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# The Influence of Porosity on Stress and Strain State of Porous Polymer Materials

**D. Zeleniakienė*, T. Kleveckas, J. Liukaitis, G. Marazas**

*Department of Clothing and Polymer Products Technology, Kaunas University of Technology, Studentų 56, LT-3031 Kaunas, Lithuania*

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The determination of microstructure influence on porous materials macro properties can be applied to predict behaviour of material. The numerical finite element method was used to identify stress and strain state in porous polymer material microstructure in dependence on porosity value and mode under tensile loading by constant force. The highest local stress values were found in the free surface of polymer located at the boundary with pore. Both pores size and their distribution mode influence values of the stress. The stresses and deformability increase with increasing porosity value. The lowest deformability and stress values were obtained up to material porosity 0.5. In this case influence of porosity mode on the stress and strain state is insignificant. The high material porosity ($\gamma_p > 0.5$) and the absence of large interpores zones cause the relatively low stress values and high deformability of material.
*Keywords:* porous polymer, porosity, porosity mode, stress, strain, finite element method.

## INTRODUCTION

Microstructural modification of materials appears to be a promising route to change their mechanical properties for different applications. The prediction of effective properties of heterogeneous systems such as porous media or so-called porous composites, which exhibit a complex macrostructure, is of considerable interest [1]. Porous polymers, elastomers, which contain gas-filled inclusions or pores, represent a class of composite material with unique, tailorable properties. They exhibit several advantageous properties over the nonporous version of the matrix [2]. These materials can be significantly lower in density and more flexible than the nonporous polymers. Therefore, they have many fields of applications, including furniture, car, sewing, footwear trades, packaging, cushioning, shock absorption, and noise abatement.

Porous polymers may be fabricated by the addition of either a second phase with a lower density or by the addition of a foaming agent prior to curing [3]. The porosity value and mode, size distribution and arrangement of the pores, density of material depend on amount of aforesaid additions, technological processes and other factors.

Photographs of typical regions within the microstructure of the porous polymer are shown in Fig. 1.

The mechanical properties at the macroscopic level of porous materials are highly governed by their microstructure [4], which is characterised by the mechanical behaviour, geometrical arrangement, size and shape of pores presented in microstructure. Optimisation of these macroscopic mechanical properties can be achieved by carefully adapting the microstructure.

Porous materials usually are applied in the constructions or individual elements of them, which work under creep conditions. One of typical case of loading is the deformation of material by a constant force. For example, components of furniture, footwear, and shock absorbers work under constant value of impact loading, flexing, tensile conditions, for which large geometry and volume changes are characteristic. In such kinds of constructions the high stresses and regions of its concentrations are created [5, 6]. It results in failure initiation and latest fracture of element, which were periodically fatigued [7]. So, it is in great importance to know, which of factors has the greatest influence on failure initiation, i.e. influences the creation of high stress values during external loading conditions.

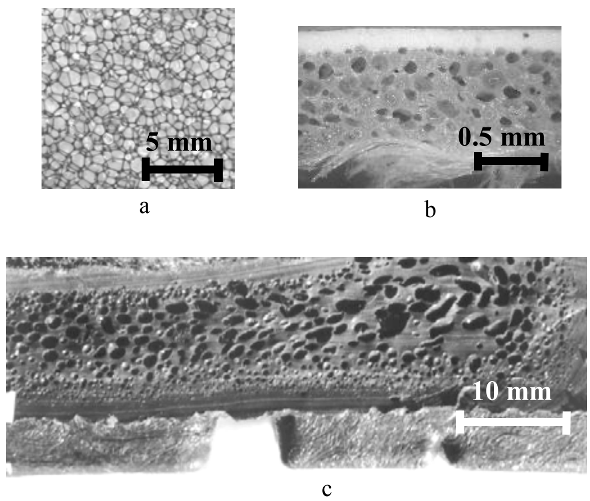


**Fig. 1.** Porous polymer structures: a – PU foam for furniture trade, b – artificial leather, c – PVC shoe sole

The development of such porous materials is generally done empirically, that is, a large number of samples with different microstructures are fabricated and tested, until specific requirements on the mechanical behaviour of these materials are fulfilled. These trial and error methods can be time consuming and expensive. The more fundamental studies are needed for a better understanding of the mechanical behaviour of these advanced materials. Relations between the microstructure and the macroscopic

*Corresponding author. Tel.: +370-37-300205; fax: + 370-37-353989.
E-mail address: *Daiva.Zeleniakiene@ktu.lt* (D. Zeleniakienė)

deformation behaviour are indispensable to predict macroscopic properties from the microstructure of the material.

