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Factors Affecting the Strength of the Glass (Review)

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Abstract: The article provides a brief description of types of glass strength and explained the causes of significant discrepancies between the theoretical and the real strength. Presented elements of the mechanism of breakage. Discussed in detail the factors which affect the strength of the glass: the surface defects (cracks), edge defects, uniformity of the chemical composition, the duration of the loading, characteristics of glass manufacturing techniques, including annealing, environmental parameters, the geometry of the sample. For each factor the experimental data are shown to estimate the level of impact on strength. It is noted that to reach the level of the theoretical strength is possible with appropriate adjustments glass manufacturing technology and application of methods of strengthening.

Key words: Glass · Strength · Fragility · Defects · Cracks · Uniformity · The environment · Technology

INTRODUCTION

The strength and hardness of the glass is its most important characteristics, which, combined with transparency and chemical resistance cause the broad application of glass products. However, fragility and sometimes insufficient strength of the initial (raw) glass restrict its use, for example, in construction.

Modern high-rise residential and commercial buildings, sports complexes, military and space technology, all types of transport and even life require glasses with high strength. Especially because glass by nature and the structure is a high strength material. The theoretical strength of glass is at a level of 25-30 GPa. [1] However, different conditions of its production, cutting, storage, transportation, environmental effects reduce the natural strength of the glass in the tens or hundreds of times. Therefore, to minimize the factors that reduce the natural strength and development of methods of strengthening of the glass according to areas of application are important tasks of glassmaking. It is base of intensive development of innovative technologies of strengthening for large-tonnage glass (architectural, transportation, bottled) and technical glass [2, 3].

Types of Glass Strength: The strength of glass is characterized by the ability to resist fracture when exposed to external loads. Measure of strength is the limit of strength - the maximum stress, causing the destruction of material under static load. Depending on the type of load acting distinguish the limits of strength in tension, compression, bending, impact, torsion, etc.

Glass behaves differently in different types of distortion. When compressing the glass has a high real strength ($[sigma]_{compr.}$= 0,5-2,5 GPa), bending lower ($[sigma]_{bend.}$ = 0,03-0,12 Gpa), to impact even lower. The tensile strength in the range of bending strength. It should be noted when it comes to the strength of glass without the designation of the means that the lowest values, i.e. $[Sigma]_{bend}$.

Strength of glass in real constructions, i.e. in abrasion dust wiping effect of the atmosphere, the mechanical and thermal stresses are significantly lower strength of the original glass. Therefore, at using glass in the constructions is introduced term 'structural strength' ($[sigma]_{constr.}$), Which is calculated by the formula:

$$\sigma_{constr.} = K_1 \bullet K_2 \bullet K_3 \bullet \sigma_{techn.},$$

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where K_1 - the degree of surface defects (K_1 ~ 0.25), K_2 - the scale factor (K_2 ~ 0.15), K_3 - the duration of the load (K_3 ~ 0,33); $[sigma]_{techn.}$ - average technical strength of the glass. K_2 should be calculated for each case, as it depends on the thickness and geometry of the glass [4].

Technical strength characterizes the strength of the real products obtained in testing and statistical analysis of the results.

The theoretical strength of glass ($[sigma]_{theor.}$) is a calculated value for the perfect (defect-free, homogeneous) material under quasi-static loading at ordinary temperatures and is determined by the nature and strength of chemical bonds in the glass.

Direct calculations of the theoretical strength are very difficult due to the disordered structure of glass, so it is estimated by indirect methods. For example, according to the Orowan equation $[sigma]_{theor.} \approx (0,1 \div 0,2)$ E for silicate glass with a modulus of elasticity (E) equal to the value of 68 GPa $[sigma]_{theor.}$ is 6,8-13,6 Gpa.

Approximate values of the theoretical strength calculated by various authors (A. Griffiths, E. Kordon, Naray-Szabo, Ladik, N.M. Bobkov, Orowan, V.F. Solinov, etc.), for silicate glasses are in the range of 7-25 GPa [1, 5-7].

A comparison of theoretical and actual technical strength of the glass shows how they differ from each other by 2-3 orders of magnitude. The reason for discrepancies, as first suggested by A.A. Griffiths (1921), are superficial and internal cracks in the sample. Accordingly, when the stress at the crack tip reaches the theoretical strength, crack dramatically lengthened and the sample is destroyed.

