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Macroporous hydroxyapatite as alloplastic material for dental applications

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In the dentistry field, synthetic hydroxyapatite can be conveniently used as semiabsorbable alloplastic material to solve a number of clinical problems. The hydroxyapatite structure influences bone ingrowth as well as its resorption. In particular, pore size must exceed 100 μm to allow new bone ingrowth. Because of its brittleness, highly porous hydroxyapatite is difficult to handle without causing damage, and, therefore, its mechanical performance has to be improved placing the material on a dense hydroxyapatite substrate. Dense/porous hydroxyapatite laminates can be obtained by slip casting technology. The method starts with the preparation of a ceramic powder–binder–solvent system. This slurry produces, after solvent evaporation, a soft green tape, that is successively baked at 300 °C to remove all organic component, and finally sintered at high temperature (1200 °C). The material porosity cannot be significantly modified by changes in the slurry composition and sintering temperature; therefore, the macroporous hydroxyapatite layer must be obtained using a porous hydroxyapatite powder. The powder is prepared by grinding of green tape pieces and the resulting coarse material is successively baked at 300 °C. Such material is mixed with a polymer solution and cast on a green tape substrate. Layer fractures are not observed in both film bulks and interface, because during sintering the consolidation of two layers happens simultaneously. In the resulting material, the first layer consisted of macroporous hydroxyapatite with high osteoconductive properties, and the second layer was a dense hydroxyapatite substrate able to improve the laminate mechanical properties.

1. Introduction

Nowadays, in dentistry a number of clinical situations require the solution of bone defects with different characteristics and extensions. In particular, in addition to the classical reconstruction of periodontal and traumatic bone lesions, several situations related to the use of osteointegrated implants, in the presence of a more or less serious loosening of the bone support, are possible. The necessity to replace a portion of the lost bone tissue has induced the development of specific biomaterials, so as to avoid the necessity of drawing autologous bone, an operation involving a longer surgical procedure and the possibility of postoperative complications.

The available materials are classified as alloplastic, homologous and heterologous. The alloplastic materials include: hydroxyapatite (HA), calcium phosphate, corals, and bioglass. The hydroxyapatite is included in the alloplastic materials, i.e., materials characterized by an osteoconductive activity, because they act as a substrate for the bone tissue ingrowth, but they do not have osteoinductive and osteoproliferative properties. The alloplastic materials can be classified as bioresorbable and non-bioresorbable. The first materials are principally indicated for the filling of cavity defects, interdental craters, and postoperative sites (to prevent the collapse of the alveolar ridge). Instead, the second type of material is preferably used, in combination with autologous bone, for the reconstruction of alveolar ridges. However, some disagreements about the alloplastic material properties are still present in the literature. In particular, some authors support the idea that the alloplastic materials can promote the formation of new bone by an osteoconductive mechanism [1–4], but most of the clinical studies describe exclusively their filling function, without evidence of osteoconductive properties. An evident advantage of these materials is that they are free from possible risks of disease transmission, whilst all this is possible with homologous

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and heterologous bone, that, on the other hand, are characterized by higher osteoconductive and osteoproliferative properties.

The structure of an apatite ceramic influences the bone ingrowth as well as its resorption. In particular, pore size or spaces between particles must exceed 100 μm for bone cell ingrowth to occur. A comparison between normal bone and porous HA structures shows a large similarity of both channels and space required for bone cell ingrowth. This is the reason for its considerable interest as a bone substitute. Mechanical properties are also very important factors that determine the subsequent easy handling of the bone-ceramic construct. The mechanical properties of porous calcium phosphate ceramics are currently a limiting factor in their widespread utilization [5]. These materials are extremely brittle, have a poor fatigue life, and fail in a brittle way with very little deformation to failure. Much research is currently being conducted to improve mechanical properties by altering the stoichiometry of the ceramic compounds. Weakness is, therefore, the principal limitation of a highly porous HA ceramic but dense HA has improved properties and, consequently, a dense/porous layered HA ceramic is expected to be a good compromise for a number of applications for the combination of high bonding–osteogenesis characteristics and adequate mechanical properties [6].

