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THE INFLUENCE OF DEFECTS ON THE PHYSICO-MECHANICAL PROPERTIES OF POLYMER COMPOSITE MATERIALS AND PRODUCTS

Rasim BASHIROV[1,a*], Fuzuli RASULOV[1,b], Ilhama HAMDULLAYEVA[1,c], Nijat ISMAILOV[1,d]

[1]Department of special materials and tools Azerbaijan Technical University, Baku, Azerbaijan

E-mail:[a]rasim_agma@aztu.edu.az, [b]resulovfr@gmail.com, [c]İlhame.hemdullayeva@aztu.edu.az, [d]nicatismayilov1994@mail.ru

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Abstract: The issues of the formation of physical and mechanical properties in polymer composite materials consisting of reinforcement (glass fiber) and a matrix (resin) are considered. The reasons causing failures in polymer composite materials of the specified type and products based on them are given. The dependence of the average strength and ultimate relative strain of monofilaments on their length and diameter has been studied. The effect of defects on the surface of reinforcing glass fibers on their strength has been studied. It is shown that with an increase in the length of glass fiber, defects of various types are formed on its surface. An empirical formula for the rate of fiberglass cracking is given. It is shown that the second stage of the glass fiber destruction process is poorly described by a power function with a constant exponent when the level of unloading stresses changes. The dependence of the nominal voltage on the actual voltage in glass fibers is obtained for various values of the coefficients of variation. It is shown that the main processes of interaction between the resin and the fiber occur either at their interface or in the border zone.

Keywords: *length, diameter, polymer composition. matrix, fiber, strength, elongation, failure, cracking*

Introduction.

The problem of quality and reliability of materials, products and structures is one of the pressing problems of modern scientific and technological development. This problem is very important for products and structures made from structurally inhomogeneous heterogeneous materials, which include polymer-based composite materials. These materials are characterized, along with high performance characteristics, by significant variability in physical and mechanical properties, the existence of various defects in them, and heterogeneity of composition and structure. Therefore, when designing products and structures from these materials, it is necessary to significantly increase the safety factors, which lead to an increase in their metal consumption, as well as in cost [1,2,3,4,5]. Of particular importance in solving the problem of quality and reliability of products and structures made of polymer composite materials (PCM) are effective methods and means of control. In this case, the greatest attention is paid to non-destructive methods and means of control. Thus, the use of non-destructive methods and control means allows for express analysis of the emerging technological characteristics of the product material and structure during its manufacturing process without any testing or stopping the production process. This ensures stability of the values of technological modes and contributes to a significant reduction in the number of defects formed in the finished structure.

Discussion of results.

In the figure and table. The dependence of the average strength of microfibers on the length and diameter of the fiber is given.

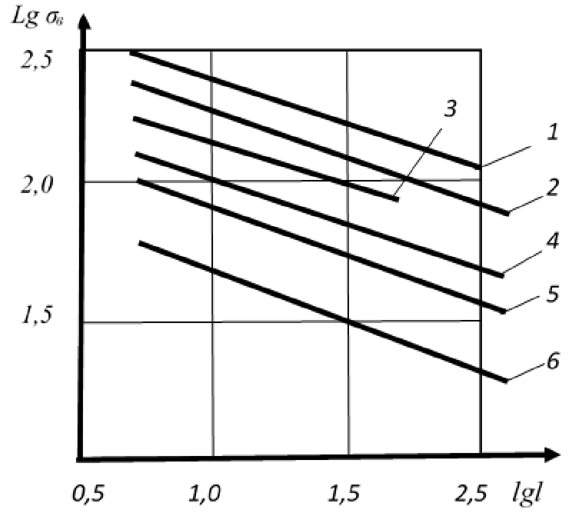


Figure. 1. The dependence of the average strength σ_b of monofilaments on their length: l - monofilament diameter; d=5µm; 2-d=6.0 µm; d=12.4 µm; 4-d=22.0 µm; 3-d=40µm; 6-d=120µm;

Table.1. Strength of the fiber depending on its diameter and length.

Length of fiber l, mm	Diameter of fiber d, µm	Tensile strength σb, MPa
5	9,0	1550
10	9,7	1250
20	10,0	1200
45	9,0	1160
90	9,6	750
190	9,6	850
1600	10	700

This study shows that the elastic modulus of PCM is not affected by the diameter and length of the fibers, that is, the elastic modulus of the fibers practically does not depend on their size. [6,7,8]. The dependence of strength and ultimate (failure) relative deformation on fiber diameter is shown in Figure 2, from which it can be seen that the dependence is linear until failure; with increasing fiber diameter, the ultimate deformation decreases. [9,10,11].

