STRENGTH OF OPTICAL GLASS UNDER CONDITIONS OF AXIAL COMPRESSION

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Glass and pyrocerams can be effectively used in structures operating under high external pressure, as well as in other products of new technology subjected to compression. In some cases it is indispensable to use transparent materials with good optical properties, but so far only insufficient data are available on the structural strength of optical glass and pyrocerams under compression [1-4], and this limits the possibilities of designing highly stressed structural elements.

The object of the present work was to investigate the structural strength of different kinds of optical glass under axial compression, with a view to the effect of the chemical composition, the shape of the cross section, and the conditions of support of the specimens, as well as the length of their storage after their production.

We studied optical glass types LK5, K8, TK3, TK114 belonging to the group of crown glasses (containing lead oxide PbO < 3%), and F1, F101, TF101, TF10 belonging to the group of flint glasses (containing lead oxide PbO > 3%). Information on the chemical composition, specific weight, and some optical properties of the investigated types of glass is presented in Table 1.

Light crown glass (glass LK5) belongs to the five-component system $R_2O-B_2O_3-Al_2O_3-SiO_2-F$. Crown glass K8 belongs to the system $K_2O-Na_2O-B_2O_3-SiO_2$ containing a small amount (10-12%) of oxides of bivalent metals PbO, BaO, ZnO, CaO, MgO. Heavy crown glass (TK3, TK114) is based on the ternary system $BaO-B_2O_3-SiO_2$.

The basis of the second group of glass, flint glass (F1, F101) and heavy flint glass (TF101, TF10), is the system $K_2O-PbO-SiO_2$. Flint glass contains up to 22% lead oxide, heavy flint glass 1.5-2 times more.

Some data on the characteristics of strength and elasticity of optical glass and pyrocerams from the literature are presented in Table 2 from which it can be seen that in regard to the principal mechanical characteristics (bending strength σ_b, tensile strength σ_t, modulus of elasticity E, Poisson ratio μ, and compressive strength on plane supports σ_{cc}) the optical compositions are comparable with technical glass [1].

We point out that the last characteristic is usually determined in tests of cubic, prismatic, or cylindrical specimens on smooth metal supports. As ultimate strength σ_{cc} we adopted the ratio of the maximum load at the instant of exhaustion of the load-bearing capacity to the initial cross-sectional area of the specimen.

The basic shortcomings of such a way of testing are that the specimen is not subjected to uniform uniaxial compression but is exposed to the effect of high contact stresses. The maximum level of these stresses applied to the edges of the bearing part of the specimen is a multiple of the level of the mean compressive stresses.

Tests of technical glass and pyrocerams showed that destruction in the form of spalling of the bearing edges and cracking of the specimens on account of longitudinal cracks begins long before the limit load is attained. When the load is further increased, this process is intensified and the area of the bearing sections of the specimen becomes smaller.

The results obtained in such tests are always considerably lower than in uniaxial compression, they are characterized by large scatter (variation coefficient v up to 20-30% — Table 2), and they cannot be used as objective indicators of the compressive strength of glass and similar brittle materials [1, 11].

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TABLE 1. Chemical Composition and Optical Characteristics of the Investigated Types of Glass [5]

Type of glass	Content of principal components, %					Refractive index m	Dispersion coefficient ν	Specific weight γ, g/cm³†
	SiO_2	B_2O_3	PbO	RO	R_2O			
LK	72...74	8...21	—	1...2	5...10	<1,500	67* / 0,0075	2,14
K	60...79	0...21	—	0...18	10...19	1,500...1,540	67...55	2,42
TK	34...66	4...28	—	15...46	0...9	1,555...1,665	64...50,5	3,22
F	67...74	—	17...22	—	6...7	1,600...1,640	35...39	3,51
TF	57...69	—	23...40	—	2...8	1,640...1,900	35...22	4,66

*Under the line the mean dispersion is given.
†The specific weight of pyroceram S0115M is equal to 2.48 g/cm³.

