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Bioactivity and mechanical properties of $Na_2O{\cdot}CaO{\cdot}SiO_2{\cdot}P_2O_5$ modified glasses

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Abstract

The purpose of this work was to study the influence of B_2O_3 and Al_2O_3 additions on the bioactivity and mechanical properties (modulus of rupture; MOR) of eight glasses in the $Na_2O{\cdot}CaO{\cdot}SiO_2{\cdot}P_2O_5$ system, so that a bioactive glass with the good mechanical properties compares to others is obtained. For investigating their bioactive capacity these glasses were soaked in a simulated body fluid (SBF) at different time intervals. The changes in surface structure were examined by scanning electron microscopy (SEM) and EDX line scan and X-ray microanalysis to determine the compositional profiles through the substrate up to the surface. In some glasses the presence of a rich calcium and phosphorous layer was observed that, according to other studies, correspond to the apatite layer growing in all glasses with B_2O_3/Al_2O_3 ratio between 0.5 and 0.55. For MOR determination of these glasses, the three point loading test was used.

Keywords: Bioactive glasses; B. Electron microscopy; E. Biomedical applications

1. Introduction

Bioactive glasses are materials, which can adhere to bone and tissues through the formation of calcium phosphate (hydroxyapatite; HAp) at the interface of the material. This layer is chemically and structurally equivalent to the mineral phase in bone and is responsible for interfacial bonding. A small change in the composition can produce a drastic effect on its behavior, whether it is inert, resorbable or bioactive. There are a wide range of bioactive glasses, however, the time dependence of bonding, the strength of the bond, the mechanism of bonding and the thickness of the bonding zone differ for various materials [1–4]. On the other hand, certain bioactive glass compositions can bond to soft and hard tissues [5,6].

In previous studies, it has been shown that there are three key compositional features of bioactive glasses that distinguish them from traditional $Na_2O{\cdot}CaO{\cdot}SiO_2{\cdot}P_2O_5$ glasses and make the surface highly reactive when exposed to aqueous medium: (1) less than 53 mol% SiO_2 and (2) high Na_2O and CaO content and (3) CaO/P_2O_5 ratio >5 [4]. Gross et al. [3] have described bonding from a biological point of view. The overall reactions resulted in the formation of a silica-rich layer, which attaches firmly to the bone. This type of glasses can have a high dissolution, which can reduce its long-term reliability. Addition of alumina is the traditional way to reduce the solubility of glass, but it can inhibit bone bonding on bioactive glasses [7,8], nevertheless, additions up to 1.5 wt.% Al_2O_3 can be used without interfering with mineralization of the osteoid [8].

In the present study, formation of the apatite layer on the surface of $SiO_2{\cdot}Na_2O{\cdot}CaO{\cdot}P_2O_5$ glass and the effect of B_2O_3/Al_2O_3 ratio addition were investigated in simulated body fluid (SBF), an acellular aqueous solution, which has ion concentration equal to that of human blood plasma [9].

2. Experimental procedure

The glasses were prepared taking into account the index of bioactivity I_B, introduced by Hench [10], using the ternary diagram SiO_2–CaO–Na_2O with P_2O_5 constant. The index is

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given by the relationship $I_B = 100/t_{0.5bb}$ where $t_{0.5bb}$ is the time for more than 50% of the surface to get attached to the bone. Andersson et al. [11] described in vivo behavior of the glasses of the system used in this work, developing a phenomenological model. By regression analysis it was found that a relationship exists between the glass and its behavior with tissues, which was called reaction number (RN) and that for the glass to be bioactive, it should have a value above 5. All the glasses prepared in this work should be bioactive as they agree with the two former statements and the three key compositional features previously mentioned.

The raw materials were SiO_2, $CHNaO_3$, $CaCO_3$, P_2O_5, B_2O_3, and Al_2O_3 with 99% purity. The different mixtures of the nominal compositions shown in Table 1 were melted in a platinum crucible for 6 h, at a heating rate of 5 °C/min, a holding time of 60 min at 1000 °C for eliminating carbonates and 1 h at 1450 °C for glass homogenization. The melt was poured on to 500 °C preheated graphite molds of cylindrical shape with 10 mm diameter. At least five pieces were prepared for each glass and their surfaces were polished with 3–4 μm diamond paste.

