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# Properties of Basalt Plastics and of Composites Reinforced by Hybrid Fibers in Operating Conditions

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Additional information is available at the end of the chapter

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## 1. Introduction

Polymeric reinforced materials are characterized by a number of advantages over traditional structural materials since they offer such unique properties as high specific strength in some cases, in combination with light transmission, radio transparency, high electrical insulating characteristics, non-magnetic properties, corrosion resistance.

The possibility of the preparation of new materials with predetermined characteristics is one of the main advantages of reinforced plastics. In Table 1 the standard mechanical characteristics of the most abundant structural materials as well as averaged standard characteristics, for example, of oriented and randomly reinforced glass-plastics are given.

In recent years an information on new type of polymeric composite-basalt plastic (BP), in which the basalt fiber is used instead of glass reinforcing one [1,2], is of frequent occurrence. Basalt fibers are practically highly competitive with glass ones by main mechanical characteristics and surpasses them by some of them, in particular, by water-resistance and chemical stability (is shown below). But in the form of twisted and non-twisted threads, rovings, roving cloth and discrete fibers, basalt ones represent an alternative and promising reinforcing element for composites. In addition, at solving of a series of specific problems, for example, for preparation of materials with predetermined strength and deformation characteristics in different directions of load application, the combination of glass, high-strength basalt, high-strength and high-modulus carbon fibers were used, that is to say, the production of composites, reinforced by hybrid fibers (HFRC) was organized [3-8].

Here we don't detail the properties of these and other types of reinforcing fibers. We have restricted ourselves to the comparison of glass, basalt and carbon fibers (Table 2).

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Material	Density Kg.m <sup>-3</sup>	Tensile strength, MPa	Tensile modulus, GPa	Specific strength km	Specific rigidity km
<b>Metals</b>					
Steel	7800	400	200	5.1	2560
Aluminum alloy	2800	300	72	10.7	2580
Titanium	4500	350	115	17.8	2560
<b>Wood</b>					
Oak	720	130	15	15.2	1750
<b>Plastics</b>					
Polyethylene	960	20	0.5	2.1	52
Vinyl plastic	1400	60	3	4.3	210
<b>Glass reinforced plastics</b>					
Unidirectional	2000	1600	56	80.0	2800
Glass-cloth-base laminate	1900	500	30	26.2	1570
Randomly oriented	1400	100	8	6.7	530

**Table 1.** Mechanical properties of structural materials

Fiber	Density gr. m <sup>-3</sup>	Failure stress, GPa	Extension at failure, %	Elasticity modulus GPa
Glass	2.4-2.5	2.8-3.0	4.7-5.6	74-95
Basalt	2.6-2.8	1.9-2.6	3.5-4.5	70-90
Carbon	1.9-2.1	2.2-7.2	0.5-2.4	200-785

Remark: Indexes are given for the production of the firms of various countries.

**Table 2.** Properties of reinforcing fibers

In parallel with the advantages, BP and HFRC, undoubtedly, are characterized by some disadvantages, which must be taken into account at the preparation and operation of structures and items with the use of BP and HFRC. These disadvantages involve:

- Structural non-uniformity and inadequate stability of the technology of preparation leads to considerable dissipation of mechanical and other indexes, which may attain to 15-20% in relation to average values even at standard short-term testing. At long-term testing the dissipation increased.
- Polymeric nature of a matrix determines an enhanced sensitivity of materials to the prehistory of preparation and to temperature-time regime of further operation, which is responsible for determines strength and deformation properties of BP and HFRC. At moderate temperatures for traditional structural materials a temperature-time dependence of mechanical and other properties appears only slightly, whereas the

presence of polymeric matrix in considered materials predetermines an impossibility of the evaluation of strength or deformability at room temperature without specifying of time in the course of which the materials are in stressed state.

- Directional locating of reinforcing fibers in the plane of reinforcement as well as a lamination of the structure in the direction perpendicular to mentioned plane, causes an anisotropy of mechanical and other properties. As a rule, a number of characteristics, necessary for determination of one or another properties of reinforced plastics, is considerably more than for isotropic materials. Moreover, the regularities of the behavior of reinforced plastics at mechanical testing depend on the direction of load application. For example, for oriented composites a tension diagram in the direction of reinforcement is governed by Hooke's law. At loading at an angle to the direction of reinforcement, this diagram becomes essentially non-linear. A lamination of the structure of polymeric composites predetermines their low resistance to interlayer shear and to transverse breaking off. Therefore, at bending, these materials may be destroyed because of the fact that tangential stresses will be higher than material's resistance to interlayer shear instead of the fact that normal stresses (extending or compressing) may attain the limiting values.
- Deformations, generated perpendicularly to reinforcing fibers, are mainly realized in matrix interlayers because of low rigidity of the latter in comparison with glass, basalt or carbon fibers; this fact leads to the formation of the cracks in the interlayers of a binder between the fibers or at phase boundaries. Low crack resistance is particularly characteristic of oriented plastics. The cracks have little or no effect on the values of characteristics, obtained as a result of short-term testing. However, such characteristics of a material as hermeticity, resistance to corrosive media, mechanical and electrotechnical properties in the conditions of long-term operation at the appearance and intergrowth of the track are significantly impaired.
- Relatively low value of elasticity modulus of reinforced plastics and composites leads to the fact that load-carrying ability of thin-wall structures is limited by deformability and stability instead of the strength. For complete use of high strength characteristics of the composites it is profitable to design the item and structure as three-layered or to provide the stiffening ribs. Designing must be carried out in such a way as to the material will operate on tension instead of compression, whenever possible. However, it should be noted that in some cases the low elasticity modulus is a definite advantage of reinforced polymers (for example, pipe-lines from mentioned materials without the compensators of temperature deformation and etc.)

Considered peculiarities of reinforced polymers, generally, and of BP and HFRC, in particular, must be taken into account at designing and at the use of structures and items from mentioned materials.

Appearance of new generation of reinforced polymers – BP and HFRC is due to the quest for preparation of the materials, characterized by higher initial mechanical and other indexes and by higher stability of these indexes at the action of various operating factors.

At the present time the volumes of the production and of the use of the composites, reinforced by high-strength and high-modulus fibers, are insignificant. The main consumers of mentioned materials are aviation and rocket-space engineering. The main barrier for widening of the fields of the use of such materials (for example, in wind power engineering, chemical production and etc.) is their high cost.

In regard to the cost of BP and HFRC, it should be noted that the ways for their cost reduction, probably, are associated with a cheapening of initial materials as well as of mechanization of the production instead of the increase of the output, concentration and specialization of the production. In this connection, the problem of the cost reduction for composites by, if only for, partial replacement of expensive and scarce carbon fiber by considerably cheaper (by an order) basalt one without significant impairment of main operating properties of the material is highly topical. Moreover, the share of reinforcing fibers as well as of a binder in the expenses of raw materials is distinct for the composites of various types. For the composites, in which the nonwoven reinforcing elements are used in the form of threads and mats, the expenses of reinforcing materials attain to 30-35% of all material expenses. At the same time the expenses of reinforcing materials in the form of the cloths may attain to 50-70% at the preparation of basalt plastics. Therefore an essential effect in the reduction of composite's cost may be attained by replacing of the cloths from twisted threads by nonwoven reinforcing materials and roving cloths.

Price cost reduction for BP and HFRC is also possible at the expense of introducing of efficient fillers-reinforcers into the matrix composition. This method allows a considerable decrease of fiber content without an essential reduction of characteristics of the resulting material.

One more way for enhancement of the efficiency of the use of BP and HFRC in action is a rational design and the use of the items from them with regard to the effect of real environment on the material. Below the primary attention is given to more or less detailed consideration of these problems.

## 2. General methodology of investigations

At designing of structures and items from composite materials, primarily the values of their calculated resistances are necessary. By long-term calculated resistance ( $R_{cl}$ ) of the material in normal conditions the product of normative resistance of the material by coefficient of long-term resistance and by coefficient of the uniformity of its mechanical characteristics is meant:

$$R_{cl} = R_{nor} K_{l-t} K_u$$

Normative resistance ( $R_{nor}$ ) was determined a strength limit of the materials under study by the results of short-term testing of small samples, carried out in accordance with acting standards. Coefficient of long-term resistance ( $K_{l-t}$ ) was determined by testing to failure of the series of the samples of the materials at long-term loading at the stresses comprising a definite part from a strength limit of the material. Uniformity coefficient ( $K_u$ ) was

determined by well-known three sigma rule by calculation of arithmetic mean and by root-mean-square deviation of the strength, which are defined on the basis of statistical analysis of the results of mass testing of strength properties of BP and HFRC.

Calculated resistances of the materials, operating at the joint action of static load and regimes, different from normal ones (elevated temperature, high humidity, corrosive medium and etc.) were determined by multiplying the long-term calculated resistances into corresponding coefficients of operating conditions:

$$R_{cl}^T = R_{cl} \cdot K_T, \quad R_{cl}^w = R_{cl} \cdot K_w, \quad R_{cl}^{cor} = R_{cl} \cdot K_{cor}, \quad R_{cl}^{atm} = R_{cl} \cdot K_{atm}$$

where  $K_T$ ,  $K_w$ ,  $K_{cor}$ ,  $K_{atm}$  - coefficients of operating conditions of composites, service of which is provided, respectively, at elevated temperature, in water or at high humidity at the action of corrosive media, in atmospheric conditions, as well as at synchronous long-term action of load as well as of external factors. In some cases the coefficients of operating conditions were determined at the joint action of various factors, for example, of temperature, water /humidity ( $K_{T,w}$ ).