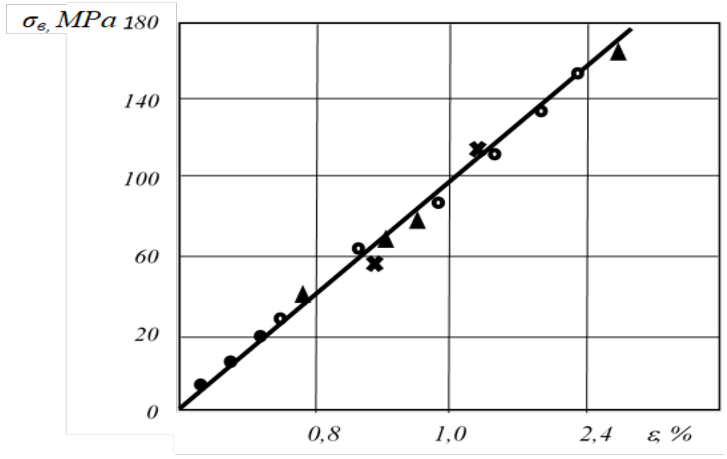
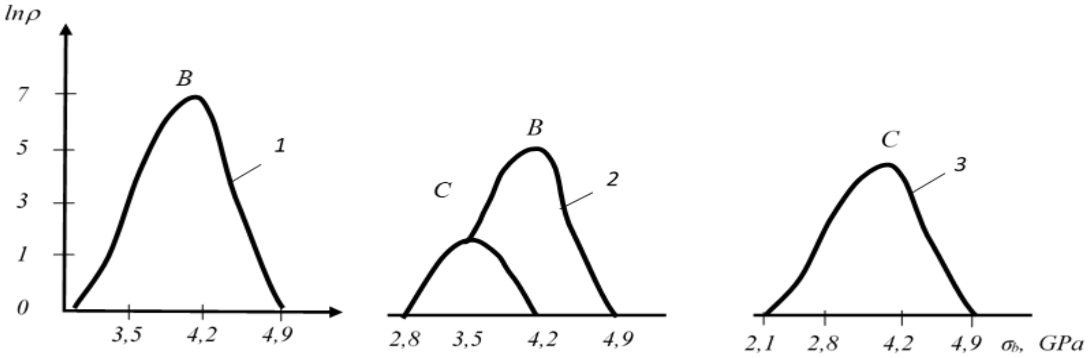


Figure. 2. Dependence of strength σ_b and maximum relative deformation ε on fiber diameter: ● – d = 100 µm; Δ – d =50 µm; ✖ - d=20 µm; ο- d=20 µm.

From the data given in Table 1 it is clear that with increasing length of a fiber of constant diameter, a change in these parameters occurs due to defects randomly distributed along its length.

a)



b)

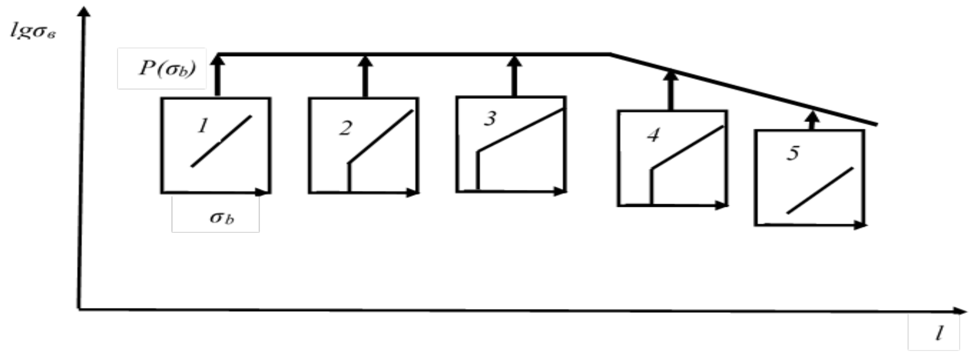


Figure. 3. Effect of defects on the strength of glass fibers:
a – probability density curves of strength limits,
b – integral distribution curves of strength limits in the presence of defects of types A and C.