The immersion fluid, called simulated body fluid had ion concentration almost equal to that of human blood plasma [9]. It was prepared by dissolving reagent-grade chemicals of NaCl, $NaHCO_3$, KCl, $K_2HPO_4{\cdot}3H_2O$, $MgCl_2{\cdot}6H_2O$, $CaCl_2$, and Na_2SO_4 in distilled water. It was buffered at pH 7.25 with 50 nm tris(hydroxymethyl)-aminomethane ($NH_2C(CH_2OH)_3$) and 45 nm hydrochloric acid (HCl). The fluid temperature was kept at 36.5 ± 0.5 °C, and was completely free from living cell or organic substances [12]. The samples immersed in permanently agitated SBF were taken out at different week intervals, gently washed by acetone, and embedded in a cold epoxy resin. The cross sections were polished down to 1 μm, and then coated by a conductive carbon film to be analyzed by electron microscopy (SEM)-EDX.

The modulus of rupture was determined from three-point loading method, using rectangular specimens of dimension 6 mm × 6 mm × 30 mm. All specimens were abraded and carefully polished for diminishing residual stresses. The span length was 20 mm, and a loading rate of 0.42 kg/mm^2 min was employed. For each glass, nine measurements were made. The modulus of rupture (S) was calculated from the Eq. (1), where L is a breaking load; a, separation of adjacent loading and support edges; b, width of specimen and d, thickness of specimen [13].

$$S = \frac{3La}{bd^2} \quad (1)$$

Table 1
Glass composition by synthesis (wt.%)

Glass	SiO_2	Na_2O	CaO	P_2O_5	B_2O_3	Al_2O_3	B_2O_3/Al_2O_3
1	49.0	23.0	23.0	4.0	0.4	0.6	0.66
2	49.0	23.6	22.0	4.0	0.5	0.9	0.55
3	49.0	23.8	21.6	3.8	0.6	1.2	0.50
4	49.0	24.0	21.0	3.6	0.9	1.5	0.60
5	48.0	24.9	20.8	3.5	1.0	1.8	0.55
6	47.0	25.5	20.7	3.4	1.3	2.1	0.62
7	46.0	26.3	20.0	3.7	1.6	2.4	0.66
8	46.0	26.2	19.8	3.3	2.0	2.7	0.74

3. Results and discussion

3.1. Bioactivity

A biomaterial for bone substitution is called bioactive if it elicits a specific biological response at the interface of the material, which results in the formation of an attachment between the tissues and the material [4]. The basis of the bone bonding property of bioactive glasses is the chemical reactivity of the glass in body fluids. The interface reactions between a bioactive glass and bone allow the development of SiO_2-rich and Ca and P-rich layers. The silica-rich layer is due to the Na^+ exchange with H^+ or H_3O^+ from the simulated body fluid. This exchange is easy because Na^+ ions are not part of the glass network, they only modify it by forming non-bridging oxygen bonds. The release of network-modifying ions is rapid for highly bioactive glasses. The dissolution process occurs by breaking Si–O–Si bonds through the action of hydroxyl ions (OH^-), releasing silicon into the solution as $Si(OH)^{4-}$, this silica layer acts as a preferential nucleation site for the CaP layer. Migration of Ca^{2+} and $P_2O_5^{3-}$ groups to the surface through the SiO_2-rich layer and incorporation of soluble calcium and phosphorous from the solution generated the formation and growth of an amorphous $CaO–P_2O_5$-rich film, which was previously identified by other authors [14].