TABLE 2. Characteristics of Strength and Elasticity of Optical Glass and Pyroceram from the Literature

Material	σ_{c_c}, MPa	σ_b, MPa	σ_t, MPa	$E\cdot10^{-5}$, MPa	μ
Glass K8 [7, 8, 9]	238 (29,8)*	60 (6,7)	29 (31,5)	0,823	—
Glass LK5 [10]	1000—1200	160	—	—	0,18
Pyroceram S0115M [3, 4]	930 (22,2)	82 (14,3)	59,1 (15,6)	0,76	
Pyroceram S01 [1]	680—790	76	—	0,68—0,79	—
Pyroceram 11575 [2]	1290 (18,0)	19,2 † (25,6)	—	0,84	—
Pyroceram 7009/5 [2]	1310 (5,27)	154 † (40,4)	—	0,80	—
Pyroceram STL-1 [6]	681	104	—	0,81	0,26
Pyroceram STL-2 [6]	799	116	—	0,90	0,29
Pyroceram STL-3 [6]	652	100	—	0,82	0,28
Pyroceram STL-4 [6]	690	115	—	0,85	0,29

*In parentheses is the sample variation coefficient.
†Obtained in completely reversed bending of plates.

In the present work, the ultimate strength σ_{cc} was regarded as a nominal quantitative characteristic expressing the ability of the material to resist the effect of high contact loads. Such data may be useful in comparisons of the structural properties of various brands of glass and pyrocerams, in particular, in the evaluation of their durability in highly stressed joints of components made from heterogeneous materials in which the role of contact stresses is very important.

However, identifying ultimate strength in contact loading with the ultimate strength in uniaxial compression, as is done by authors of technical and scientific literature on the mechanical properties of glass and pyrocerams [6, 10, 12, 13], may lead to considerable errors.

The strength of the investigated kinds of glass under uniaxial compression was determined by a previously described method [11, 14]: it involves gluing the end faces of cylindrical specimens (diameter 10 mm, height 30 mm) into steel rings; it is thereby possible to increase the load-bearing capacity of the support sections by inducing triaxial compression in the local zone to such an extent that fracture sets in and proceeds in the central working part of the specimens alone, these parts being subjected to uniform uniaxial compression [1]. It was shown in [1, 2, 3, 11] that in this case the level of rupture stresses σ_c of technical and optical glass and of pyrocerams is 1.5-3 times higher than σ_{cc}, and the variation coefficient (v = 5-10%) is comparable with the variation coefficient for metallic structural materials.

The height of the microunevennesses of the working part of all tested specimens after grinding with a diamond tool satisfied the condition $R_z \leqslant 1.25$ μm. The loading rate was 20-30 MPa/sec.

The magnitude of σ_{c_c} was determined with the aid of a fixture described in [3]. In this case, the end faces of the specimens had a height of unevennesses not exceeding 0.63 μm, and under load they were in contact with supports of steel U8A which were heat-treated to a hardness HRC 56-60.

Elements of structures made of optical glass may have sharp edges made in flat grinding. Some features of this kind of diamond processing and the presence of sharp edges usually make

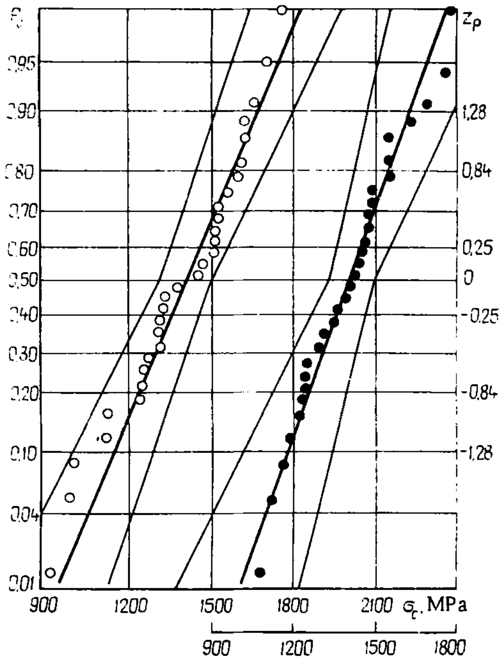

Fig. 1. Empirical distribution functions of the ultimate strengths in axial compression σ_c with confidence intervals at the confidence level α = 95% of optical glass TK114 (light dots) and KF (dark dots). (P_j are accumulations of purity; z_p is the quantile of normalized normal distribution.)

