PROPERTIES OF GLASS-FIBER REINFORCED POLYCARBONATES FOR CENTRIFUGAL PUMPS IMPELLERS

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ABSTRACT

A significant number of properties of composites based on polycarbonates, unfilled and filled with 10 - 30 % short glass fibers of E-glass, treated with 3-(aminopropyl) triethoxy silane, were studied. The purpose of the study is to determine whether these composites can be used to manufacture impellers for centrifugal pumps.

It was found that with increasing the amount of filler, the properties of polycarbonate composites change as follows: in general, the physico-mechanical parameters (all modules, tensile strength), stiffness and flexural strength increase, maximum deformation, as well as elastic and impact resistance decrease somewhat. The volume and surface resistivity decrease, the coefficient of thermal conductivity increases. The main reason for these changes in the properties of the composites is the good adhesion at the polymer matrix-fiber interphase which is attributed to the strong physical interaction due to silane used and as a result of the good wetting of the fibers from the polycarbonate matrix and improved compatibility. Based on the results obtained, it can be concluded that polycarbonate composites, filled with 10 - 30 % short glass fibers can be successfully used for the production of centrifugal pumps impellers, as they meet a significant number of requirements for materials with such application.

Keywords: polycarbonates, short glass fibers, reinforcing, centrifugal pumps, impellers.

INTRODUCTION

Composite materials have a combination of properties that cannot be achieved using pure metals, ceramics or polymers. The creation of polymer composites with desired specific properties allows these materials to replace in mechanical engineering a number of parts produced from more expensive and more valuable materials.

Natural thermoplastic polycarbonate (PC) and composites based on it are widely used as engineering plastics due to their high hardness, strength, heat resistance and electrical insulating properties [1]. Logically, the demand for polycarbonate worldwide is constantly growing (Fig. 1). In 2011 it was 3.6 million tons, in 2018 - 4.54 million tons, and in 2024 it is expected to reach 5.5 million tons [2].

Many studies are aimed at improving the mechanical properties of polymers (especially polyamide, polystyrene, etc.) by reinforcing them or filling them with short glass fibers [3 - 6]. The main problem associated with the filling of polycarbonates with glass fibers is caused by the fact that the untreated E-glass fibers have low adhesion to the thermoplastic matrix. However, this difficulty is easily overcome by treating the surface of E-glass fibers with 3-aminopropyltriethoxy silane as a bonding agent improving adhesion and compatibility [7 - 9] between polymer matrix and the short glass fiber.

Mustafa Gamal et al. [10] characterize polycarbonate (PC) composites filled with short glass fibers (SGF) up to 15 %. They found that as the SGF content in the composite increases, the tensile strength and Young's modulus increase also and the impact strength gradually decreased. Filling the PC with SGF over 5 % significantly

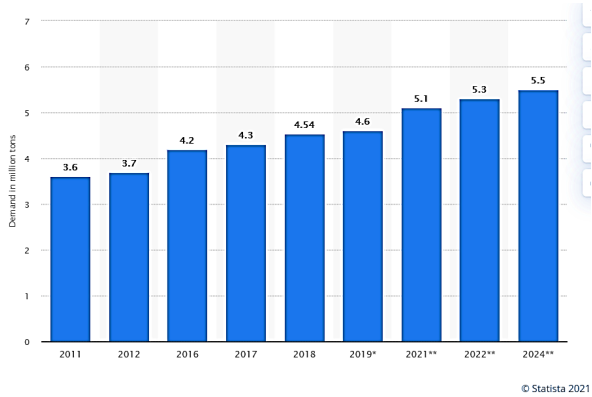


Fig. 1. Trends in the use of polycarbonates for the period 2011-2024

improves the hardness of the composite material. The authors prove that the studied composites also have better abrasion resistance. N. Dayananda Jawali et al. [11], which investigated the physicomechanical and morphological properties of polycarbonate composites filled with 10 %, 20 % and 30 % short glass fibers, also found a significant improvement in tensile behavior.

One feature of these composites that must be taken into account is the increase in the viscosity of the polymer melt with the filling. As the length of the fiberglass increases, the viscosity of the composite melt also increases. In addition, the glass-filled thermoplastic hardens faster. When it is processed by injection molding or extrusion, a certain orientation of the filler can be obtained, which leads to anisotropy in the mechanical characteristics. Therefore, the processing of such composites requires higher pressures and temperatures than those required for unfilled thermoplastics. Unfortunately, the certificates of the manufacturers of these composites provide values characterizing the material in a very wide range, which often makes it difficult to assess the applicability of the engineered polymer composite for the production of a specific product.