Dense/porous HA laminates can be easily made by slip casting [7]. This technique has been used for many years in the electronic ceramics industry for the manufacture of capacitors [8–11], and has more recently been developed for use in the production of structural ceramics. Bioceramics with different porosity and their laminates can be prepared directly by slip casting of the powders. Essentially, the method entails the dispersion of a ceramic powder in a suitable solvent, followed by addition of plasticizers and binders, which control the viscosity of the slip and provide strength and flexibility to the tape after drying. This slurry is then cast onto a glass plate, and once the solvent has evaporated, it contains 50–60% of ceramic powders by volume, the remainder being made of polymers and a small amount of porosity. The tape is at this stage flexible and can usually be removed without difficulties from the glass plate. The so produced green tapes, can be fired to make a thin dense ceramic film. This technology is really suitable for the preparation of dense-porous bioceramics because it offers the possibility to produce films with a graded microstructure through lamination of multiple tapes, that can be also formed into more complex shapes by pushing the sheet into a die cavity at modest temperatures (about 100 °C).

Here, the preparation by slip casting technology of layered HA films has been investigated. Two layers are contained in the laminates. The first one is a highly porous HA ceramic, with elevated osteophilic–osteoconductive characteristics, the second one is a dense HA ceramic with the function to improve the mechanical properties of the porous layer. Because the porosity scale required for bone cell ingrowth cannot be obtained just by adjusting the slurry composition and/or the sintering temperature, porous HA grains have been prepared by a slip casting–calcination process, and then used to prepare a highly porous HA layer by the same technology. Scanning electron microscopy (SEM) and dilatometry have been used to characterize the powder morphology, the structure of films obtained under different conditions, and the sintering process.

2. Experimental procedure

The HA powder used in this study was a commercially available product ($Ca_{10}(PO_4)_6(OH)_2$, hydroxyapatite for bioceramics, Merck, Germany) with a particle density value of 2.9 g cm^{-3}.

The two slurry formulations used are given in Table I. They were based on that already developed for Al_2O_3 and Al_2O_3/ZrO_2 powders, but adapted to the current case. In particular, these formulations are able to avoid variations in the HAp stoichiometry for the absence of phosphate-base dispersants. The slip-casting slurry was made by slowly dispersing the HA powder, in the dispersant solution (under stirring), followed by strong sonic treatment (5 min). The polymer (i.e. binder and plasticizer) was then added, and the slurry was stirred for about 24 h. Once prepared, the tapes were allowed to dry for 24 h and then stripped from the glass surface. Good quality tapes, without particle segregation, were obtained with thickness ranging from 150 to 200 μm.

A two-stage firing cycle (in air) was used in this study. During the first stage, the samples were heated slowly (70 °C h^{-1}) up to 600 °C. Literature works [11–13] and the dilatometric study of the densification process (made by a Linseis-Dilatometer Model 2046), have shown that the polymer used in this system burns in air at temperatures below 600 °C. The slow heating is required to minimize the potential risks for cracking due to the gas pressure built up, and to ensure a complete polymer combustion. This step was followed with a more rapid temperature rise (200 °C h^{-1}) up to the sintering temperature (i.e. 1200 °C), followed by a hold for 2 h.