We have made a classification of glass fiber defects, which are divided into three main types: A - internal submicrocracks measuring 10-4 cm; B and C surface cracks of various sizes. Moreover, the size of type B defects is smaller than the size of type C defects, which are less common. It was found that in fibers with a length of 10-2 to 10 cm, mainly type B defects are observed, but the presence of type A and C defects is also possible. In fibers over 10 cm in length, type C defects are predominant. Apparently, fibers with a length of less than 10-2 cm should contain type A defects, but it is very difficult to experimentally determine the presence of this type of defects on fibers of such length.

We also considered the influence of defects on the strength of the fiber, the length of which changed from 0.05 to 1.5 cm. It was found that the probability density curves of the tensile strength of glass fibers with a length ℓ of up to 0.05 cm. (curve l, Figure 3, a) have one maximum, which indicates the influence of only type B defects, and the integral dependence represents a straight line (Graph 1, Figure 3, b). As the length of the glass fiber increases, defects of types B and C appear on its surface; at the same time, the probability density curve of the strength limits already has two maxima (curve 2, Fig. 3, a) and in the integral dependence (graph 2) a turning point is observed, depending on the ratio of the number of failures caused by defects of type B and C.

From Figure 2b (graphs 2, 3, 4) it is clear that with increasing length, some of the glass fibers are destroyed by type B defects, and some by C defects, since they are most dangerous and characteristic of long fibers. The probability density curve of the strength limits in this case has one maximum (curve 3, Fig. 3, a) and the corresponding integral curve (graph 5, Fig. 2 a) does not have a break, but its slope differs from the slope of the curve in graph 1. As the length of glass fibers increases, the direction of the slope of the curves changes towards lower failure stresses, while the minimum strength can be found when testing long fibers.

It should be noted that the process of fiber failure (failure) depends on its defects and environmental conditions (temperature, moisture, vacuum, etc.). The process of statistical destruction at the initial temperature occurs in two stages. Initially, cracks develop from defects existing in the composition, and then the process of fiber destruction proceeds at an increasing speed [12,13,14]. In this case, the cracking rate is well described by the empirical dependence, which for an E-glass fiber with a diameter of 10 μm and a length of 25 m has the following form (5).

$$V = R_1\sigma_h^n + V_0,$$

where σ_H - normal stress, R_1 - a constant, n - an exponent (for fibers of various types the values are n = 16÷26); V_0 − the cracking rate at zero stress.

The second stage of the destruction process is poorly described by a power function with a constant exponent even when the stress level changes. Therefore, based on correlation analysis, it was found that the dependence of voltage on time in logarithmic coordinates can be represented linearly. However, the behavior of a fiber bundle under load is different from that of a monofilament. When considering PCM as a statically indeterminate system consisting of fibers, which is characterized by random strength values, in general, the load on the bundle Q can be represented in the form

$$Q = N\int_{\varepsilon}^{\infty} d\varepsilon_b \int_0^{\infty} f(\varepsilon_1 E)\psi(\varepsilon_b E)dE,$$

where N - initial number of fibers in the bundle; $f(\varepsilon_1 E) -$ fiber load function; $\int_{\varepsilon}^{\infty} d\varepsilon_b \int_0^{\infty} \psi(\varepsilon_b E)dE -$ the number of fibers remaining when a quasi-equilibrium state is reached.

If the stress distribution in the bundle and the law of plane sections is valid, the relationship between the total load on the bundle Qi and the load on individual i fiber q_i can be represented in the form

$$Q_i = Nq_i \int_{q_i}^{\infty} p(q)dq,$$

where *p(q)* - probability density of failure loads for fibers.

The failure load Q_{max} for a fiber bundle at q_r=q_{kr} is equal to

$$\frac{d}{dq}\left\{q_{kr}\int_{q_i}^{\infty} p(q)dq\right\} = 0.$$

If the probability of fiber exceeding the failure load is indicated

$$p(q) = \int_0^{q} p(q)dq = a(\frac{1}{q}) = a(\omega),$$

where *a(ω)* changes from 1 to 0 when placing the fibers included in the bundle and characterizes the degree of destruction of the bundle, then the load on the bundle

$$Q = N\frac{1}{\omega}\left[1 - a(\omega)\right]$$

where $a(\omega)=1-Q\,\omega/N$ at a constant force there will be a linear relationship between a(ω) and ω.
The conditions for determining the maximum load will have the form

$$Q = \frac{N\left[1 - a(\omega)\right]}{\omega}, \quad \frac{d\left[1 - a(\omega)\right]}{d_{\omega}\omega_{\max}} = 0.$$

