The results of the compression test of some specimens made of a chromoplastic polymer show that due to the friction between their flat frontal surfaces and the cobalt discs of the test machine to which forces are applied, the state of stress in the specimens is no longer uniaxial and homogeneous, the deformations along their axis being uneven. Experimental research and numerical analysis using finite element method confirms this appreciation and the differences that occur as regards the state of tension over the situation where friction is absent.

1. Introduction

The polymer [6] represents the substance of several mers (monomers), according to a repeating principle in which the monomer is the basic structural unit. By means of covalent chemical bonds, a chain (polymer skeleton) is formed. The number of base units repeating within a chain forms the degree of polymerization. It can also be defined as the ratio between the mass of a polymer chain and the mass of the base unit. Depending on the value of this ratio can be oligomers if this ratio is small and macromolecules when the degree of polymerization is high, usually greater than 100.

Copolymers are macromolecular compounds obtained by the polymerization process of two or more particular monomers. Copolymers have new properties, quite different from those of each monomer. The process of mixed polymerization of particular monomers is called copolymerization and is one of the methods of realizing certain polymeric systems with predetermined characteristics, necessary for technical applications. Polymers, depending on their behavior under load, can be elastomers characterized by high elasticity and thermoreactive plasmids with rigid behavior.

Chromoplastic polymers [4], obtained at the Scientific Research and Technological Development in Chemical and Petrochemical Industry in Bucharest – ICECHIM, result from compounding, present the chromoplastic phenomenon, that is, they change the color at the moment of the plastic deformations, whitening when the flow occurs at the traction stress and blackening when the flow is caused by the compression load. These materials at axial stresses have the following features: elastic and linear behavior for $\varepsilon<\varepsilon_c$, plastic deformations under constant stress for $\varepsilon>\varepsilon_c$, show the chromoplastic phenomenon at normal temperature (20° C) and - if necessary until the chromoplastic phenomenon manifests intensively and is subsequently heated to over 110° C, the color disappears simultaneously with the return of the studied model to the original shape and dimensions, but the pre-treatment properties disappear; at temperatures above 110° C, the chromoplastic phenomenon is no longer present.
The hypotheses of the appearance of the chromoplastic phenomenon following the copolymerization process, the change of color at the points where the stress reaches the flow limit are:
• the admission of a molecular orientation mechanism with the change of crystallinity. Crystallinity represents a state of the molecular structure of the material characterized by uniformity and compactness attributed to the existence of solid crystals with a defined geometric shape;
• a differential solubilization of the components of the chromoplastic materials under different stresses. Solvation is a phenomenon that accompanies the dissolution of a substance in a solvent and consists in establishing bonds between the ions or molecules of the dissolved substance and the solute molecules;
• the chromoplastic phenomenon is considered as a differential diffraction effect. It is found with the naked eye a sensitivity of the chromoplastic phenomenon to these materials, characterized by the net difference in color between the required areas.
Chromoplastic polymers SDP-2 and SDP-7 [1], [4] exhibit a characteristic curve similar to the Prandtl schematic curve (Fig. 1a), and the CSDP-30 characteristic curve is similar with a slight consolidation tendency (Fig. 1b).

The characteristic curves of chromoplastic polymers fall within the schematic characteristic curve variants used usually in the strength of material calculations for engineering structures [3].

![Figure 1. Characteristic curves of the chromoplastic materials for small strains](image)

With the help of tests carried out on chromoplastic models, information on the moment of the first plastic deformations, the type of stresses (traction or compression), the amount of the loads they produced, the areas in which they occur, and their evolution as the load increases can be obtained. Analytical calculation or numerical modeling using finite element analyses (FEA) of the distribution of stresses produced by external force in chromoplastic materials requires knowledge of the mechanical characteristics of the used material [2], [5]. Only on this foundation the results obtained by calculation and experimentation may be compared and some conclusions can be drawn. To this end, in the following, materials having a characteristic curve of the Prandtl type [3] were experimentally tested to obtain the characteristic compression curve and then to determine the Young's modulus and the yield limit of the material.

