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ESTIMATION OF THE RELATION OF STRENGTH AND ULTRASOUND SPEED IN GLASS-REINFORCE PLASTIC

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In mining machinery, details and products made of composite materials are widely used, especially from GRP (glass-reinforce plastic). The work evaluates the relationship between the strength and the speed of ultrasound for nondestructive testing of strength in an article made of composite materials such as GDR with the use of a pulsed ultrasonic method. Methods for estimating the connection, the method of mechanical compression tests and mathematical processing and establishing the relationship between the ultrasonic velocity and the strength of GRP are considered. The results of experimental studies on establishing the relationship between the strength of GRP on compression and the speed of longitudinal ultrasonic waves are presented. As a result of statistical processing of the experimental results, equations of the relationship between the compressive strength and the ultrasonic velocity in fiberglass are obtained.

***Key words*:** mining mechanical engineering, fiberglass, nondestructive testing, pulsed ultrasonic method, strength, correlation equations

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Introduction. In modern mining engineering widely used parts and products of composite materials, especially from GRP. The most effective is their use in the repair and restoration of parts of mining machines. To assess the quality of repair, non-destructive physical methods of control are used.

The development of modern non-destructive methods of control of physicomechanical and, in particular, strength characteristics of materials and structures occurs in various directions:

1) establishment of functional theoretical relationships between the strength and physical parameters of materials;

2) estimation of empirical statistical correlation of strength and physical parameter of the material under study;

3) development of complex multi-parameter control methods;

4) creation of non-destructive methods for controlling the integral strength of products and designs.

Research, development and experimental confirmation of the functional theoretical relationships between the ultimate strength and the physical parameters of GRP represent significant difficulties due to the complex structural heterogeneity of the composition, the unevenness of the influence of structure defects and poor quality of components on strength and physical parameters, the uneven distribution of various stress types in the product (compression, bending, stretching, shearing, torsion, etc.) [1-3, 7, 9].

A simpler and more objective way to control the strength is a method based on establishing an empirical statistical relationship between the strength values and one or more physical parameters of GRP.

Of considerable interest are studies on the development of integrated methods of control. The use of several physical parameters (for example, the speed and damping of elastic waves, dielectric permittivity and tangent of dielectric losses, thermal conductivity and thermal diffusivity, the relative degree of passage of microwave and infrared direct and polarized radiation, and γ rays) allows us to increase the reliability and reliability of control strength characteristics of the material in the product. As a result of the research, it was found that the use of various physical parameters (longitudinal wave velocities, acoustic emission parameters, thermal conductivity and permittivity) instead of one (longitudinal wave velocity) for glass-textolite increases the value of the correlation coefficient from 0.610 to 0.956, which significantly increases the accuracy of determination of the tensile strength of this glass-textolite at bending [4-6, 8, 10, 11, 15].

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Based on the analysis of the results given in the technical literature, sufficient information has been established on the study of glass-textolite and oriented glass-fiber reinforced plastics by non-destructive methods and, on the contrary, there is absolutely insufficient research to determine the empirical relationship between the strength and physical parameters for glass fibers [12-14, 16-19].

It is known that for glass fiber products the most optimal kind of stresses are compressive stresses, while for glass-textolite and oriented glass-plastics tensile stresses are used. Therefore, for glass fibers we conducted studies on establishing an empirical relationship between the compressive strength and the velocity of propagation of longitudinal waves.

Method of mechanical compression tests. The procedure for carrying out mechanical tests of samples of glass fiber reinforced plastic and other materials is currently fairly well reflected in the literature and in the relevant standard regulatory documents [1-3, 7, 9].

However, the need to assess the strength of fiberglass plastic in the speed of propagation of elastic waves with a thorough statistical analysis, and in this regard, a large amount of experimental studies predetermined the requirements for the dimensions of samples and the choice of a method for the mechanical testing of fiberglass.

It is known that the smallest dimensions of the samples are required in the compression test. This type of test was chosen in connection with the insufficient study of the relationship between the strength of glass fibers during compression and the speed of longitudinal waves, the preferred work of this material in the article under this type of stressed state and the possibility of testing on a large number of samples. For carrying out ultrasonic tests, it was necessary to provide the maximum possible measurement base in order to obtain sufficient accuracy in determining the velocity of longitudinal waves.