There are many investigations, in which the influence of material porosity, cavity size, amount and distribution mode on the strength, thermal, filtering and other properties have been investigated [1, 4, 8 – 15]. These data related to soft polymer materials behaviour were observed only in case of loading by the constant displacement [16]. The main difference between solid and soft polymers is that for latter one is characteristic high deformability at low stress values. In that time fracture of solids appears at low deformation values (up to 3 %).

The aim of this investigation was to simulate the influence of pores size and its distribution mode as a function of main structural parameter of material heterogeneity in order to find out relation between soft polymer materials structure and its behaviour under creep.

## EXPERIMENTAL

The finite element method (FEM) was used to identify influence of material porosity mode on distribution of local stresses and strains. Analysis was performed by commercial finite element code ALGOR. The plane 2D model was made to utilize symmetry and periodicity, assuming that there are no trough-the thickness stresses in the plane. Four-node quadri-lateral "PLANE" elements with four degrees of freedom in each node were used. The exact number of elements of each model depends on model type and porosity.

The obtained models are over-simplified representation of porous materials structure, which was observed in many natural or artificial composite materials (Fig. 1). In order to obtain the influence of porosity mode, three types of plane models, which differ from each other in porous size and its distribution mode, were investigated. Model I (Fig. 2, a) was designed with one-sized pores, which lay in parallel rows with equal distance between porous in each direction. The diameter of these pores was $d_1$. Model II (Fig. 2, b) was created on the basis of Model I: symmetrically additional porous elements, diameter of which was $d_2 < d_1$, were added in interpores zones, located between pores $d_1$. Model III consisted pores of three sizes that varied according selected criteria: $d_3 < d_2 < d_1$. Schematically this model is presented in Fig. 2, c.

All models were deformed by constant tensile force ($F = 1.33$ N). The value of force was chosen in that way that a problem would be solved within plane of plasticity. The deformation scheme is presented in Fig. 3.

Young's modulus of matrices material was $E = 3.98$ MPa and Poison's rate – $\mu = 0.46$. This material was used for previous investigations, so the choise of this material is done for comparison purposes.

In order to predict properties, or properly interpret relationship between tensile behaviour and microstructure of porous material, the influence of main structural parameter – material porosity for all types of models has been investigated. This parameter was evaluated according to the changes of pores diameter $d_1$, $d_2$ and $d_3$. The ratio between pores diameter and main measure of model $l$ ($l = 50$ mm) was proportionally changed according to these

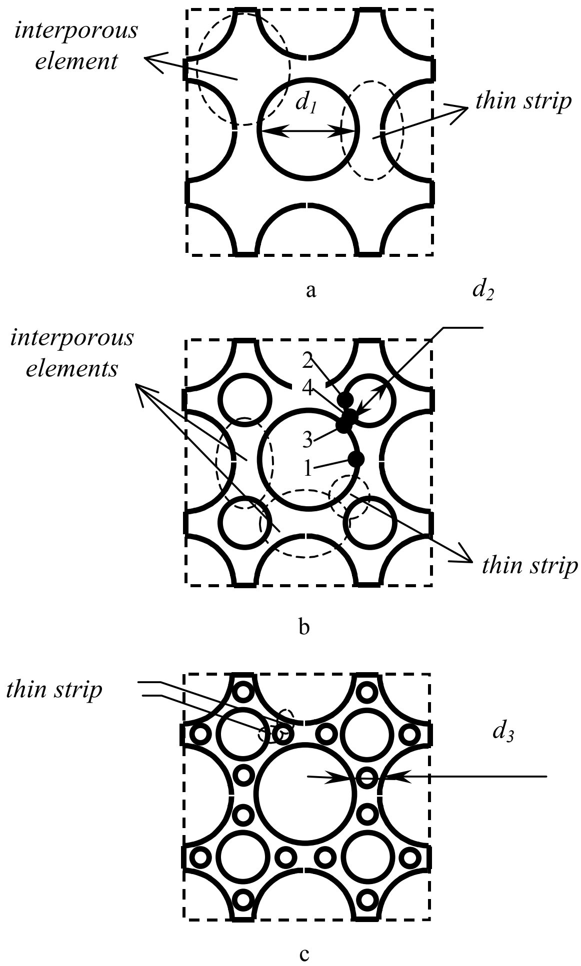


**Fig. 2.** Schematic presentation of Model I (a), Model II (b) and Model III (c); 1, 2, 3, 4 – the location of control points for stress state evaluation

