, and in polymer coatings. The maximum local stresses were determined through stress concentration factors.

We found that with an increase in the cross-sectional area of the samples, the sensitivity of the material to stress concentration increased, but the effective stress concentration coefficient remained less than unity, i.e., in the initial state at a test temperature of 23 ± 2 °C, materials based on PP were insensitive to stress concentrators.

The experimental data on the average values and standard deviations in tensile strength, the strength of the samples with a stress concentrator, and an effective stress concentration factor for polymeric materials based on polystyrene (UPS-825, ABS-2020), polycarbonate PK-2, and glass-filled polyamide PA 610-1-108 are given in Table 2.

When calculating the strength of the parts made of polymeric materials with large cross sections, it is necessary to take into account the influence of the scale factor and stress concentration.

On the basis of the statistical reliability model, the probability of the failure-free operation was calculated for products made of PP 21060-16 and asbestos-filled PP 21060-A20, operating under conditions of a uniaxial stress state (Figure 3). The safety factor for a cross-sectional area of 2.5 mm² was 1.5 for both materials.

The safety factor was determined as the ratio of the average value of the yield strength σ_m to the average value of the equivalent stress σ_{eq} . As the cross-sectional area increases, the probability of failure-free operation decreases. For thermoplastic PP 21060-A20, with an increase in the cross-sectional area of the samples from 2.5 to 200 mm², the probability of failure-free operation decreases from 0.999 to almost 0.6, while the safety factor remains greater than one.

At the production stage, the technological factors that affect the variability of the mechanical and thermal properties of materials are analyzed. Technological factors include material processing modes, as well as the content of technological and industrial waste.

Table 2. Effective Stress Concentration Factor for Thermoplastics.

Material	Description	σ_{rm} , MPa	$S\sigma_{rm}$, MPa	σ_{rmc} , MPa	$S\sigma_{rmc}$, MPa	K_e
UPS 825 black	High-impact molded polystyrene. Grade 825 is a high impact injection molded polystyrene. The ability of this polymer to be molded with accelerated cycles with minimal stresses gives an exceptional property—the preservation of impact strength.	27.3	0.58	25.9	0.76	1.05
ABS 2020	2020 ABS plastic of the highest grade. Izod impact strength: not less than 24.5 kJ/m ² (25.0 kgf cm/cm ²). Tensile yield strength: not less than 38.2 MPa (390 kgf/cm ²). Elongation at break: not less than 22%. Vicat heat resistance: not lower than 100 °C. Melt flow index: within 10–12 g/10 min. Bending temperature under load: not less than 100 °C. Mass fraction of water: no more than 0.28%.	40.7	0.65	36.2	0.9	1.12
PA 610-1-108	Polyamide PA 610-1-108 is a reliable and practical material in production. The material is a synthetic polymer product with high physical and chemical properties. The main advantages of the material over similar polyamides are low moisture absorption, excellent electrical insulation, and resistance to petrochemical attacks. When additives are added to the raw material composition of the product during the production process, there is no reaction of foaming, decomposition, and deformation of the original structure. The material perfectly tolerates thermal effects, as well as sudden changes in pressure levels.	134.0	8.62	100.1	3.46	1.34
Polycarbonate PK-2	Melt flow index is within 4–11 g/10 min. Tensile yield strength: not less than 57 MPa. Elongation at break: not less than 60%. Impact strength of the sample with a notch: not less than 30 kJ/m ² . Electrical strength: not less than 19 kV/mm. Polycarbonate is used for casting thin-walled parts of the complex configuration with metal fittings with increased resistance to high temperatures and humidity.	62.2	1.19	52.0	2.46	1.20

where σ_{rm} , $S\sigma_{rm}$, σ_{rmc} , $S\sigma_{rmc}$ are an average value, standard deviation of tensile strength without and with a stress concentrator, and MRA; K_e is the effective stress concentration factor.