The objects of investigations were:

## 2.1. Basalt reinforced plastics

**BP-1.** Sheet basalt plastic. Thickness ( $\delta$ )-1.5-2.5mm; density ( $\rho$ )-1360-1380 kg.m<sup>-3</sup>; Matrix – unsaturated polyester resin of Turkish production (65 mass%). Reinforcing element – chopped fiber, obtained by cutting of basalt roving of Georgian production with following characteristics: rectilinear density 600-4800 tex; elemental fiber diameter 10-16  $\mu$ ; specific tenacity 350-450 mN/tex.

The mode of preparation: contact moulding (without pressure and temperature).

Expected field of application: light-transparent guarding building structure.

**BP-2.** Basalt cloth – based laminate.  $\delta = 0.7$ -5.0 mm;  $\rho = 1530$ -1560 kg.m<sup>-3</sup>. Matrix-phenol-formaldehyde resin of Ukrainian production (25-35 mass%). Reinforcing element – cloth from twisted threads of Georgian production with following characteristics: thickness 0.25-0.35 mm; surface density 150-450 g/m<sup>2</sup>; density in warp 4-8 th/cm; density in weft 6-12 th/cm, or cloth from basalt roving with the indexes: thickness 0.4-0.9 mm; surface density 300-700 g/m<sup>2</sup>; density in warp – 1.7-3.5 th/cm; density in weft 2.9-4.0 th/cm;

The mode of preparation: direct pressing, pressure 45-55 kgf/cm<sup>2</sup>, pressing temperature 413-443K, holding time on 1 mm-5-12 min.

Expected field of application: shells of three-layered building panels (among them for corrosive media).

**BP-3.** Oriented basalt plastic.  $\delta = 1.0$ -7.0 mm;  $\rho = 1520$ -1540 kg.m<sup>-3</sup>. Matrix-epoxy-phenol resin of Ukrainian production (25-32 mass%). Reinforcing element-permanently oriented basalt fiber in the form of roving (data see in BP-1).



The mode of preparation: production of veneer, its impregnation by a binder, direct pressing of semifinished item.

Expected field of application- auxiliary structural elements and details.

**BP-4.** Pressed basalt plastic.  $\delta = 2.0-8.0$  mm;  $\rho = 1850-1950$  kg.m<sup>-3</sup>. Matrix – modified phenol-formaldehyde resin of Ukrainian production (25-35 mass%). Reinforcing element-chopped or permanently oriented basalt fiber (data see in BP-1, BP-2).

The mode of preparation: preliminary impregnation of reinforcing element, direct pressing at the temperatures of 140-160°C; pressure 250-350 kgf/cm<sup>2</sup>, holding time 2-5 min on 1 mm of material.

Expected field of application: auxiliary structural details for corrosive media.

## 2.2. Composites on the basis of hybrid fibers

**HFRC-1** . Oriented bi-directional composite.  $\delta = 1.5-2.5$  mm;  $\rho = 1450-1550$  kg.m<sup>-3</sup>. Matrix – epoxy resin of Ukrainian production (70-75 mass%). Reinforcing elements – glass and carbon fibers (GF, CF), located in the composite by the scheme, presented in Fig.1. Glass fibers of alkalineless composition are presented in the form of roving of Ukrainian production. Polyacrylonitrile carbon rovings of Russian production offer the strength 2.3 GPa and elasticity modulus 220 GPa. Ratio GF : CF = 0.3÷0.7 (by mass).

The mode of preparation: production of prepreg, its direct pressing.

Expected field of application: shell of wind turbine blade.

**HFRC-2.** The same, but 20% of carbon fiber is replaced by basalt one in the form of roving.

**HFRC-3.** Oriented composite.  $\delta = 2-3$  mm,  $\rho = 1450-1550$  kg.m<sup>-3</sup>. Matrix – the same as in the case of HFRC-1 and HFRC-2; Reinforcing elements – the same as in the case of HFRC-1 and HFRC-2 . They are located by the scheme, shown in fig. 2.

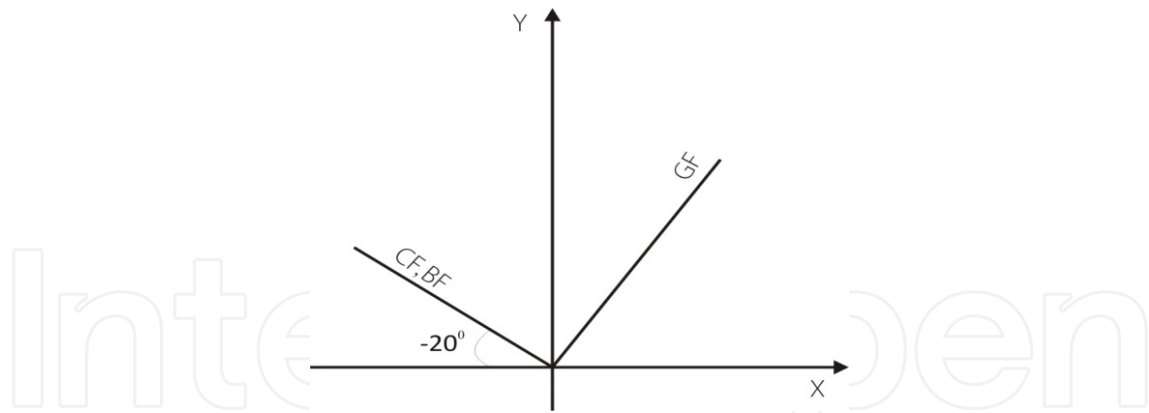
The mode of preparation: the same as in the case of HFRC-1 and HFRC-2.

Expected field of application: the spar of wind turbine blade.

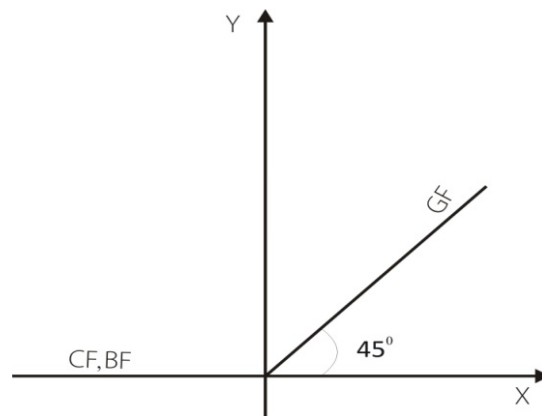
**HFRC-4.** The material similar to the composite HFRC-3, but 20% of carbon fiber is replaced by basalt one in the form of roving.

The results of determination of normative resistances at various types of stressed state (tension, bending, compressing, shear -  $R_{nor}^t, R_{nor}^b, R_{nor}^c, R_{nor}^{sh}$  as well as of short-term elasticity modulus at tension, bending and compressing ( $E_{s-t}^t, E_{s-t}^b, E_{s-t}^c$ ) and coefficients of uniformity of strength properties of the materials under study are given in Table 3.

Returning to the problem on uniformity coefficient of material, it should be noted that testing, carried out for its determination were performed at room temperature – humid conditions. Incidentally, in the course of operating of the structures by the use of plastic materials, they may undergo to various temperature- humid effects and it may be suggested



**Figure 1.** Structure of composite intended for shell



**Figure 2.** Structure of composite intended for spar

that these effects may exert some influence not only to the variation of absolute values of mechanical properties of BP and HFRC, but, to some extent, they may reflect on the indexes of uniformity of strength properties of the materials. To check this suggestion the investigations were carried out to reveal the influence of preliminary action on the indexes of uniformity of strength properties of BP-1, BP-2, HFRC-2 and HFRC-4 at tension. In Table 4 the results of these testing are given. They involve the data necessary to calculate the uniformity coefficient (number of testing –  $n$ , arithmetic – mean value for strength –  $\sigma_{av}$ , mean square deviation –  $\sigma'$  as well as variation coefficient –  $V$ ). The regimes of preliminary action on the samples of the material were: №1 – holding in laboratory room; №2 – heating at 353K over 10 days; №3 – steeping over 1 day; №4 - steeping over 10 days; №5 – steeping over 10 days by further drying over 10 days; №6 - steeping over 10 days at 353K.

As is seen from Table 4, the variation of  $K_u$  is relatively small and maximum reduction of  $K_u$  comprises 9 % for BP and 6 % for HFRC. Hence, the value of  $K_u$ , obtained by testing in normal temperature- humid conditions, may be used by confidence at practical calculations.

Under prolonged (long-term) strength of the solid the dependence of time duration up to its failure on the stress and temperature is meant. The coefficient of long-term resistance is a value, determined by testing of a series of the materials samples under prolonged loading to failure at the stresses, constituent a definite part from material strength limit. Thus, in the terms “long-term resistance” and “durability” an equal meaning is assigned.



Material	$R_{nor}^t$ , MPa	$R_{nor}^b$ , MPa	$R_{nor}^c$ , MPa	$R_{nor}^{sh}$ , MPa	$E_{s-t}^t$ , GPa	$E_{s-t}^b$ , GPa	$E_{s-t}^c$ , GPa	$K_u$
BP - 1	69.0	145.0	105.6	55.0	6.0	-	-	0.65
BP - 2	250.8	130.0	105.5	75.0	26.0	-	-	0.78
BP - 3	480.6	750.8	410.2	190.0	31.5	-	-	0.75
BP - 4	85.0	130.0	110.0	-	19.3	-	-	0.75
	<u>560.0</u>	<u>260.0</u>	<u>210.5</u>		<u>19.5</u>			
HFRC-1	195.6	480.2	261.1	10.2	9.4	14.5	10.6	0.72
	<u>163.1</u>	<u>270.3</u>	<u>219.1</u>	<u>8.1</u>	<u>3.9</u>	<u>3.4</u>	<u>4.2</u>	
HFRC-2	292.5	567.2	410.2	12.2	15.0	23.4	14.6	0.68
	<u>228.2</u>	<u>351.4</u>	<u>319.9</u>	<u>10.2</u>	<u>5.4</u>	<u>5.4</u>	<u>5.8</u>	
HFRC-3	455.4	718.1	420.8	24.8	96.9	78.6	78.1	0.74
	<u>6.9</u>	<u>19.9</u>	<u>8.0</u>	<u>1.2</u>	<u>5.8</u>	<u>5.2</u>	<u>4.1</u>	
	<u>132.2</u>	<u>415.7</u>	<u>160.2</u>	<u>8.8</u>	<u>49.7</u>	<u>58.8</u>	<u>51.0</u>	
HFRC-4	85.6	95.9	107.7	2.4	19.8	16.4	16.7	0.70

Remark: 1 BP-1. Resistances at shear are given in the direction, perpendicular to sheet plane.  
 2. BP-2. For efforts acting in the direction of the base of basalt cloth ( $\delta=7\text{mm}$ ).  
 3. BP-3. At the ratio between longitudinal and transverse fibers, equal to 1:1 for efforts, acting in the direction of fibers.  
 4. BP-4. In numerator and denominator at reinforcing by chopped and oriented fibers, respectively.  
 5. HFRC-1, HFRC-2, HFRC-3, HFRC-4. In numerator and denominator the values along and transversely to X axis, respectively (Fig. 1,2).

