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Effecting of Modified HDPE Composition on the Stress-Strain State of Constructions

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Abstract. The physico-mechanical parameters of one class of polymers can be considerably variated depending on different conditions: temperature, the injection of additives, irradiation of the material, etc. First of all, this affects the stress-strain state of structures made of these materials. And especially the development of highly elastic deformations in the form of creep deformations developing in time. As an example, the article considers a structural element of a cylindrical shape, made of high-density polyethylene (HDPE). It is defined and shows the change in the stress-strain state at the time of various material compositions. It is also presented that the change in the principal stresses is more pronounced than the base stresses (radial, circumferential and axial).

1. Introduction

"Movement is life, and life is a movement" – says the old saying. But if the movement is impossible or limited, a bright and emotional life can turn into existence.

In medicine, this problem is solved by implantation and prosthetics. But the search for the best artificial material that would be suitable for this task is still relevant today.

High-density polyethylene (HDPE) is one of the most common artificial materials used in the manufacture of implants and prostheses. The reason for this is its biocompatibility, which means that its characteristics coincide with the characteristics of natural bone [1]. This characteristic is very important, as it excludes the possibility of developing osteoporosis during the operation of the prosthesis. But rheology, low modulus of elasticity and low biological activity impose some limitations on its use.

In [2-3], attempts were made to improve the above characteristics, including the addition of various impurities to the basic composition of HDPE. One such additive may be hydroxyapatite (HA), which positively affects the composite stiffness and biological activity. The strength of HDPE is ensured by itself. The viscoelastic behavior of the material is easily described in time and allows us to make a prediction about the long-term strength [4-6]. Thus, the use of HA as a reinforcing element of polymeric material has a beneficial effect on the biological activity and rheological behavior of HDPE.

Gamma radiation is one of the most frequently used methods of sterilization in medicine of many drugs, as it decomposes the DNA molecules of any living organisms. But that is not all. Radiation causes a change in the molecular structure of the polymer. Under the influence of gamma radiation, the cohesion density of long molecular chains and the concentration of binding molecules increase. Thus, sterilization favorably affects the process of cross-linking the molecule of the composite.

2. Experimental method

The stress-strain state (SSS) of a structure depends on many factors: geometry, fixing method, type of loading, material composition and many other. And if the question concerns polymers, then the composition should be given special attention. Because depending on what kind of polymer, whether there were additives and in what quantity, whether the material was irradiated, the physico-mechanical parameters vary considerably. That very significantly affects the SSS of the structure.

The scholars of prof. B.M. Yazyev`s science school obtained expressions that determine the physic-mechanical parameters of HDPE as a function of the fraction of HA and the level of irradiation Φ. They have the following form:

Elastic modulus:

$$E(HA,\Phi) = 694 + 1251 \times HA + 2.908 \times \Phi - 4.498 \times HA \times \Phi, [\text{MPa}]. \quad (1)$$

The high elasticity module:

$$E_{\infty}(HA,\Phi) = 228.9 + 1093 \times HA + 2.276 \times \Phi - 1.5 \times HA \times \Phi, [\text{MPa}]. \quad (2)$$

Velocity module:

$$m^{*}(HA,\Phi) = 5.545 + 8.501 \times HA + 0.01283 \times \Phi + 0.05456 \times HA \times \Phi, [\text{MPa}]. \quad (3)$$

Coefficient of initial relaxation viscosity:

$$\eta_0^{*}(HA,\Phi) = 1113 + 2398 \times HA + 8.877 \times \Phi - 32.64 \times HA \times \Phi, [MPa \times h]. \quad (4)$$

The analysis of expressions (1)-(4) shows that with an increase in the fraction of HA and the level of irradiation Φ, all the elastic and rheological parameters increase. Some exception is the coefficient of initial relaxation viscosity, which, when the HA is injected and the material is irradiated at the same time, has a value approximately the same as when injecting HA or only irradiating HDPE.

To assess the effect on the stress-strain state of a polymer body of various combinations of additives and the level of ionizing radiation, the following problem was considered: flat puck under a compressive load which may be a primitive prosthesis model. The statement of the problem and the calculation scheme are shown in Figure 1.

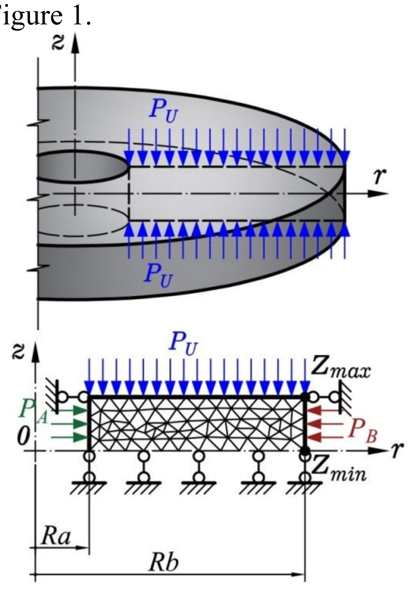

Figure 1. Compressed cylindrical body of finite length: statement of the problem and the calculation scheme.