It should be noted that for large N and any fiber strength distribution function, if the probability of fiber failure p(q) is such that 1–p(q) tends to zero faster than 1/q, the distribution of average failure stresses for bundles asymptotically tends to normal distribution with mathematical expectation

$$\bar{q}_b = q_{\max}\left[1 - p(q_{\max})\right]$$

and standard deviation

$$S_{qb} = q_{\max}\sqrt{\frac{1}{N}p(q_{\max})\{[1 - p(q_{\max})]\}}$$

The maximum stress can be determined by maximizing the value represented as the product of the force in the fiber and the number of unbroken fibers, i.e.

$$\frac{d}{dq}\{q[1 - p(q)]\}_{q=q_{\max}} = 0.$$

When determining the failure load on a large bundle, knowing the strength limits of the fibers, it is possible to arrange the failure loads in a variation series in decreasing order, q1>q2>q3...>qr. Equilibrium condition will be as follows in the form

$$Q \le q_r,$$

where r is the sequence number of the thread in the row.

Then the maximum load can be determined by the formula

$$Q_{max}=max[rq_r].$$

This formula can be confirmed by research results. In this regard, the behavior of a bundle of parallel glass fibers, the strength of which is distributed according to the normal law, was studied. It was found that the maximum load on the beam

$$Q_{\max} = Nq_{kp}\int_{q_{k_r}}^{\infty}\bar{p}(q)dq$$

and the rated load on the fiber at the start of rapid rupture

$$q_H = \frac{Q_{\max}}{N} = q_{kp}\int_{q_{k_r}}^{\infty}\bar{p}(q)dq$$

is determined from the maximization condition i.e.

$$\frac{dQ}{dq_{kp}} = \int_{q_{kp}}^{\infty} p(q)dq - q_{kp}p(q_{kp}) = 0.$$

This equation is a function of q_{kp} and can be solved graphically.

We also obtained the dependence of the nominal stresses σ_H in the fibers on the actual σ, which has the form $\sigma_H = \sigma\int_0^{\infty} p(\sigma)d\sigma.$ Graphically this dependence is shown in Fig. 4. From this dependence it is possible to find the stresses corresponding to the maximum effective load on the bundle depending on the dispersion of the monofilament strength, Curves 1-5 correspond to coefficients of variation 0; 90; 17.5; 30 and 75% $\sigma_К^{l}$ и $\sigma^{//}$- intervals of possible equilibrium states σ_{kmax} and σ_{Hmax} - failure points.

Regardless of the dispersion, curves 1-5 intersect at the point ($\bar{\sigma}$, $\bar{\sigma}$/2), which indicates that any beam can withstand a load that gives a normal voltage $\bar{\sigma}$ /2. Thus, the minimum load can be determined by the formula

$$Q_{\min} = \frac{\bar{\sigma}}{2}Nf,$$

where *f* the cross-sectional area of one fiber, $\bar{\sigma}$ - the average strength of the fibers in the bundle.

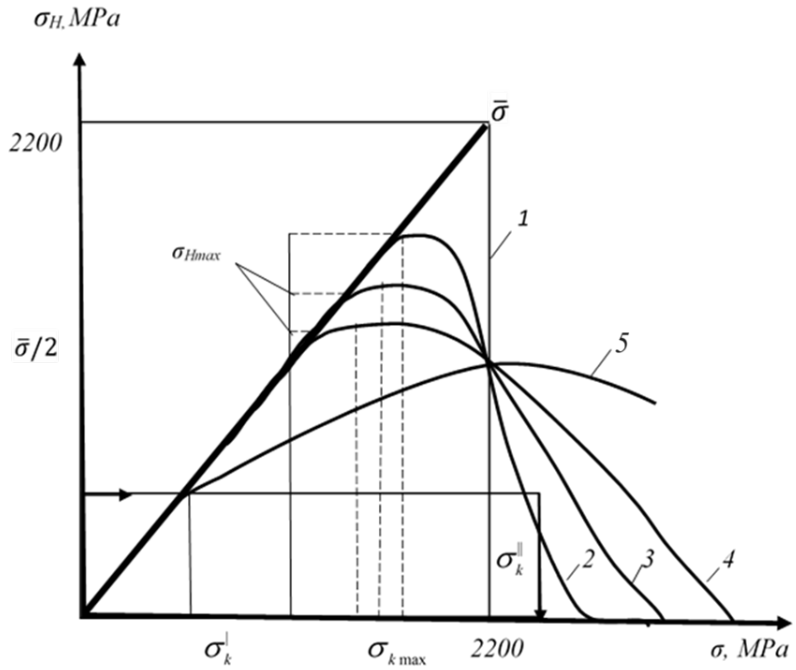


Figure. 4. Dependence of the nominal stress σ_H on the actual stress σ in glass fibers at different values of the coefficients of variation