The aim of the work is to study the specific characteristics of composites based on polycarbonates filled with short glass fibers in order to evaluate the possibilities of their use for the production of a specific product - wheels for a centrifugal pumps (impellers). The designed materials with low water permeability under loading must withstand tensile strength level of 85 MPa with elastic deformation of 0.3 % [12].

A number of authors have conducted research in this direction, using computer methods for simulation and calculation of wheel parameters. A. Allali, S. Belbachir, A. Lousdad [13] emphasize that these materials are more useful in the manufacture of centrifugal pumps organs by their good aging and resistance to corrosion. Their computations were made using finite element method (FEM) within ABAQUS code. Metin Güner and Mehmet Melih Özbayer [14] define the requirements for materials with similar application as follows:

- Physical properties (size, shape, density);
- Mechanical properties (density, yield and tensile strength, ductility, hardness, fatigue strength, friction strength, torsion, fracture toughness, brittleness);
- Chemical and electrochemical properties (chemical composition, solubility, oxidation, corrosion);
- Electrical and magnetic properties (self-conductivity, electrical conductivity, magnetism);
- Thermal properties (heat conduction coefficient, melting temperature, specific heat, heat capacity);
- Optical properties (reflecting and passing light, color, light swallowing, refractive index);
- Acoustic features (sound, voice, sound, reflection);
- Technological properties (fabricability, welding, casting, processability, compatibility);
- Economic features (price, reliability, availability, cost);
- Estetic properties (appearance, touch, feel);
- Cost.

The authors in [14] emphasize, that centrifugal pump body and impeller may be made of thermoplastic materials. The thermoplastic wheel is lightweight and does not rust or decay, suitable for working in sea water and corrosive environments, works without vibration. Pump impellers may be made of polycarbonate (PC), noryl (blend of PPO + PS), molded rubber and glass. In [15] carbon-fiber reinforced polymer material impeller is designed for the centrifugal pump in the chemical and pharmaceutical industries. As a polymer matrix is used epoxy resin. The short carbon-fiber reinforced epoxy resin material for impellers has characteristic parameters at room temperature as follows: density (g cm^{-3}) - 1.7, elastic modulus (GPa) - 132, poisson ratio - 0.321, tensile strength (MPa) - 1222, compress strength (MPa) - 536. In [16] elastomer based impellers are proposed. In this paper, a new class of high-performance composites and a method of their production based on the carbonization of an elastomeric matrix are studied. In contrast to

classical elastomeric materials, the nitrile butadiene rubber (NBR)-based compounds were highly filled (300 parts per hundred rubber-PHR) with different carbon fillers and silicon carbide; then cured and carbonized at low-temperature 360°C with the carbonization cycle of 12 h. The feasibility of the production method was validated through the manufacturing of products with complex shapes - impellers for electric centrifugal pumps. It was found that the carbonized composites have good chemical resistance and low water absorption. The composites have high Shore D hardnesses (93 - 96), ultimate tensile strengths (62 - 85 MPa), Young's moduli (17 - 24 GPa), and compressive strengths (155 - 181 MPa). In [17] the economic efficiency, which is achieved by replacing the metal parts in centrifugal pumps with polymer ones, is considered. It is stated that the metal impeller weighs 315 g and the polymer - 60 g, i.e. there is a difference of 255 g. About 60 % cheaper are impellers made of polymeric materials, indicating that as such can be used thermoplastic, polyester resin, epoxy resin and vinyl ester resin.

We could not find in the literature specific data and characteristics of composites based on polycarbonates, filling with short glass fibers for use as wheels in centrifugal pumps (impellers).

EXPERIMENTAL

Materials

- Polycarbonate brand TISARBON® H UNR K04 R01, manufactured by TISAN, Turkey. It is a natural transparent impact-resistant polycarbonate, designed for injection molding;
- Short glass fibers CS 7938, E-glass with a fiber diameter of 11 microns and a length of 3 mm, manufactured by Lanxess. The fibers were treated with 3-(aminopropyl) triethoxy silane, produced by Sigma-Aldrich.

