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Spark Plasma Sintered Reactive Calcium Phosphates: Toward highly bioresorbable materials for biomedical applications

Marina Luginina^{1*}, Christophe Drouet², Fabien Brouillet², David Grossin², Geoffroy Chevallier²,
Roberto Orrù¹, Giacomo Cao¹

1 Dipartimento di Ingegneria Meccanica, Chimica e dei Materiali, Università degli Studi di Cagliari, Cagliari, Italy;

2 CIRIMAT, Université de Toulouse, CNRS, Toulouse, France.

**Corresponding author: m.luginina@gmail.com*

Highlights

- Highly carbonated amorphous calcium phosphates and low-crystallinity apatite can be consolidated by SPS at low temperature (150 °C)
- Certain Mg,CO₃-doped amorphous calcium phosphate remains amorphous after SPS

1. Introduction

Bone mineral is composed of non-stoichiometric polysubstituted apatite nanocrystals, consisting in an apatitic core and a non-apatitic surface hydrated layer with labile ions. It is possible to prepare biomimetic analogs by soft chemistry, e.g. coprecipitation [1]. The presence of this hydrated ionic layer was found for non-carbonated biomimetic apatites to allow effective low-temperature consolidation by SPS, typically at 150°C and 100 MPa [2]. Soft, non-conventional consolidation approaches are indeed required to prevent the alteration of the metastable nanocrystals. In order to approach further the composition of bone mineral, close to $\text{Ca}_{8.3}(\text{PO}_4)_{4.3}(\text{CO}_3, \text{HPO}_4)_{1.7}(\text{CO}_3, \text{OH})_{0.3}$ [3], and to increase the bioresorbability of the consolidated scaffolds, the effect of carbonate substitution into biomimetic apatites was recently investigated [4]. Results pointed out, however, decreased SPS consolidation efficiency. The use of carbonated amorphous calcium phosphates (cACP) was envisioned; ACP being another promising bioresorbable material [5] used for example in coatings of metallic endoprostheses, cements and fillers in dentistry. However, all attempts to preserve the amorphous character of the starting materials failed, as all cACP tested in that study transformed into well crystallized apatite after SPS. In this light, the goal of this work was to investigate the influence of ion substitutions on the processing ability of different nanocrystalline apatites and amorphous compounds, with the general aim to increase their bioresorbability. In biomimetic apatites, increasing carbonation may allow favoring their solubility and limiting post-maturation in solution. For ACP, ion substitution may also appear as a possible approach to stabilize the amorphous structure. In this contribution, nanocrystalline apatites with different levels of carbonation and ACP doped with different amounts of carbonate and magnesium, two crystallization inhibitors, were prepared by soft chemistry and sintered by SPS at 150°C. The structure, chemical composition and mechanical resistance of the processed ceramics were investigated.

2. Methods

Synthesis of apatite and amorphous powders

Carbonated nanocrystalline apatites (hac) and amorphous calcium phosphates (ACP) powders were synthesized by double decomposition. For obtaining hac, a calcium nitrate solution was added to a di-ammonium hydrogenphosphate and sodium bicarbonate (NaHCO_3) solution at room temperature (RT). The precipitates were left to mature for 1, 3, 7, 10 and 15 days, and then filtered, washed with the DI water and freeze-dried. Different amounts of NaHCO_3 were added to obtain highly carbonated powders. For ACP, a calcium and magnesium nitrates solution (prepared with $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and 5 or 15, 30, 40 wt% $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) was added to di-ammonium hydrogenphosphate and NaHCO_3 solution at RT and $\text{pH} \approx 10$. To avoid ACP crystallization, the precipitate was immediately filtered, washed by DI water and freeze-dried.

Spark Plasma Sintering (SPS) and sample characterization

SPS experiments were performed on a 2080 Sumitomo Coal Mining equipment under argon atmosphere. Powder samples (0.35 g) were placed in a graphite die ($\varnothing = 8$ mm). Experiments were carried out with temperature and pressure programmed sequences (both for the heating and cooling steps).