**Table 3.** Normative resistances, short-term elasticity modulus and uniformity coefficients for BP and HFRC

Material	Act. reg.	n	$\sigma_{av}$ , MPa	$\sigma'$ , MPa	V, %	$K_u$	Material	Act. reg.	n	$\sigma_{av}$ , MPa	$\sigma'$ , MPa	V, %	$K_u$
BP-1 ( $\delta=1.5\text{mm}$ )	№1	95	72	8	11.1	0.67	HFRC-2 ( $\delta=1.5\text{mm}$ )	№1	92	292	29	9.9	0.70
	№2	100	75	9	12.0	0.64		№2	95	262	25	9.5	0.71
	№3	96	65	8	12.3	0.63		№3	99	277	29	10.5	0.69
	№4	98	62	7	11.3	0.66		№4	100	295	30	10.2	0.69
	№5	92	66	7	10.6	0.68		№5	93	290	31	10.7	0.68
	№6	97	69	9	13.0	0.61		№6	95	277	30	10.8	0.68
BP-2 ( $\delta=0.8\text{mm}$ )	№1	98	359	28	7.8	0.77	HFRC-4 ( $\delta=0.8\text{mm}$ )	№1	100	155	10	6.5	0.80
	№2	95	349	30	8.6	0.74		№2	100	166	18	10.8	0.67
	№3	90	367	30	8.2	0.72		№3	95	125	12	9.6	0.71
	№4	92	228	18	7.9	0.80		№4	96	115	12	10.4	0.69
	№5	93	341	27	7.9	0.76		№5	99	140	14	10.0	0.70
	№6	95	361	30	8.3	0.74		№6	91	111	12	10.8	0.68

**Table 4.** Statistical processing of the result of testing to reveal the influence of preliminary action of various factors on uniformity indexes.

The equation of temperature-time dependence of the solids, as it well known, relates durability ( $\tau$ ), stress ( $\sigma$ ) and temperature ( $T$ ) to each other [9,10]:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right) \quad (1)$$

where  $\tau_0$  - is a constant, approximately equal to  $10^{-13}$  sec, which in order of a value is near to the period of thermal oscillations of atoms;  $U_0$  - initial activation energy of the process of material destruction;  $k$  - Boltzmann's constant;  $\gamma$  - average coefficient of overstresses.

Physical meaning of the formula (1) may be explained by means of thermal fluctuation theory of strength. According to this theory, destruction is kinetic, thermally fluctuating process of permanent accumulation of damages, developed in the body since the load application to its destruction. Breaking of interatomic bonds, activated by applied stress, is an elementary act of destruction process.

In the course of experiments it has been established that BP and HFRC under our study are, mainly, obey the temperature-time dependence. Along with it, it should be noted, that in relation to BP and HFRC, which are bi or more component composites, physical meaning of the values  $\tau_0$ ,  $U_0$  and  $\gamma$  is not reasonably evident. But it should be taken into account that the main goal of our investigations is to obtain the empirical relationships between long-term resistance (durability) of new types of structural materials and the conditions of their operation. In this case the question about physical meaning of above-mentioned values does not need to be posed.

From (1) the following is obtained:

$$\sigma = \frac{U_0 - kT \lg \frac{\tau}{\tau_0}}{\gamma} \quad (2)$$

If in formula (2) it is granted that  $\tau = \tau_i = const$ , we obtain

$$\sigma = \frac{U_0}{\gamma} - BT \quad (3)$$

where  $B = \frac{K \lg \frac{\tau_i}{\tau_0}}{\gamma \lg e}$

Thus, the linear dependence between material strength and temperature at  $\tau = const$  is in existence. At elevating of testing temperature, primarily, the adhesion bonds are broken at the boundaries of basalt (glass) - binder and in the matrix the cracks, parallel to the fiber, are formed, since  $U_0$  values for silicate fibers are equal to 350-385 kJ/mole and the values of activation energy of destruction of polymeric matrix comprise 125-190 kJ/mole. Intensity of breaking of adhesion bond: carbon-binder is of lesser importance, since  $U_0$  for

polyacrylonitrile is near to  $U_0$  for binder (200 kJ/mole). In spite of this fact, in materials under study, breaking of adhesion bond doesn't lead to their destruction since reinforcing element continues an operation as the bundle of non-bound fibers. In this case minimal breaking stress for uni-directional basalt plastics is estimated as a half of breaking stress, obtained by standard testing of the material at normal temperature.

### 3. Mechanical properties of BP and HFRC

#### 3.1. Effect of duration of static loading and temperature on strength

Dependence of breaking stress of BP and HFRC on temperature was estimated by the coefficients of operating conditions  $K_T = \sigma_T / \sigma_{s-t}$ , where  $\sigma_T$  and  $\sigma_{s-t}$  are breaking stresses for the samples after temperature action and at short-term testing, respectively. The values of  $K_T$  are presented in Table 5.

If in formula (1) it is granted that

$$T = T_i = const, \text{ then } \sigma = \frac{U_0}{\gamma} - A \lg \frac{\tau}{\tau_0} \quad (4)$$

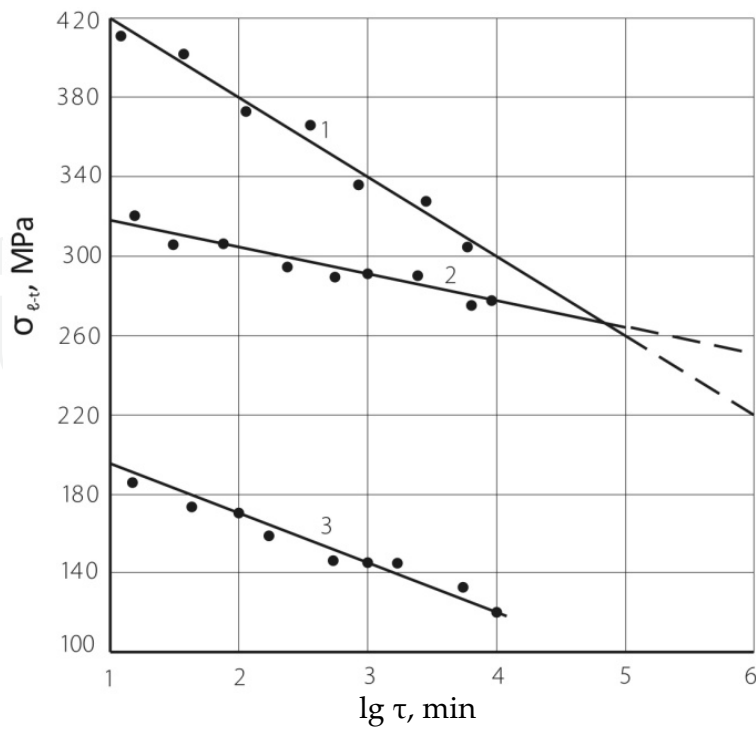
where  $A_i = \frac{kT_i}{\gamma \lg e}$ .

Material	Temperature, K					
	313			333		
	Tension, Compression	Bending	Shearing	Tension, Compression	Bending	Shearing
BP-1	0.65	0.85	0.67	0.60	0.79	0.63
BP-2, BP-3	0.88	0.79	0.78	0.77	0.72	0.72
BP-4	0.70	0.88	0.72	0.63	0.78	0.66
HFRC-1	0.72	0.88	0.77	0.70	0.85	0.72
HFRC-2	0.72	0.82	0.82	0.70	0.79	0.77
HFRC-3	0.74	0.86	0.88	0.71	0.81	0.80
HFRC-4	0.75	0.85	0.79	0.74	0.78	0.75

Remark: 1. Coefficients of operating conditions of materials in the structures at temperature 273 K are taken to be unity; 2. At intermediate temperatures  $K_T$  may be determined by interpolation.

