University of Pannonia
Chemical Engineering and Material Sciences Doctoral School

The production of biomorphous ceramics and glass-ceramics

Ph.D. THESIS

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2022

Introduction and Aim of Research

In the field of human implantology, a wide variety of metal and ceramic-based material systems have been developed over the past 50 years to replace bone deficiencies due to various causes. However, the development of suitable bone substitutes requires material systems that, in addition to having appropriate mechanical properties, should stimulate osteointegration through the metabolic processes of the human body. This thesis deals with the preparation of new types of bioactive biomorphic composites and the study of their physical, chemical and biological properties as a function of composition and technological parameters.

In the Department of Materials Engineering, bio-glass-ceramic composites using bovine bone have been successfully produced in previous years, showing excellent mechanical and bioactive properties. These materials were successfully used to form coatings on titanium-based substrates by plasma sputtering. In my research work related to this topic, I used pretreated bovine bone as a substrate on which I intended to develop a bio-glass-ceramic coating by impregnation technology.

The aim of my doctoral thesis is to increase the mechanical properties of the pre-treated animal bone scaffold by using bio-glass based coatings and to develop a coating with different solubility of with calcium phosphate additives, which solubility can be controlled by its composition in simulated body fluids. In addition to these properties, I investigated the correlation between the raw materials, the structure of the developed coatings and the impregnation parameters used, and verified the cytotoxicity of the test specimens by a succinate dehydrogenase-based viability test.

A further aim of my research is to determine the dependence of the properties of magnetic hydroxyapatite composites on the fabrication parameters. The nanocomposites are prepared by a wet-chemical route, by precipitation of magnetite and hydroxyapatite phases in parallel and in two separate steps, respectively. In this part of my PhD thesis, I investigate the influence of the preparation method on the phase composition and microstructure of magnetic nanocomposites, the relationship between the magnetic properties of the single- and two-step composites and the colour coordinates, the behaviour of magnetic hydroxyapatite composites in simulated body fluids, and the dependence of bioactivity and magnetic properties on the preparation parameters.

Experimental

In my doctoral thesis, animal bone, bio-glass and calcium phosphates was used to produce a composite material system that is novel based on the literature discovered during the research. In the experiments, I developed a bio-glass based coating of different composition on the surface of pretreated bovine bone used as a bio-template, using an impregnation method. The quality of the impregnant, dry matter content, amount of excipients and coating conditions were systematically varied to optimise the production parameters. After determining the appropriate manufacturing parameters, bio-glass-ceramic composites with different phase compositions and solubilities of calcium phosphate containing bio-glass-ceramic coatings suitable for bone grafting were prepared. The experiments were carried out to investigate the elemental and phase composition, thermal properties, microstructure, mechanical properties, bioactivity and cytotoxicity of the heat-treated bovine bone, the bio-glass frit and the test specimens coated with different additives (mixtures containing hydroxyapatite, β-whitlockite and α-whitlockite). The microstructure was studied by investigating the crystalline phases formed and the thickness of the coating formed. The thermal properties were characterized by measuring the coefficients of thermal expansion, apparent porosity and body density. The wetting of the biosemplate surface by bio-glass melt was investigated by heating microscopy. The mechanical properties of the specimens were determined by measuring Vickers microhardness, flexural- and compressive strength. The bioactivity of the biosheets with different composition of coatings was determined by simulated body fluid solubility assay and cytotoxicity was checked by mitochondrial succinate dehydrogenase viability assay.

A further aim of my research was the preparation of magnetic iron oxide nanocomposites embedded in hydroxyapatite. Two different wet chemical synthesis methods were used to prepare the nanoparticles. The properties and applicability of the nanocomposites were determined by examining the phase composition, magnetic properties, solubility in simulated body fluids and color finger properties. The phase composition of the composites was characterized by X-ray diffraction and the microstructure by electron microscopy. Magnetic properties were investigated by measuring the susceptibility and the colour coordinates of the nanocomposites were determined by color measurement. The bioactivity of the particles was characterized by their solubility in simulated body fluids.