It must be pointed out that the primary advantage of bioactive glasses is their rapid rate of surface reaction, which leads to fast tissue bonding. Fig. 1 shows the development of the reaction layer; the silica-rich layer and the CaP-rich, layer with soaking time for composition 1. After 2 weeks of immersion only a silica layer is obtained, after 3 weeks there is the development of the CaP-rich layer, starting from 16 to 23 μm for 3 and 5 weeks of soaking, respectively. In spite of having the highest RN value, the B_2O_3/Al_2O_3 ratio is 0.66 and it can be seen that the CaP layer growth begins after 2 weeks; therefore, glasses of composition 1 could be considered biocompatible but not as bioactive glasses due to the fact that the CaP layer is not produced rapidly enough so as to establish a stable bond with the bone or the soft tissues.

The Fig. 2(a) and (b) correspond to composition 2 and, Fig. 2(c) and (d) to composition 3 at two different soaking times: 2 and 5 weeks. It shows the Si and CaP layers for all conditions; however, the sample of composition 3 soaked during 5 weeks depicted higher porosity on the silica-rich layer. This could be due to a higher Na^+ mobility towards the surface. These compositions having a higher B_2O_3 content, as compared to glass 1, could be considered as bioactive

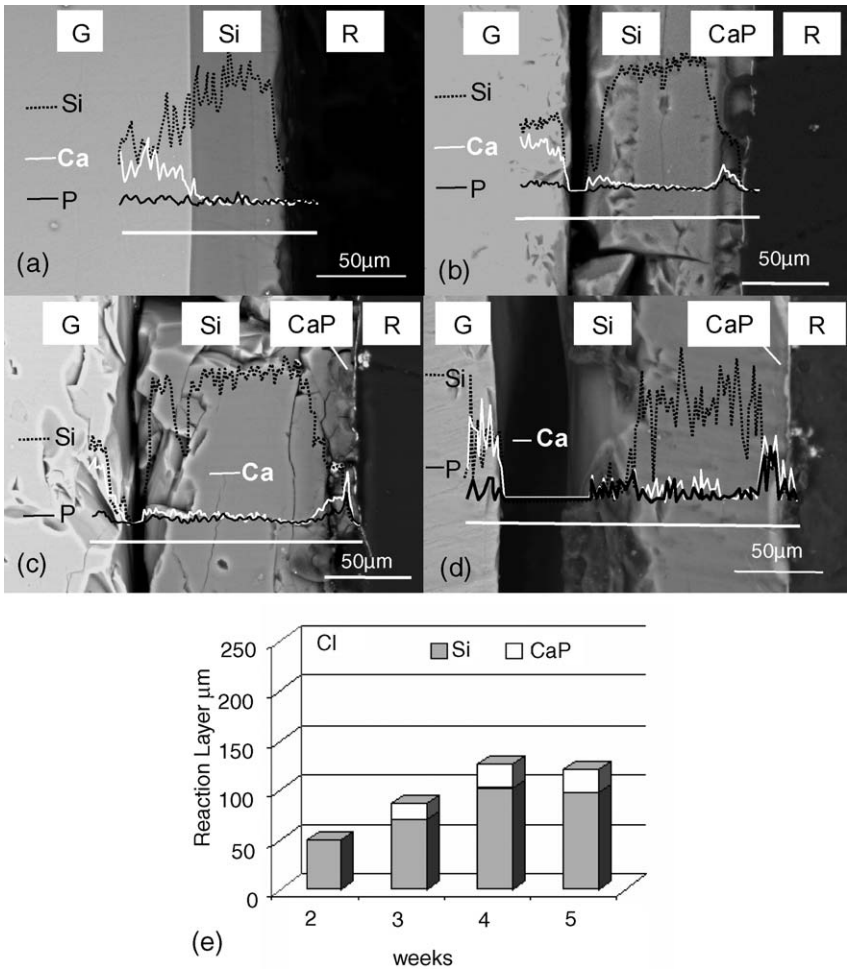

Fig. 1. (a–d) shows the SEM images of a cross-section of glass C1, soaked in simulated body fluid for: (a) 2, (b) 3, (c) 4, and (d) 5 weeks with its line scan profiles superimposed, the reaction layer is characterized by the different gray tones: G-glass, Si-Silicon-rich layer, CaP-calcium and phosphorous-rich layer. (e) Shows the reaction layer Si and CaP development with time in this type of glass.