Methods

Preparation of composites made of PC and SGF

Polymer compounds were prepared using 45 mm single-screw extruder with L:D = 25, (produced by Esmos, Bulgaria). The heating is electric. The temperature mode of extrusion is as follows:

I zone – 260°C; II zone – 265°C; III zone– 270°C, IV zone 260°C.

Table 1. Compositions of the prepared PC composites.

N	PC, %	SGF, %
1	100	0
2	90	10
3	80	20
4	70	30

After drying the starting materials at 105°C for 4 hours, compounds of 400 g PC and SGF each were prepared with the compositions shown in Table 1.

The obtained polymer composites in the form of extrudate were ground with the help of a knife mill to a size of 2 - 3 mm and are packed in an airtight polyethylene package.

Test samples preparation

From the obtained materials were cast under pressure with an injection molding machine (KUASY, Germany) test samples, which in shape and size meet the relevant standards. The temperature mode of injection molding is selected depending on the composition of the processed composite material. The nozzle temperature is varied in the range 245°C - 265°C; rotation speed - 50 min^{-1}; injection time - 3 sec; cooling time - 14 sec.

Samples testing

Physicomechanical indicators (EN ISO 527-1.2:2020)

A Zwick/Roell Z010 dynamometer was used to perform tests on physicomechanical parameters. The following indicators were determined:

- ε_t, MPa, tensile modulus, test speed - 1 mm min^{-1}
- σ_m, MPa, tensile strength, test speed - 50 mm min^{-1}
- σ_m, %, strain at tensile strength - test speed 50 mm min^{-1}
- σ_b, MPa, stress at break, test speed - 50 mm min^{-1}
- σ_{low}, MPa, tensile modulus, begin
- σ_{high}, MPa, tensile modulus, end
- ε_e, %, elastic deformation

Hardness

The hardness was measured using a Shore A hardness tester according to BDS ISO 7619-2001.

Flexural strength – in correspondence to ISO 178:2019

Determination of Charpy impact strength - in correspondence to EN ISO 179-2:2020. Test samples with sizes 10 mm x 4 mm x 80 mm (width/thickness/length) were used. Two types of samples were examined: notched and unnotched, pre-tempered at 23°C.

Determination of the thermal conductivity coefficient of the studied vulcanizates

A laboratory method was used, taking into account the current, which is proportional to the difference between the temperature of the tested sample and a standard with a known coefficient of thermal conductivity. The equations used are:

$$\lambda_1 = \lambda_2 \frac{\alpha_1}{\alpha_2} \frac{n_3 - n_2}{n_2 - n_1}$$

$$\lambda_3 = \lambda_2 \frac{\alpha_3}{\alpha_2} \frac{n_3 - n_2}{n_4 - n_3}$$

$$\lambda = \frac{\lambda_1 + \lambda_3}{2}$$

where: λ - coefficient of thermal conductivity of the tested sample, W $m^{-1}.K^{-1}$;

λ_2 – thermal conductivity of the standart used / polymethyl methacrylate, with a known coefficient of thermal conductivity, $\lambda_2 = 0{,}186$ W $m^{-1}.K^{-1}$;

$\alpha_1 = \alpha_3$ - Thickness of the polymethyl methacrylate standard, mm;

α_2 - thickness of the measured sample, mm;

n - the galvanometer readings corresponding to the current in the thermocouples.

Determination of the volume resistivity of the tested samples

Laboratory methodology was used. The volume resistivity (ρ_v, Ω.m) for flat samples, in a uniform electric field, is calculated by the formula:

$\rho_v = R_v \cdot S / h$

where: R_v - the measured electrical resistance, Ω;

S - the area of the measuring electrode, m^2;

h - sample thickness, m.

The volume resistivity of the studied composites was measured by flat electrodes. For this purpose, a Teralin III Teraohmmeter (manufactured in Germany) with a range of 10^4 to 10^{12} Ω and a Wheatstone bridge with a range of 10^{-1} to 10^6 Ω were used. The sample is placed between the electrodes. The resistance is measured at a constant current 1 minute after the voltage is applied. The electrodes used are brass (volt and measuring), the measuring electrode has a cross section of 0.0022 m^2 and a weight creating a pressure on the sample of 9.4 kPa.

Determination of the surface resistivity of the tested samples

The surface resistivity is measured on laboratory equipment, described above, and instead of the volt electrode a second tubular cylindrical measuring electrode is connected, in which the measuring electrode is placed (there is an insulating layer between the two electrodes so that they do not come into contact each other).