For the preparation of laminated films with a high porous HA layer, HA grains with a certain level of porosity were obtained by grinding pieces of dry tape (uncalcined), made by the slurry with composition A, up to obtain a coarse powder. The powder was then calcined at 600 °C, so to burnout all organic components. Ten grams of the obtained porous grains were wetted with

TABLE I Slurry compositions

	HA	BuOH	T80	PVB (20%)	Santicizer (20% in BuOH)
Function	Ceramic mat	Solvent	Dispersant	Binder	Plasticizer
Sample A Amount (g)	4.022	6.007	0.101	8.657	0.535
Sample B Amount (g)	4.033	4.75	0.25	5.375	0.498

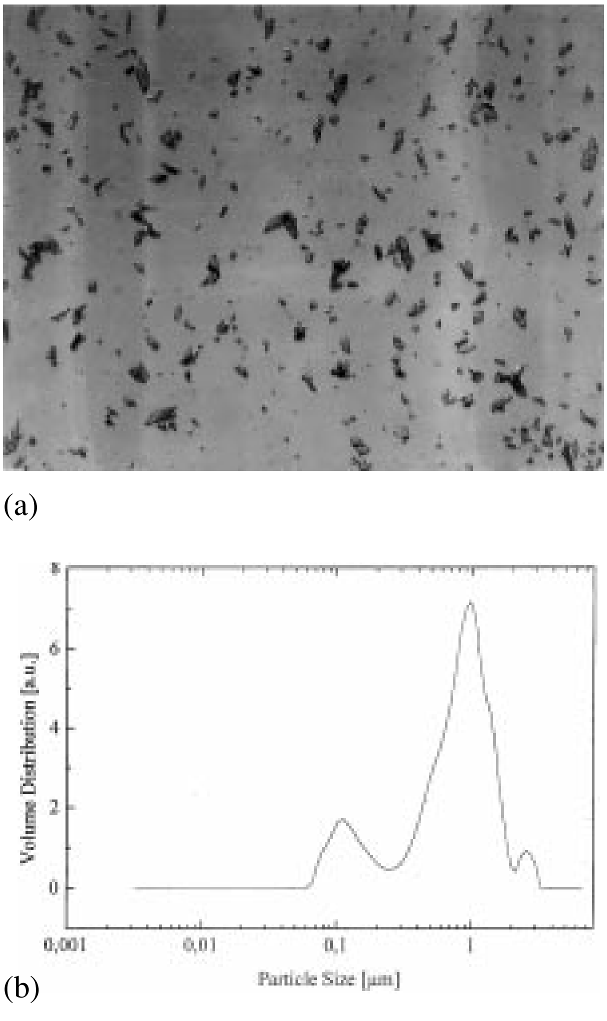
BuOH, and used to prepare a new slurry by addition of 21.5 g of binder solution in BuOH (20% by weight) and 1.3 g of Santicizer. Then, the slurry was cast on a piece of film prepared as described above (composition A), and fired for 2 h at 1200 °C.

SEM (Jeol AX-840A) was used to study the morphology of the specimen surfaces. The samples were mounted and sputter-coated with gold to reduce charging and to improve image quality.

3. Results and discussion

The microstructure of the starting HA powder is shown in Fig. 1. The HA particles had a needle-like shape of about 0.1×0.01 μm in size. A partial particle aggregation was visible in the powder. Consequently, the powder particle size distribution showed a trimodal behavior. No phases other than HA were revealed by X-ray diffraction (XRD).

The best slip-casting results were obtained using the slurry compositions given in Table I. The criteria for the selection of binders, solvents, plasticizers and other organic additives used in the preparation of these slurries are discussed in some detail. Alcohol can be used as solvent because it dissolves each one of the required organic components, and wets the HA particles without their dissolution. In particular, butanol was preferred because it showed a high ability to carry the powder in an order dispersion and the evaporation rate was slow enough to live a dense and uniform organic-ceramic composite. Both stearic acid and Tween80 (a mixture of oleic acid, sorbitol, and poly(ethylene oxide), ICI Speciality Chemicals) were optimum wetting agents because of their ability to keep the HA particles in a stable suspension by steric hydrance effect. In addition, during the solvent evaporation, these components permitted the particles to settle into a sufficiently dense packed green tape. A ratio dispersant/powder by weights equal to 0.0025 was found to be the optimum one. This quantity was theoretically evaluated on the basis of the powder specific surface area (56 $m^2 g^{-1}$ from Brunauer–Emmett–Teller (BET) measurements) and wetting agent dimensions. Poly(vinyl butyral) (MW = 40 000–70 000) was used as binder because it can be dissolved in BuOH, enhancing its viscosity and forming a thixotropic slurry. After solvent evaporation, the binder-coated HA particles were bonded together forming a strong dense green tape. Finally, a plasticizer (polyethylene glycol, MW 200 or, butylbenzylphthalate, Santicizer) was added to the polymer to expand it and to improve its distribution into the slurry. The decrease of the polymer glass transition point causes the required flexibility of the green tape. The plasticizer percentage in the polymer phase was about 24 wt %, and the polymer/powder weight ratio was 1.6. Antifoam agents were not required with both systems.