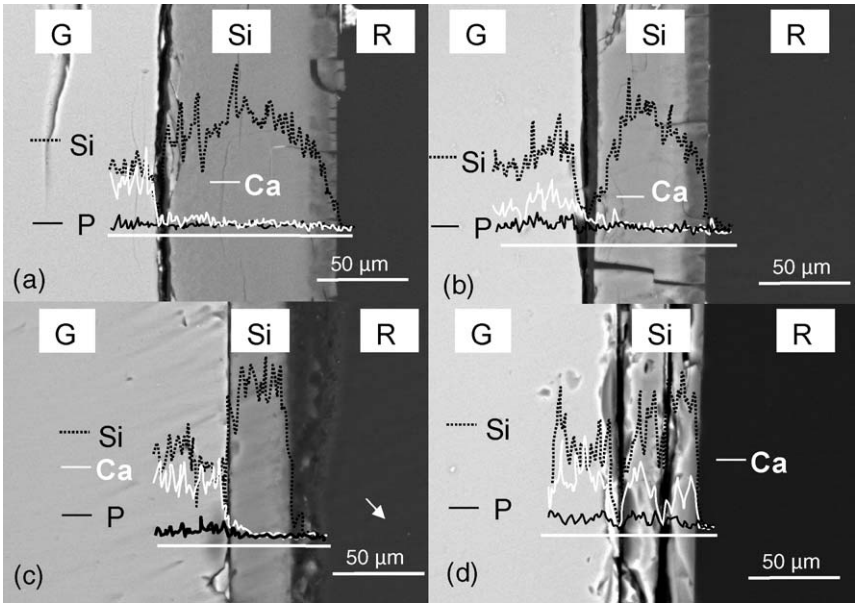

Fig. 2. Scanning electron microscopy images of a cross section of glasses C2 (a and b) and C3 (c and d) soaked in simulated body fluid for 2 (a and c) and 5 (b and d) weeks, with their line scan profiles superimposed.

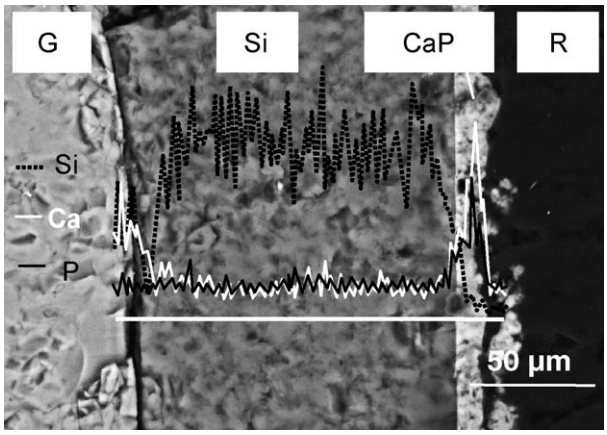

Fig. 3. Scanning electron microscopy image of Glass 5 at 5 weeks soaking time, with their line scan profile superimposed.

glasses due to the CaP layer formation at the shortest soaking time tested.

Fig. 3 shows the scanning electron microscopy image of a cross section of glass composition 5 (C5) after 5 weeks soaking time; it can be observed that in the presence of both Si-rich and CaP-rich layer, again the silica layer presents high porosity due to Na^+ diffusion which increases the Ca^{2+} and $P_2O_5^{3-}$ migration towards the surface to promote the CaP-rich layer formation. The B_2O_3/Al_2O_3 ratio in this case is 0.55.