Several effective standards regulate the shape and size of samples, the level and speed of application of loads in determining the ultimate strength of plastics in compression. However, the methodology proposed in them has a number of significant drawbacks, distorting the experimental data obtained in significant extent.

So, according to GOST 4651-82, samples in the form of a parallelepiped with a square base are recommended. The ratio of the height of the sample to the side of the base should be 1.5. The dimensions of the samples are 10 × 15 mm.

The test speed is indicated in the normative and technical documentation. If such an indication is not available, the test speed V in millimeters per minute (depending on the height of the sample) is calculated from the formula

$$V = 0{,}03h / t,$$

where h is the height of the sample, mm; t is a constant value equal to 1 min.

The test speed can vary within ± 50 % of the calculated value.

It is known that in the compression test absolutely free deformation of the sample is impossible, and the transverse deformations of the end sections of the specimen are usually limited by a crack. When the parallelepiped of an isotropic material is compressed between two absolutely stiff press-tools, the stress state in it is neither linear nor homogeneous. Thus, the resistance values obtained as a result of the compression test cannot be regarded as physical characteristics of the strength of the material: they are only approximate technical characteristics of strength.

The degree of heterogeneity of the stress state of the sample under compression will attenuate the sample from the ends to the middle and the smaller will be in the middle of the longer and thinner working portion of the sample. When studying the influence of the ratio of geometric dimensions: width, height and thickness of prismatic specimens on the compressive strength of specimens cut from plates 10 and 15 mm thick, it is established that the compressive strength is practically independent of these ratios. However, in the compression test of samples in the form of a two-sided and two-plane blade, the tensile strengths were 13-50 % higher than the results of testing prismatic samples. Thus, samples with an elongated prismatic working part are the most optimal in the form of joint ultrasonic and mechanical tests, but excessive elongation of the sample can lead to a slight

eccentric application of the compressive load to increased bending stresses that will cause the sample to break due to loss of stability: width 25 mm, height 25 mm, thickness 6-8 mm.

Mechanical tests were carried out on the universal machine ZDM-30. Since low creep rates show the creep effect of fiberglass, the speed recommended by many researchers is 100-150 MPa per minute. To ensure the central application of the load to the samples on the test machine, ball supports were installed.

It is known that when cutting specimens from slabs due to machining in the edge zone, the continuity of the material of the samples is disrupted, such as tearing up the reinforcing material, stratifying, and sometimes partially breaking the resin. As a consequence, during mechanical tests, the stresses along the width of the sample will be distributed non-uniformly. To reduce the effect of machining on the value of the edge zone of the specimen, special attention was paid to the choice of cutting regimes.

Samples were made on a horizontal milling machine with three disk cutters mounted on a single mandrel. The distance between the cutters corresponded to the width of the sample. Such a cutting scheme ensured the parallelism of the ends of the samples. The fiberglass slab was rigidly fixed on the table of the machine. When cutting, cutters with a diameter of 80 mm were used and the following milling modes were chosen:

Cutting speed, mm/min 100-120
Feed, mm/tooth 0.1-0.3
Depth of cut, mm 5-6

The technique of taking into account the influence of the edge underloaded zone on the strength indices of samples cut from fiberglass is known. The effect of the edge zone can be estimated by comparing the results of testing samples of different widths. In view of the scattering of the values of the strength of glass plastics, it is necessary to evaluate statistically the degree of difference in the strength characteristics between series of samples of different widths. This evaluation was carried out using the Student's test for two series of samples 10 and 30 mm wide, 10 pieces in each series. This technique is used to assess the randomness or significance of the difference in the arithmetic mean values of the compressive strength of samples with a width of 10 mm (σ') and 30 mm (σ'').