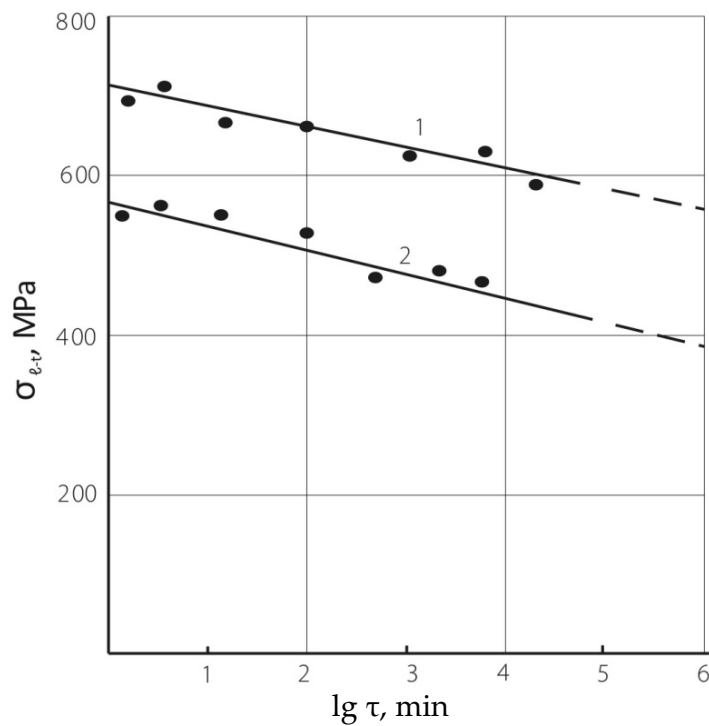
**Table 5.** Coefficients of operating condition  $K_T$  in the structures, operating at elevated temperatures

In regard to material under study, the linear relationship between strength and durability logarithm is mainly obeyed at normal as well as at the temperatures of 313K and 333K. Mentioned temperatures are considerably less than temperature of forced elasticity of BP and HFRC and because of this fact the dependence  $\sigma - \lg \tau$  on tension hasn't a kink, characteristic of the case of the action of high (>350K) temperatures. Below these dependences are presented in the coordinates  $\sigma - \lg \tau$  in contrast to the coordinates  $\lg \tau - \sigma$ , used in the theory of the strength of the solids (Fig. 3, 4).



**Figure 3.** Curves of long-term strength of BP-3, BP-4 (tension): 1-BP-3; 2-BP-4, uni-directional; 3 – BP-4, full strength.

To estimate a time dependence of the strength, the coefficients of operating conditions of the material were used:  $K_{\tau} = \sigma_{\tau} / \sigma_{s-t}$ , where  $\sigma_{\tau}$  breaking stress after the time interval, corresponding to service life of the structure or item. The values  $K_{\tau}$  for BP and HFRC are given in Table 6.



**Figure 4.** Curves of long-term strength of BP-1 at various temperatures (bending). 1 – 313K; 2 – 333K

Material	Tension			Compression			Bending		
	10 <sup>3</sup> h	10 <sup>4</sup> h	10 <sup>5</sup> h	10 <sup>3</sup> h	10 <sup>4</sup> h	10 <sup>5</sup> h	10 <sup>3</sup> h	10 <sup>4</sup> h	10 <sup>5</sup> h
BP-1	0.71	0.65	0.60	0.71	0.68	0.58	0.68	0.56	0.45
BP-2	0.86	0.75	0.68	0.81	0.67	0.59	0.83	0.72	0.55
BP-3	-	0.68	0.56	0.88	0.77	0.61	0.87	0.74	0.59
BP-4	0.81	0.77	0.70	0.89	0.78	0.51	0.78	0.72	0.63
HFRC - 1	0.91	0.79	0.69	0.85	0.76	0.62	0.78	0.69	0.55
HFRC - 2	0.88	0.73	0.66	0.82	0.71	0.59	0.80	0.63	0.51
HFRC - 3	0.90	0.76	0.71	0.88	0.77	0.68	0.82	0.66	0.59
HFRC - 4	0.81	0.72	0.62	0.79	0.70	0.62	0.80	0.63	0.49

**Table 6.** The values of the coefficient  $K_{\tau}$  at various types of stressed state

Direct experimental determination of  $\sigma_{\tau}$  is fraught with great difficulties: the maintenance of constant external conditions and predetermined stress over a long period of time is necessary. Therefore the values  $\sigma_{\tau}$  were determined for three values: 1, 10<sup>2</sup>, 10<sup>3</sup> hours by extrapolating on the basis of equation (1), obtained curve and by assuming that external factors don't distort a linear character of temporal dependence of the strength.

Hence, we have, separately, the coefficients of operating conditions providing the temperature influence as well as considering the loading duration. Over many years the method of multiplying of these coefficients has been used to account the joint effect of these factors on long-term resistance. But as it was shown in [11], this method leads to considerable overstating of calculated resistances of glass plastics, especially at the temperatures close to glass transition temperature of a binder. To check this fact, a materials under study were subjected to the joint action of loading and temperature (313 K, 333 K), correlating the data, obtained in this case with the values of the coefficients of operating conditions  $K_{\tau}$  and  $K_T$  (Table 7).

Coefficient	Temperature, K	BP - 1	BP - 2	BP - 3	BP - 4
$K_T$	313	0.84	0.88	0.90	0.85
	333	0.65	0.72	0.85	0.79
$K_{\tau}$ ( $\tau = 5$ years)		0.52	0.82	0.89	0.83
$K_T \cdot K_{\tau}$	313	0.44	0.72	0.80	0.71
	333	0.34	0.59	0.76	0.66
$K_{\tau}^T$ ( $\tau = 5$ years)	313	0.41	0.69	0.75	0.65
	333	0.28	0.49	0.69	0.59
$\frac{K_{\tau}^T}{K_T \cdot K_{\tau}}$	313	0.93	0.95	0.94	0.91
	333	0.82	0.83	0.91	0.89

**Table 7.** Values of coefficients of operating conditions of BP at bending

The analysis of the data of Table 7 confirms the fact that the method of coefficients multiplying really leads to enhanced values of the coefficients of operating conditions and consequently to overstating of calculated resistances of BP. Thus, it was decided to determine the coefficients of operating conditions for the joint action of external factors and loading.

### 3.2. Effect of the time of loading action and temperature on deformation characteristics

Deformability of the materials under study, caused by force action, was estimated by short-term and long-term elasticity and shear modulus ( $E_{s-t}$ ,  $E_{l-t}$ ,  $G_{s-t}$ ,  $G_{l-t}$ ) were determined by short-term static testing of small standard samples as a ratio between the increment of stress and the increment of relative deformation of a sample.  $E_{l-t}$ ,  $G_{l-t}$  were obtained by long-term static testing of the samples at stresses equal to calculated long-term resistance of materials as a ratio between the stress and maximum relative deformation of the sample at damping of creeping. It should be noted that the term "long-term elasticity modulus" is conventional in this case, since deformations of polymeric composites at long-term loading, in reality, aren't elastic.

At the temperatures, no greater than the temperature of beginning of binder destruction, reinforcing fibers act as linear-elastic materials. Binders are characterized by visco-elastic properties. Therefore, deformations of BP and HFRC, generally, depend significantly on duration and temperature of operation.

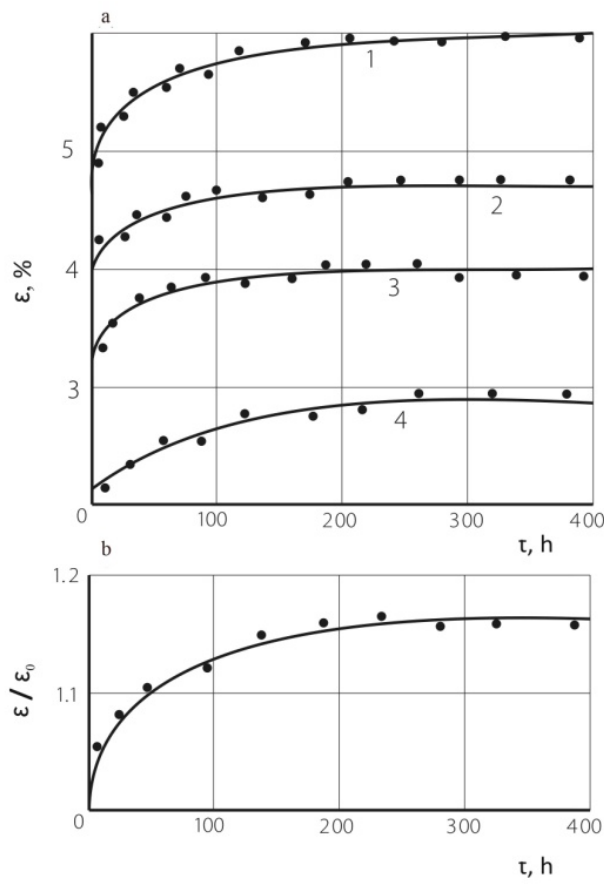
As might be expected, in uni-directional or orthogonally-reinforced BP and HFRC, the creeping is formed at the action of constant loading applied to the direction of reinforcement. But after a time, this process is practically terminated. This fact is quite clear since at first an effort is distributed between fibers and binder, but stresses in binder relax and all stresses are progressively imparted to fibers.

At loading of BP and HFRC, randomly reinforced and oriented at angle to loading direction, creeping isn't damped and is continued up to material destruction. Creeping anisotropy of these materials is expressed to a considerable more extent than an anisotropy of elastic properties and sharply enhances with temperature elevation.

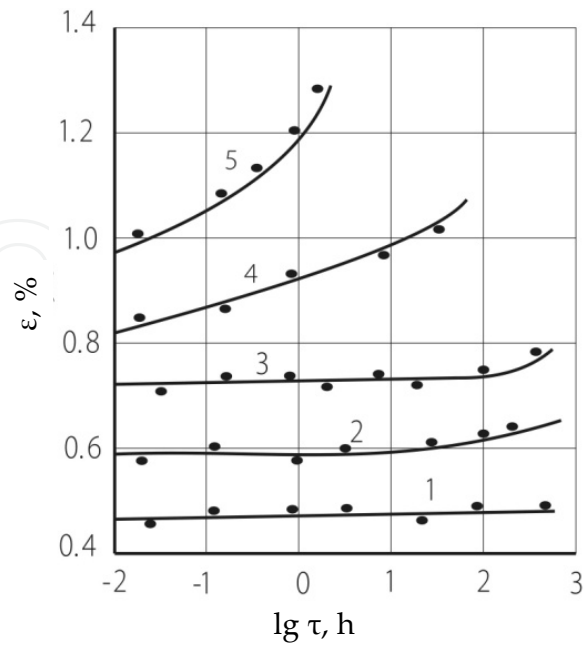
The goal of experiments for determination of creeping of BP and HFRC was an establishment of functional relationship between stress, deformation and duration of loading action. Some results of the study of BP and HFRC creeping are given in Fig. 5.