In Fig. 4(a–c) the behavior of the other glass compositions studied, C4-4 (a), C6-4 (b), and C7-4 (c) can be observed. They showed only a silica-rich layer probably due to B_2O_3/Al_2O_3 ratio, which is above 0.6. In these cases, both multivalent ions oxides could have a network role in the glass structure, therefore, the substrate has a high chemical resistance, and the silica-rich layer is stabilized. As there is no formation of the Ca- and P-rich layer, these glasses of compositions 4, 6, and 7 could be identified as biocompatible. Fig. 4(d) shows the cross section and compositional analysis of glass composition 8 (C8) without any compositional change. The reaction process was completely inhibited due to the decrease in glass solubility. Glasses of this composition could be considered as bioinert.

The behavior of glasses was measured from the growth of Si and CaP layers at different times, the results being given in Fig. 5. Here, it can be seen that all compositions which should be bioactive, they follow the necessary conditions, i.e., they have a RN above 5, leading to behave in different ways. It must be pointed out that although the glass of composition 2 has a content of multivalent ion oxides near to 1.5 wt.% and, glasses of compositions 3 and 5 above this percentage; its bioactivity is not affected. These glasses show a bioactive behavior, due to the presence of B_2O_3 presence that somehow allows a better Na^+ ions migration towards the glass surface when it is combined with Al_2O_3 in a specific ratio. It was found that bioactivity is controlled by B_2O_3/Al_2O_3 ratio between 0.5 and 0.55 in the composition range selected in this work; apparently the B_2O_3/Al_2O_3 ratio is a dominant factor in Na_2O, CaO, SiO_2, and P_2O_5 glasses.

3.2. Modulus of rupture (MOR)

The Fig. 6 shows the modulus of rupture behavior for different glasses and with B_2O_3/Al_2O_3 ratio. The value represented in this figure is an average of nine measurements, being in a range between 90 and 180 MPa. Comparing these results with values obtained by other authors in glasses of similar composition such as 20 MPa

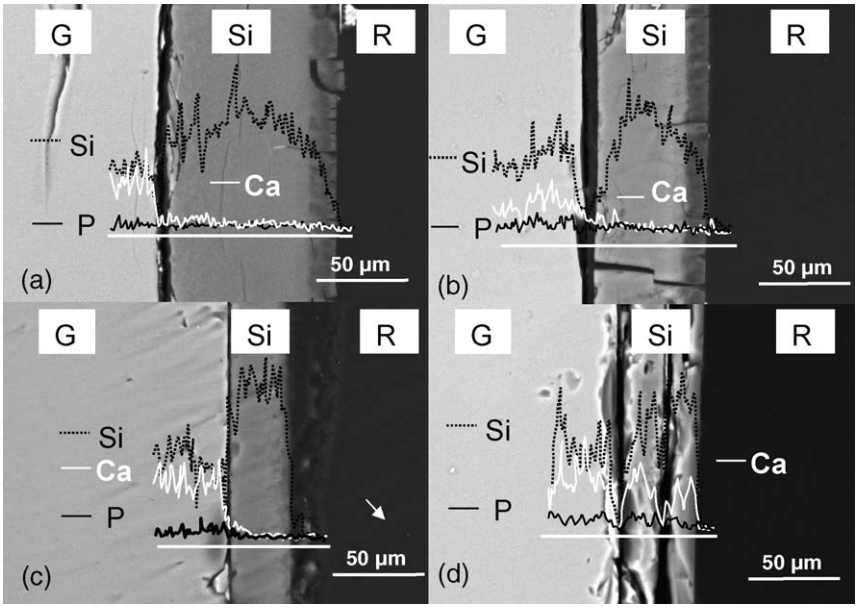

Fig. 4. Scanning electron microscopy images of a cross section of glasses C4 (a), C6 (b), C7 (c), and C8 (d) soaked in simulated body fluid for 5 weeks, with their line scan profiles superimposed.

