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Researches of mechanical behaviour of the bone micro volumes and porous ceramics under uniaxial compression

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Abstract. The research results of the mechanics are presented and the effective mechanical characteristics under uniaxial compression of the simulative micro volume of the compact bone are defined subject to the direction of the collagen-mineral fibers, porosity and mineral content. The experimental and computer studies of the mechanics are performed and the effective mechanical characteristics of the porous zirconium oxide ceramics are defined. The recommendations are developed on the selection of the ceramic samples designed to replace the fragment of the compact bone of a definite structure and mineral content.

1. Introduction

The long-term experience of the synthetic materials' use to repair the bone elements by means of endoprosthesis replacement points out that the biochemical compatibility of the implant with the body is an essential [1, 2], although insufficient, condition for functioning of the implant - bone system as a whole. Their biomechanical compatibility is an important condition. It is known that a substantial difference in the elasticity of the bone and implant can result in the loss of the latter due to the subsequent resorption of the bone tissue, which is in contact with the implant.

As regards the biochemical compatibility with the body, the preferred materials for the endoprosthesis replacement of the bone tissue are those referred to the ceramics class. Ceramics are identical to the inorganic bone matrix in the type of chemical bond.

The goal of research within the context of this paper is to develop the recommendations on the selection of the individual ceramic implants designed to replace the fragment of the compact bone of a definite structure and mineral content.

To achieve this goal in the course of the research the mechanical behavior is studied and the effective mechanical characteristics under uniaxial compression of the simulative micro volume of the compact bone and porous ceramics are defined; the experimental studies of the mechanical behavior of the produced porous zirconium oxide ceramics are performed and its effective mechanical characteristics are defined.

2. Materials and methods

The computer simulation of the mechanics of compact bone fragments and ceramic samples was performed in the software package ANSYS.

The geometrical model of the compact bone tissue micro volume (Figure 1) was based on a real image of the natural bone microstructure.

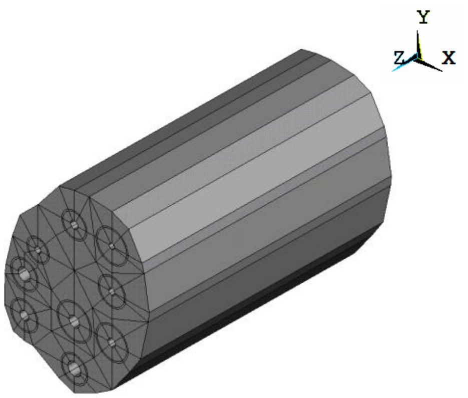

Figure 1. Geometrical model of compact bone tissue

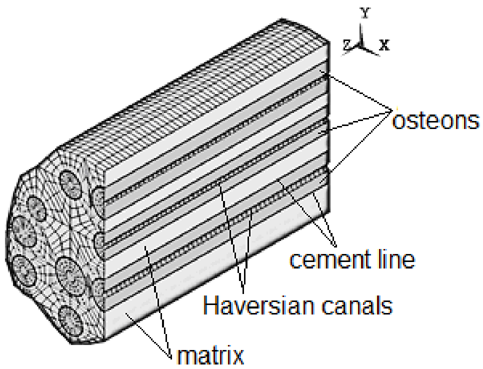

Figure 2. Finite element model of compact bone tissue micro volume

The micro volume was simulated as a reinforced composite material comprising the reinforcing structural elements, i.e. the osteons with the Haversian canals inside, the matrix and the cement streak separating the osteons and the matrix (Fig. 2). The total porosity of the simulative fragment of the compact bone P was derived by Haversian canals being explicitly simulated (Fig. 2), and Volkmann's canals being implicitly considered in the calculation of the effective mechanical characteristics of the structural elements of the simulative micro volume.

The material of the structural elements of the simulative micro volume of the compact bone was considered transversely isotropic. The effective mechanical properties of the matrix material and the reinforcing elements, osteons, were calculated subject to the volume ratio of the collagen and mineral components, the direction of the collagen- mineral fibers [3], the porosity due to the presence of Volkmann's canals.

The ceramics samples of porosity from 7 to 70 % were produced from the fine powder of zirconium oxide partially stabilized with yttrium oxide. The available pores in the ceramics structure on one side intend to ensure the ceramics integration with the bone tissue, and on the other side - to reduce the elasticity modules to the values comparable with elasticity modules of the bone. The adequate level of the ceramic samples porosity has been achieved both by using the pore-forming additives and without them. Figure 3 shows the histograms of pore size distribution of the obtained ceramic samples with porosity 7% and 60%. The uniaxial compression tests were performed on the universal testing machine "Instron-1185" at the constant loading rate of $3•10^{-4}$ c^{-1}.