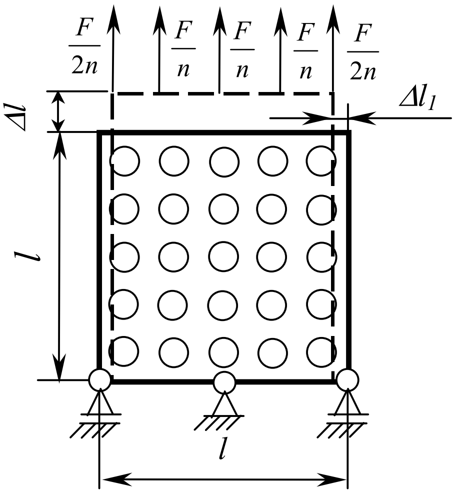


**Fig. 3.** The deformation scheme used for investigations; $l$ – edge of model, $F$ – tensile force, $n$ – the amount of finite elements by the edge of model

expressions: $d_1/l = 0.01 \div 0.20$, $d_2/l = 0.02 \div 0.12$, $d_3/l = 0.02 \div 0.04$. In all cases the distance between pores centres was constant.

As a rule, materials porosity is defined as a ratio of the volume of voids to the total volume of material. As the simulation was related to plane models, porosity $\gamma_p$ can be determined from relation:

$$\gamma_p = \frac{\sum_{i=1}^{m} S'_{pi}}{S'_{mod}} = \frac{\pi(n_1^2 d_1^2 + n_2^2 d_2^2 + n_3^2 d_3^2)}{4l^2}, \quad (1)$$

where $S'_p$, $S'_{mod}$ are the areas of pores and model, respectively; $n_1$, $n_2$, $n_3$, are the amount of pores in the row (the subnumbers relates to pores diameter $d_1$, $d_2$, $d_3$); $l$ is the plane dimensions of model; $m$ is the amount of pores types.

If presumption is made that dimensions of plane model are equal in cross-section dimensions of cubic model with gradually distributed spherical pores, the volume porosity $\gamma_t$ can be expressed as:

$$\gamma_t = \gamma_p \frac{2(n_1^3 d_1^3 + n_2^3 d_2^3 + n_3^3 d_3^3)}{3l(n_1^2 d_1^2 + n_2^2 d_2^2 + n_3^2 d_3^2)}. \quad (2)$$

However, it is possible to pass an infinite number of sections through a cubic model. The chosen section depends on the stress and strain state. Two dangerous sections of the cubic model element are shown in Fig. 4, for the loading conditions presented in Fig. 3. The section A–A element is adequate to the element of plane Model I, which length and width are equal to $a$. The width of element from section B–B is equal to $a$, also, but the length is $\sqrt{2}\,a$. So, if the plane Model I was based on the elements of cross-section B–B elements, the porosity $\gamma_p$ would be less and (2) would be invalid. The previous results showed that the higher stresses were induced in model constructed from A–A elements. Due to that for investigations the 2D model was based on section A–A, because it was more dangerous in the viewpoint of fracture.

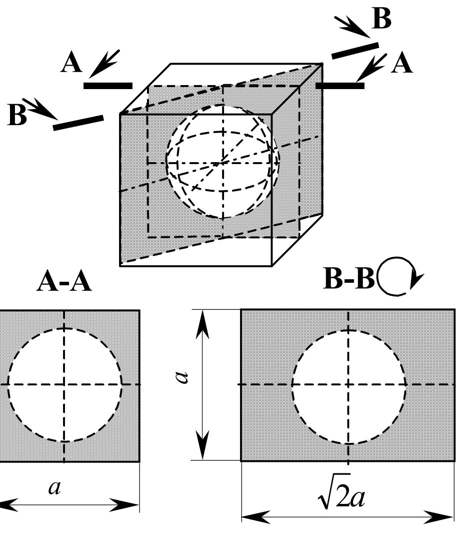


**Fig. 4.** The cross-sections of cubic model elements

The influence of material porosity on the stress state changes was evaluated according to the obtained principal stress $\sigma_1$ values at the control points presented in Fig. 2, b. The influence of material porosity on the strain state changes was evaluated according to total strain of model and strain values of polymer in the contour zone of each pore.