The surface resistivity (ρ_s, Ω) for flat samples, in a uniform electric field, is calculated by the formula:

$\rho_s = \pi.D_0.R_s/g$

where: R_s - the measured surface electrical resistance, Ω;

$D_0 = (d_1+d_2)/2$;

d_1 – the diameter of the measuring electrode, cm;

d_2 – outer diameter of the second tubular electrode, cm;

g – the distance between the two electrodes, cm.

Light microscopy

Using a light microscope operating with transmitted and reflected light, the test compositions of Table 1 were observed to visually determine the quality of homogenization of the polymer matrix with the filler.

RESULTS AND DISCUSSION

Physicomechanical properties of polycarbonate composites filled with different amounts of SGF

Some important properties of the compositions shown in Table 1 are summarized in Table 2.

Cervical formation was observed only in sample 1 (unfilled PC).

As the amount of filler increases, the tensile strength increases also. The maximum achieved tensile strength of the tested composites is illustrated in Fig. 2.

In general, all physicomechanical parameters

Table 2. Test results of the compositions from Table 1.

Indicators	1	2	3	4
1. ε_t, MPa	1970	5240	5250	6190
2. σ_m, MPa	63.1	125	128	150
3. ε_m, %	6.4	3.4	3.6	3.5
4. σ_b, MPa	48.2	125	128	150
5. σ_{low}, MPa	1.049	1.709	2.802	3.293
6. σ_{high}, MPa	4.994	7.217	13.326	15.719
ε_e, %	0.3	0.25	0.2	0.2

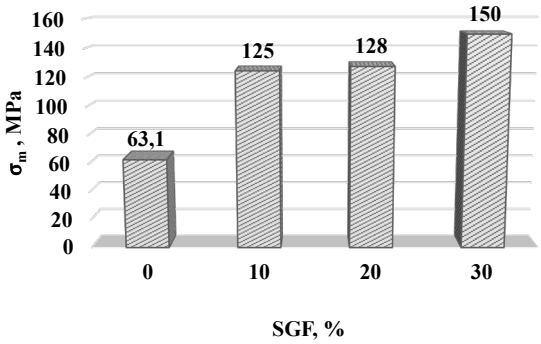


Fig 2. Change in tensile strength (σm, MPa) of polycarbonate composites filled with different amount of SGF (%).

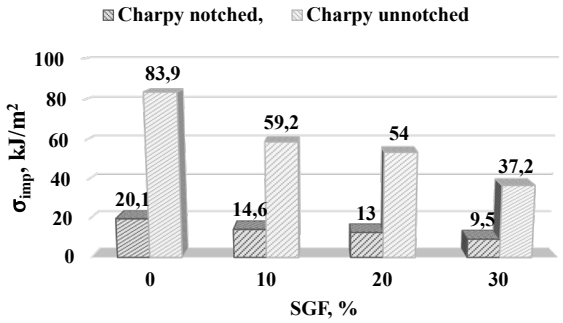


Fig. 3. Change in impact strength of a polycarbonate composites filled with a different amount of SGF.

improve with increasing filling, the maximum deformation at break and the elastic deformation decrease naturally. The strongest influence of filling on the tensile strength, which increases almost twice, is observed at a filler concentration of 10 %. Although to a lesser extent, the strength continues to increase with increasing amount of SGF. This makes filling cost-effective because the composite has increasing strength and decreasing cost, as the cost of the filler is lower than that of the polymer matrix. The observed changes in physicomechanical parameters are due to the good adhesion between polycarbonate and short glass fibers due to the successfully selected silane (3-aminopropyltriethoxy silane) as well as to the high mechanical strength and good wettability and dispersibility of the SGF used). Other authors emphasize [18] that good adhesion is the main reason for improving the physicomechanical properties of the composite. This is attributed to the strong physical interaction at the fiber-matrix interphases due to the good wetting of the fibers from the polycarbonate matrix and improved compatibility. The good interfacial bending will facilitate the stress transfer from polymer matrix to fiber [19 - 20]. The length of the fibers, which must be optimal, also has a positive effect on the significantly improved physicomechanical parameters, because the fibers will be pulled out when the fiber length is shorter than the critical fiber length [20]. Good physical and mechanical parameters show that the length of the fibers we use is optimal or close to it. The pull out of the fibers which are coated with the polycarbonate matrix due to silane used will be more difficult. Apart from fiber matrix interfacial bonding, another possible factor that may influence the tensile strength of PC composites is the fiber aspect ratio. Shorter fiber lengths will create more fiber ends, which eventually act as stress concentration points where failure often occurs at these sites [18]. The significant increase in tensile strength (Fig. 3) in our case shows that the value of the aspect ratio is also appropriate. Impact strength test results of the composites investigated are shown in Fig. 3.