The geometric models of ceramic samples with porosity 7%, 40% and 60% were constructed based on the histograms of pore size distribution of ceramics obtained experimentally (Fig. 3). Figure 4 shows the finite element models of ceramic samples with different geometry of pore space.

The stress-strain state of the model samples of the compact bone tissue and ceramics was calculated using the method of the finite elements.The task was solved within the context of the linear elasticity theory.

3. Results and Discussion

Figure 5 presents the calculation results of the longitudinal elastic modules of the compact bone tissue samples with the different directions of the collagen-mineral fibers (I type - transverse fibers, I±45º type - fibers are arranged at an angle of ±45º in the neighboring osteon lamellas, II type – the fibers change their direction from perpendicular on parallel to a bone axis in the osteon lamellas, III type - longitudinal fibers) with different mass fraction of the minerals α and porosity P under axial compression as compared to the experimental results of P. Zioupos et al [4], X. N. Dong, X. E. Guo [5].

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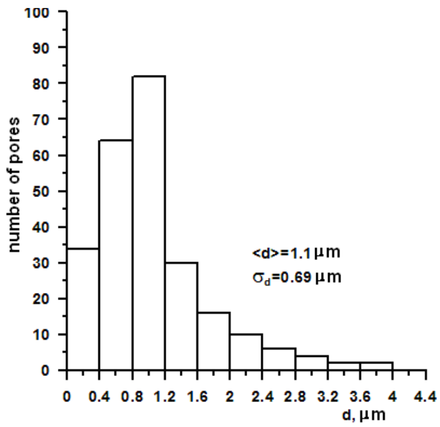
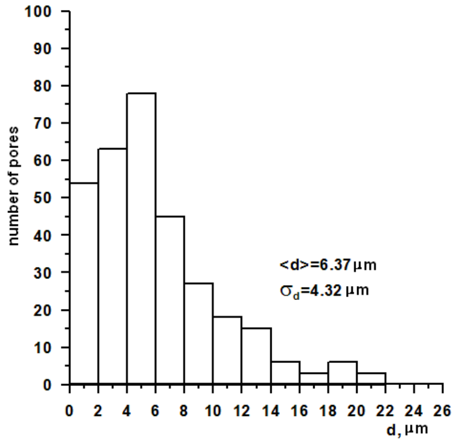


θ=7% (a)



θ=60% (b)

Figure 3. The histograms of pore size distribution of the obtained ceramic samples

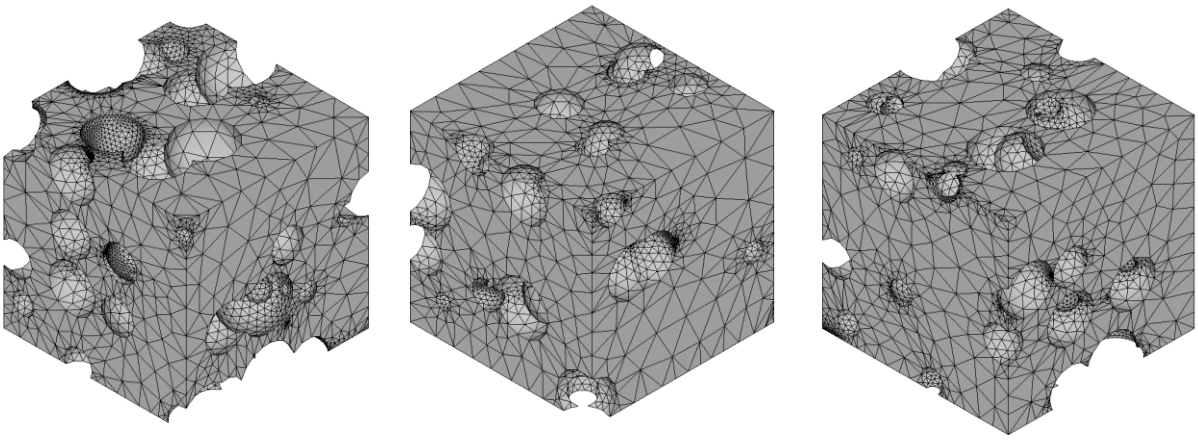


Figure 4. Finite element models of ceramic samples with different geometry of pore space (θ=7%)