(a)

(b)

Figure 1 Starting HA powder microstructure (× 850) (a), and size distribution (b).

Both selected binder/plasticizer/defloculant systems are able to burnout at a relatively low temperature (< 500 °C) and in a non-oxidizing atmosphere. According to dilatometry (see Fig. 2) the solvent was totally removed under 200 °C and low-molecular-weight components disappear at 300 °C; instead the binder was burnt out at 400 °C. In both samples, the densification process started at about 800 °C and proceeded gradually with increasing temperature to result in the highest relative density at 1300 °C, as shown in Fig. 2. The double nature of the sintering jump can be explained on the basis of the microstructure observed for the HA powder. The sintering process starts involving just the particles located inside the aggregates, then a second process involving primary crystals follows.

The SEM micrographs in Fig. 3a, b show the microstructure of the sintered body (2 h at 1200 °C) of a sample obtained using the slurry of composition A. For materials made using the highest sintering temperature, the full particle coalescence and grain growth was observed. A low level of porosity was contained in the film, as shown in the fracture surface micrograph (Fig. 3b). The slurry composition can influence the sample morphology. Films obtained under the same sintering conditions (i.e. 2 h at 1200 °C), but using the slurry of composition B, showed a different microstructure. A particle bonding characterized by the formation of extensive interparticle necks was observed (see Fig. 4a, b). Essentially, the densification process was just a rearrangement of the particles contained in the grains with an initial neck formation at the contact points. The rearrangement consisted of slight movement or rotations of adjacent unities, so to increase the contact surface. The bonding occurred where the material transport was