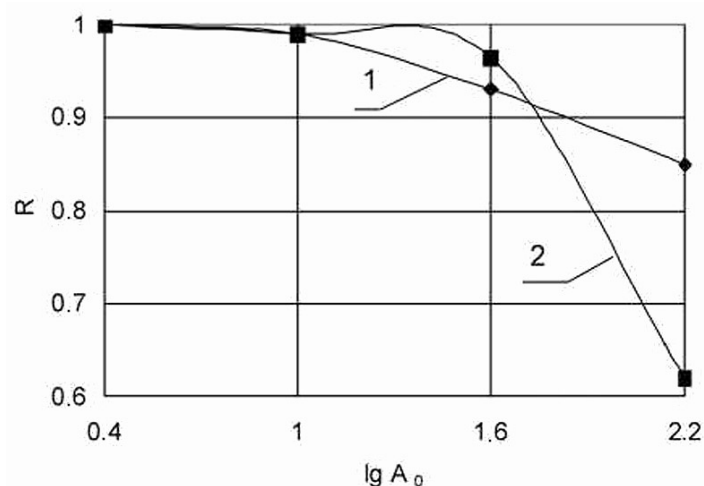


Figure 3. Dependence of the probability of the failure-free operation on \lg of the cross-sectional area of the samples for thermoplastics based on polypropylene: (1) PP 21060-16, colorless; (2) PP 21060-A20.

Figure 4 shows the dependence of the probability of the failure-free operation according to the strength criterion on the pressure exposure time for the material PP 21060-16 for various casting temperatures. A decrease in the holding time under pressure and an

increase in the casting temperature are shown to entail a decrease in the probability of failure-free operation. This is due to a slight decrease in the average value of the yield strength of the material and an increase in its standard deviation.

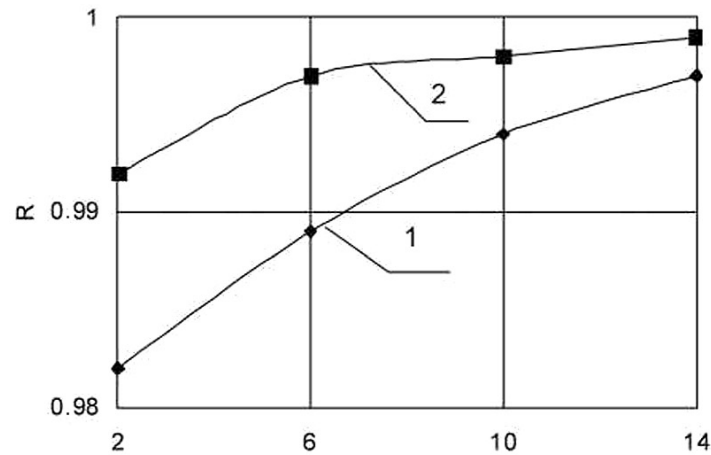


Figure 4. Dependence of the failure-free operation probability on the holding time under pressure PP 21060-16 and the casting temperature at a casting pressure of 80 MPa: (1) 270; (2) 200 °C.

In this way, the real curves of changes in the reliability level of the polymer material were obtained, which depend on two parameters: the holding time under pressure and the material temperature.

The operation stage allows analyzing the external factors that affect the variability of the material science characteristics included in the strength reliability calculation model and the variability of the ultimate strength characteristics. External factors include natural and artificial climatic factors, radiation exposure, and ionizing radiation.

To assess the influence of operational factors on the reliability of products made of polymeric materials operating under load, the influence of natural climatic factors is considered.

Figure 5 shows the mean value and standard deviation of the yield strength versus the aging time for the samples with various cross-sections of the thermoplastic block copolymer of propylene with ethylene BSPE 22007 in cold climates. The material samples were exposed to a cold climate with an average annual temperature of $-8-9$ °C.