Body height $h = 1$ cm $= 0.010$ m. Due to the fact that the body is symmetrical relative to the horizontal axis it suffices to consider only half the sample. As a result of which the original data takes the following form: pressure on the inner face of the cylinder $P_A = 0$ MPa, pressure on the outer face of the cylinder $P_B = 0$ MPa, pressure at the upper end of the cylinder $P_U = -10$ MPa (minus - compression), inner radius $R_a = 0.010$ m, outer radius $R_b = 0.050$ m, lower point coordinate $z_{\min} = 0$ m, coordinate of the top point $z_{\max} = h/2 = 0.005$ m. The time limit to which the calculation is made *limTime* = 10 h, number of time-partitioned intervals *qnIntT* = 20 pieces. Time intervals are variable, the ratio of the last time interval to the very first – 100. The simulation was performed by the finite element method. Elements used were triangular so that the side of the element does not exceed the value, so that the height of the cylinder can accommodate at least 10 elements.

3. Results and its discussion

The stress-strain state of the polymer structure was calculated using the nonlinear generalized Maxwell-Gurevich connection equation [6]. As a result of the calculations, two-dimensional graphs of the distribution of radial, circumferential, axial and tangential stresses at different instants of time were made. They depend on the fraction of HA and the presence of ionizing radiation. Analyzing these graphs, we can conclude that the stress at the end of the calculation period, compared with the initial increase in 2-2.5 times. These graphs are not given in the article, since they are cumbersome and uninformative. More informative are the graphs of the distribution of the maximum and minimum values of the radial, circumferential, axial and tangential stresses in time, shown in Figure 2 and Fifure 3 (black line – σ_r; blue line – σ_θ ; green line – σ_z; red line – τ_{rz}).

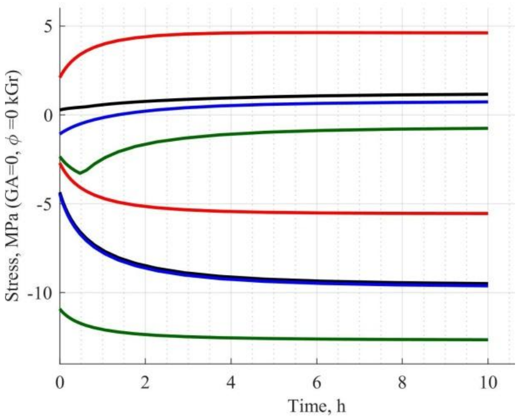

Figure 2. Distribution of the maximum and minimum values of radial, circumferential, axial and tangential stresses (*HA* = 0 %, Φ = 0 kGy) in time.

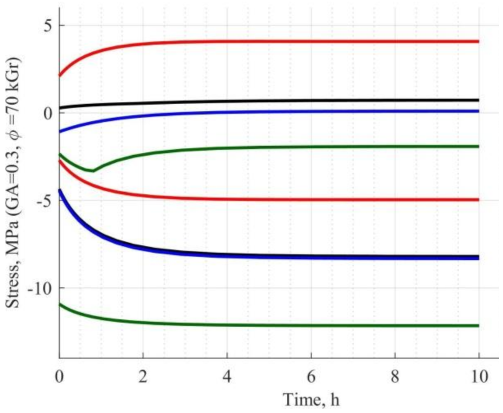

Figure 3. Distribution of the maximum and minimum values of radial, circumferential, axial and tangential stresses (*HA* = 30 %, Φ = 70 kGy) in time.

The analysis of the change in the principal stresses was also made: the maximum σ_1 and the minimum σ_3 (Figure 4). For this purpose we have been allocated the maximum and minimum stress values, and then the graphs of the change of these parameters in time have been plotted. They clearly show the change in the stress level over time in 2-2.5 times. The exception is the main stresses, which have significant values at the initial time and increase no more than in 1.5 times at the end of the calculation period.

The difference between the basic stresses (radial, circumferential, axial and tangential) from the main stresses also lies in the difference in the demonstration of rheological processes. So, in the absence of additives and the presence of ionizing radiation, the base stresses stabilized after 7 hours from the moment the load was applied, if we analyze the changes in the main stresses, they did not stabilize even after 10 hours, that is, by the end of the calculated period. In the case of the presence of maximum additions of HA in the polymer and irradiation with ionizing radiation, the level of both base and principal stresses decreases by ≈ 10 %, compared with an untouched polymer sample. In addition, the stabilization of the basic stresses is observed after about 4 hours from the beginning of the calculation, the main ones after 6 hours. A sample in which HA was added and irradiated with a half dose showed approximately the average characteristics between the "pure" sample and the sample, with the total addition of HA and the total level of ionizing radiation.