The average value of the critical stress ($[sigma]_{cr.}$) In the sample window in which it occurs gap defined by [5, 7]:

$$\sigma_{cr.} = \sqrt{\frac{2\gamma E}{\pi l}} = const \cdot l^{-0,5} \quad (1)$$

where l - length of the crack, m (for glass length of the crack ~ 1...10 micron), [gamma] - surface energy J/m^2.

Equation (1) indicates a predominant influence on the strength of the material surface defect size.

For real glasses and characterized by a certain chemical micro-heterogeneity with the size of the order of 1-10 nm assuming that the size of the defect is commensurate with the areas micro-heterogeneity, the limit of strength ($[sigma]_{lim.}$) on Griffith's theory would be:

$$s_{lim.} \approx \sqrt{7,2E}$$

Given the most probable value of the strength of glass ($[sigma]_{techn.}$), which is determined according to the statistics, the relative deficiency (D) of the glass is determined by the relationship [8]:

$$D = \left(s_{lim.} / s_{techn.} \right)^2$$

Practically proved that the strength of the glass depends on the technology, micro-heterogeneity and surface defects. Possible glass strength obtained with the prevention of surface damage is 1.0-1.7 GPa, i.e. close to the theoretical strength. Maximum strength in these samples up to 5.3 GPa [8].

Thus, the strength of the glass is determined by the strength of the chemical bonds and imperfection. Therefore, for the reliable determination of the strength of the number of tests should be 10...100 with a mandatory statistical analysis of the results.

Elements of the Mechanism of Breakage: The destruction of the glass is a complex process, the development of which depends on the structure, parameters of defects, the nature of the stress state, the loading rate, temperature and composition of the environment, etc. [9].

Deformation and fracture of glass are the result of the elementary phenomena that occur at the atomic and molecular levels of the structure. Development process of deformation and fracture occurs in dependence on the ability to accumulate deformation energy volume and distribution of the sample volume and dissipation of energy [8].

According to the cluster approach, the glass can be viewed as a medium containing rigid and relatively weak bonds (Fig. 1).

If such a medium load, the load is distributed to all bonds. Over time, the first to lose their stiffness weak bonds and the entire load will accept hard. This redistribution of the load is equivalent to reducing the cross section of the loaded sample. Finally the rise of the load on hard bonds can surpass their strength, resulting in cracking and brittle fracture [2, 9, 10].

The accumulation of bond cleavages in the most stressed areas is under the influence of thermal fluctuations [9], which is attached to the weaker sections of the structure, give rise to embryos micro cracks [2, 10].

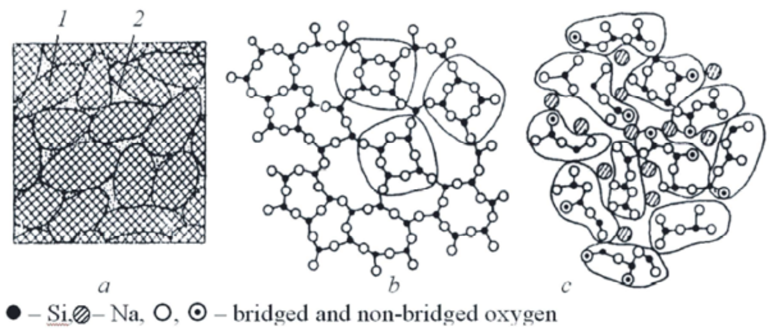

Fig. 1: Glass structure [2]: a - a general scheme (1 - complex with strong structural bonds, 2 - with a weakened area of the structure); b, c - structural complexes quartz glass and sodium silicate, respectively (circled complexes with strong bonds)

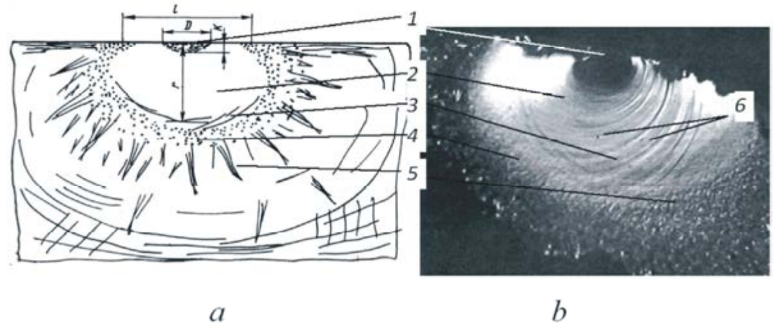

Fig. 2: Scheme (a) and a picture (b) the fracture glass [13, 15]
1 - focus on fracture (D and K - length and depth of the surface defect), 2 – mirror zone (l and r - the length and the depth of the mirror area), 3 - undulating zone 4 - mat zone, 5 - rough area, 6 - defects (inclusions)

With increasing load the crack length remains unchanged, until a value [sigma]$_{cr.}$, then begins the process of its development. In this predominantly develops only the longest crack with the highest tensile stresses at the top. Subsequently, it goes into a rapid development of unsustainable growth.