For this check, the values of the statistical parameters were calculated:

$$\sigma' = \frac{1}{n'}\sum_{i=1}^{i=n'}\sigma'_i = 144 \text{ MPa}; \ \sigma'' = \frac{1}{n''}\sum_{i=1}^{i=n''}\sigma''_i = 146 \text{ MPa};$$

$$S = \sqrt{\frac{n'+n''}{n'n''}\frac{\sum_{i=1}^{i=n'}(\sigma'-\sigma'_i)+\sum_{i=1}^{i=n''}(\sigma''-\sigma'_i)}{n'+n''-2}} = 57 \text{ MPa},$$

where n' and n'' is the number of samples with a width of 10 and 30 mm.

From the Student's distribution table, determine t by the value of t_0, which in our case equal to 2.228 (for significance level $P_{t0} = 0.05$).

Since $t_0 > t$, the discrepancy in the mean values of the tensile strength for samples of different widths is statistically insignificant. In this regard, the correction for the recording of the marginal zone in determining the compressive strength for specimens 25 mm wide is not expedient to introduce.

Method of mathematical processing and establishing the connection between the speed of ultra sound and the strength of GRP. To control the strength characteristics of fiberglass in products it is necessary to establish an empirical relationship between the strength parameters and the values determined by non-destructive methods. The reliability, accuracy and effectiveness of control will depend on the tightness of the correlation and the reliability of the mathematical processing of the experimental results.

Based on the analysis of various methods of mathematical processing and correlation establishment, a technique based on the use of distribution moments was chosen, which significantly reduces the computational work. The studies were carried out on batches with a large volume of experimental data (100-150 pcs). The initial stage of processing included the compilation of correlation summaries and the calculation of the means (X and Y) for the mean square values (S_x and S_v) of the experimental results x and y, i.e. values of compressive strength and velocity of longitudinal waves in each sample. After this, the partial averages for each row of the correlation table were calculated by formulas

$$\overline{X}_y = \frac{\sum n_i x_i}{n_{y_i}};\ \overline{Y}_y = \frac{\sum n_i y_i}{n_{x_i}}.$$

To determine the correlation coefficient r_k, it is necessary to calculate the first initial moment $v_{1/1}$ of two random experimental values product, the first initial $v_{1,x}$ and the second central $\mu_{2,x}$, the moments of values and the similar moments $v_{2,x}$, $\mu_{2,y}$ values y by the following formulas

$$v_{1/1} = \frac{1}{n}\sum_{i=1}^{k_i}\sum_{j=1}^{k} n_{xy}\frac{x_i - \overline{X}}{c_x}\frac{y_i - \overline{Y}}{c_y},$$

where c_x and c_t – the prices of the digits of the values x_i and y_i,

$$v_i = \frac{1}{n}\sum n_i x_i;$$

$$\mu_{2,x} = \frac{1}{n}\sum n_i (x_i - \overline{X})^2,$$

$$r_k = \frac{v_{1/1} - v_{1,x}v_{1,y}}{\sqrt{\mu_{2,x}}\sqrt{\mu_{2,y}}}.$$

The significance of the correlation coefficient was evaluated by the Fisher criterion:

$$P_{z=0} = 0{,}5 - \Phi(t).$$

The values of the function $\Phi(t)$ can be found in the reference books, while the value of t is calculated by the formula $t = z/\sigma_z$, where $\sigma_z = 1/\sqrt{n-3}$.

If at a significance level of 0.05 or 0.01 $P_z = 0 > 0.01 \div 0.05$, then the value of σ can be considered received randomly, and the random variables under study do not have a correlation with each other.

To estimate the tightness of the connection for nonlinear correlation, the correlation ratio η_x and η_y was determined:

$$n_x = \frac{S(\overline{X}_y)}{S_x},$$

$$S(\overline{X}_y) = \sqrt{\frac{1}{n}\sum\nolimits_{ny} \overline{X}_y^2 - X^2}.$$

If the relationship is linear, then $\eta = |r_k|$.