As is seen, experimental points of all curves, plotted for various levels of stresses in the coordinates  $\varepsilon - \tau$ , fall on one curve, constructed in the coordinates  $\varepsilon / \varepsilon_0 - \tau$ , which allows to consider the material under study as linearly visco-elastic. Isochrones, constructed for this reason, are straight lines, reflecting a linear relationship between deformations and stresses for each fixed instant of time  $\tau_i$ .





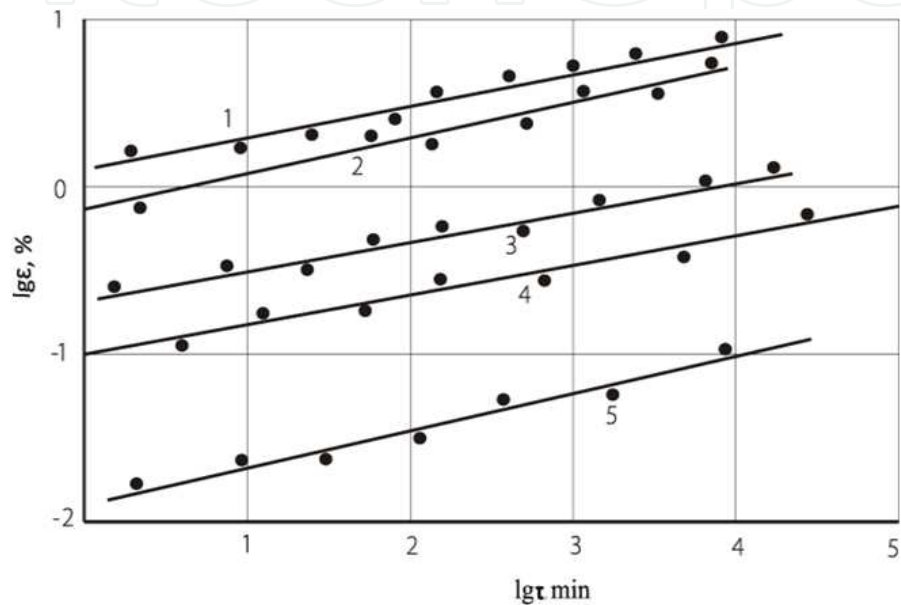
**Figure 5.** Curves of creeping (a) and generalized curve of creeping (b) for basalt cloth-base laminate at compression on cloth weft. Stresses: 1-90 MPa, 2 – 85MPa; 3 – 65MPa; 4 – 50 MPa.



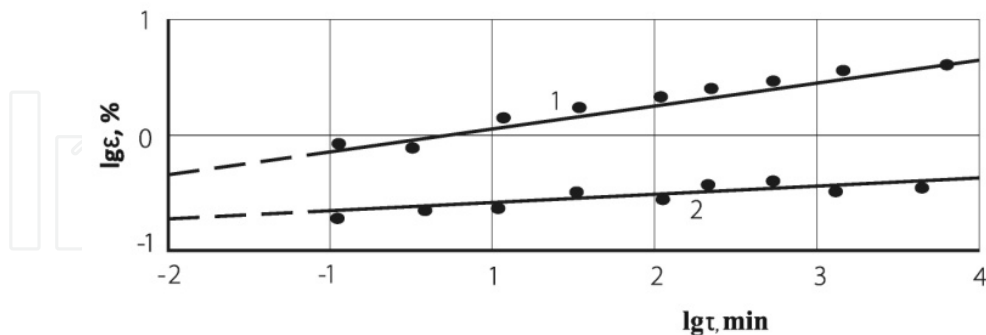
**Figure 6.** Creeping of the composite HFRC-4. 1,2,3,4,5, respectively, are the levels of relative stress: 0.4; 0.5; 0.6; 0.7; 0.8.

Creeping of HFRC has been investigated. The levels of relative stress, that is to say, ratio between acting stress and breaking one comprised 0.4; 0.5; 0.6; 0.7; 0.8; Experimental curves of creeping of the composite HFRC are presented in Fig. 6. By creeping curves the families of isochronic curves  $\sigma - \varepsilon$  were constructed, by which the dependence of elasticity modulus on time was found. After  $10^4$  hours the reduction of elasticity modulus comprised 10-12%.

Creeping of BP-1 exhibits non-damped character. Deformation of creeping at tension over  $5 \cdot 10^3 - 1 \cdot 10^4$  hours appears to be several times more than instantly-elastic ones (Fig.7). Similar picture is observed for other types of stressed state (Fig.8).



**Figure 7.** Curves of BP-1 creeping at tension 1-70MPa; 2-65 MPa; 3-40 MPa; 4-20 MPa; 5-10MPa.



**Figure 8.** Curves of BP-1 creeping at bending for stress levels: 1-50MPa; 2-20 MPa.

Creeping plots at the coordinates  $lg\varepsilon - lg\tau$  present a series of parallel straight lines, which is indicative of the presence of power dependence of deformation creeping on time.

In Table 8, 9 the values of the coefficients of operating conditions are given, considering the variation of deformation characteristics of BP and HFRC depending on duration of loading action and on temperature variation.

Material	Index	$K_{\tau}$ , after hours		
		$10^3$	$10^4$	$10^5$
BP-1	E <sup>t</sup>	0.72	0.61	0.52
	G	0.69	0.59	0.50
BP-2	E <sup>t</sup>	0.91	0.82	0.78
	G	0.89	0.85	0.79
BP-3	E <sup>t</sup>	0.95	0.89	0.82
	G	0.72	0.68	0.62
BP-4	E <sup>t</sup>	0.91	0.86	0.82
	G	0.85	0.79	0.71
HFRC - 1	E <sup>t</sup>	0.92	0.87	0.85
	G	0.85	0.76	0.69
HFRC - 2	E <sup>t</sup>	0.88	0.82	0.79
	G	0.79	0.71	0.62
HFRC - 3	E <sup>t</sup>	0.95	0.89	0.85
	G	0.91	0.86	0.78
HFRC - 4	E <sup>t</sup>	0.89	0.82	0.75
	G	0.81	0.72	0.69

**Table 8.** The values of the coefficients of operating conditions  $K_{\tau}$  by deformation properties

Material	Index	$K_{\tau}$ at temperatures		Material	Index	$K_{\tau}$ at temperatures	
		313K	333K			313K	333K
BP-1	E <sup>t</sup>	0.53	0.42	HFRC-1	E <sup>t</sup>	0.85	0.79
	G	0.51	0.39		G	0.82	0.75
BP-2	E <sup>t</sup>	0.71	0.64	HFRC-2	E <sup>t</sup>	0.82	0.72
	G	0.81	0.74		G	0.79	0.71
BP-3	E <sup>t</sup>	0.88	0.76	HFRC-3	E <sup>t</sup>	0.89	0.82
	G	0.83	0.74		G	0.85	0.79
BP-4	E <sup>t</sup>	0.78	0.61	HFRC-4	E <sup>t</sup>	0.82	0.85
	G	0.77	0.85		G	0.80	0.72

**Table 9.** The values of the coefficients of operating conditions  $K_{\tau}$  by deformation properties

## 4. Resistance of BP and HFRC to environment

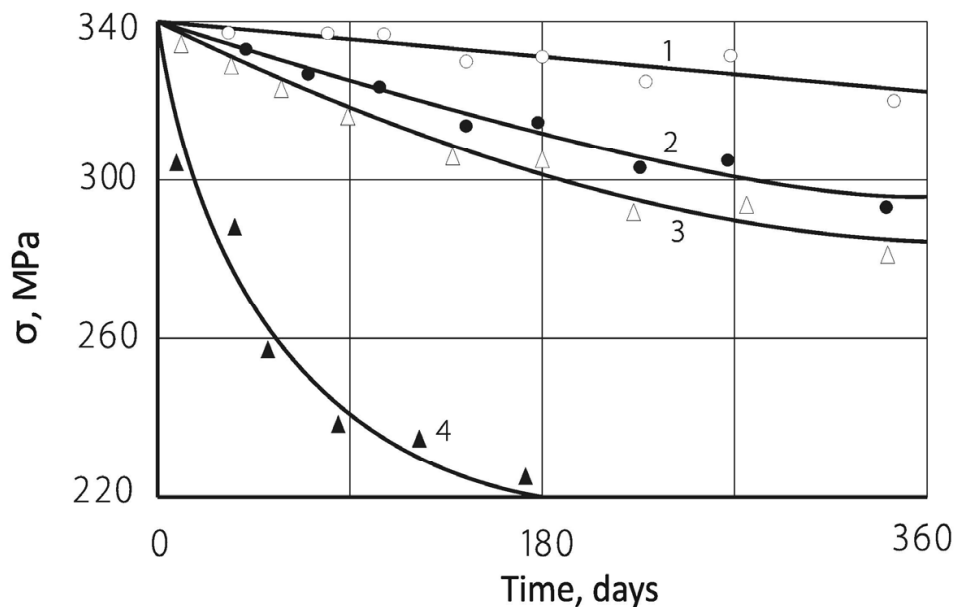
### 4.1. Mechanical characteristics at atmospheric action

It is well known that by selecting of corresponding regimes of accelerated testing on atmospheric resistance the reduction of mechanical characteristics of materials may be relatively readily attained. But the determination of reasonably accurate correlation between the results of natural and accelerated testing on ageing of polymeric composites was unsuccessful. So far as we know, this problem wasn't solved up till now in relation to inorganic as well as to organic materials. In this connection it was decided to perform the

bench testing on natural ageing of BP and HFRC in environmental conditions of South Caucasus.