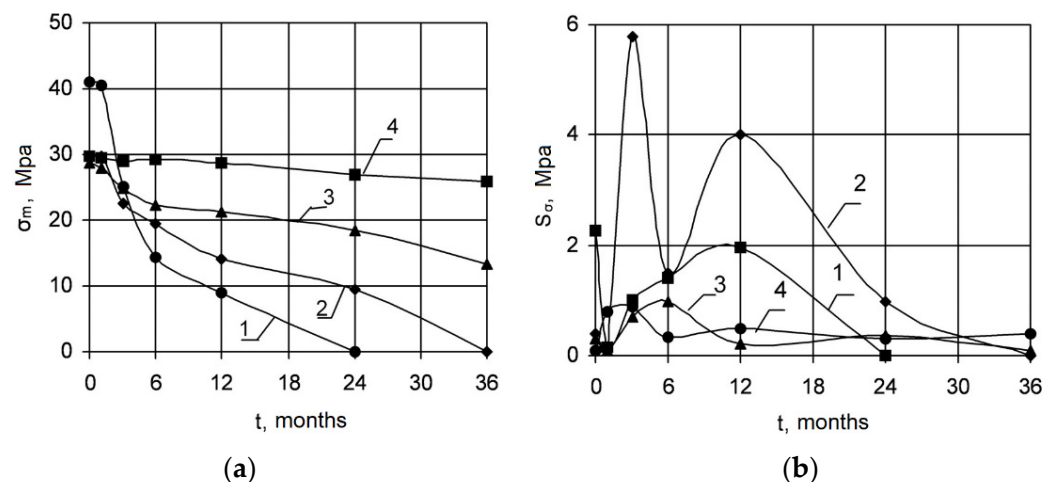


Figure 5. Dependence of (a) the average value and (b) the standard deviation of the yield strength on the aging time in cold climate conditions for the BSPE 22007-16 material. The cross-sectional areas of the samples: (1) 1×2.5 ; (2) 2×5 ; (3) 3×13 ; (4) 8×25 mm².

Due to the fact that the solar radiation effect changes the structure in the surface layers of the samples, the effect of this process on the material during natural aging should depend on the thickness of the samples. Indeed, for the colorless materials of the block copolymer of propylene with ethylene BSPE 22007 and frost-resistant polypropylene MPP 15-04, the yield strength of the samples 1 mm thick decreases sharply already after 1 month of exposure. After two years of exposure, the samples of materials MPP 15-04 (colorless) and BSPE 22007-16 (1 mm thick) completely lose their strength. In this case, the samples are scattered at the moment of removal from the stand of the climatic station.

With an increase in the thickness of the samples, the resistance of the material to aging increases. This is due to the fact that in the process of aging, after saturation of the surface layers with oxygen-containing products and closing the channels of free access of oxygen to the deeper layers of the material, a monotonous decrease in strength is observed [5].

The standard deviation of the tensile yield strength initially increases along with increases in the aging time, and then decreases after reaching the limit value.

Polypropylene-based thermoplastics require material modifications, especially in cold climates. Modified materials must be frost-resistant and resistant to solar radiation.

The MPP 15-04-901 material, which is light-stabilized with soot, throughout its entire thickness did not show a significant change in the properties during 3 years of aging in a cold climate.

In view of this, we have obtained dependences for research purposes that can actually increase the reliability of polymeric materials and products made from them, depending on the aging of materials and their strength characteristics. In addition, like all numerical studies, the numerical determination of the reliability provides an excellent opportunity not only to determine the reliability characteristics of individual materials, but to obtain a family of characteristics for different groups of polymers, to compare their aging characteristics, changes in strength and reliability, and to choose the least degradable materials with the same modeling parameters.

Figure 6a shows the dependence of the failure-free operation probability on the aging time of standard samples of thermoplastics 2 mm thick based on polypropylene in a cold climate. The failure-free operation probability is calculated for the case of a uniaxial stress state with an initial safety factor of 1.5 for the materials. The acting stresses during aging were determined for permanent deformation with a change in the elastic modulus.