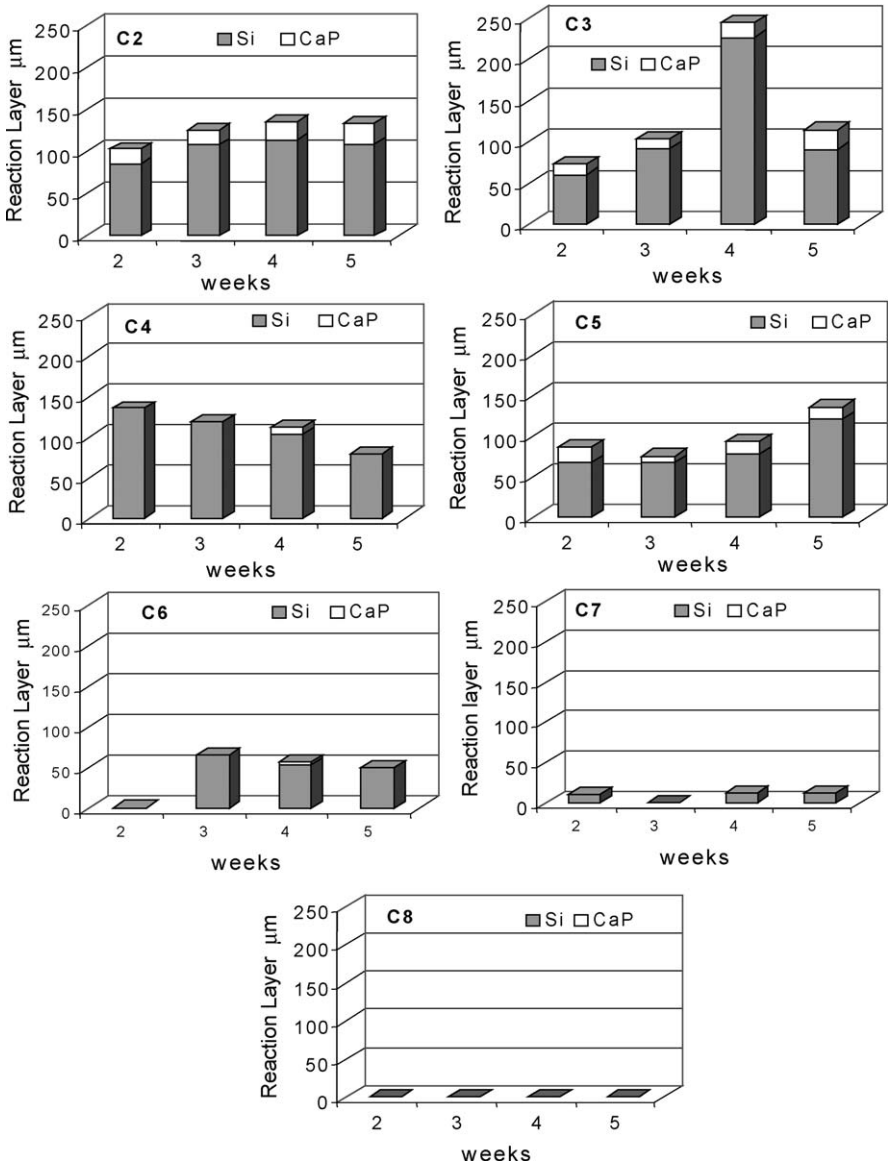

Fig. 5. Reaction layers development due to bioactivity reaction in SBF, with time for C2–C8 glasses, the RN and B_2O_3/Al_2O_3 for this glasses are included.

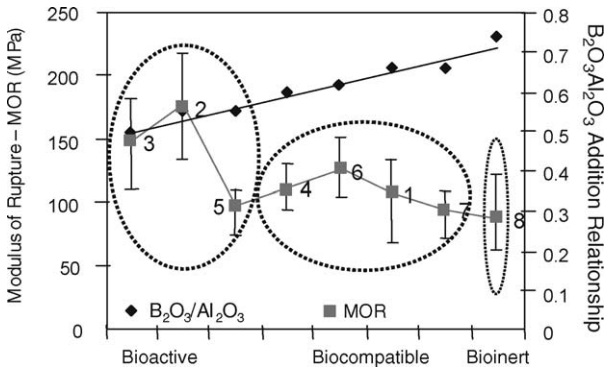

Fig. 6. Modulus of rupture for the different glasses; the composition is numbered on the MOR values, the type of glass is selected by circles and the B_2O_3/Al_2O_3 is included.

and 40–60 MPa by Andersson et al. [11] and Hench [14], respectively, an improvement in the modulus of rupture can be observed .