Ageing of BP and HFRC, intended for operation in atmospheric conditions, is a result of complex action of such factors as chain reaction of oxidation, temperature-humid deformation of a binder, penetration of moisture into material with further leaching of fiber, abrasive action of dust.

Exposure of BP and HFRC in unloaded state and under stresses, close to calculated resistances of materials, revealed a considerable difference in the character of development of ageing processes in loaded and unloaded composites, as well as a difference between the values of long-term resistance and creeping of the samples, tested in atmospheric and laboratory conditions. For example, in Fig 9 the behavior of the samples of BP-2, unloaded and loaded by various intensity are shown.



**Figure 9.** Dependence of strength at BP-2 tension on ageing time at open air and on the level of action stress: 1 - zero stress, 2 -  $0.2 \sigma_{s-t}$ , 3 -  $0.45 \sigma_{s-t}$ , 4 -  $0.70 \sigma_{s-t}$

Binder nature has a pronounced effect on atmospheric resistance of BP and HFRC. It is difficult to judge about atmospheric ageing of BP and HFRC on the basis of polyester matrix, since the process of binder hardening isn't finished; this leads to enhancement of elasticity modulus by 5-15%. True enough, the strength reduction by 8-17% still takes place.

As a result of atmospheric ageing, mechanical characteristics of BP and HFRC on the basis of epoxy and phenol-formaldehyde matrixes are gradually decreased depending on material thickness and applied stress. Difference in the variation of mechanical indexes of loaded and unloaded samples is revealed to a greater extent than in BP and HFRC on the basis of polyester matrix. Ageing process of materials are developed, mainly, on the surface; in this connection their atmospheric resistance significantly depends on material thickness. Existence of stressed state has a pronounced effect on intensification of ageing of BP and

HFRC on the basis of epoxy and phenol-formaldehyde binders in atmospheric conditions; in this case the effect of materials thickness is reflected to the greatest extent. Thus, a great number of BP-2 samples of 1.0 mm thickness, exposed at stress of  $0.75 \sigma_{s-t}$ , were destructed immediately at the stand before expected exposure time, whereas the samples of 4.5 mm thickness weren't destroyed. The results of mechanical testing have shown a slight reduction of the strength of these samples (stresses in both cases were equal).

As a result of performed investigations, the values of the coefficients of operating conditions of BP and HFRC in service, have been obtained (Table 10).

Material	For calculated resistances	For long-term elasticity modulus	Remark
BP-1	0.69	0.80	Presented coefficients are given for BP-1 of 1.5-3.0 mm thickness, for BP-2, BP-3 and BP-4 of 2.0-7.0 mm thickness and for all types of HFRC – 5.0-8.0 mm of thickness.
BP-2	0.75	0.82	
BP-3	0.79	0.83	
BP-4	0.72	0.75	
HFRC-1	0.82	0.85	
HFRC-2	0.79	0.81	
HFRC-3	0.85	0.88	
HFRC-4	0.79	0.82	

**Table 10.** Coefficients of operating conditions –  $K_{atm}$  of BP and HFRC

#### 4.2. Mechanical characteristics at the action of water and some corrosive liquid media

Stability of mechanical properties of BP and HFRC is determined by resistance of reinforcing component of material, matrix and adhesion bond between them to aqueous and chemical media. An advantage of basalt fiber over other ones, in addition to higher thermal stability, must consist in water resistance and chemical endurance. In order to prove this fact, the action of alkali and mineral acids of various concentration (up to 60%) was studied on threads strength from alkalineless, alkaline and basalt glass, used in composites. Chemical composition of these glasses is the following (in mass%): aluminumborosilicate (alkalineless) –  $\text{SiO}_2$ -54;  $\text{Al}_2\text{O}_3$  – 14;  $\text{B}_2\text{O}_3$  – 10;  $\text{CaO}$ -16;  $\text{MgO}$ -4;  $\text{Na}_2\text{O}$  – 2; sodiumcalciumsilicate (alkaline) -  $\text{SiO}_2$ -71;  $\text{Al}_2\text{O}_3$  – 3;  $\text{CaO}$ -8;  $\text{MgO}$ -3;  $\text{Na}_2\text{O}$  – 15; basalt one:  $\text{SiO}_2$ -49;  $\text{Al}_2\text{O}_3$  – 16;  $\text{Fe}_2\text{O}_3$  – 10;  $\text{CaO}$  – 9;  $\text{MgO}$ -7;  $\text{Na}_2\text{O}$ -4;  $\text{MnO}$ <1;  $\text{TiO}_2$ <1. It was studied the behavior of roving, offering the non-twisted strand with a diameter of elementary fiber of the order of 10-16 $\mu$ .

Testing was carried out in water and in the media, most characteristic for chemical production: in caustic soda, sulphuric and nitric acids. Solution temperature comprised 291-295K. Before testing the samples were preliminary conditioned. Duration of static action of corrosive medium on threads was taken to be 240 hours, since the most intensive reduction

of strength of fibers and of materials on their base at normal temperature is observed within first 200-240 hours, after which some stabilization of their strength indexes takes place. After maintenance in corrosive media the samples of threads were tested on the machine at relative humidity of air – 75-78% by determination of breaking load – P (P<sub>0</sub> – breaking load of dry threads). Because of some reversibility of strength reduction in fibers at the action of corrosive media, the samples of threads didn't dried before testing on the machine.

As is seen from the data of Table 11, 5-10% solutions of caustic soda have the most destructive effect on alkalineless threads. With increasing of the concentration of NaOH, the stability of strength characteristics of threads enhanced.

With increasing of the temperature of alkaline solution the total solubility of glass fiber enhances. In this case maximum solubility is slightly smoothed, in doing so its displacement is observed to the realm of higher concentrations. For basalt threads, in principle, the same character of the strength dependence on temperature and solution concentration is observed, but the values of mass loss is significantly lower (Table 12).

The most intensive strength reduction for glass threads is also observed at the action of 5-10% NaOH. Residual strength of basalt threads is considerably higher (Fig10).

Corrosive media*	Residual strength $\frac{p}{p_0} \cdot 100\%$				
	1%	5%	10%	25%	≥ 45%**
Caustic soda	$\frac{35}{45}$	$\frac{32}{41}$	$\frac{33}{45}$	$\frac{56}{67}$	$\frac{59}{72}$
Sulphuric acid	$\frac{22}{27}$	$\frac{4}{18}$	$\frac{5}{21}$	$\frac{16}{31}$	$\frac{18}{42}$
Nitric acid	$\frac{6}{21}$	$\frac{4}{19}$	$\frac{5}{24}$	$\frac{17}{38}$	$\frac{19}{42}$

Remark: in numerator – indexes of threads from alkalineless glass; In denominator - indexes of basalt threads.

\* reduction of glass threads in water comprised 40%, of basalt threads 15%.

\*\* maximum concentration of H<sub>2</sub>SO<sub>4</sub> – 45%, of HNO<sub>3</sub>-60%.

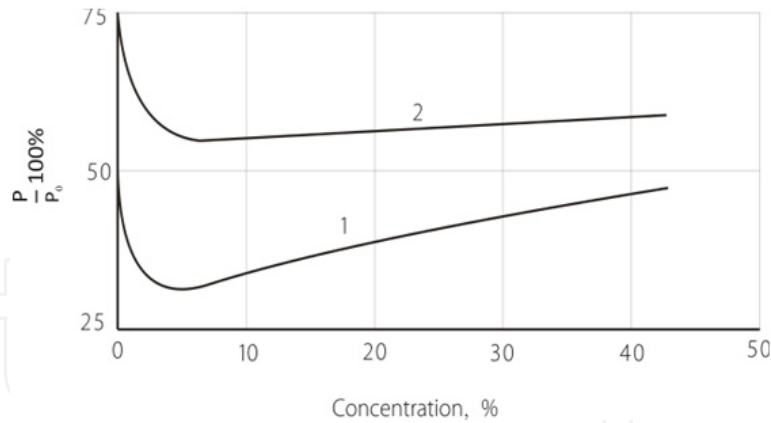
**Table 11.** Reduction of breaking strength of threads in corrosive media of various concentration

Temperature, K	313	323	333	343	363
Mass loss, mg.cm <sup>-2</sup> , hour <sup>-1</sup>	$\frac{0.03}{0.01}$	$\frac{0.06}{0.03}$	$\frac{0.03}{0.01}$	$\frac{0.03}{0.01}$	$\frac{2.33}{1.49}$

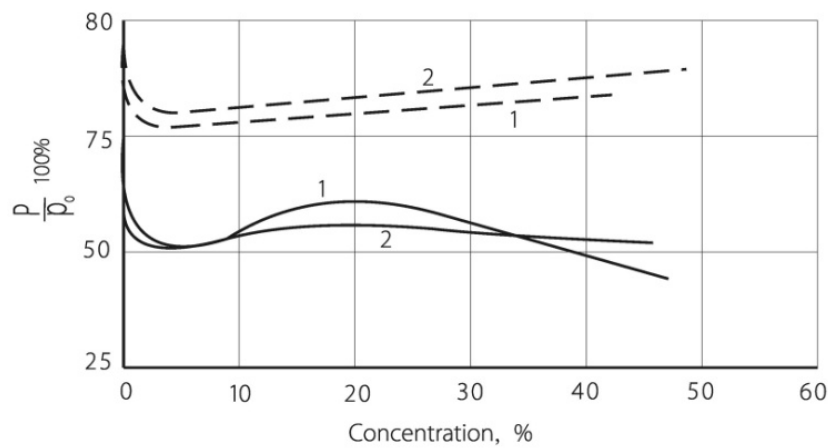
Remark: in numerator – the values of glass threads of alkalineless composition; In denominator-the values for basalt threads.