As the amount of filler increases, the impact strength of the composites decreases. The reason for this is the reduced toughness and plasticity of the composites. As the amount of filler increases, the effort required to destroy the sample increases, but its fragility also increases.

The high impact properties of pure PC are contributed by the carbonate groups that exist in its structure, by giving high flexibility to the material [21]. The presence of stiff SGF in PC had increased the stiffness of the composites, which consequently brought about lowering of toughness, and thus reduced the impact strengths. As expected, the introduction of notches into the specimens leads to a further drop in the impact strength values. Notched impact strength revealed the energy required to propagate an existing crack in a sample, whilst unnotched impact strength represented the energy required to initiate and propagate a crack [22]. If we compare the results obtained by us with those of other authors [10], it can be seen that the same regularities are observed in the composites studied by us, but the values obtained for impact strength differ. These differences are probably due to the fiber size and the type of silane used to ensure adhesion between the polymer matrix and SGF. Flexural strength test results of the composites investigated are shown in Fig. 4.

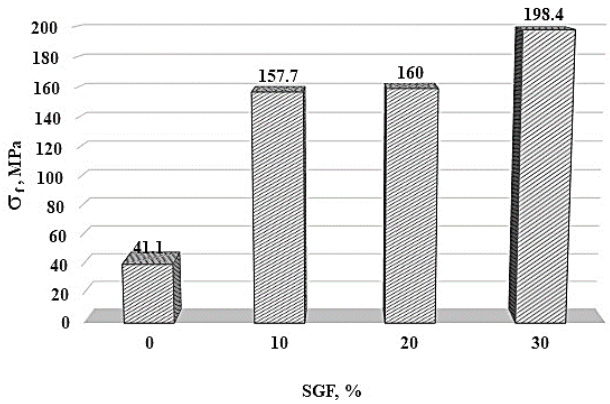


Fig. 4. Change in flexural strength of a polycarbonate composites filled with a different amount of SGF (%).

From the performed research it can be concluded that the addition of 10 % SGF to the polycarbonate matrix is completely sufficient to drastically increase the bending resistance and changes it from 41.1 to 157.7 MPa. Filling with 30 % short glass fibers leads to an increase in flexural strength to 198.4 MPa. With the incorporation of fibers, flexural strength increased, showing a similar trend as observed in tensile strength (Fig. 2). The flexural strength increased gradually as more amounts of fibers are incorporated in the matrix. As mentioned earlier, this may be attributed to the better fiber-matrix interactions between SGF and PC. The relatively better interfacial bonding allows a more efficient stress transfer at the interfacial region, which consequently leads to the higher strength of the resulting composites [23]. As a result, flexural modulus of PC increased dramatically upon the incorporation of fibers. Hardness test results of the composites investigated are summarized in Table 3. They allow to conclude that the hardness of PC/SGF composites increases with the increasing of SGF content.

Glass fibre has a higher hardness and strength than polycarbonate. So, it is expected that addition of glass fibre will increase the strength and hardness [24]. When analyzing the obtained results, it is noticeable that for all measurements very close results are obtained for

Table 3. Shore A Hardness of PC/SGF composites.

N	PC, %	SGF, %	Shore A Hardness
1	100	0	95
2	90	10	97
3	80	20	97
4	70	30	99

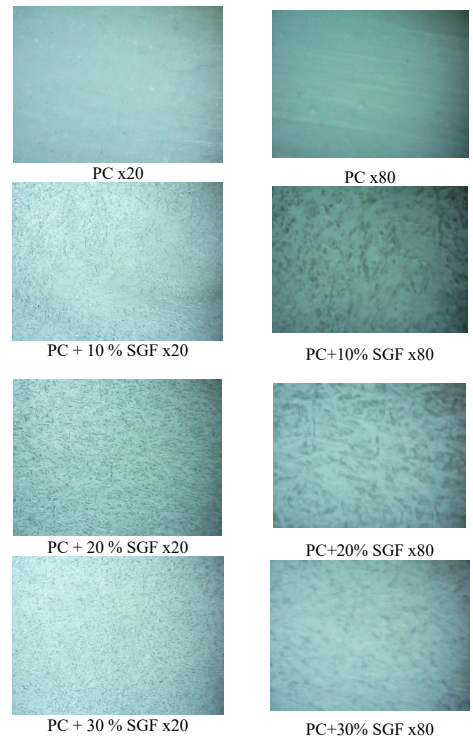


Fig. 5. Optical microscopic images of PC composites filled with different amounts of SGF.