## RESULTS AND DISCUSSIONS

**Model I.** The influence of material porosity $\gamma_p$ on the stress changes for Model I (Fig. 2, a) is presented in Fig. 5. The plot indicates that increase of model porosity results in the increase of stress values. It seems that increase of porosity up to 0.5, stress values increase insignificantly, i.e., the stresses increase about two times. The increase of porosity from 0.5 up to 0.75 results in the drastic increase of stress values in control point 1. In the case of porosity equal to $\gamma_p = 0.75$, stresses are about 20 times higher than those in the case of porosity equal to $\gamma_p = 0.002$. As a reason of this it can be changes in material geometry, i.e., between pores in equator zones only thin material strips are formed, while interpores zones are relatively large and wide (Fig. 2, a).

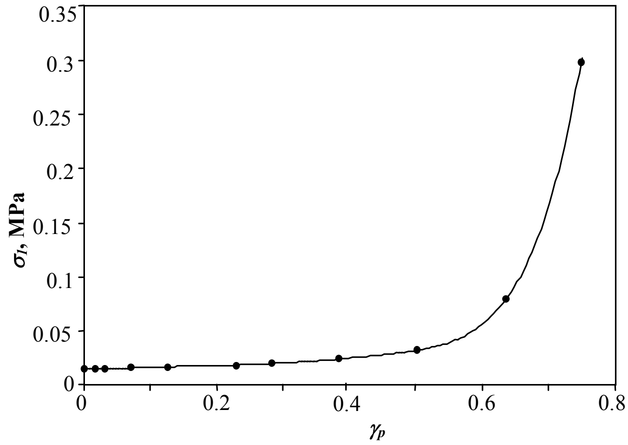


**Fig. 5.** The influence of porosity $\gamma_p$ on principal stress $\sigma_1$ changes for Model I in control point 1

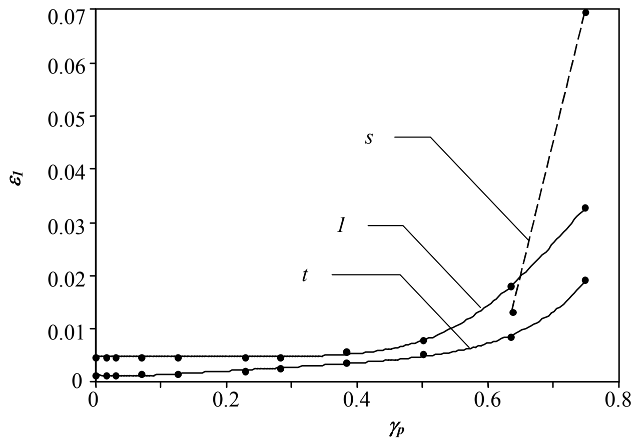


**Fig. 6** The influence of porosity $\gamma_p$ on principal strain $\varepsilon_1$ changes for Model I: *1* – strain of polymer in the contour zone of pore $d_1$, *t* – total strain, *s* – strain of strip

The influence of porosity $\gamma_p$ on strain $\varepsilon_1$ is shown in Fig. 6. It seems that the total strain and the strain of polymer in the contour zone of pore increase insignificantly as the material porosity increases up to 0.5. As the porosity is higher than 0.5, deformability increase is more significant. In the case of porosity $\gamma_p = 0.75$ total strain of Model I is equal to 0.02 (2 %). It is 14 times higher than that for nonporous material at the same loading conditions. The strain of thin strip is 4 times higher than total strain of model. Due to this the significant increase of stresses is obtained in these thin strips (Fig. 5).

**Model II.** The model containing pores of diameter $d_1$ and $d_2$ has been investigated (Fig. 2, b). The model was created in such way that diameter of pores $d_1$ would be equal to $0.16l$, because there was no significant increase of stresses in Model I in this porosity case ($\gamma_p$ =0.5). The porosity was changed only by variation in pores diameter $d_2$ and $d_1 = const$. The influence of material porosity $\gamma_p$ on the stress state changes is shown in Fig. 7. For comparison purposes, in the range of $\gamma_p = 0.5 \div 0.75$, stress changes for Model I is shown, also. The data indicate that stresses of Model II increase with the increasing of porosity like in the case of Model I. Up to porosity 0.7 principal stress values in Model II are only insignificantly higher than those for Model I; at highest porosity values they are lower than those for Model I. It seems that the stress state is influenced not only by the porosity value and mode, but by the control point location, also. As the material porosity increases, redistribution of stresses appears. Maximum stress values are obtained not in the point 1 zone, but in this of points 3 and 4 (Fig. 2, b). Changes of the material porosity practically do not influence in the stress values on control point 1. In that time for control points 3 and 4 significant increase of stress values with increase of material porosity is characteristic.