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Maximum temperature was 150 °C, mechanical pressure 100 MPa and dwell time 13 min. Both initial powders and consolidated pellets were characterized. X-ray diffraction (XRD) patterns and Fourier-transform infrared (FTIR) spectra were recorded. Microstructure was investigated by scanning electron microscopy (SEM). Mechanical resistance (tensile strength) after SPS was measured by Brazilian test.

3. Results and discussion

Biomimetic nanocrystalline carbonated apatites (hac) with a high level of carbonation up to 6.3 wt% were synthesized using a different methodology from [4], using close-to-physiological conditions such as a lower Ca/P ratio, RT, and neutral pH. The carbonation level was increased by increasing maturation time and NaHCO_3 amount. SPS consolidation was found to be effective at 150°C / 100 MPa, leading to single-phased biomimetic apatite exhibiting a low crystallinity. FTIR data confirmed the biomimetic features of the hac consolidated scaffolds (Fig.1), although a decrease of overall carbonation can be noted (-1.4 wt%) as well as a partial transformation of B-type (PO_4 substitution) to A-type (OH^- substitution) carbonates noticeable in the 878-872 cm^{-1} region. However, increasing the carbonation level somewhat decreased the densification rate, leading to greater residual porosity. A tensile strength up to 13 MPa was obtained. Carbonated and Mg-doped ACP with extremely high levels of carbonation up to 21 wt% (higher than what reported before [4]) were successfully obtained. For cACP (without Mg or with 5, 15% Mg) crystallization into poorly nanocrystalline apatite was noticed after SPS, although a very low crystallinity was observed. This high degree of carbonation allied to the very low crystallinity allows expecting a high bioresorbability for these compounds. Using 40wt% led to a secondary phase identified as $\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$. In contrast, in the case of 30%Mg-cACP, XRD and FTIR data revealed, for the first time, the possibility to retain the amorphous character after SPS (Fig.2). The preservation of this amorphous state is thought to be related to the strong inhibiting effect of the Mg^{2+} ion regarding apatite crystallization. This still-amorphous carbonate calcium phosphate compound after SPS treatment represents a significant progress towards the development of a new family of highly-bioresorbable bone substitutes.

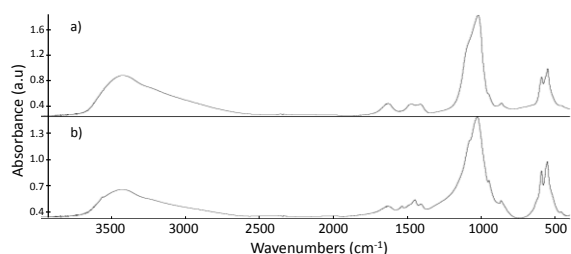


Figure 1. FTIR spectra of: (a) initial carbonated nanocrystalline apatite (1 day maturation), (b) sample after SPS

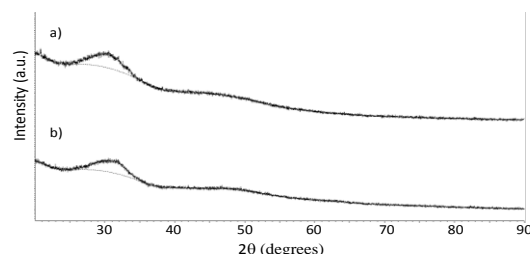


Figure 2. XRD patterns of: (a) initial carbonated Mg30%-doped amorphous phosphate, (b) sample after SPS

4. Conclusions

Low temperature SPS can be considered as a suitable technique to consolidate highly carbonated nanocrystalline apatites (hac) and amorphous calcium phosphates (cACP). For apatites, maturation time and NaHCO_3 content allow increasing the carbonation level. For cACP, carbonate and magnesium ions act as crystallization inhibitors. For the first time, we point out here the possibility to retain the amorphous character of an ACP compound, despite SPS consolidation, due to adequate MgCO_3 substitutions. Both highly-carbonated hac and cACP are promising resorbable materials for bone repair. The evaluation of biological properties of such low-temperature consolidated ceramics is in progress.

References

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Keywords

Cold sintering; Nanocrystalline apatite; Amorphous calcium phosphate; Spark Plasma Sintering; Bioceramics.