4. Summary

The results suggest that in modified bioactive glasses containing B_2O_3 and Al_2O_3, it is necessary to control the B_2O_3/Al_2O_3 ratio due to its influence on the alumina stabilization effect, in order to allow the CaP deposition. A bioactivity behavior was found in glasses exceeding the multivalent ion additions with Al_2O_3 content higher than 1.5 wt.% and for a B_2O_3/Al_2O_3 ratio between 0.5 and 0.55. The MOR values improved, as the B_2O_3/Al_2O_3 relationship

allows the Al_2O_3 addition to increase with the consequent mechanical improvement.

References

[1] L.L. Hench, E.C. Ethridge, Biomaterials: An interfacial Approach, Academic Press, NY, 1982.

[2] L.L. Hench, E.C. Ethridge, Bioactive ceramics, in: P. Ducheyne, L.L. Lemons (Eds.), Bioceramics Materials Characteristics Versus In vivo Behavior, vol. 523, 1988, p. 54.

[3] U. Gross, R. Kinne, H.J. Schmitz, V. Strunz, e response of bone to surface active glass/glass ceramic, CRC Crit. Rev. Biocompat. 4 (2) (1988).

[4] L.L. Hench, R.J. Splinter, W.C. Allen, T.K. Greenlee Jr., Bonding mechanism at the interface of ceramic prosthetic marterials, J. Biomed. Mater. Res. 2 (1) (1972) 117–141.

[5] J. Wilson, G.H. Pigott, F.J. Shoen, L.L. Hench, Toxicology and biocompatibility of bioglass, J. Biomed. Mater. Res. 15 (1976) 805.

[6] J. Wilson, D. Noletti, Bonding of soft tissues to bioglass, in: T. Yamamuro, L.L. Hench, J. Wilson (Eds.), Handbook of Bioactive Ceramics, Bioactive Glasses and Glass Ceramics, 1, CRC Press, Boca Raton, FL, 1990, pp. 280–302.

[7] U. Gross, V. Strunz, The interface of various glasses and glass ceramics with bony implantation bed, J. Biomed. Mater. Res. 19 (1985) 251.

[8] O.H. Andersson, K.H. Karlsson, K. Kagasniemi, A. Yli-Urpo, Models for physical properties and bioactivity of phosphate opal glasses, Glasstech. Ber. 61 (1988) 300–305.

[9] J. Gamble, Chemical Anatomy, Physiology and Pathology of Extracellular Fluid, sixth ed., Harvard University Press, Cambridge, 1967.

[10] L.L. Hench, Bioceramics: from concept to clinic, J. Am. Ceram. Soc. 74 (7) (1991) 1487–1510.

[11] O.H. Andersson, G. Liu, K.H. Karlsson, L. Niemi, J. Miettinen, Juhanoja, In vivo behaviour of glasses in the SiO_2–Na_2O–CaO–P_2O_5–Al_2O_3–B_2O_3 system, J. Mater. Sci.: Mater. Med. (1990) 219–227.

[12] Y. Ebisawa, T. Kokubo, K. Ohura, T. Yamamuro, Bioactivity of $CaO{\cdot}SiO_2$ based glasses: in vitro evaluation, J. Mater. Sci.: Mater. Med. (1990) 239–244.

[13] ASTM C, 158–80 designation, Standard methods of flexure testing of glass, determination of modulus of rupture, in: Annual Book of ASTM Standards, 1991, pp. 108–113, ASM; Engineered Materials Handbook, Ceramics and Glasses, vol. 4.

[14] L.L. Hench, J. Wilson, An introduction to bioceramics, in: Advanced Series in Ceramics, vol. 1, World Scientific, London, 1993, p. 45.