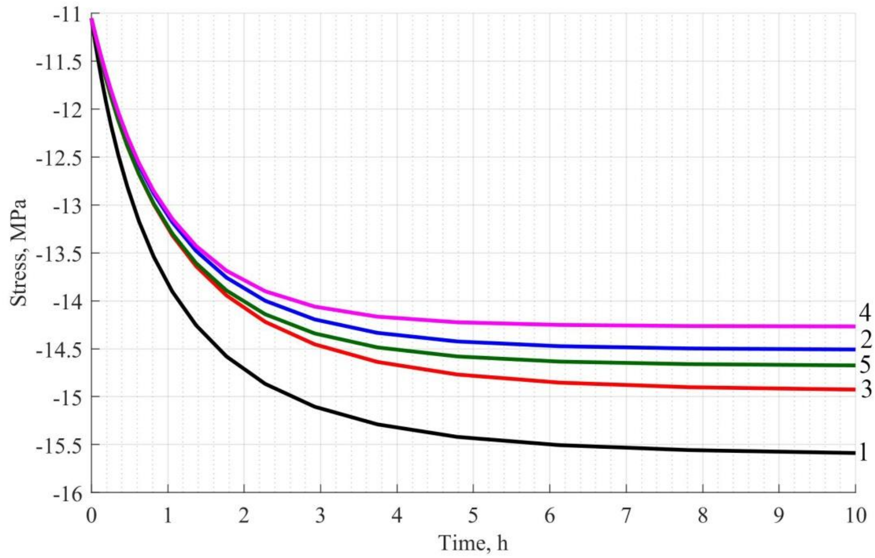

Figure 4. The change in time of the smallest principal (compressive) stresses σ_3 in the body over time: 1 — *HA* = 0 %, Φ = 0 kGy; 2 — *HA* = 30 %, Φ = 0 kGy; 3 — *HA* = 0 %, Φ = 70 kGy; 4 — *HA* = 30 %, Φ = 70 kGy; 5 — *HA* = 15 %, Φ = 35 kGy.

4. Conclusion

As a result of the research, the goal was fully achieved. As a result of the analysis of the stressed-strain state of the polymer body over time, it is proved that the base stresses (radial, circumferential and axial) change not in phase with the main stresses, so, to assess the strength characteristics of the structure it is necessary to evaluate the main stresses.

From the research it can be concluded that the assessment of stress-strain state of polymer bodies is still a relevant problem.

The proposed method can be easily used in practice.

Further development can be related to the analysis of the stress-strain state of polymer structures not only on the presence of HA and ionizing radiation, but also on the presence of other additives and external influences.

The above procedure for the determination of stresses and deformations in the body can only be proved by carrying out full-scale experimental studies.

It was also revealed on the basis of the solution of the test problem that, despite a significant change in the properties of the polymer by various modifiers, the stress-strain state of the finished structural element varies very slightly (the stress state changes within 10 %). As a result of this, it is impossible to judge the operational parameters of the polymer or improve its practical applications without modeling a particular construction.

The calculations presented in the article are one of the possibilities to achieve an increase in the accuracy of the calculation of polymer materials. И achieving the maximum accordance of theoretical calculations to practical results is one of the goals of polymer mechanics. The proposed mathematical calculations in the scientific environment are very rarely studied.

The finite element method is realized in many complexes and has a stable algorithm of realization. But the equations proposed in the article complicated, resulting the restrictions on their implementation. In this case, the accuracy was not so high in comparison with the classical algorithm of the finite element method.

Finally, it is obvious, that this study showed the impossibility of using universal software complexes on the basis of the finite element method for calculating the stress-strain state of polymer bodies according with the absence in their mathematical apparatus of the necessary equations for the connection between stresses and strains.

Presented a study on the optimization are problems in cylindrical coordinates. However, they do not give any effect if we consider them in a rectangular Cartesian coordinate system. In the case of a spherical coordinate system, further research is needed.

The study is limited to several factors: only one numerical method is used - the finite element method; equations are given for the case of a geometrically linear problem; the theory of small deformations is used etc. Each of these factors can affect the result to a greater or lesser extent, however, in this case, we are faced with a new large task requiring considerable research.

The production of new polymeric materials focuses on the material parameters at the elastic stage. Very little attention is paid to the creep of the material. Even less studied is the durability of polymer materials, taking into account the mechanical parameters of the material (temperature, presence of additives, ionizing radiation, etc.). The research presented in this article was one of the steps aimed at achieving greater accuracy of calculations, leaving many opportunities to take into account other factors that positively influence the outcome. As a result of the research it became possible to fully evaluate the results obtained by other authors.

Calculations can be used in the field of polymer mechanics to determine the stress-strain state of cylindrical bodies in an axisymmetric setting, as well as in the production of polymer pipes and other industries.

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