To clarify the existence of a nonlinear correlation between x_i and y_i, the correlation ratio η_x was compared with the correlation coefficient r_k by the Romanovsky criterion. The correlation was assumed to be linear if the difference between η_x and r_k is unimportant, i.e. the following relation is performed

$$\frac{\Theta_{k_2-1}}{\sigma_{\Theta_{k_2}}} < 3;$$

and besides

$$\Theta_{k_2} = \frac{n - s' - 2}{s' - 2} \frac{n_x^2 - r_k^2}{1 - \eta_x^2},$$

$$\sigma_{\Theta_{k_2}} = \sqrt{\frac{2(n-4)}{(s'-2)(n-s'-4)}},$$

where s' is the number of columns of the correlation report.

If the relationship is linear, then the correlation equation will have the following form:

$$\overline{X}_y = \rho_x Y + (X - \rho_x Y),$$

where $\rho_x = rS_x / S_y$.

In the case of nonlinear correlation, there are no uniform rules and theoretical justifications for the statistical representation of the connection. Usually, to establish the communication equation, use known methods, for example, apply the method of least squares.

In the practice of engineering calculations, a technique is used to establish a nonlinear connection, in accordance with which they are given a set of functions that most fully cover possible types of communication, and then perform equalization with respect to these functions. In the process of mathematical processing of experimental results, we chose as initial parabolas of the first, second, third and fourth orders, an exponential function of the form $y = ab^x$, a power function of the form $y = ax^b$, and the logarithmic function $y = a + b \lg x$.

The basis for the decision on leveling the dependence is the Lagrange principle, according to which the sum of the squares of the deviations of the empirical values of y from y_i must be the smallest.

Alignment is considered satisfactory if the main approximation error

$$\sigma_0 = \sqrt{\frac{\sum (y_i - y)^2}{n-1}} < 0{,}1\overline{Y}.$$

Statistical relationship between compressive strength and ultrasound velocity in glass-reinforced plastic. The change in the values of strength and velocity of elastic waves comes from the same parameters. The most significant effect on these characteristics is due to the glass content, porosity and orientation of the filler. Taking these factors into account is of great importance for establishing objective correlation ratios, which depend on the degree of influence of these factors on the strength and speed of elastic waves. At the same time, their simultaneous action often complicates the form of the empirical connection and reduces its effectiveness.

In the course of experimental studies it was found that the effectiveness of ultrasonic tests in determining the strength characteristics depends on the correct choice of the direction of the test. It is known that glass fibers, despite the chaotic arrangement of the filler, have transversely isotropic properties, i.e. Isotropic properties are noted in the molding plane, anisotropic properties perpendicular to the molding plane.

Analysis of the experimental results of ultrasonic testing of GRP showed that the values of the speed of elastic waves along the sheet are much higher than from the plane of the sheet, i.e. the change in the velocity of elastic waves in the glass fiber, like the change in velocity in a transversely isotropic medium . As a result of tests of glass fiber samples with a large change in porosity, it was found that the degree of variation in the longitudinal wave velocity as a function of the pore content in the test perpendicular to the molding plane is significantly greater than when testing the samples in the forming plane.

Indeed, considering glass fibers as a transversely isotropic medium, according to Lichteneker's formula, the velocity of longitudinal waves depends on the pore content:

$$v_{vl.p}^{k} = v_{vl}^{k}(1-F) + v_{a}^{k}.$$

where $v_{vl.p}^{k}$ and v_{vl}^{k} is the velocity of longitudinal waves in fiberglass with and without pores; F - volume content of air in fiberglass; v_{a}^{k} - the velocity of longitudinal waves in the air.

The coefficient k depends on the direction of the test and takes the values: +1 – when tested in the molding plane and –1 – when tested perpendicular to the molding plane.

An analysis of Lichteneker's formula shows that when tested in the molding plane, the last term does not give a significant change in velocity due to its smallness in comparison with other terms, i.e. the change in porosity does not lead to a significant change in the velocity of longitudinal waves when tested in this direction:

$$\frac{1}{v_{vl.p}} = \frac{1-F}{v_{vl}} + \frac{F}{v_{a}}.$$

Consequently, the decrease in the ultrasound velocity is due mainly to the last summand and insignificantly due to change of the first summand.

The analysis of the formulas did not take into account the phenomena of diffraction, refraction, and reflection of elastic waves at media interfaces - the medium was considered homogeneous, since the wavelength of the oscillations was much larger than the dimensions of the individual components of the medium.