With the development of cracks of the energy converted into elastic deformation, formation new surface, heating, acoustic [10] and electromagnetic radiation and also in the micro plastic deformation of [2, 8, 10-13]. These scattering effects lead to the fact that the stress at the crack tip can be 1.5-3 times larger than the macroscopic yield strength [5, 14]!

Considering the kinetics of breakage, can be divided into two successive stages: growth of micro cracks with acceleration and any one crack growth with a constant high speed until complete destruction. Moreover, more than 90% of the whole process is the first step [9, 13]. Accordingly, to improve the impact strength is necessary in the first step.

Stages of development of cracks are easily found on the fracture (Fig. 2), the first stage corresponds to the mirror area, the second - rough.

In general, the elucidation of the mechanism of fracture and strength assessment associated with considerable difficulties due to the amorphous structure of the glass. In addition, the process of destruction must be considered at all levels of the organization of matter (atomic and molecular structure, micro-cracks and microtension, macro-cracks and macrostresses, the product as a whole).

Defectiveness of the Surface: Strength of glass depends largely on the state of its surface. Micro-scratches, cracks, inclusions act as stress concentrators under load, which contributes to the destruction.

In most cases, cracks are formed on the forming and annealing of glass. Thus, when glass is forming, a thin surface layer of glass quickly solidifies, while the volume remains in the plastic state. Under its own weight or under the influence of forming machines and due to different thermal expansion of the glass in the volume and on the surface, this surface layer get micro-cracks [8].

The dependence of the strength of the glass on the size of the defect, according to the formula Griffiths, presented in Fig. 3

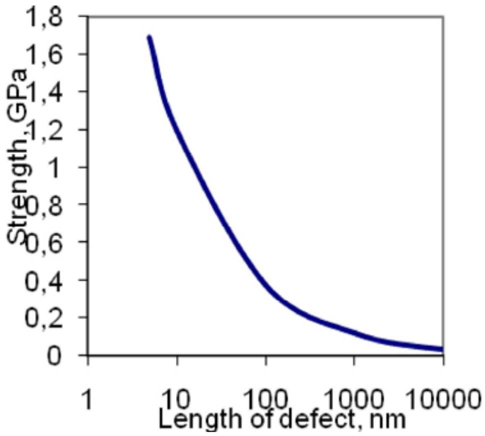

Fig. 3: The dependence of the strength of glass of the defect size

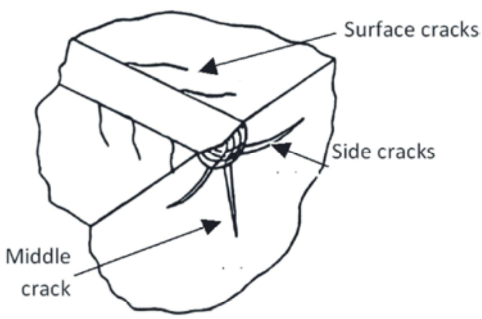

Fig. 4: Scheme formation of cracks in a glass cutter wheel [19]

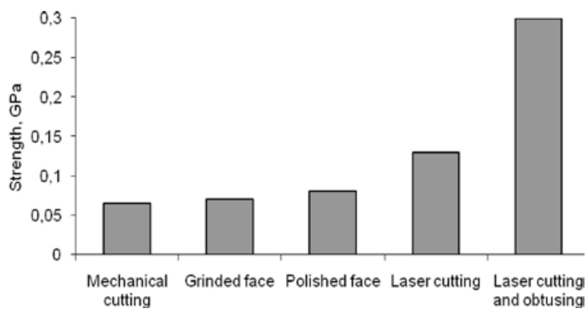

Fig. 5: The strength of glass with different methods of edging [22, 23]

Table 1: Influence of surface conditions on the strength of glass [18]

The surface condition	Strength, GPa
Untouched, melted	0,9-1,0
After forming	0,22-0,28
Polished fine abrasive	0,13-0,14
Polished largest abrasive	0,035-0,041

Detect cracks at the nanoscale by using an electron microscope in the preliminary ones in the vapor of hydrofluoric acid [9], as well as optical and ultrasonic methods [16, 17].