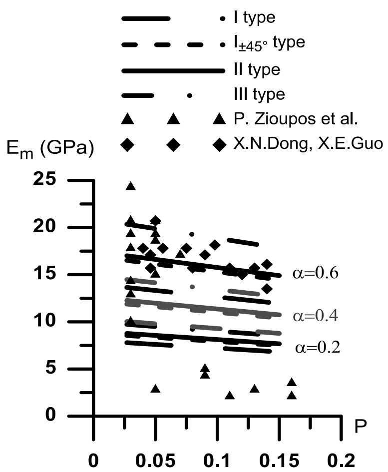


Figure 5. Dependence of longitudinal elastic modules of micro volumes of compact bone tissue with different mineral content (α) from porosity (P)

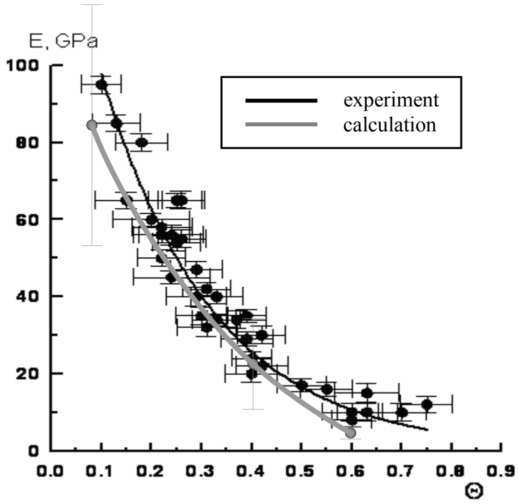


Figure 6. The dependence of the effective elastic modulus of the ceramics on the specific pore volume

The micro volume of the cortical bone of I ±45º type and the micro volume of type II, independent of their porosity, have the relatively equal longitudinal elastic modules (Fig. 5), though differ in the character of the stress and strain distribution, that is determined by the varied non-uniform deformation response of micro volume in the directions mutually transverse to the load application.

Calculations of elastic modules of model ceramic samples with different geometry of the pore space under uniaxial compression were conducted (Fig. 6). Results showed that the geometry of the pore space of the ceramic samples significantly influences the value of the modulus of elasticity.

As a result of the uniaxial compression tests of the zirconium ceramics samples $ZrO_2(Y_2O_3)$ there has been derived the dependence of the longitudinal elastic modulus (Fig. 6) and the ultimate compression strength of the ceramic samples on the specific volume of pores θ.

The comparison of the produced calculated elastic modules, the ultimate compression strength of the bone fragments, calculated using the expression of C. J. Hernandez [6], and experimentally produced mechanical properties of the ceramics (see the table below) demonstrated, that the ceramics with a specific pore volume of 50 to 60 % have the elasticity modules close to the compact bone with the mineral weight percent of 40 to 55 % and the porosity of 3 to 15 %.

Table 1. The calculated and experimental effective mechanical parameters of the compact bone tissue and ceramics

Ceramics $ZrO_2(Y_2O_3)$ (experiment)			**Compact bone (calculation)**				
θ	**E, GPa**	**σ_c, MPa**	**α**	**P**	**Type**	**Em, GPa**	**σ_c, MPa**
0.50	16.87	110.0	0.55	0.15	III	16.4	109.7
0.52	15.50	98.0	0.50	0.10	III	15.8	93.8
			0.45	0.027	III	15.5	81.2
0.54	14.17	87.3	0.45	0.15	III	13.7	62.7
			0.40	0.027	III	14.2	58.5
0.56	12.98	77.7	0.40	0.10	III	13.2	50.3
			0.40	0.15	III	12.6	45.1
0.58	11.89	69.2	0.45	0.15	II	11.6	62.7
			0.40	0.027	$I_{\pm45^o}$	11.9	58.5
0.60	10.89	61.6	0.40	0.15	II	10.7	45.1
			0.40	0.15	$I_{\pm45^o}$	10.5	45.1

4. Conclusion

The effective mechanical characteristics of the model micro volumes of compact bone and ceramic samples are defined. Results showed that the micro volume of the cortical bone of I ±45º type and the micro volume of type II, independent of their porosity, have the relatively equal longitudinal elastic modules, the geometry of the pore space of the ceramic samples significantly influences the value of the modulus of elasticity. The experimental studies of the mechanical behavior of the produced porous zirconium oxide ceramics were carried out. Its effective mechanical characteristics are defined. The recommendations were obtained on the selection of the ceramic samples designed to replace the fragment of the compact bone of a definite structure and mineral content. The ceramics with the porosity of 50-56 % may become a candidate to replace the compact bone fragment that has the collagen-mineral fibers arranged parallel to a bone axis. The ceramics with the porosity of 58 to 60 % may become a candidate to replace the compact bone fragment that has the collagen-mineral fibers, changing its direction from one to another lamellas or the one arranged at angles ±45º.

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