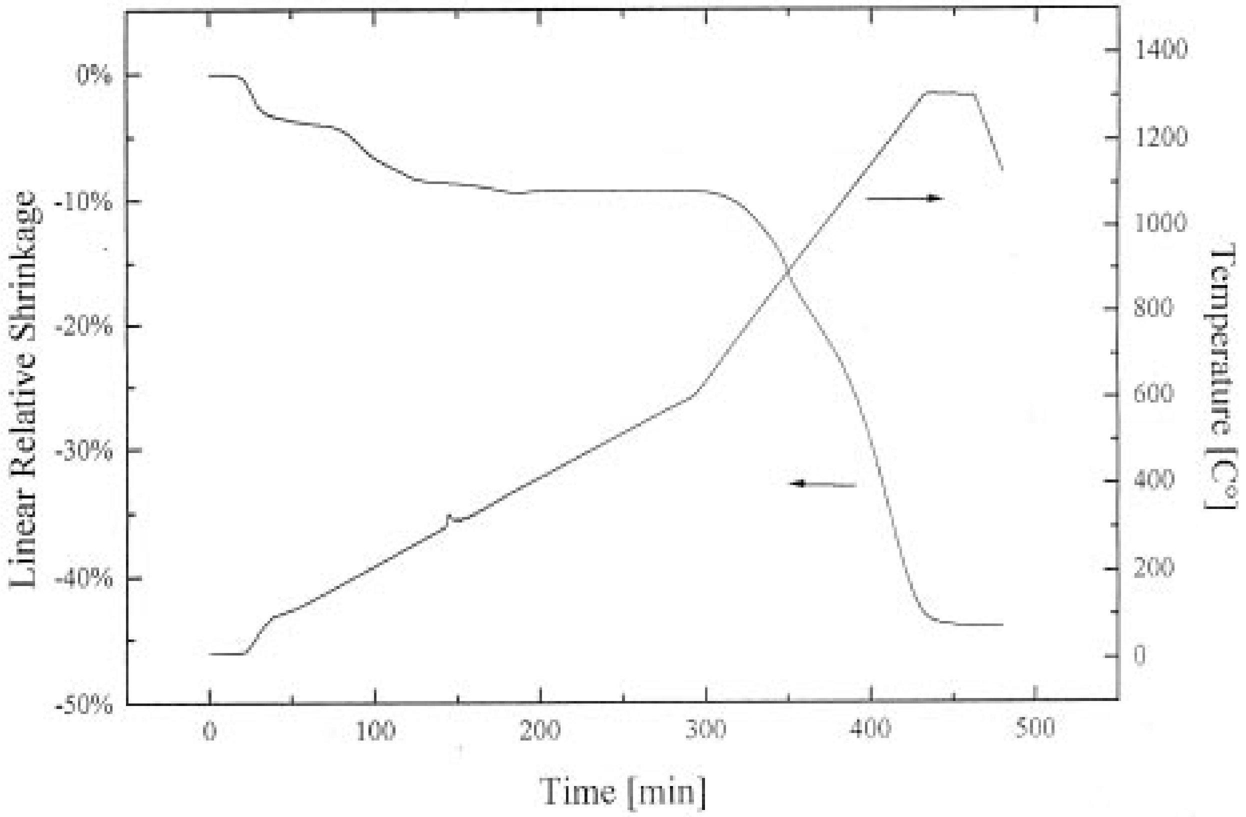
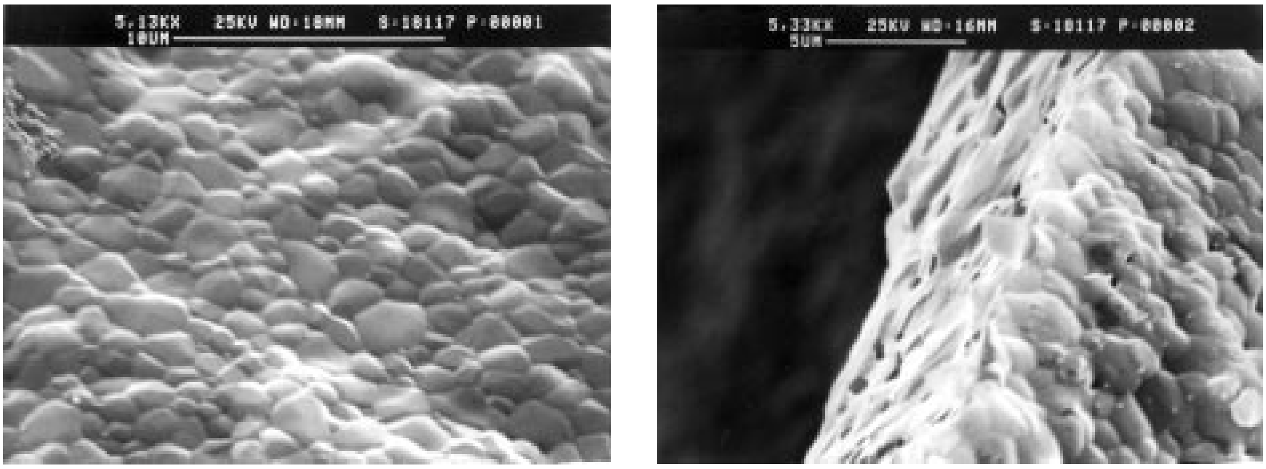


Figure 2 Behavior of the linear relative shrinkage with temperature for a sample prepared using the slurry with composition A.

possible and the surface energy was the highest. However, the channel sizes were lower than 100 μm, as required for bone cell ingrowth.