New scientific results: thesis statements of the doctoral dissertation

1.) I was the first who formed a homogeneous bio-glass based coating on the surface of pretreated bovine bone using an impregnation method without the use of excipients. I have demonstrated that using ethanol as dispersant, a suspension with an average particle size below 5 μm and a dry solids content of 5 m/m% is optimal for the preparation of the coating (Jakab et al. 2021).

2.) By determining the thermal properties of the coating materials, I have demonstrated that the bio-glass I use wets the substrate surface well and forms a compressive stress coating upon annealing. I have demonstrated that the application of bio-glass coatings containing hydroxyapatite, β-whitlockite and α-whitlockite crystalline phase can increase the microhardness, compressive and flexural strength of animal-derived template (Jakab et al. 2021).

3.) I have demonstrated experimentally that the use of hydroxyapatite with an atomic ratio of 1.67 Ca/P, β-whitlockite with a Ca/P ratio of 1.52 and α-whitlockite with a Ca/P ratio of 1.44 can control the leaching of Ca and P in simulated body fluids and increase the bioactivity of scaffolds compared to bio-glass frit and pretreated bovine bone (Jakab et al., 2022).

4.) Using a succinate dehydrogenase-based viability assay, I demonstrated that a bioglass-based coating on the surface of biosheets reduces cytotoxicity compared to a heat-treated, protein-embedded biosheet (Jakab et al. 2021).

5.) I have demonstrated by X-ray diffraction and electron microscopy studies that the rate of crystallization of magnetic hydroxyapatite composites can be controlled depending on the preparation method. Furthermore, I have demonstrated that the crystallite size of magnetite and hydroxyapatite produced by co-deposition of phases is nearly the same, but significantly smaller, than that of nanocomposites prepared in two steps (Jakab et al. 2019).

6.) Through the determination of magnetic susceptibility and color vibration characteristics, I have demonstrated that the susceptibility of nanocomposites prepared by parallel synthesis of magnetite and hydroxyapatite and the change in color shift relative to magnetite are inversely proportional, while there is a direct proportionality when precipitated in two steps. My experiments have demonstrated that the CIELAB colour coordinate measurements can be used to estimate the magnetic property of nanocomposites as a function of the preparation method (Jakab et al. 2019).

7.) Using simulated body fluid precipitation studies, I have demonstrated that co-deposition of magnetite and hydroxyapatite can produce a nanocomposite of higher bioactivity (Jakab et al. 2019).

Core publications from the PhD thesis work

Publications in international periodicals:

Jakab, M., Enisz-Bódogh, M., Makó, É., Kovács, K., Orbán, Sz., Horváth, B. (2020) Influence of wet chemical processing conditions on structure and properties of magnetic hydroxyapatite nanocomposites, *Processing and Application of Ceramics,* 14(4), 321-328 (Q3, IF: 1,804)

Jakab, M., Enisz-Bódogh, M., Kovács, K., Keil, E., Babos, Gy., Feczkó, T. (2021) Structure and properties of bovine bone-glass ceramic composite scaffolds, *Processing and Application of Ceramics,* 15(4), 428-435 (Q3, IF: 1,504)

Jakab, M., Enisz-Bódogh, M., Kovács, K. (2022) Apatite forming ability of bioglass coated bovine bone scaffolds, *Processing and Application of Ceramics,* 16(3), 276-282 (Q3, IF: 1,504)

English language posters:

Jakab, M., Enisz-Bódogh, M. (2019) From wood to bone: How to convert wood structures into biomimetic hydroxyapatite scaffolds, *Twenty-first Annual Conference YUCOMAT 2019 & Eleventh World Round Table Conference on Sintering,* ISBN: 978-86-919111-4-0, 146

Jakab, M., Enisz-Bódogh, M. (2019) The production of biomorphous cermaics and glass-ceramics, *5th Conference of the Serbian Society for Ceramic Materials,* ISBN: 978-86-80109-22-0, 46