Exemplary values of the tensile strength of glass of normal composition depending on the surface conditions shown in Table. 1.

The quality of the glass edges defined by the quality of the cut, has a significant influence on the strength of the glass and is of paramount importance in reducing the marriage and improve the reliability of products [19]. According [19, 20-23] cut reduces the mechanical strength of the glass by an average of 60%, due to the formation of microcracks in different directions (Fig. 4).

Mechanical grinding followed by polishing the edges increase the strength by 30%, laser cutting - is 2.5-3 times and additional laser blunting the sharp edges - 6 times (Fig. 5).

S.I. Silvestrovich [8] established the existence of a destructive surface layer on each and every investigated glass rods, which were obtained by different methods and with different subsequent heat treatment. Destructive layer on glass surface is a network of microcracks. Destructive layer depend from speed of formation and have depth 10-60 microns.

Methods of statistical analysis showed that defects decreases on surface of the glass container with decreasing temperature gradient between the molten glass (drop) and temperature of formation [25].

High strength glass fibers (3-5 GPa) is due to a high rate of cooling, which eliminates the surface crystallization, the formation of micro-cracks and irregularities [2, 26].

The Influence of the Glass Composition: Identification of patterns "glass composition - strength" difficult strongly influenced by surface defects. Therefore, to evaluate these patterns using micro-hardness, which, like the theoretical strength, determined by the modulus of elasticity and the interatomic forces, but is almost independent of the surface defects [5].

Microhardness of alkali-silicate glasses decreases with the increase in the proportion of their alkali metal oxides (Fig. 6), due to the destruction of the silicon-oxygen net and the advent of more weak bonds R-O.

These patterns are consistent with the binding energy: for Li-O, Na-O and K-O are equal to 151, 84 and 54 kJ / mol, respectively [27].

When added to the glass composition $Na_2O \bullet 5SiO_2$ divalent oxides, the highest microhardness values in a series of BeO - CaO - MgO - SrO - ZnO - CdO - BaO - PbO characteristic of BeO, the smallest - PbO. Al_2O_3 increases the microhardness of sodium silicate glasses, if the composition promotes the formation of tetrahedral AlO_4, increase the proportion of net bonds [5].

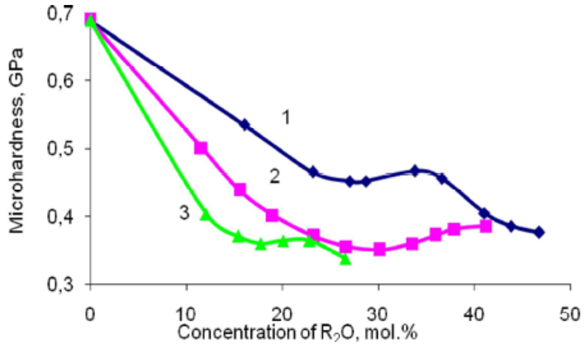

Fig. 6: According to type micro hardness of alkali-silicate glasses of composition [5]: 1 - $R_2O = Li_2O$, 2 - $R_2O = Na_2O$, 3 - $R_2O = K_2O$

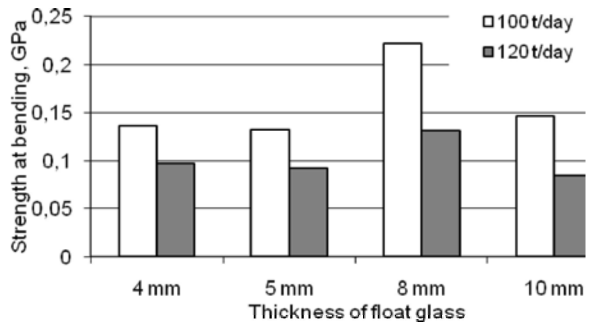

Fig. 7: The dependence of the strength of the upper surface of the glass on the performance of float line for different thicknesses [31]

Table 2: The values of mechanical strength for any side of the float glass [29]

	The strength of glass, GPa		
The glass surface	Minimum	Medium	Maximum
Top	0,098	0,224	0,343
Lower	0,039	0,107	0,257

Microhardness of glasses in the system R_2O-B_2O_3-SiO_2 have a maximum, which is due to the formation of the most linked glass network due to the introduction into it BO_4-tetrahedra [5].

In general, an increase in the glass composition of glass-forming oxides improves strength.