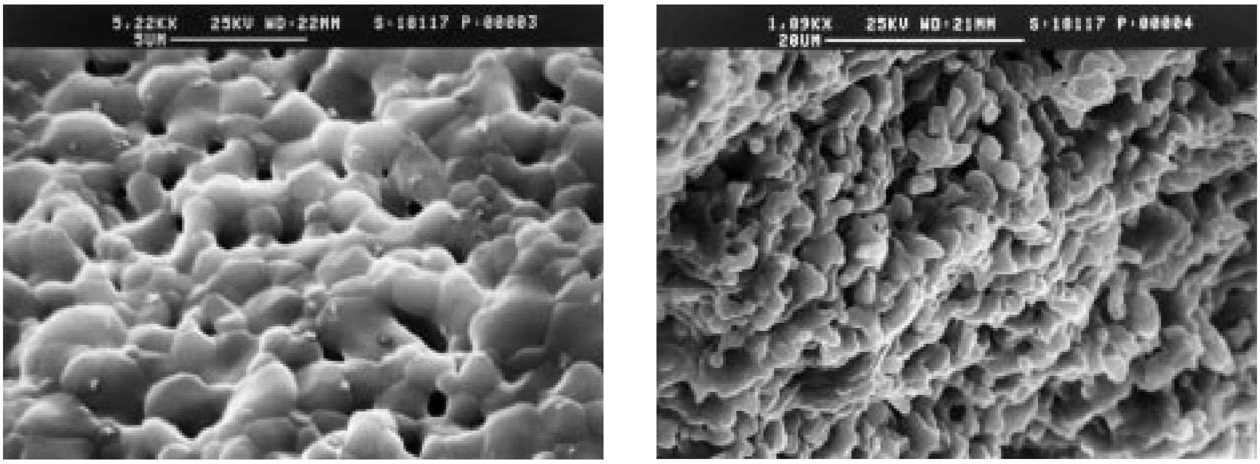
Because the porosity scale was relatively insensitive to the sintering temperature the required highly porous microstructure cannot be achieved by optimization of these parameters. Therefore, to tailor the porosity requirement, porous grains were used to prepare a new slurry then cast on a tape substrate, and cofired for 2 h at 1200 °C. The A slurry composition was preferred, so to have a dense structure in the laminate. A sintering of both layers, without a differential volume contraction, was observed. The resulting laminate microstructure is shown in Fig. 5a. As visible in the picture, the layer on the bottom of the laminate had a full dense structure, instead, a largely porous microstructure characterized the top side. However, the skeleton of the porous layer had a densification level comparable with that in the substrate, as visible in Fig. 5b.

In particular, before sintering, the porous hydroxyapatite layer was constituted of primary particles (100–300 μm) stacked together to produce a porosity of large size (macroporosity). Each primary particle included many small secondary particles (0.1–0.001 μm) strictly stacked together producing a microporosity. The experimental conditions selected for the sintering process were able to cause the full coalescence of the secondary particles which reduced strongly the microporosity, but, because of the large distance between the primary particles, the macroporosity did not disappear. Consequently, a macroporous HA layer, characterized by dense HA walls, resulted at end of the process.