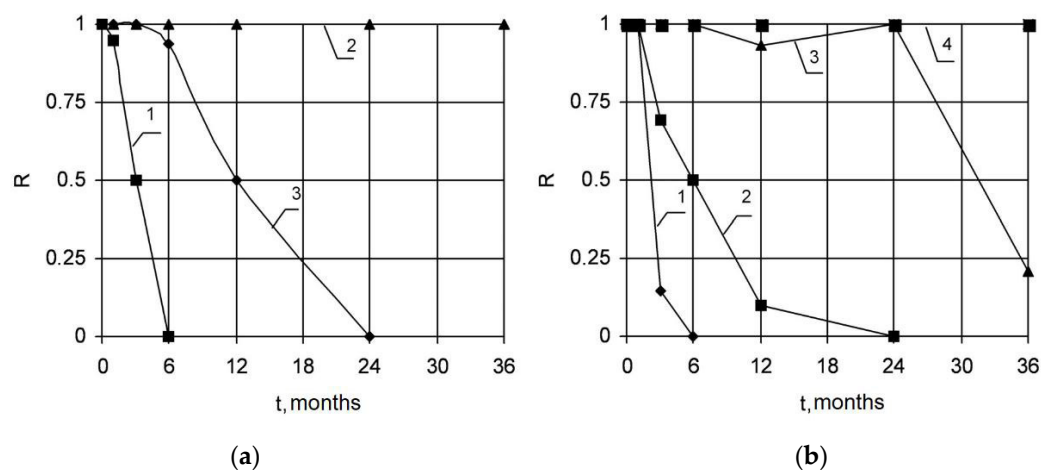


Figure 6. Dependence of the failure-free operation probability in cold climate conditions on the aging time of thermoplastics based on polypropylene: (1) MPP 15-04, colorless; (2) polycarbonate with short fiberglass; (3) BSPE 22007-16—(a); for the samples made of thermoplastic BSPE 22007-16 with the following cross-sectional areas: (1) 1×2.5 ; (2) 2×5 ; (3) 3×13 ; (4) 8×25 mm—(b).

The graph shows that the failure-free operation probability for the considered model depends significantly on the aging time, especially in the case of poorly stabilized colorless thermoplastics. The probability of failure-free operation drops to 0.5 within 3 months for a block copolymer of propylene with ethylene, and within 12 months for frost-resistant polypropylene.

The failure-free operation probability did not change over the studied period of time for thermoplastic MPP 15-04-901.

Polycarbonate with short fiberglass showed the highest resistance to aging in cold climates.

The dependence of the failure-free operation probability on the aging time, considering the scale factor of the BSPE 22007-16 thermoplastic under cold climate conditions is shown in Figure 6b.

Even for a weakly stabilized colorless thermoplastic BSPE 22007-16, with an increase in the thickness of the samples, the failure-free operation probability is shown to increase, and it is close to unity for a sample 8 mm thick during the entire aging time.

In view of this, after analyzing the obtained dependences, we can say that reliability plays an important role in predicting the changes in the properties of materials depending on the time at which critical failures of materials occur. By setting certain optimal levels of the acceptable reliability of the selected composite polymer in the range R from 0 to 1, it is possible to determine the service life of parts made of it. In addition, thanks to the proposed models of changes in the reliability and properties of materials over time, it is possible to evaluate the reliability of a complex system (for example, a centrifugal pump), which consists of several parts based on a composite polymer. At the same time, by setting greater reliability for critical parts and assemblies of the system (for example, centrifugal pump blades), with R from 0.95 and higher, it is possible to significantly increase the technical system reliability as a whole. In addition, it is possible to solve the inverse problem, which is especially important for service engineers, by setting a certain reliability level for a particular part or assembly material. One can gain additional service time for the part, followed by the replacement of this part according to the regulations in order to maintain the required reliability level of the technical system. In this way, in fact, it is possible to form technical regulations for system maintenance with a given guaranteed reliability level depending on time, for almost every unit or part. Speaking about the reliability level, it should be noted that within the framework of this article, the theory of the reliability choice is not specified, but there are two main approaches to this choice:

1. Choosing the reliability level that is optimal in terms of economic expenditures for operation.
2. Choosing the reliability level in terms of the inadmissibility of emergency situations associated with major man-made consequences and human injuries.

It should also be noted that the obtained models of reliability changes in polymer parts and assemblies could be useful not only for operational specialists, but also for developers of technical systems based on composite polymers. Developers, in turn, by setting the reliability of the system parts and determining the reliability of the system as a whole, can determine the system warranty period for consumers, reducing the material costs for additional tests on the aging of materials.

In this way, we were able to obtain specific recommendations for research engineers and manufacturers of the products from the presented polymer composites, depending on the actual performance indicators: operating time, ambient temperature at different material strength factors included in the samples, and effective stresses of the material, taking into account changes in the elastic modulus of the material.

3.1. Study of Composite Material Properties with a Clearly Expressed Inhomogeneous Structure

As an example, let us take the PCM used to manufacture centrifugal pump wheels. It consists of a polycarbonate matrix and fiberglass as a reinforcing element.

If the polymer composite material has a heterogeneous structure and a large number of inclusions that differ greatly in properties, then its properties should be evaluated according to the method described below.