the compressive strength of prismatic specimens of technical glass by 5-10% lower than the strength of cylindrical specimens [1]. To take the mentioned effect into account in evaluating the structural strength, we did not test cylindrical specimens alone but also prismatic specimens made from most of the investigated materials. The base of such a specimen had a side 10 mm long, which was one third of its height. The height of the microunevennesses was the same as on cylindrical rods.

In the course of the tests we determined the mathematical expectation $\bar{\sigma}_c$ or $\bar{\sigma}_{cc}$ and the confidence intervals for it $\bar{\sigma}_{cmin}$, $\bar{\sigma}_{cmax}$. The admissibility of normal distribution of the ultimate strengths is shown on the example of glass TK114 and glass K8 (Fig. 1). An analogous dependence was also found to apply to the other kinds of glasses, as well as to optical pyroceram S0115M in axial tension and compression [3].

To ensure the reliability of the obtained results, in determining the ultimate strength σ_c we tested 30 specimens, and for σ_{cc} 20-25 specimens. The sample in loading prismatic rods, and also of specimens of the second batch, was one-half to two-thirds smaller.

Most of the cylindrical specimens (first batch) were made and tested at the Institute of the Strength of Materials, Academy of Sciences of the UkrSSR. The rest of the specimens (second batch) were made under industrial conditions. Between production and the tests more than three years elapsed. The object of testing these batches of specimens was to evaluate the stability of the mechanical properties of optical materials in lengthy storage, and also to determine the effect of traits of the production technology under laboratory and industrial conditions on the experimental data.

The results of the investigations are presented in Tables 3-5 which also contain the upper and lower confidence limits at a confidence level α = 95%.

It was established that the strength of optical glass in uniaxial compression is one-third to one-half lower than the strength of high-strength technical glass, e.g., glass 13v (σ_c = 2200 MPa [1]). Moreover, the test results are characterized by lower stability. The sample variation coefficient in the investigation of samples containing 30 specimens of optical glass attains 10-15%, which is 50-100% more than with glass 13v or pyroceram STL-10. This requires higher safety factors for strength in the design of highly stressed products of the materials in question.

TABLE 3. Strength of Optical Glass under Axial Compression

Brand of glass	σ_c, MPa	$\sigma_{c\,min}$, MPa	$\sigma_{c\,max}$, MPa	v_c, %	Size of sample of specimens n	$\frac{\sigma_c}{\gamma}\cdot 10^{-3}$, m	Ratio of ultimate strengths of second and first batches of specimens
LK5							
First batch	1210	1180	1240	6,8	30	56,6	1,1
Second batch	1330	1270	1390	7,0	11	62,2	
K8							
First batch	1395	1330	1460	12,2	30	54,9	0,95
Second batch	1330	1250	1410	8,6	11	51,6	
TK114	1410	1335	1485	14,2	30	43,7	—
F101							
First batch	1180	1140	1215	8,7	30	33,6	0,90
Second batch	1050	990	1110	9,0	12	29,9	
F1	850	—	—	—	10	24,2	—
TF101	1155	1100	1215	13,3	30	24,8	—
TF10	1000	960	1035	10,1	30	21,5	—
Pyroceram SO115M							
First batch	2005 [3]	1950	2060	13,7	99	80,8	1,0
Second batch	2020	1845	2190	17,2	10	81,3	

TABLE 4. Strength in Uniaxial Compression σ_{c_u} of Prismatic Specimens of Technical Glass