**Table 12.** Effect of temperature and caustic soda concentration on mass variation of fibers from alkalineless glass and from basalt.





**Figure 10.** Strength reduction of threads from alkaline glass (1) and from basalt (2) in caustic soda.



**Figure 11.** Variation of strength of alkaline glass threads (—) and basalt ones (---) in sulphuric (1) and nitric (2) acids.

Testing of glass and basalt threads in sulphuric and nitric acids has shown that a factor of concentration exerts a lesser influence on the variation of strength characteristics. By the example of behavior of alkaline glass threads it may be noted a some increased influence of sulphuric and nitric acids on them in concentration range of 5-10%. But effect of this influence is very limited. Especially it may be said in relation to basalt threads (Fig 11).

Action of acids in the range of higher (>20%) concentrations is different. Concentration factor of nitric acid doesn't effect on strength of glass threads as well as of basalt ones. At the action of sulphuric acid (40%) a sharp decrease of the strength of glass threads is observed and an effect on the strength of basalt threads is not so noticeable (Fig 11).

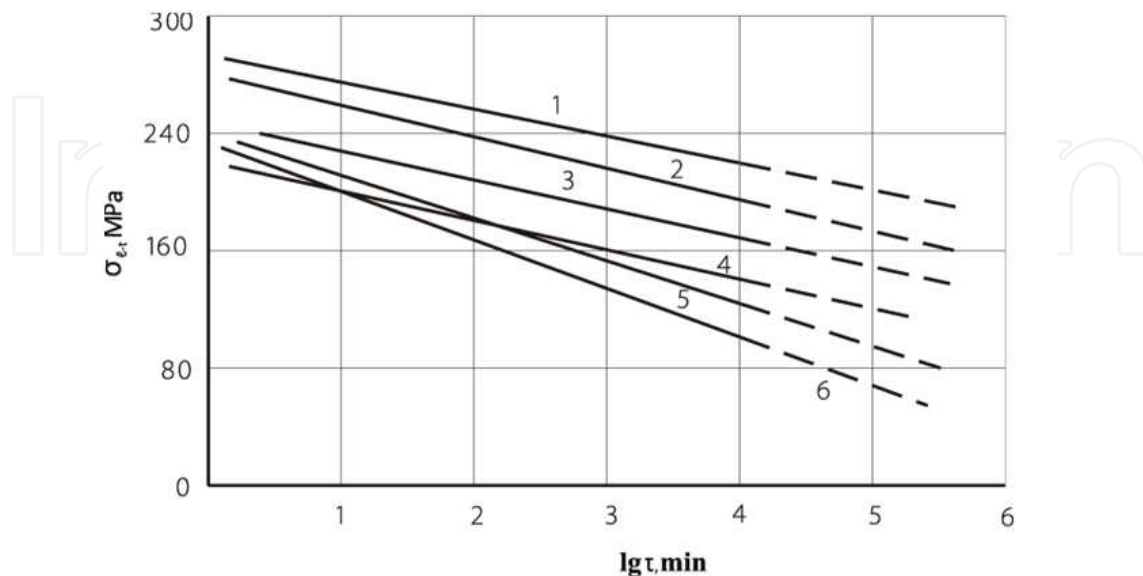
Data on strength reduction in threads from alkalineless glass and basalt threads in sulphuric and nitric acids are presented in Table 11. Sulphuric acid acts considerably more aggressively in concentration range of 5-10%. Concentration factor of nitric acid doesn't effect significantly on the value of strength reduction of glass threads. The character of acid action on basalt threads remains identical but a level of residual strength of these threads after exposure in the media remains higher in comparison with a level of the strength of alkalineless glass threads.

Similar character in discordance of the values of the coefficients of operating conditions was also found at accounting of one more factor – temperature. Diagrams of long-term resistance of BP-1 at air and in water at the temperatures of 293K, 313K and 333K, presented in Fig. 12, as an example, permit to determine  $K_{T,\tau}^W$ , the comparison of which with  $K_T \cdot K_\tau \cdot K_w$  once again convinces in incorrectness of the method of coefficients multiplying (Table 14).

As indicated earlier, the joint effect of environment and time of its action on long-term resistance of materials to destruction is every so often estimated by multiplying of corresponding coefficients of operating conditions. But as with separate accounting of the effect of duration of the action stresses and temperature, this method causes the considerable errors in direction of reduction of safety factor. This fact is evident by the data of Table 13, where  $K_w$  and  $K_\tau^w$  are coefficients of operating conditions in aqueous medium, and at the joint effect of water and duration of its action, respectively.

Material	$K_w$	$K_\tau$	$K_\tau \cdot K_w$	$K_\tau^w$	$\frac{K_\tau^w}{K_\tau \cdot K_w}$
BP-1	0.89	0.52	0.46	0.40	0.87
BP-2	0.79	0.82	0.65	0.59	0.91
BP-3	0.82	0.89	0.72	0.60	0.83
BP-4	0.85	0.83	0.71	0.66	0.93
HFRC-1	0.90	0.88	0.79	0.70	0.89
HFRC-2	0.83	0.83	0.69	0.62	0.90
HFRC-3	0.89	0.82	0.73	0.68	0.93
HFRC-4	0.83	0.79	0.66	0.61	0.92

**Table 13.** Comparison of the coefficients of operating conditions obtained by accounting of separate and joint action of water and of duration of its action on materials (at  $\tau = 10^4$  hours).



**Figure 12.** Long-term resistance of HFRC-2 at air and in water at the temperatures 293K(1,4), 313K (2,5) and 333K (3,6). 1, 2, 3 - at air; 4, 5, 6 - in water

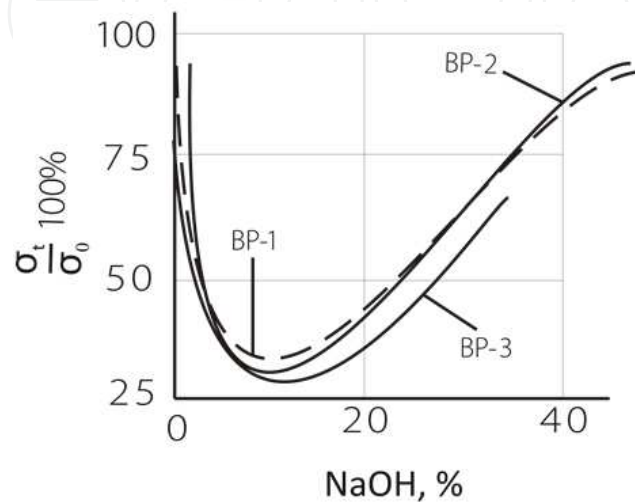
Material	Temperature, K	$K_T$	$K_w$	$K_\tau$	$K_T \cdot K_w \cdot K_\tau$	$K_{T,\tau}^w$	$\frac{K_{T,\tau}^w}{K_T \cdot K_w \cdot K_\tau}$
BP-1	293	0.95	0.89		0.44	0.42	0.95
	313	0.85	0.86	0.52	0.38	0.30	0.79
	333	0.72	0.86		0.32	0.20	0.62
BP-2	293	0.96	0.79		0.62	0.61	0.98
	313	0.87	0.78	0.82	0.56	0.35	0.62
	333	0.73	0.76		0.45	0.27	0.60
BP-3	293	0.95	0.82		0.69	0.67	0.97
	313	0.83	0.82	0.89	0.61	0.43	0.70
	333	0.70	0.69		0.43	0.28	0.65
BP-4	293	0.97	0.85		0.68	0.65	0.96
	313	0.82	0.85	0.83	0.58	0.57	0.98
	333	0.74	0.80		0.49	0.30	0.61
HFRC-1	293	0.98	0.90		0.78	0.77	0.99
	313	0.85	0.85	0.88	0.64	0.54	0.84
	333	0.78	0.81		0.56	0.33	0.59
HFRC-2	293	1.00	0.83		0.69	0.66	0.96
	313	0.90	0.81	0.83	0.61	0.54	0.89
	333	0.81	0.79		0.53	0.32	0.60
HFRC-3	293	1.00	0.89		0.73	0.70	0.96
	313	0.88	0.87	0.82	0.63	0.57	0.90
	333	0.80	0.82		0.54	0.33	0.61
HFRC-4	293	1.00	0.84		0.66	0.61	0.92
	313	0.84	0.83	0.79	0.55	0.43	0.78
	333	0.72	0.80		0.46	0.27	0.59

**Table 14.** Comparison of the coefficients of operating conditions, calculated by accounting of separate and joint effects of water, temperature and duration of their action on materials (at  $\tau=10^4$  hours)

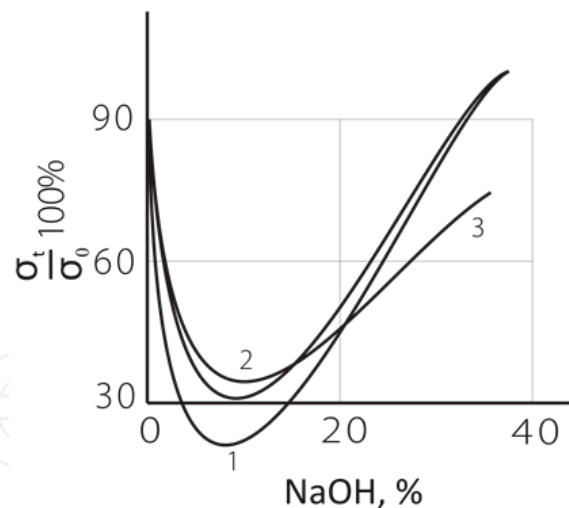
Analysis of obtained data permits to conclude that if at room temperature the physical character of water action on BP and HFRC is dominated, then by temperature elevation the chemical activity of aqueous medium becomes predominant. It may be also concluded that a long-term operation of materials under study don't cause a sharp decrease of their load-carrying capacity and destruction, since the medium temperature (313K, 333K) is significantly lower than the glass transition temperature of the binders and reinforcing elements (basalt, glass, carbon) are sufficiently stable in these conditions.