The algorithm for modeling the mechanical characteristics of such two-phase filled composites is based on the theory of J. Eshelby. Based on the theory of Asheby and the Mori–Tanaka theorem, Tandom and Weng calculated the elastic modulus for fibrous and dispersion-strengthened isotropic matrix composites. The equations below define five independent constants corresponding to Young's modulus, shear and bulk moduli, and Poisson's ratio of the composite material [18,20].

$$\frac{E_{11}}{E_m} = \frac{1}{1 + (c_r(A_1 + 2\nu_m A_2))/(A)} \quad (8)$$

$$\frac{E_{22}}{E_m} = \frac{E_{33}}{E_m} = \frac{1}{1 + (c_r[-2\nu_m A_3 + (1 - \nu_m)A_4 + (1 + \nu_m)A_5 A])/(2A)} \quad (9)$$

$$\frac{\mu_{12}}{\mu_m} = 1 + \frac{c_r}{2c_m S_{1212} + (\mu_m)/(\mu_r - \mu_m)} \quad (10)$$

$$\frac{\mu_{23}}{\mu_m} = 1 + \frac{c_r}{2c_m S_{2323} + (\mu_m)/(\mu_r - \mu_m)} \quad (11)$$

$$\frac{\kappa_{23}}{\kappa_m} = \frac{(1 + \nu_m)(1 - 2\nu_m)}{1 - \nu_m(1 + 2\nu_{12}) + c_r[2(\nu_{12} - \nu_m)A_3 + A_4(1 - \nu_m(1 + 2\nu_{12}))]/A} \quad (12)$$

$$\nu_{12} = \frac{\nu_m A - c_r(A_3 - \nu_m A_4)}{A + c_r(A_1 + 2\nu_m A_2)} \quad (13)$$

where E_{ig} is the Young's modulus in the direction of the axes; c_r is the volume fraction of the fiberglass filler; A_1, A_2, A_3, A_4, A_5 , and A are scale factors; ν_m is the matrix shift module; μ_{ig} is the Poisson's ratio in the direction of axes x, y, z ; μ_r is the Poisson's ratio in the direction of the fiberglass filler; μ_m is the matrix Poisson's ratio; S_{igkl} is the Eshebli tensor component; k is the matrix volumetric module; k_{ig} is the volumetric module in the direction of axes x, y, z ; ν_{ig} is the shift module in the direction of axes x, y, z .

Expressions for coefficients A_1, A_2, \dots, A_5 and the Eshebli tensor component S_{igkl} , depending on the shape of the inclusions and the elastic characteristics of the phases can be found in [17]. The elasticity coefficients introduced in this way are effective quantities that determine the macroscopic elastic properties of the material.

The above theories make it possible to determine engineering constants for the designed polymer composite materials. To determine the strength of the structure as a whole, it is necessary to use the equivalent stress criteria, as well as the Tsai–Hill criterion for transversely isotropic bodies (3D), using the setting of the first destroyed FPGF pseudo-grain [36,37]:

$$\frac{1}{2} \left\{ \left(\frac{1}{\sigma_{B11}^2} + \frac{1}{\sigma_{B22}^2} - \frac{1}{\sigma_{B33}^2} \right) (\sigma_{11} - \sigma_{22})^2 + \left(-\frac{1}{\sigma_{B11}^2} + \frac{1}{\sigma_{B22}^2} + \frac{1}{\sigma_{B33}^2} \right) (\sigma_{22} - \sigma_{33})^2 + \left(\frac{1}{\sigma_{B11}^2} - \frac{1}{\sigma_{B22}^2} + \frac{1}{\sigma_{B33}^2} \right) (\sigma_{11} - \sigma_{33})^2 \right\} + \frac{1}{\tau_{B12}^2} \tau_{12}^2 + \frac{1}{\tau_{B23}^2} \tau_{23}^2 + \frac{1}{\tau_{B13}^2} \tau_{13}^2 = 1,$$

where σ_{ii} and τ_{ij} are axial and shear components of the Cauchy stress tensor; σ_{Bii} and τ_{Bij} are the ultimate strength along the respective directions [38].

To implement the simulation (Figure 7), the software product MSC Digimat MF (e-Xstream—HEXAGON, Luxembourg, Luxembourg) was used.

The results of modeling the properties of a composite made from a polycarbonate matrix containing glass fibers in the volume are presented in Table 3.

The simulation results show that a content increase in the glass fiber in PCM with a polycarbonate matrix leads to an increase in the ultimate strength, modulus of elasticity, and overall reliability.