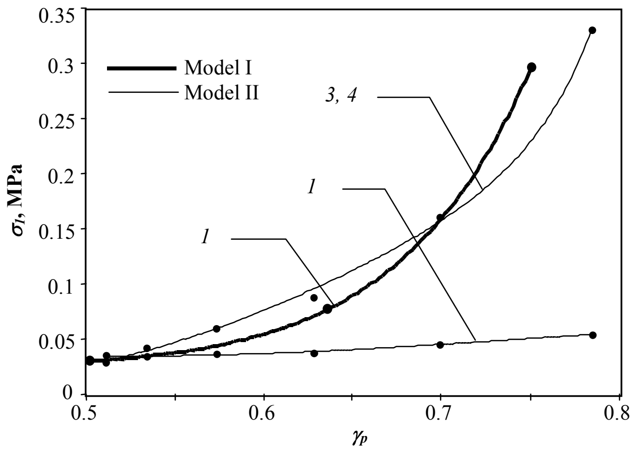


**Fig. 7.** The influence of material porosity $\gamma_p$ on stress $\sigma_1$ for Models I and II (curves numbered as in Fig. 2, b)

In Fig. 8 the influence of material porosity $\gamma_p$ on strain $\varepsilon_1$ for Model II is shown. For the comparison of obtained results, the influence of porosity in the range of $0.5 < \gamma_p < 0.75$ on the total strain of Model I is presented, also. The increase of the material porosity in Model II results in the increase of material deformability. When porosity is $\gamma_p = 0.75$, total strain for Model II is equal to 0.06 (6 %) and it is 3 times higher than that for Model I. When $\gamma_p = 0.79$, the total strain is 0.08. Besides, when porosity is in the range of $0.51 < \gamma_p < 0.65$ higher deformability of the polymer in the contour zone of pore $d_2$ is found. Otherwise, in the case of porosity $0.65 < \gamma_p < 0.78$ higher value of strain was found in the zone of pores $d_2$. The explanation of this behaviour can be related to the decrease of interporous element stiffness with the increase of pore diameter $d_2$. So, the stiffness decreases only near pores $d_2$, when $d_2$ is relatively low. Due to this polymer near this pore $d_2$ can be deformed more than near $d_1$. The small pores do not influence on the deformation behaviour of polymer layers located near pore $d_1$. When diameter of pores $d_2$ is higher ($\gamma_p > 0.65$) the distance between pores contours decreases and results in the loss of interpore element stiffness. Then pores $d_1$ diameter along tension direction increases and shows that deformability of all over polymer increases. Especially it is expressed for polymer layers located in the zone of 45° degrees in respect to the tension direction, i.e. in the zone of control points 3 and 4 (Fig. 2, b).

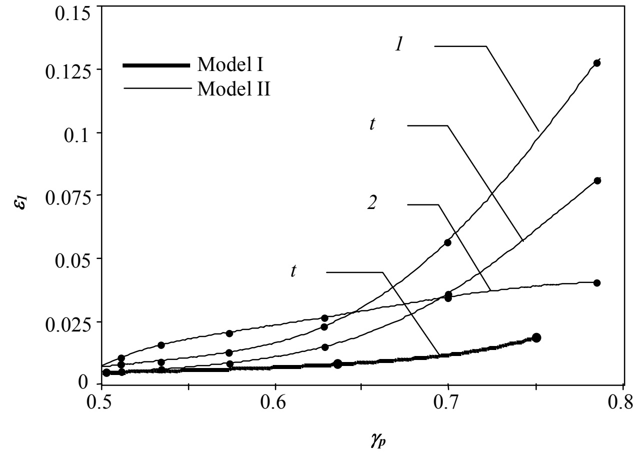


**Fig. 8.** The influence of material porosity $\gamma_p$ on strain $\varepsilon_1$ for Models I and II; 1, 2 – strains of polymer in the contour zone of pores $d_1$ and $d_2$, $t$ – total strain

The above-presented results suggest that at similar stress values Model II shows higher deformability than Model I.