2. Experimental determinations
Compression tests to obtain the characteristic curve of the material were performed according to standard SREN ISO 604/2004 [8]. Four specimens of a SDP-7 [4] chromoplastic material plate having the diameter \(d_0\) equal to the initial length \(l_0\) were completed. The specimens were tested between the chromium-nickel steel discs of the INSTRON 8801 universal machine and the compressive force was applied at a speed of 0.1 mm/min. Increasing the load, the specimens lose their initial cylindrical shape and form a barrel shape, as is the case with tenacious materials, and the ultimate strength can not be determined. The initial and final dimensions of the specimens are shown in Table 1.
Figure 2 shows the characteristic diagrams for the four specimens in Table 1, for the slowly increasing compression force. The figure also shows a characteristic diagram obtained with the mean values for the four specimens. A quasi-linear behavior for stress is observed until the maximum value in this case is the material yield limit. At this stress value, the corresponding specific deformation increases greatly, the stress remaining constant. The behavior of this polymer on compression is typical of tenacious materials. From the recording of the characteristic diagrams, a mean value of yielding limit \( \sigma = 64.9 \text{ MPa} \) and the Young’s modulus at compression \( E = 2130 \text{ MPa} \) were obtained. These values are higher than the real ones because the stress was calculated with the relationship

\[
\sigma = \frac{P}{A_0}.
\]  

(1)

**Table 1.** Initial and final dimensions of test specimens

| Epruveta | \( l_0 \) [mm] | \( d_0 \) [mm] | \( l_1 \) [mm] | \( d_1 \) [mm] |
|----------|----------------|----------------|----------------|----------------|
| 1        | 12.7           | 12.7           | 12.1           | 13.4           |
| 2        | 12.7           | 12.7           | 12.1           | 13.4           |
| 3        | 12.6           | 12.7           | 12.0           | 13.4           |
| 4        | 12.7           | 12.7           | 12.1           | 13.5           |

In reality, the cross-section area of the specimens changes during the load tests. Taking into account the volume invariance, the area of the specimen is

\[
A' = \frac{A_0}{1 - \varepsilon_c},
\]  

(2)

and the normal stress will be less than that resulting from the relationship (1).

**Figure 2.** Characteristic curves obtained experimentally for compression tests

Figure 3 shows the final aspect of the specimens. Investigating the front surfaces of the specimens it is observed that at their center and over the contour the color is dark grey, indicating a compressive stress and between these areas a gradual evolution towards a light field indicative of a material tension area. This tension distribution is also found in a normal cross-section throughout the center of gravity on the longitudinal axis of the specimen (Figs. 4c, d and e). Figs. 4a and b show the aspect of some sections through a longitudinal plane containing the axis of the specimen.
The compressive flow area of the maximum deformation of darkness is clearly delimited by the tensile (light colored) area of minimum deformation. The results obtained show that due to the influence of friction between the front surfaces of the polymer specimens and the cobalt discs of the test machine by which the compressive forces are applied, the state of the stress is no longer uniaxial and homogeneous. The compressive force applied to the specimen and the frictional force between the surfaces in contact (Fig. 5) are comprised of a resultant acting angled against the longitudinal axis of the specimen and produces an uneven distribution of the deformation along the specimen axis.

Figure 3. The final aspect of the test specimens

Figure 4. Sections through test specimens

Figure 5. The forces acting on the specimens during the test
Reducing the influence of friction can be done by using an ointment, e.g. paraffin, the value of the friction coefficient decreasing in this case from 0.22 to 0.07. A less significant influence on the test results may be the errors in the specimen processing, especially the planarity and parallelism of the front surfaces, the degree of unevenness of the material or the eccentric application of the load. The latter can be avoided by using a disc provided with a spherical cap.