The Influence of Technological Factors: Defectiveness of the surface and, consequently, the strength, determined by the parameters of the process: the speed of formation, geometry of products, performance glass furnace, temperature condition during forming, annealing conditions, etc. So for the method of vertical drawing sheet glass strength increases by about 1.6 times an increase in the rate of withdrawal, reducing the thickness of the tape and the molding temperature [28].

Contact glass with other fluids and materials (molten tin and the protective atmosphere in the float bath, the metal molds and lubricant in the manufacture of hollow products, the material conveying rolls) affects the strength of the finished glass. For example, the strength of the upper surface of the float glass, in contact with a protective atmosphere, at about 1.1-2.7 times greater than the bottom, in contact with the molten tin (Table 2).

This is due to mechanical damage from contact the lower surface of the glass with conveyer rollers [30, 31], large compressive stress on the upper surface [32], loosening the lower surface of the introduction into it of tin [30]. Accordingly, in the construction of float glass must be positioned so that the upper surface of the tensile load perceived [20, 30, 33, 34].

It should be noted that the strength of the float glass is the non-uniform distributed across the width [31] and increase in productivity of the line reduces the homogeneity and strength of the finished glass window (Fig. 7).

When blowing or pressing of glass products, contact with the cold form leads to the formation of high surface defect due to abrupt solidification of a thin surface layer. With increasing temperature of the mold surface defects is reduced and the strength of the glass increases. But, forming a superheated forms greatly reduces the strength of products due to violations of further annealing process [2, 25].

It is known that approximately 40% of construction glass is lost during shipping, storage and installation, this is due not only to the mechanical damage to the surface, but the corrosion processes [29]. Thus, glass dust, which is formed by cutting a float-glass, is often caused by corrosion (in contact with moisture) and scratching.

In general, due to optimization of process conditions in the production of glass strength can be increased by 70% and more, as well as significantly reduce the loss of glass.

Homogeneity: Heterogeneity window formed in the glassmaking because about 30% of grain quartz did not react with the components of the batch, then slowly dissolve in the primary melt, forming SiO_2-rich areas. In this case, clearly observed correlation uniformity and yield of products of industrial production (Fig. 8).

In addition to these species are not homogeneous, substantially reduce the strength of glasses and larger inclusions crystals (Si diameter of 200-300 microns [14], NiS [14, 35], chromite, iron [36]), schlieren, striae, bubbles [37] microinclusions tin in the float glass, lamination

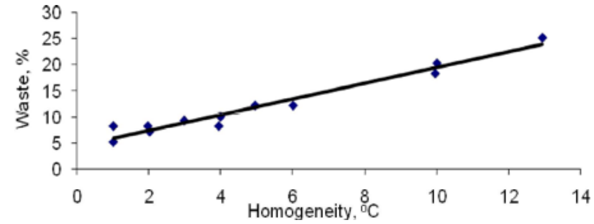

Fig. 8: Dependence of marriage of medicine glass vs homogeneity (authors data)

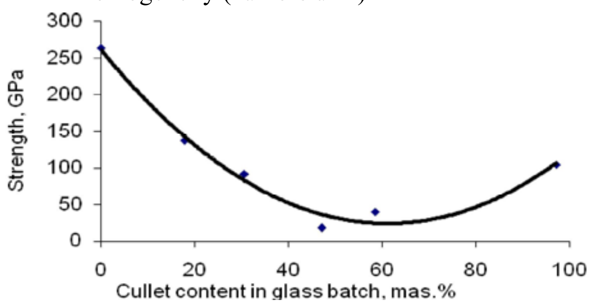

Fig. 9: The dependence of the strength of the content of cullet in the batch [40]

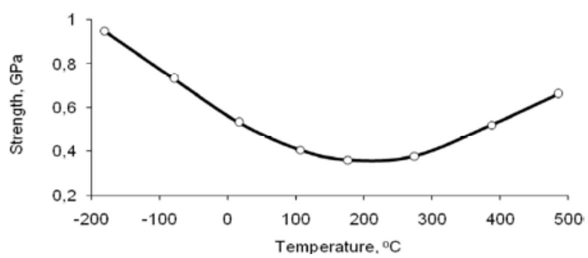

Fig. 10: The dependence of the strength of the glass temperature [18]

[38, 39]. Around inclusions during cooling of products develops stress that when the tensile strength leads to cracking and even breakage. Sometimes these types of defects in glass lead to sudden self-destruction.