**Model III.** The porosity of this model was changed by the increase of pores with diameter $d_3$ (Fig. 2, c). The size of pores $d_1$ and $d_2$ was constant and equal like those in Model II at porosity $\gamma_p = 0.7$, because stress values at this porosity mode were lowest.

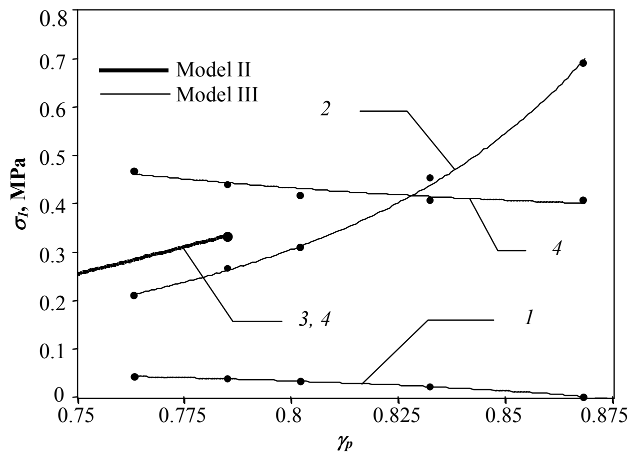


**Fig. 9.** The influence of material porosity $\gamma_p$ on stress $\sigma_1$ for Models II and III (curves numbered as in Fig. 2, b)

The obtained data are presented in Fig. 9. It seems that stresses increase as porosity increases. In this case clear dependence of the porosity mode on the stress state was obtained, also. When the pores diameter $d_3$ is relatively

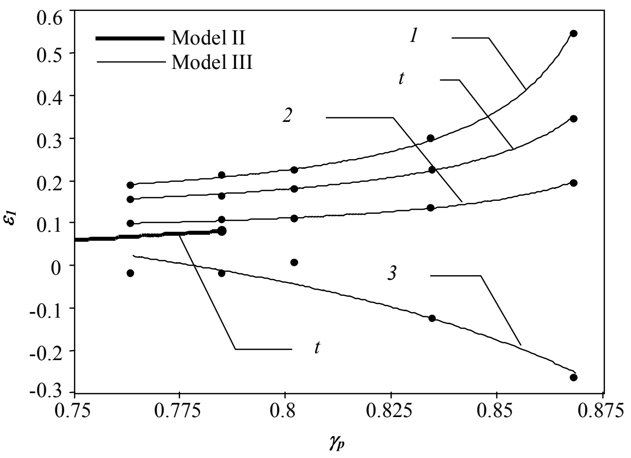


**Fig. 10.** The influence of material porosity $\gamma_p$ on strain $\varepsilon_1$ for Models II and III; 1, 2, 3 – strains of polymer in the contour zone of pores $d_1$, $d_2$ and $d_3$, $t$ – total strain

low, highest stress values are obtained in the zone of control points 3 and 4. That is the same as for Model II. But for the porosity higher than 0.84 stresses are higher in the zone of point 2. Explanation of the obtained results can be based on the analogical reasoning as for Model II: the increase of the material porosity results in the reduction of interpores zones near pores $d_3$ (Fig. 2, c). The maximal stress values were obtained in thin strips, axis of which is perpendicular to the tension direction. The control point 2 is located exactly in this zone and that is why the stress values in this point are highest. In all investigated porosity range stresses in Model III are higher than those in Model II, but the differences between them are not significant. Otherwise, the deformability of Model III is markedly higher than that for Model II. The total strain of Model III is about 6 times higher than those obtained for Model II (Fig. 10).

## CONCLUSIONS

The numerical finite element method was used for the identification stress and strain state in porous polymer material under creep conditions in dependence on the porosity mode.

By the variation of porosity mode it was obtained that at similar stress state different deformability can be reached.

The highest local stresses were found in the boundary between polymer and pore. Values of them are influenced by both porosity size and their distribution. The increase of porosity results in the increase of stresses and deformability. The low porosity values (up to $\gamma_p = 0.5$) only marginally influence in the stress state and deformability. The high material porosity value ($\gamma_p > 0.5$) and the absence of large interpores zones cause the relatively low stresses and increase deformability of material.

The determination of microstructure influence on the porous materials macro properties can be applied for prediction of material behaviour.

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