Going to the problem of chemical resistance of BP and HFRC, first and foremost it should be noted that the character of variation of their strength in alkaline media to a large extent depends on the composition of reinforcing component of materials, whereas an acid effect depends, mainly, on acid resistance of a matrix. Correlation of strength indexes of materials with epoxy, phenol-formaldehyde and polyester binders depending on the concentration of

caustic soda after 240-hour maintenance shows that general character of strength variation is identical in all cases (Fig. 13). The greatest reduction of strength is observed in 5-10% solutions of caustic soda. In concentrated solutions the strength, practically, remains at initial level. Such character of strength variation is retained for all structural directions of BP and HFRC. In Fig.14 strength variation for main structural directions is presented at bending of HFRC-4 after 240 hour maintenance in the solution of caustic soda. It is evident that maximum reduction of strength limit, in all cases, takes place in the range of concentration of caustic soda of 5-10%.



**Figure 13.** Strength reduction at tension of BP in caustic soda

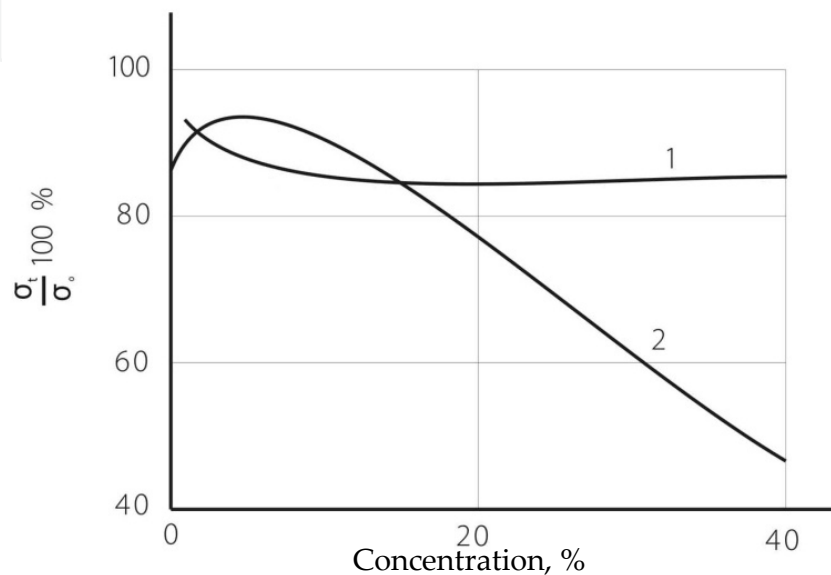


**Figure 14.** Strength reduction at various structural directions at bending of BP-2 in caustic soda. 1-on warp; 2-on weft; 3-at an angle of 45°

The character of strength variation for BP and HFRC, depending on acid concentration, is determined, mainly, by inertia of a binder and by its adhesion to reinforcing fiber. Polyester BP, in comparison with phenol-formaldehyde ones, exhibit better resistance to the action of mineral acids, their strength properties are more stable. In 5-10% solutions of sulphuric acid the penetration of liquid into phenol-formaldehyde BP takes place; this fact reduces an adhesion of a binder to basalt fiber and causes the swelling of the samples of BP-4. Its

strength limit at tension is gradually reduced and in the range of medium concentrations is practically unchanged (Fig. 15).

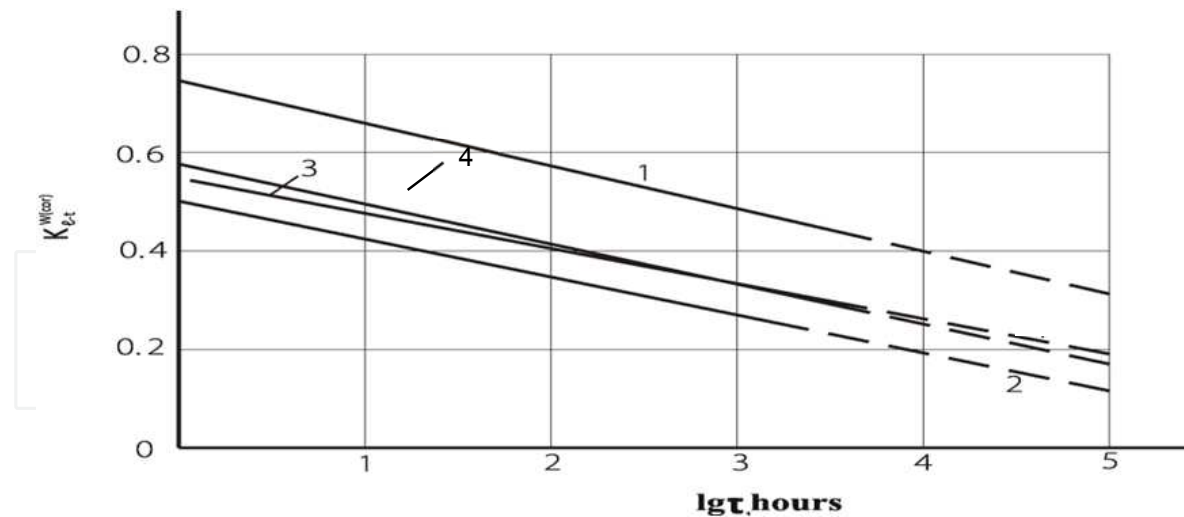
Nitric acid is a powerful oxidizer and even at low temperatures causes the breakage of the surface of phenol-formaldehyde BP, with leads to definite losses in its mass. By increasing of acid concentration the swelling of the samples of BP-2 takes place but its strength in the range of low concentrations is varied moderately. By increasing of acid concentration strength drop is continued (Fig.15).



**Figure 15.** Strength variation at tension of BP-2 in sulphuric (1) and nitric (2) acids

At long-term action of sulphuric acid on polyester BP the breaking of the surface of the samples of BP-1 takes place accompanying by the loss of its mass and strength reduction. True enough, this process occurs only at low concentrations (up to 5%) and in the solutions of higher concentrations the strength remains at original level. Concentrated nitric acid depending on the time of action on polyester BP, causes an intensive swelling or washing-out of the samples. Strength of BP-1 is gradually decreased by increasing of the concentration of nitric acid.

The further stage of the work was the determination of long-term resistance of BP and HFRC in water and in 1 % solutions of caustic soda, sulphuric and nitric acids. Long-term resistance of BP and HFRC on bending was studied by the procedure, described in [12]. Long-term resistance of the materials, operating in water and corrosive liquid media, is nothing more nor less than the coefficient of their operating conditions, accounting the joint action of temporal factor and of water or anyone corrosive medium on the materials. For example, in fig.16, the dependence of  $K_{\ell-t}^{w(cor)}$  on logarithm of durability for BP-1 is presented. At predetermined operating time for this material –  $10^5$  hours (11.4 years) conventional  $K_{\ell-t}^{w(cor)}$  obtained by extrapolating of experimental data, depending on testing medium, comprises from 0.28 to 0.11. Results of testing presented in Fig. 16, permit to propose the following coefficients of long-term resistance of BP-1 on bending at its assumed operation in stressed state in water and in 1% solutions of caustic soda, sulphuric and nitric acids (Table15).



1 – water; 2 – H<sub>2</sub>SO<sub>4</sub>; 3 – HNO<sub>3</sub>; 4 – NaOH

**Figure 16.** Dependence of  $K_{t-t}^{w(cor)}$  on a logarithm of durability at the bending of BP-1.

Operating conditions	Proposed time of exploitation			
	Up to 1 year	To 3 years	To 5 years	To 10 years
Dry state	0.67	0.64	0.62	0.58
Water	0.42	0.36	0.33	0.29
1% NaOH	0.22	0.20	0.18	0.15
1% H <sub>2</sub> SO <sub>4</sub>	0.20	0.18	0.15	0.11
1 % HNO <sub>3</sub>	0.25	0.21	0.19	0.16

**Table 15.** Coefficients of long-term resistances of BP-1 in water and in the solutions of caustic soda and acids

Processing of these and other above-presented results of investigations, for all materials, considered in this work, permitted to obtain the reference data on long-term calculated resistances of BP and HFRC. These data, by our opinion, may be beneficial at designing of structures and items by the use of BP and HFRC.

## 5. Conclusion

At present a sufficient experience is accumulated in world practice in the field of the technology of preparation of basalt plastics and composite materials with reinforcing structures from hybrid fibers. Development of the works along this line is determined by possibility of preparation of new generation of materials with a wide spectrum of properties. Along with it, a diversity of the requirements, imposed to structural materials, tended to the fact that none of newly elaborated materials can occupy the dominant place at current stage of technology development, at least, in the immediate future. Each type of materials may be optimal in certain specific cases, as shown in presented work. A wide spectrum of needed materials, apart from considered here, may be prepared by the use of a number of reinforcing fibers with various elastic and strength characteristics and combined



with carbides and oxides of the binders, as well as of reinforcing schemes which permit a purposeful control of strength, rigidity and other properties of materials.

In parallel with it, it should be noted that at present the data for physical-mechanical properties of basalt plastics and composites on the basis of hybrid fibers as well as for variation of these properties in expected operating conditions are extremely limited, which retards their use as structural materials.

We hope that the engineers of various specialties may find in this work the practical recommendations on the approach of estimation of serviceability of materials in operating media, generally, as well as the data on calculated resistances of basalt plastics and composites on the basis of hybrid reinforcing fibers, in particular.

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