Material	σ_{c_u}, MPa	$\sigma_{c_{u\,min}}$, MPa	$\sigma_{c_{u\,max}}$, MPa	v_u, %	n, pcs.	$\frac{\sigma_{c_u}}{\sigma_c}$	$\frac{v_u}{v_c}$
Glass LK5	1660	1415	1905	20,1	10	1,35	2 96
Glass K8	1070	980	1160	13,4	12	0,78	1,10
Glass TK3	1210	1040	1380	22,9	13	—	—
Glass F1	860	750	970	17,5	10	1,01	—
Glass F101	1430	1335	1525	9,1	10	1,20	2,02
Pyroceram SO115M	1620	1475	1765	10,6	10	0,81	0,78

TABLE 5. Contact Strength σ_{c_c} in Axial Compression of Optical Glass by Plane Metallic Supports

Characteristic	Optical pyroceram SO115M [2]	Glass TK114	Glass K8	Glass F101	Glass TF10
σ_{c_c}, MPa	930*	565	545	355	320
$\sigma_{c_{c\,min}}$, MPa	820	505	530	340	254
$\sigma_{c_{c\,max}}$, MPa	1040	625	560	370	386
v_c, %	22,3	22,0	35,4	48,8	50
n, pcs.	20	20	20	23	26
σ_{c_c}/σ_c	0,46	0,4	0,39	0,3	0,32
v_c/v_{σ_c}	1,6	1,6	3,0	5,6	5

*Obtained on cubic specimens with edges 8 mm long.

The results of the investigation (Table 3) showed that the ultimate strength of optical glass depends on its chemical composition. Regardless of the chemical composition, better characteristics (from 1200 to 1400 MPa) correspond to the crown glasses TK114, K8, LK5. The experimental data (Tables 2 and 3) and the literature data [10] on the strength of glass LK5 practically coincided. The lowest strength (from 800 to 1000 MPa) is found in the lead-containing compositions F1, TF10. The strength of the investigated types of glass depends on the specific weight of the material. When it is necessary to ensure minimum weight of a structure, an important characteristic of the material is its specific strength, described by the ratio σ_c/γ. This parameter is equal to $115\cdot 10^3$ m for pyroceram STL-10 and $88\cdot 10^3$ m for glass 13v. For optical glass this parameter lies within the limits $(21.5\text{–}56.6)\cdot 10^3$ m (Table 3), and it is functionally correlated with the specific weight by the dependence shown in Fig. 2.

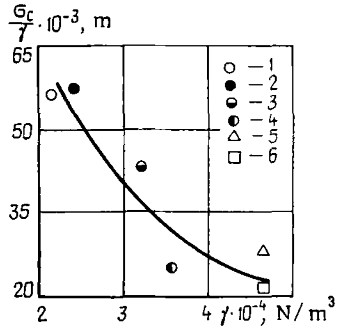

Fig. 2

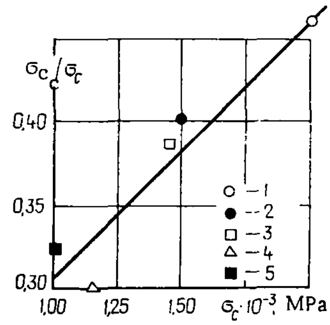

Fig. 3

Fig. 2. Dependence of specific strength σ_c in axial compression on the specific weight γ for optical glasses LK5 (1), K8 (2), TK114 (3), F1 (4), TF101 (5), and TF10 (6).

Fig. 3. Dependence of the ratio of the mean level of rupture stresses σ_{c_c} in loading by smooth metallic supports to ultimate strength σ_c on ultimate strength σ_c for optical pyroceram S0115M (1), glass TK114 (2), K8 (3), F101 (4), and TF10 (5).

When we compare the characteristics of strength of optical glass and pyroceram S0115M (Table 3), we have to note that the strength of the latter is 1.5 times as high as the strength of crown glasses, and in specific strength pyroceram S0115M is comparable to glass 13v ($\sigma_c/\gamma = 81\cdot 10^3$ m).

