EFFECT OF POROSITY ON THE STRENGTH OF A GLASS LAMINATE

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The results of a microstructural analysis of glass laminates based on various resins are presented; the pore-size distribution is shown to depend on the total porosity. The effect of porosity on the static bending strength of glass laminate specimens in the starting state, after boiling in water, and after drying is established. The effect of the testing procedure on the strength-porosity dependence is considered.

Voids and other structural defects in solids weaken the cross section and lead to local stress concentrations and reduced performance. In actual glass-reinforced plastics with a developed system of pores and cracks the presence of even a single defect of the critical size will control the fracture of the specimen at a given stress.

We still lack a consistent theory relating the mechanical constants of glass-reinforced plastics with the number, shape, and distribution of the defects and, in particular, the porosity. Nonetheless, there is an obvious need for a thorough experimental and theoretical investigation of this problem with a view to developing engineering methods of calculating the strength of glass-reinforced plastic products with allowance for their actual structure.

Certain data relating to the experimental verification of the structure sensitivity of the mechanical properties of glass-reinforced plastics have been published; however, the quantitative effect of the pores has not yet received sufficient attention. Thus, in (1) it was established that a low level of porosity has a considerable effect on the strength of a unidirectional glass-reinforced plastic. Especially dangerous are pores 20–50 μm in size (d is the fiber diameter). Such pores result in a considerable reduction in shear and bond strength (by as much as 100%). According to (2), to obtain a glass laminate (textolite) with a tensile strength of 52 kgf/mm², the size of the defects in a direction perpendicular to the load should not exceed 150–170 μ; otherwise they will act as stress raisers. In (3) it was shown that depending on the porosity the strength of a glass laminate may vary between 51 and 19 kgf/mm².

However, certain authors arrive at other conclusions. Thus, Corten considers that the pores have only a slight effect on the strength of composite structures, but in (4) he gives the following expression for the tensile strength: \( \sigma = \sigma_s [1 - (V/V_0)^{1/3}] \), where \( \sigma_s \) is the strength of the glass laminate without the voids; \( V_0 \) is the volume of the voids; and \( V \) is the total volume of the specimen. This relation is in good agreement with the experiment data, but it does not take into account the effect of the pores as stress raisers.

On the other hand, citing McGarry’s research (5), Corten arrives at the conclusion that "from the standpoint of the mechanical properties of the investigated plastics, the voids are not critical defects."

In our opinion, these contradictory data can be attributed to the fact that glass-reinforced plastic specimens of different porosity are usually obtained by broadly varying the molding pressure. Thus, in (6) the pressure was varied from 0.07 to 3.5 kgf/cm². A reduction in pressure leads to an increase in porosity and, at the same time, to a decrease in the volume glass content of the material. Both these factors tend to reduce the strength of the plastic. In a number of cases, although it reduces the porosity, an increase in pressure leads to a resin deficiency, which weakens the bond between the glass fibers and the polymer matrix.

* Polyester glass laminate with porosities varying from 0.38 to 3.82%.

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In our case the experimental glass-laminate panels were made by impregnation under pressure in a rigid mold, which made it possible to keep the thickness of the panel within tolerances of ±0.1 mm. As the parameter determining the possibility of comparing the mechanical properties we selected equality of the volume glass contents of the specimens. This was achieved by laying up the same number of layers of glass fabric. The volume glass content of the specimens was 52% and was not allowed to fluctuate by more than ±1.5%. In practice, the reinforcing ratio (the ratio of the cross-sectional area of the reinforcing fibers to the cross-sectional area of the glass-reinforced plastic) may be assumed constant. In this case an increase in porosity leads only to a decrease in the volume resin fraction, i.e., whereas for a two-component glass-reinforced plastic the volume \( V \) is equal to \( V = V_g + V_{ir} \) (where \( V_g \) and \( V_{ir} \) are the volumes of glass and resin in the plastic), for a three-component system the volume \( V = V_g + V_{ir} + V_v \) (where \( V_v \) is the volume of voids, and \( V_{ir} < V_{ir} \), \( V_{ir} = V_{ir} - V_v \)).

Thus, any local increase in porosity leads to a decrease in the volume resin content, the volume glass content remaining constant.

The glass-laminate panels were made from EDT-10 heat-cured liquid epoxy resin and ASTT (b)-S2-style glass fabric. The dry reinforcement was laid in the mold and the free spaces filled with resin under pressure. The curing conditions were as follows: heating and holding at 90°C for 1 h; the same at 120°C for 1 h; the same at 160°C for 2 h.

Differences in porosity were achieved by varying the impregnation process. In order to obtain panels with minimum porosity the resin and the reinforcement were degassed and impregnation was continued until the air bubbles completely disappeared from the resin at the mold outlet. Porous specimens were obtained by not removing the air completely from the resin and the reinforcement (impregnation of resin containing air inclusions, increase in impregnation rate, impregnation without changing the resin volume in the mold, etc.). In this way we were able to obtain panels whose porosity varied from 2 to 16%.

By obtaining specimens of different porosity from the same panel it is possible to eliminate the undesirable effect of certain technological factors on the porosity of specimens cut from different panels (fluctuation of the curing conditions during the molding of a batch of panels, variation of the atmospheric humidity and the moisture content of the raw materials, the use of starting materials from different batches, etc.). In order to obtain such a panel the glass reinforcement was laid in a closed rigid mold and impregnated with liquid resin under pressure. Specimens cut from area adjacent to the resin front had greater porosity, since the resin in the boundary region usually contains more air bubbles "washed out" of the reinforcement. This system of impregnation makes it possible to obtain a material whose porosity gradually increases from the edge of the panel to the line of the resin front (from 8.5 to 17.9%).

The structure of the glass laminates was analyzed under a MIM-7 optical microscope in accordance with the method described in [7, 8].

Specimens of glass laminate of variable porosity measuring 9.6 × 15 × 120 mm were subjected to static bending tests in accordance with Soviet standard GOST 4648-56 in the starting state, after boiling for 2 h in distilled water, and after drying according to the following schedule: heating to 130°C in the course of 1.5 h and holding at that temperature for 2 h. In each case not less than 60-80 specimens were tested. The results of the tests were subjected to a statistical analysis [9].

In order to estimate the effect of porosity on the bending strength we conducted tests in accordance with the procedure developed in [10]. This makes it possible to exclude the effect of shears on the stress distribution. The tests were performed on specimens measuring 9.6 × 10 × 220 mm at a distance between supports of 180 mm. For comparison the same method was used to perform parallel tests on short specimens measuring 9.6 × 10 × 60 mm at a distance between supports of 40 mm. Not less than 5 specimens were tested for each point.

Glass-reinforced plastics are usually treated as a certain heterogeneous system consisting of two principal components — the glass-fiber reinforcement and the resin matrix. However, as a result of the chemical and physical processes associated with their manufacture, all glass-reinforced plastics have a certain porosity.

Microstructural investigations have revealed [11] that specimens of glass laminates based on liquid epoxy resins that do not contain passive solvents have the lowest porosity (2-5%). Liquid polyester resins

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