3. Numerical analysis
The numerical analysis [7] for determining the distribution of stresses and displacements in the compression test specimen was performed by FEA in three variants:
1. vertical displacement of the metallic upper disc of the test machine by 0.6 mm, taking into account the friction between the specimen and the discs;
2. vertical displacement of the metallic upper disc by 2.5 mm, taking again into account the friction between the specimen and the discs;
3. vertical displacement of the metallic upper disc by 2.5 mm without considering friction between the specimen and the discs.
Practically the displacement of the disc of the test machine is the shortening of the studied specimen.

The FEA was performed on one of the specimens of the experimentally investigated chromoplastic polymer, respecting the initial dimensions, \( l_0 = d_0 = 12.7 \text{ mm} \) and the elastic characteristics of the material, \( E = 2130 \text{ MPa} \), the Poisson's ratio \( \nu = 0.34 \). The chromoplastic material was modeled using a bilinear characteristic curve considering \( \sigma_c = 60 \text{ MPa} \) and tangent modulus \( E_{pl} = E/1000 \). Two small radial parts of the discs were included into model for obtaining the contact forces. The coefficient of dry friction between the metallic disc of the test machine and the studied polymer was considered \( \mu = 0.22 \). The coefficient of friction between the metal and the polymer is 50% higher than the metal-to-metal friction [6] since the superficial layer of the polymer is transferred to the metal contact surface of the disc in the form of small rollers which contribute to increased frictional force. In general, the friction coefficient value increases in the case of a contact pressure, as is the case with the compression load. Since the specimen exhibits axi-symmetric symmetry for stress and strain, the geometrical model (Fig. 6) is considered according to axi-symmetrical finite element models, the global system of coordinate axis \( OY \) being along the axis of symmetry. The commercial finite element code ANSYS 18.0 was used.

**Figure 6.** Axial symmetric finite element model and all boundary conditions

**Figure 7.** Variation of contact friction pressure for the first variant of load
For the maximal experimental shortening by compressing of the specimen, $s = 0.6$ mm, the variation of the frictional pressure (Fig. 7), the contact pressure (Fig. 8) between the discs and sample and distribution of stresses (Fig. 9), are presented. Figure 9 shows the variation of the normal stress $\sigma$, and in Fig. 10 the equivalent stress $\sigma_{eq}$ in the specimen. It can be ascertained that in the axis of symmetry, at the disc-specimen contact, the calculated pressure value (48.03 MPa) is very close to the value of the stress $\sigma$ (48.41 MPa) and the distribution of the equivalent stress (Fig. 10) is the same as that obtained experimentally Fig. 4a.

In the case of a shortening of 2.5 mm specimen, taking into account the friction, tensions and displacements are no longer constant in any section of the specimen. It can be seen from Fig. 11 that the variation of displacements along the x-axis records a maximum value of 0.93 mm in the section.
where the center of gravity of the specimen is located. In the same section, the maximum stress is 83.7 MPa (Fig. 12) versus -60.4 MPa in the absence of friction (Fig. 13).

**Figure 12.** Stress variation $\sigma_y$ for the second variant of load  
**Figure 13.** Stress distribution for the third variant of load, in the absence of friction

4. Conclusions

Chromoplastic polymers give information on yielding areas when external forces act on them. This property allows the verification of elasto-plastic calculations in structure models made from these materials. In the case of the investigation of the influence of the friction between the front faces of the specimen and the metal discs through which the compressive forces were applied, the following were pointed out:

- experimental determinations are checked for stress and contact pressure distribution, numerical calculation performed by FEA;
- the numerical analysis performed by FEA on a chromoplastic polymer specimen for a shortening of 2.5 mm shows that the distribution of stresses and displacements changes without becoming uniform when there is friction against the absence of friction between the specimen and the discs. The specimen gets a barrel shape and the maximum stress increases by almost 50%.

5. References

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