The results of research are considered to explain the physical process of the behavior of unbonded fibers when exposed to a load. It should be noted that the process of destruction of PCM fibers differs from the destruction of a bundle of fibers in that the destruction of a fiber at any point in the bundle means its weakening and leads to an increase in effective stress, while the destruction of individual PCM fibers (connected bundle) occurring in different sections leads to redistribute the load on fibers located closely in the rupture zone. Therefore, the main role in ensuring collaboration in the forming fibers is played by the binding polymer matrix. In this case, the main interaction processes between the matrix and the fiber occur either at the interface or in the border region [15,16]. The main characteristic of this interaction is the interlayer shear strength of the composition.

In addition to the adhesive characteristics of the fiber, the surface structure of the fibers and their chemical composition play a significant role in increasing the interlayer shear strength. Thus, in work [2] it is shown that the destruction of fiberglass does not occur at the glass-resin boundary, but along the binder layer located near the fibers (at a distance of 1-2 μm) where the weakening of the strength of the binder is caused by the inhibitory effect of the fibers on the curing process of the binders. The relationship between adhesive strength and tensile strength of PCM has also been established [17,18,19]. A similar relationship for oriented fiberglass plastics based on various binders is shown in Figure 5.

The solidity and high shear strength of PCM is ensured mainly by the binding, i.e., polymer matrix, therefore special requirements are placed on it not only in terms of adhesive properties, but also in terms of deformation [20,21].

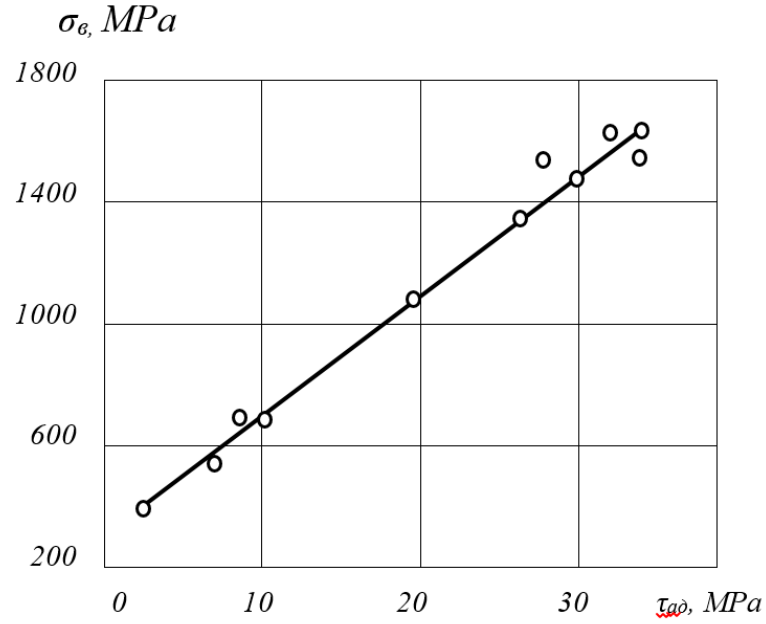


Figure. 5. Dependence of adhesive strength τ_{ad} on tensile strength $\sigma_{в}$ PCM.

For PCM, the optimal fiber content (50 - 75%) is that the relative elongation of the matrix should be 6-15 times greater than in the fiber. In order to eliminate cracking and increase the load-bearing capacity of shells made of oriented fiberglass with a volumetric fiber content of 30-70%, we recommend that the relative elongation of the binder be 4-26%.

Conclusions. 1. It has been shown that the strength of a fiber in PCM depends on its diameter, i.e., the larger the fiber diameter, the lower its strength, which is determined by the nature and location of defects on the surface. The relationship between strength and maximum relative deformation also depends significantly on the fiber diameter. Higher values of these parameters are achieved with small fiber diameters.

2. The strength of fiberglass reinforcement depends on the nature of the defects on its surface. It has been established that surface defects are the most dangerous for long fibers. However, the behavior of a fiber bundle under load is different from that of a monofilament. The stresses corresponding to the maximum effective load on the bundle depend on the strength dispersion of the monofilaments.

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

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