composites containing 10 % and 20 % SGF, which differ significantly from those of unfilled composites and from filled with 30 % SGF. Such anomalies are also observed in the results of other researchers, for example Mustafa Gamal Sadek et al. [10], who examined composites from PC filled with 5, 10 and 15 % SGF and also obtained very similar values for the studied indicators. It is probably an effect of gradual quantitative accumulations in the structure of the composite, which above a certain value of filling grow into sharper qualitative changes.

Examination by optical microscopy of polycarbonate composites

The optical-microscopic images of the tested composites are shown in Fig. 5.

The photos show that the short glass fibers are randomly but evenly distributed in the polycarbonate matrix, even at higher filling levels. No orientation was observed and the samples appeared homogeneous. Also it can be concluded that when using the injection mode and more precisely temperatures and injection rates, products with improved physicomechanical parameters will be obtained due to their homogeneity and lack of anisotropy.

Table 4. Electrophysical and thermophysical properties of polycarbonate composites filled with short glass fibers.

N	PC, %	SGF, %	ρ_v, Ω.m	ρ_s, Ω	λ, w/m.K
1	100	0	10^{14}	10^{15}	0.190
2	90	10	10^{14}	10^{14}	0.192
3	80	20	10^{12}	10^{13}	0.220
4	70	30	10^{11}	10^{12}	0.320

Note: ρ_v, Ω.m – volume resistivity; ρ_s, Ω – surface resistivity; λ, W m^{-1} K^{-1}- coefficient of thermal conductivity

Electrophysical and thermophysical properties of polycarbonate composites filled with short glass fibers

The electrophysical and thermophysical properties of polycarbonate composites filled with short glass fibers are summarized in Table 4.

As can be seen from the results in Table 4, all the tested compositions have very good electrical insulating properties. There is a slight tendency to their decrease with increasing the amount of the short glass fibers. It can also be seen that the surface resistivity has higher values than the volume resistivity. This means that the current flows better through the body of the material, rather than along the surface of the material [18], probably due to the influence of the silane used to improve adhesion. As the amount of SGF increases, the thermal conductivity of the composite increases. The observed effects can be explained by the difference between the electrical properties and the thermal conductivity of the polymer matrix and the filler. The short glass fibers are characterized by a lower volume and surface resistivity and a higher coefficient of thermal conductivity than the polymer matrix, due to which the tendencies described above are manifested with an increase in their quantity. The presence of stiff SGF in composites plays a vital role as a physical cross-link network, which could limit the thermal movement of the polymer chain and prevent the elastic and plastic deformation of the polymeric matrices [25], which also affects the coefficient of thermal conductivity.

CONCLUSIONS

- Composites of polycarbonate and short glass fibers in quantities of 10, 20 and 30 % are prepared by means of a single-screw extruder.
- The homogeneity of the composites was examined by optical microscopy. The photos show that the short glass fibers are evenly distributed in the polycarbonate matrix, even at higher filling levels. No orientation was observed and the samples were homogeneous.
- The influence of the amount of filler on the main physicomechanical properties of the obtained composites has been studied.

It was found that with increasing the amount of filler, the properties of polycarbonate composites change as follows: in general, the physicomechanical parameters (all modules, tensile strength), stiffness and flexural strength increase, maximum deformation, as well as elastic and impact resistance decrease somewhat. The volume and surface resistivity decrease, the coefficient of thermal conductivity increases. The main reason for these changes in the properties of the composites is the good adhesion at the polymer matrix-fiber interphase which is attributed to the strong physical interaction due to silane used and as a result the good wetting of the fibers from the polycarbonate matrix and improved compatibility.

From the study it can be concluded that the filling of polycarbonate with different amounts of SGF significantly changes its properties and expands the areas of application of this excellent engineering polymer. Composites based on it, filled with 10 - 30 % short glass fibers can be successfully used for the production of centrifugal pumps impellers, as they meet a significant number of requirements for materials with such application.

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