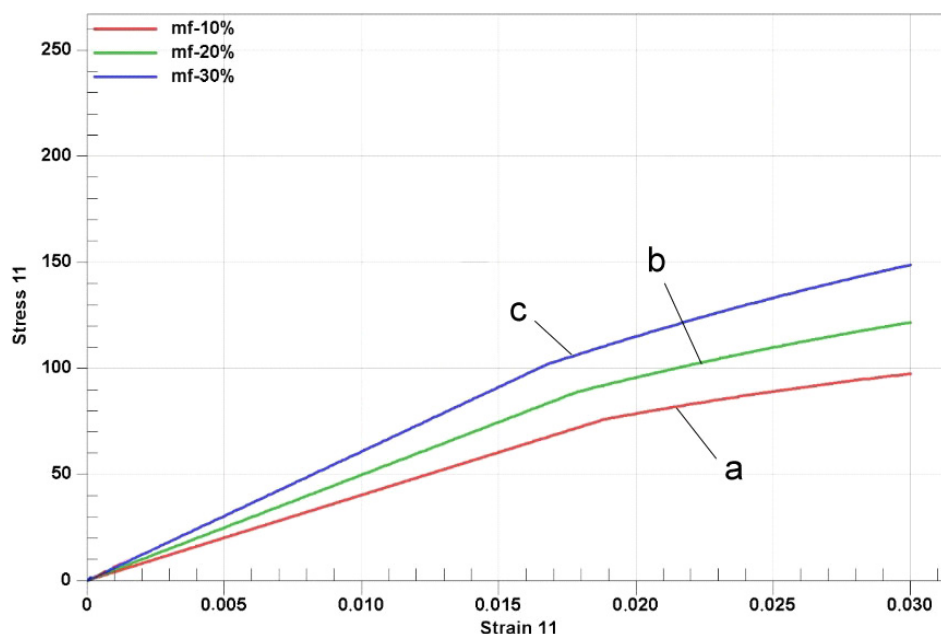


Figure 7. Stress–strain diagrams for a composite material based on a polycarbonate matrix containing: (a) 10% of inclusions (red line), (b) 20% of inclusions (green line), (c) 30% of inclusions (blue line).

Table 3. Computed properties of the studied composite (polycarbonate matrix with the content of glass fibers in the volume).

m_f -Mass Fraction, %	E , MPa	G , MPa	μ	ρ , g/cm ³	σ_m , MPa
10	3200	1156	0.35	1.26	90
20	4029	1498	0.33	1.33	120
30	5060	1895	0.32	1.415	150

The experimental work on modeling properties has shown that as a result of such calculations, it is possible to choose the optimal compositions of PCM, predict properties, evaluate and predict the reliability of materials in general in the future. In addition, the study carried out made it possible to gain experience in this area and develop a methodology for predicting the properties and reliability of the material.

The reliability prediction methodology includes the following steps:

- selection of a performance criterion based on the analysis of the product, its purpose, mode of operation, operating conditions, and type of expected failures;
- establishment of a set of mechanical and thermophysical characteristics of polymer composite materials based on the criterion of product performance;
- development of new methods and devices for determining mechanical and shrinkage characteristics, taking into account the characteristics of materials;
- development of probabilistic-statistical models for assessing the reliability of products made of polymer composite materials at the stages of design, production, and operation;
- study of the statistical variability of deformation-strength and shrinkage characteristics of the materials at the stages of the product life cycle;
- estimation of the relationships between the reliability and material characteristics included in the reliability model at the stages of design, production, and operation;
- possible reliability prediction, considering fully or partially the determining factors of the design, manufacture, and operation of the product.

This methodology can serve as a recommendation for modeling the properties of new materials.

3.2. Experimental Studies of Products Made of Polymer Composite Materials

The conducted numerical experiments have shown that, for the production of parts, a composite of a polycarbonate matrix and 30% of the mass fraction of glass fiber is optimal. The performed work on the calculation of mechanical properties makes it possible to reduce the number of full-scale tests.

The results obtained with the help of the performed calculations were verified using a full-scale experiment. The authors conducted a tensile test of the samples. We tested the PCM standard samples with a filler content (fiberglass) of 10%, 20%, and 30% (Table 4). The choice of filler content for the full-scale tests was determined by the simulation results. We took values close to the optimal value of 30%. A further increase in the filler content, according to calculations, led to a sharp drop in the properties and material embrittlement. This is also consistent with the literature data. The test results are presented in the form of histograms below (Figure 8).