Other scientific publications

Abdullah, T. A., Juzsakova, T., Rasheed, R., Ali, M., Salman, A. D., Le, P-C, Zsirka, B., Sebestyén, V., Jakab, M. (2022) V2O5, CeO2 and Their MWCNTs Nanocomposites Modified for the Removal of Kerosene from Water, *Nanomaterials*, 12, 189 (Q1, IF: 5,076)

Al-sareji, O. J., Meiczinger, M., Salman, J. M., Al-Juboori, R. A., Hashim, K. S., Somogyi, V., Jakab, M. (2022) Ketoprofen and aspirin removal by laccase immobilized on date stones, *Chemosphere*, 311 (Q1, IF: 8,943)

Boros, A., Varga, Cs., Prajda, R., Jakab, M., Korim, T. (2021) Development of Waste-Based Alkali-Activated Cement Composites, *Materials*,14, 5815 (Q2, IF: 3,748)

Bódis, E., Jakab, M., Bán, K., Károly, Z. (2022) Functionally Graded Al2O3–CTZ Ceramics Fabricated by Spark Plasma Sintering, *Materials*, 15, 1860 (Q2, IF: 3,748)

Császár, Zs., Juzsakova, T., Jakab, M., Balogh, Sz., Szegedi, Á., Solt, H., Hancsók, J., Farkas, G. (2021) Continuous Flow Friedel–Crafts Alkylation Catalyzed by Silica Supported Phosphotungstic Acid: An Environmentally Benign Process, *Topics in Catalysis* (Q2, IF: 2,47)

Hajba-Horváth, E., Németh, B., Trif, L., May, Z., Jakab, M., Fodor-Kardos, A., Feczkó T. (2022) Low temperature energy storage by bio-originated calcium alginate-octyl laurate microcapsules, *Journal of Thermal Analysis and Calorimetry* (Q2, IF: 4,755)

Keszei, J. S., Pekker, P., Fehér, Cs., Balogh, Sz., Jakab, M., Nagy, L., Skoda-Földes, R. (2020) Application of sol-gel methods to obtain silica materials decorated with ferrocenyl-ureidopyrimidine moieties. Preparation of hollow spheres and modification of a carbonelectrode. *Microporous and Mesoporous Materials*, 308, 110380 (Q1, IF: 5,34)

Kocsis, G., Szabó-Bárdos, E., Fónagy, O., Farsang, E., Juzsakova, T., Jakab, M., Pekker, P., Kovács, M., Horváth, O. (2022) Characterization of various titanium-dioxide-based catalysts regarding photocatalytic mineralization of carbamazepine also combined with ozonation. *Molecules*, 27, 8041 (Q1, IF: 4,927)

Mersel, A. M., Fodor, L., Pekker, P., Jakab, M., Makó, É., Horváth, O. (2021) Effects of Preparation Conditions on the Efficiency of Visible-Light-Driven Hydrogen Generation Based on Cd0.25Zn0.75S Photocatalysts, *Catalysts*, 11, 1534 (Q2, IF: 4,501)

Nagy, E., Hegedüs, I., Vitai, M., Jakab, M. (2020) Study of Prepared α-Chymotrypsin as Enzyme Nanoparticles and of Biocatalytic Membrane Reactor, *Catalysts*, 10, 1454 (Q2, IF: 3,520)

Wafi, A., Szabó-Bárdos, E., Horváth, O., Makó, É., Jakab, M., Zsirka, B. (2021) Coumarin-based quantification of hydroxyl radicals and other reactive species generated on excited nitrogen-doped TiO2, *Journal of Photochemistry and Photobiology A: Chemistry,* 404, 112913 (Q1, IF: 3,306)

Zsinka, V., Miskolczi, N., Juzsakova, T., Jakab, M. (2022) Pyrolysis-gasification of biomass using nickel modified catalysts: the effect of the catalyst regeneration on the product properties, *Journal of Energy Institute,* 105, 16-24 (Q1, IF: 6,47)