According to the data of Table 4, the strength in uniaxial compression of prismatic specimens on an average for all tested materials is comparable with the strength of cylindrical specimens. However, with equal size of the tested batches (10-15 specimens) the scatter of the experimental data on prismatic rods is 1.25 to 1.35 times greater than on cylindrical specimens. This is apparently due to features of machining, possibly to methodological deviations and to the shape itself of the specimens as a structural factor.

In view of the above, and also in view of the fact that for some glasses the test results obtained with prismatic specimens deviate considerably from the results obtained with cylindrical specimens, not only in small batches but also with more representative samples, it is best in evaluating the compressive strength of glass and pyroceram to test cylindrical specimens with equal height of the microunevennesses of the lateral surfaces [2].

The possibility of improving the reliability of determining the strength of materials of the given class in uniaxial compression on cylindrical specimens was noted in tests of samples of different size of glasses F101, K8, LK5, and pyroceram S0115M. With a confidence level $\alpha = 95\%$, the confidence limits for σ_c of the first and second batches practically overlap, and the largest difference in values of σ_c does not exceed 10%.

Consequently, possible deviations in the technological regimes of machining cylindrical specimens under laboratory and industrial conditions to the same height of microunevennesses, and even lengthy storage (more than three years) of specimens under normal conditions, do not have a noticeable effect on ultimate strength in uniaxial compression of glass and pyroceram.

The chemical composition has a noticeable effect, too, on the contact strength of optical glass in compression of specimens by plane supports (Table 5). On the whole we find the same relations as those noted in the study of strength in uniaxial compression. Higher values of σ_{c_c} are found in crown glass TK114 and K8. Thus, materials with high strength in uniaxial compression are also characterized by higher contact strength; this is also confirmed by the data on pyroceram S0115M (Table 5).

It is important that, whereas in technical glass and pyrocerams ultimate strength in contact compression by plane supports σ_{c_c} amounts to approximately 50-65% of the value of σ_c, in glass K8 and TK114 it does not exceed 40% of this value, and in low-strength flint glasses it goes down to 30% of σ_c. Yet for optical glass and pyroceram the ratio σ_{c_c}/σ_c is correlated by a functional dependence with ultimate strength in axial compression which may, in the first approximation, be approximated by a straight line (Fig. 3).

It should be pointed out that in optical glass the relatively low level of contact strength is combined with a considerable variation coefficient: from 22 to 50%. This shows that the problem of devising high-strength joints of components that are reliable in compression, when the components are made of optical glasses and heterogeneous materials, is more complex than in elements of shells made of technical glass.

CONCLUSIONS

1. The strength of optical glass in uniaxial compression is one-third to one-half lower than the strength of high-strength technical glass, e.g., glass 13v, the sample variation coefficient is 50 to 100% larger, and therefore a higher safety factor is required in designing highly stressed components made of the given materials.

2. The strength of optical glass under axial compression, and also under loading of specimens by smooth metallic supports, depends to a considerable extent on the chemical composition, and in glasses containing lead oxide PbO_2 it attains minimum values (800-1000 MPa).

3. The strength of prismatic specimens of optical glass and of pyroceram does not differ by more than 10% from the strength of cylindrical specimens, whereas the scatter of experimental data for the former is 1.25 to 1.35 times higher than for the latter.

4. The ratio of the mean level of rupture stresses in compression of optical glass by smooth metallic supports to their ultimate strength is correlated by a functional dependence with the ultimate strength in axial compression which in the first approximation may be approximated by a straight line.

5. Strength in axial compression, and also the upper and lower confidence limits with a confidence level $\alpha = 95\%$, are not substantially affected by peculiarities of the production technology of cylindrical specimens under laboratory and industrial conditions as to the equal height of microunevennesses or by storage of specimens after production under normal conditions for three years or more.

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