The increase in the proportion of reverse cullet in the batch up to 50% reduces the uniformity and strength of glass by 10-15% and a further increase in property partially restored (Fig. 9).

The homogeneity of the glass depends on the redox potential of glass. Thus, oscillation of the ratio Fe^{2+} / Fe^{3+} lead to including of the bottom layers of glass in working flow, which reduces the uniformity and strength of glass [41].

The homogeneity of the glass is highly dependent on the quality (homogeneity) of the batch, conditions of melting and making of product [28]. By choosing the optimum conditions in the manufacturing cycle, you can eliminate nonuniformity and to increase the strength of the approximately two times.

Annealing: After generation of products of any shape, including flat glass, in which the internal stresses are generated, which reduce the strength and sometimes leads to self-destruction. Thus, with increasing residual stress in 2 times, strength of the glass reduced by 9-12% [18]. Therefore, for removal (relaxation) of the internal stresses products must be heat treated to special temperature regime, which is calculated as a function of the glass composition, residual stresses and shape of the product [7, 42].

Influence of the Environment: The influence of the environment on the strength of the glass depends on the properties of the medium itself, the time of contact with the environment, temperature and duration of the stress and its magnitude. In terms of natural contamination of the glass surface there is a very significant loss of strength (by 25-60%) in the initial period (30-60 days) [8]. Particularly great effect of the dust particles on the airplane, ships, as well as glass of windows at tall buildings. Wind bombardment of small particles of dirt, salt, sand creates microscopic craters, which retain moisture, causing corrosion of the glass and the weakening [43].

A significant loss of strength is observed at high humidity, which is facilitated by the development of existing and creation of new microcracks. Thus, if the strength of the glass to air is - 0.053 GPa, the strength of this glass in water - 0.043 GPa [18].

Reduction in the strength of glass under the influence of moisture is due to the adsorption of water (Rebinder effect) and the corrosion processes [9]. In an environment of dry air, vacuum oil, toluene glass strength is not reduced.

Effect of Temperature: Effect of temperature on the strength of glass is complicated by the action of moisture in the ambient atmosphere and adsorbed on the glass surface. According to modern views, the outer layer of silicate glass is a gel and the moisture is absorbed into the capillaries of the gel layer. As the temperature increases the number of desorbed moisture, but also increases the corrodible of a wet environment due to chemical interaction (Fig. 10).

After heating to 100°C glass strength decreases by 25%, while the 10-hour exposure at 520°C decreases the strength of 35%. Cause weakening in the latter case is to form irregularities on the surface, but removal of this glass surface layer is partially reduced strength [8, 9].

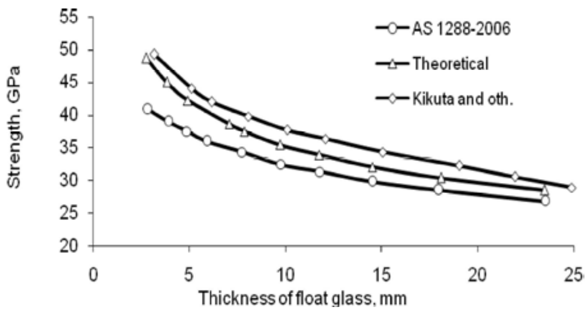

Fig. 11: The dependence of the strength of the glass on the thickness [46]

Table 3: The dependence of the strength on the loading time of polished glass [18]

The duration of loading	Flexural strength, GPa
1s	0,072
40 min	0,047
2 h	0,042
40 h	0,033

Static Fatigue of Glass: The duration of the load from the start of loading has a significant effect on strength. When longer load glass has less strength than transient (Table 3) due to the finite speed of crack growth [18, 44].

Found that if the glass rods are not destroyed by operating stress for a month, then it is able to withstand these stresses for a long time (years). Cyclic loading weaken the glass similar to the static [18].

With the phenomenon of static fatigue associated spontaneous destruction is not properly annealed and not properly quenched glass [45].

Influence of the Size of the Samples: Influence of the glass samples strength (scale factor) is manifested mainly in the thickness, which is especially seen in the float glass (Fig. 11).

Typically, increasing the sample size increased the probability of finding a sample defect dangerous therefore reduced strength.

CONCLUSION

Thus, the glass in nature is high strength material. However, the lack of the production technology and operating conditions reduce the strength characteristics. The value of the factors affecting the strength of the glass, first, allows a priori estimate its strength in operation, secondly, to determine the need for strengthening glass, thirdly, to carry out a rational choice of the method of hardening.

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