Table 4. Comparison of numerical and field experiment results.

m_f -Mass Fraction, %	10		20		30	
Type of Experiment	Field	Model	Field	Model	Field	Model
E_t , MPa	5240	3200	5250	4029	6190	5060
σ_m , MPa	125	90	128	120	150	150

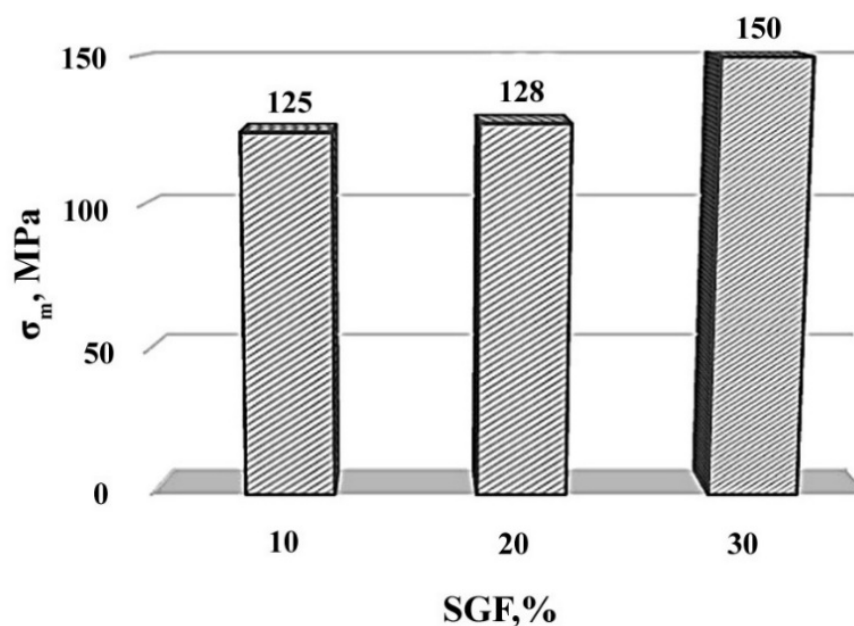


Figure 8. Change in the tensile strength (σ_m , MPa) of polycarbonate composites filled with different amounts of SGF (%).

The strength data for PCM with the addition of 20% and 30% of the filler practically do not differ from the calculated data. The difference between the data of the computational and full-scale experiments for the 10% filler content is explained by the influence of technological factors. These factors include a significant change in the cooling rate of the workpiece along with a decrease in the amount of filler to 10–12% or less. These technological factors must be taken into account to create a corrected model that allows for providing accurate results for all the filler concentrations. Since the topic of the study is useful for the introduction of PCMs, the authors of the paper will continue their work in this field of study.

4. Conclusions

1. Based on the probabilistic mathematical models, an increase in the cross-sectional area of the samples is shown to cause a decrease in the average value and a change in the standard deviation of the yield strength. At the same time, the failure-free operation probability of the studied thermoplastics decreases.
2. Functional dependences of the influence of technological modes of processing thermoplastics by injection molding on the probability of their trouble-free operation are established and presented.
3. Probabilistic modeling using the normal distribution law allows showing that with an increase in the thickness of the samples, the resistance of the material to aging and degradation increases, and the failure-free operation probability, as the main component of the material reliability, increases.
4. A mathematical algorithm has been developed for modeling the mechanical characteristics of the composite materials based on the Eshebli theory and the Mori–Tanaka theorem by Tandom and Weng, considering the Cauchy stress tensor. The mathematical method that allows obtaining analytical estimates of the effective properties of the materials that affect their reliability has been established on its basis. The results of modeling by the analytical deterministic method and the probabilistic stochastic method are similar to discrepancies of no more than 10% in the region of high filler concentrations in PCM. The discrepancy in low filler concentrations is explained by the insufficient consideration of technological factors.
5. An innovative attempt has been made to use a probabilistic mathematical apparatus not only for analyzing the mechanical properties of materials but also for a comparative assessment of the reliability parameters of these materials. With the development of the mathematical apparatus, including numerical methods for processing mathematical data, it is much more important to obtain native graphs of the functions of changing the source of materials depending on the factors of time, temperature, and other operational indicators, without linking these functions (sometimes with large errors) to the classical distribution laws of random quantities. This gives some flexibility to researchers and allows practical engineers to obtain more accurate results. They study the change in the reliability and degradation of the materials depending on changes in the operating factors in real conditions, as well as make a forecast of changes in the reliability in the future, extrapolating from the results. The authors will devote further study to mathematical and experimental models for predicting the degradation and reliability of composite materials and the creation of a universal mathematical methodology to forecast their sources.

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