When testing fiberglass plastics in which there is no porosity, but the content of the glass fibers varies, it was found that a more significant change in the ultrasonic velocity is observed when testing the samples in the molding plane.

Thus, the detected effect of the difference in speed during testing along and across the molding plane allows us to simultaneously separate the effect of porosity and glass-quenching on the ultrasound velocity when establishing the empirical equation of the relation between the speed and strength of glass fibers.

Ultrasound and mechanical tests of DSV-2R-2M glass fiber samples in a wide range of porosity changes (0-40 %) were performed to establish the tightness and form of the relationship between the compressive strength σ_c in the shaping plane and the longitudinal wave velocity across the molding plane v_x.

In accordance with the methodology described earlier, a mathematical treatment of the experimental results was carried out.

Based on the processing of the results, a correlation report was compiled (Fig.1), the statistical distribution parameters σ_c and v_x and the coordinates of the empirical regression line X_y were calculated, the correlation coefficients $r_k = 0.942$ and the correlation ratio $\eta_x = 0.989$ were determined.

The obtained value of the correlation ratio and the coordinates of the empirical line of X_y regression indicate the presence of a close nonlinear connection between σ_c and v_x. The alignment of the empirical dependence between σ_c and v_x is made according to the logarithmic function:

$$X = a + b \lg y.$$

The main alignment error is only 12.6 % of σ_c, which characterizes a satisfactory approximation.

As a result of mathematical processing, we obtained the correlation equation

$$\sigma_c = 3716.21 g v_x - 66{,}6.$$

With sufficient accuracy for engineering practice, we can write:

$$\sigma_c = 37001 g v_x - 70,$$

where v_x is the longitudinal wave velocity across the molding plane, km/s.

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$\frac{y_1-\sigma_y}{c_y}$ \ $\frac{x_1-\sigma_x}{c_x}$		–6	–5	–4	–3	–2	–1	0	1	2	3	4	5	6	n_y	X_y
	σ_{v1x_i}	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-160		
	$y=v_x$	25	35	45	55	65	75	85	95	105	115	125	135	145		
–7	1.30-1.40 1.35		1	2											3	41.7
–6	1.40-1.50 1.45	1	3	5	2										11	42.3
–5	1.50-1.60 1.55			5	9	2	1								17	53.8
–4	1.60-1.70 1.65			1	9	7	6	1							24	65.7
–3	1.70-1.80 1.75					1	2		2	2					7	67.9
–2	1.80-1.90 1.85							1	1	2	3	1			8	106.2
–1	1.90-2.00 1.95									2	2	2			6	115.0
0	2.00-2.10 2.05										2	2	4		8	130.0
1	2.10-2.20 2.15									3	1	2	2	1	9	121.6
2	2.20-2.30 2.25									1		3	1		5	123.0
3	2.30-2.40 2.35												1	2	3	141.7
4	2.40-2.50 2.45										3	3	5	1	12	128.3
5	2.50-2.60 2.55											2	1	2	5	135.0
6	2.60-2.70 2.65											1		1	2	135.0
n_x		1	4	13	20	10	9	2	3	10	11	16	14	7	120	

Fig.1. Correlation of experimental values of ultrasound velocity and strength of DSV-2P-2M glass fiber

The graph of this dependence is shown in Fig.2, where the points show the average experimental values of σ_c for each interval of the quantities v_x.

To estimate the relationship between the speed of longitudinal waves in samples tested in the molding plane and the compressive strength, numerous measurements were made of glass-fiber plates with a wide range of glass-filler content (45-60 %). As a result of the statistical processing, the correlation coefficient r_k = 0.682 and the correlation ratio η_x = 0.751 were determined. Verification by the Romanovskiy criterion showed that the ratio $\frac{\Theta_{k_2-1}}{\sigma_{\Theta_{k_2}}} = 3.41$, i.e. it is slightly greater than 3. Therefore, the alignment can be carried out both by linear and non-linear functions. The lowest leveling error was obtained when using the logarithmic function. The general correlation equation has the following form:

$$\sigma_c = (13.61gv_y - 5.5)10^2.$$

For the linear correlation function, the following equation is obtained:

$$\sigma_c = 150(v_y - 2.2),$$

where v_y is the velocity of longitudinal waves in the molding plane, km/s.