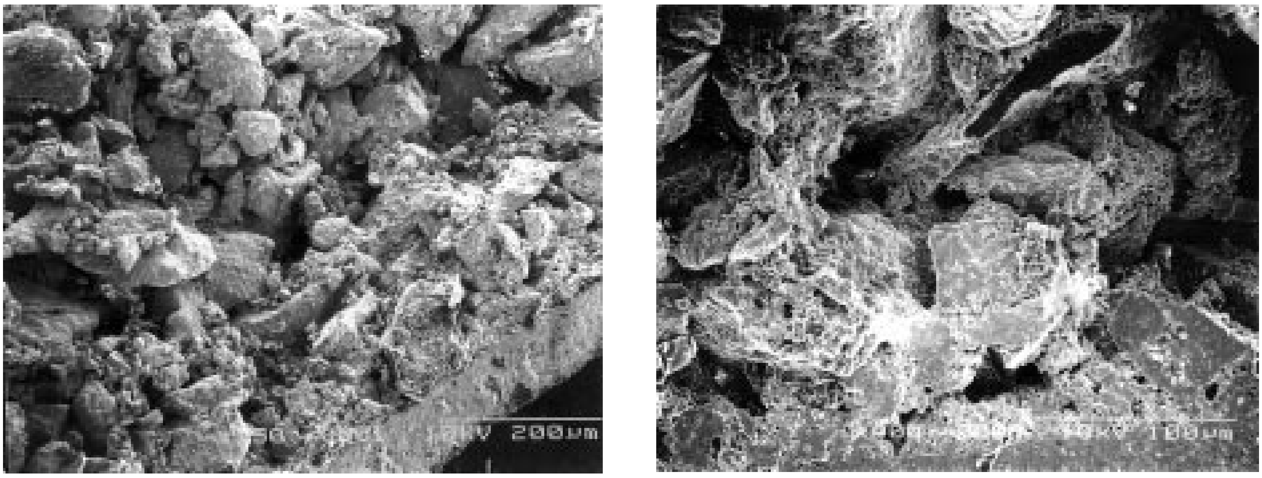
(a) (b)

Figure 3 SEM-micrographs of the sintered body microstructure (sample A fired 2 h at 1200 °C): (a) top film view; (b) fracture surface.



(a) (b)

Figure 4 SEM-micrographs of the sintered body microstructure (sample B fired 2 h at 1200 °C): (a) top film view; (b) fracture surface.



(a) (b)

Figure 5 SEM micrographs of the microstructure in the laminate sintered body (fired 2 h at 1200 °C): (a) dense-porous interface; (b) particular of the grain microstructure in the porous layer.

In particular, because the process allows the simultaneous sintering of both substrate and porous layer, a continuity between the two layers was visible after consolidation with absence of fractures, cracks and other defects.

We can conclude by offering some speculative remarks on the potential of this technology for producing HA. In addition to the preparation of dense/porous HA layers as described here, it is also possible to develop materials in which the porosity is varied as a function of depth in the component. The slip casting and lamination process are ideally suited for this application because green tapes able to produce different porosity levels can be made.

Today, the use of alloplastic materials in the oral surgery field is a usual practice. Such materials are still not perfect as bone substitute; however, they represent a valid solution for the treatment of many bone defects at alveolar, maxillary and mandibular levels. In particular, the synthetic macroporous hydroxyapatite is an alloplastic material with high osteoconductive characteristics, able to produce a framework on which the concentration of calcium and potassium ions is possible, with formation of the first mineralization nuclei, able to induce the synthesis of the proteins for the control of hydroxyapatite crystal growth.

The bone regeneration is in the pre-prosthetic and implantation fields of growing importance, and the alloplastic materials based on dense/porous hydroxyapatite can be very useful because they are able to solve most of the reconstructive necessities, present daily in the dental practice

4. Conclusions

In this study of the production of dense/porous hydroxyapatite films by slip-casting technology, we have shown a technique that ensures a promising way of preparing highly porous hydroxyapatite. In particular, dense HA ceramic layers have been obtained firing at 1200 °C tapes made using slurry of composition A, and films with a porosity size larger than 100 μm have been achieved using the same firing treatment, but casting films prepared by porous HA grains. In particular, the formulations used were able to avoid variations in the stoichiometric composition of the HA because phosphate-based dispersants were not present, so as to give superior mechanical properties for the absence of second phases.

The easiness in handling of these components allows their use as alloplastic material for many different clinical situations in oral surgery.

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