Thus, the obtained results convincingly confirm that the direction most effective is the direction perpendicular to the plane of product molding (by thickness).

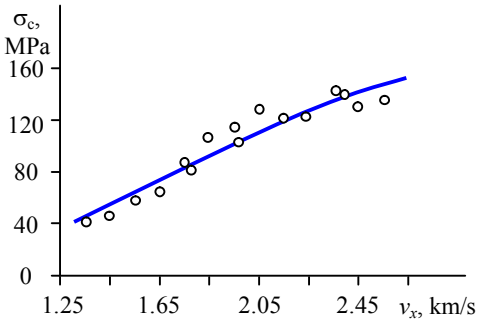


Fig.2. Dependence of strength fiberglass DSV-2R-2M when compressed from the speed of ultrasound

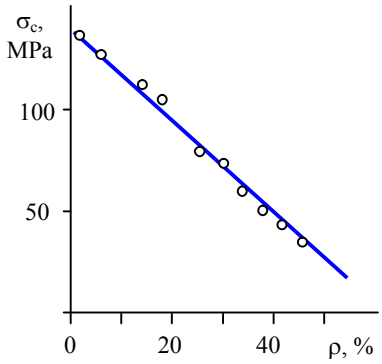


Fig.3. Dependence of strength fiberglass in compression from porosity

Of considerable interest was the study of the effect of porosity on the compressive strength:

$$P = 1 - \frac{\rho_{vl.p}}{\rho_{vl}},$$

where $\rho_{vl.p}$ – density of fiberglass with pores, g/cm^3; ρ_{vl} – density of fiberglass without pores, g/cm^3,

$$\rho_{vl} = \frac{\rho_g \rho_{vl}}{\rho_g - f(\rho_g \rho_b)},$$

ρ_g and ρ_b – density of glass and binder; f is the content of the glass-filler.

The content of glass fibers in glass fiber samples was determined by annealing in a mufel furnace to a constant weight of the residue at a temperature of 600 °C immediately after mechanical tests on the destroyed specimens. Thus, in each glass fiber sample before mechanical tests, the density $\rho_{sp.p}$, the velocity of longitudinal waves were determined, as a result of mechanical tests, the compressive strength, and after annealing, the glass content.

To compare the values of porosity and strength of glass fibers, a statistical analysis of the experimental results was carried out. It is established that the correlation coefficient $r_k = 0.97$, and the correlation ratio $\eta_x = 0.99$. The proximity of r_k and η_x is indicative of the linearity of the correlation between porosity and strength.

As a result of the processing, the following correlation equation is obtained:

$$\sigma_c = 1400 - 22.5\rho,$$

where ρ – porosity, %.

The graph of the dependence of the strength of glass fibers on porosity is shown in Fig.3, where the points indicate the partial average values of σ_c for each interval of values of ρ.

Earlier, we estimated the statistical relationship between the compressive strength and the velocity of longitudinal waves for glass fibers of the «premix» type. It is established that the relationship between these parameters for a given material is described by a linear relationship with a high correlation coefficient (r_k = 0.9). The evaluation of the relationship between the flexural strength and the velocity of longitudinal waves has shown that the correlation coefficient is much lower (r_i = = 0.69). This is due to the different nature of deformation during ultrasonic (wave, compression) and mechanical tests (bending deformations).

Conclusion

1. The main methods of non-destructive testing of physical-mechanical and, in particular, strength characteristics of composite materials are considered.

2. The technique of mechanical testing of samples of GRP for compression is given.

3. A technique for estimating the statistical relationship between compressive strength and ultrasound velocity in glass fibers is considered.

4. The obtained values for evaluating the statistical relationship between the strength and the velocity of longitudinal waves in glass fibers give grounds for using these results to determine the strength properties of glass fibers in products according to the propagation parameters of elastic waves.

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