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Smart designing of new hybrid materials based on brushite-alginate and monetite-alginate microspheres: Bio-inspired for sequential nucleation and growth

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1. Introduction

Hybrid materials offer the opportunity to combine the desirable properties of an organic matrix with those of inorganic solids [1–3]. This material category has a diverse spectrum of applications ranging from pharmaceutical to wastewater treatment [4–6]. On the other hand, the calcium phosphate materials contain a multitude of crystalline phases and have attracted considerable interest both in the scientific community and industry due to their physico-chemical properties and their value in many fields of technology [7–17]. However, the combination of calcium phosphates and biopolymer can confer favorable mechanical properties, including strength due to the inorganic phase, toughness and plasticity due to the biopolymer phase. Biopolymers differ from each other in chemical composition, molecular weight, polydispersity, crystallinity, hydrophobicity, solubility, chain length, and thermal transitions [18]. Different biopolymer-calcium orthophosphate composites have been successfully obtained with alginate [19], chitosan [20,21], cellulose [22] and starch [23,24]. Alginate is a natural polysaccharide extracted from the marine brown algae and it is composed of two uronic acid monomers derived from mannose: the acid β-L-guluronic (G) and the acid α-D-mannuronic (M) are linked by glycoside bonds β-(1→4) and α-(1→4) (see Fig. S1 in Supporting information) [25,26]. Alginate gelation occurs when multivalent ions take their place between the G blocks of guluronic monomers, forming junctions of electrostatic nature, and the bond strength varies depending on the type of cation [27,28]. Most of the published works on hybrid composite alginate–calcium phosphate are based on preparation, nucleation and growth of apatite particles in a matrix of alginate biopolymer. In this context, Rajkumar et al. synthesized a nano-hydroxyapatite alginate nanocomposite with different weight percentages of sodium alginate; its biological and mechanical properties were studied [29]. Zhang et al. prepared a series of new nanocomposite beads of sodium alginate/hydroxyapatite, in order to find a new way to slow drug release, but unfortunately they did not show the XRD spectra which can confirm if that it was really the hydroxyapatite or another phase [30].

Brushite (dicalcium phosphate dihydrate (DCPD)) and monetite (dicalcium phosphate (DCP)) cements have raised considerable interest in the last decade, because they are metastable under physiological conditions and can be resorbed more quickly than hydroxyapatite cements [31]. Several authors have suggested that it’s a precursor of bone mineralization, including biological apatites [32,33]. The brushite has been
widely used in the reconstruction materials, dental cements, as well as in formulation chemistry [34,35]. These phosphates are usually synthesized in an aqueous medium by double decomposition of a calcium salt and a phosphate salt or by neutralization of phosphoric acid in lime [36,37]. Other routes have been also explored to synthesis these calcium phosphates such as sol-gel [38], solid state [39], chemical precipitation [40], hydrothermal [41], hard templating [42], flame-spray route [43], dual irradiation of the microwave and ultrasound [44], and physiological conditions [45]. More recently, Gomez-Morales et al. have controlled the precipitation of calcium phosphate such as brushite by using vapor diffusion method in microdroplets and amino acids like organic additives [46].

This current study demonstrates for the first time that the synthesis of hybrid material phosphate–biopolymer can be achieved using gelation of alginate mixed with a phosphate source via complexation of calcium ions. The synthetic protocol reported here takes advantage of the controlled gelation of the mixture of brushite or monetite structure at room temperature.

2. Experimental section

2.1. Chemical reagents

(NH₄)₂HPO₄ and Ca(NO₃)₂·4H₂O were purchased from Aldrich and used as a precursor of the HPO₄²⁻ ligand and for gelation, respectively. Other phosphate sources are also tested namely: sodium phosphate dibasic (Na₂HPO₄) and ammonium phosphate monobasic (NH₄H₂PO₄). Sodium alginate was purchased from Aldrich and used as supplied. Deionized water was used in all experiments.

2.2. Synthesis of hybrid materials

Hydrogel material was achieved via complexation of alginate/phosphate by calcium ion (Fig. S2). Aqueous solutions of phosphorus precursor were prepared by dissolving different amounts of (NH₄)₂HPO₄, 0.1, 0.3, 0.5, and 1 M into 100 mL of distilled water, and then sodium alginate was added to diammonium phosphate solution with a concentration of 1%. The mixture was stirred for 1 h at room temperature. This gel was added dropwise using a syringe with a 0.8 mm diameter needle at room temperature to the stirred Ca(NO₃)₂·4H₂O solution (0.25 M). The formed beads immediately are abandoned overnight to ensure effective diffusion of calcium ions, and thereafter the homogeneity of the system and the growth of hybrid materials.

After that, the beads were filtered with a 100 mesh screen, and washed three times with distilled water to remove the Ca²⁺ excess and impurities on the beads surface. In the end, the beads were dried at room temperature for 24 h before various characterizations. For different (NH₄)₂HPO₄ concentration (0.1, 0.3, 0.5 and 1 M), the dried hybrid materials will be henceforth identified as Phos–Alg_1 (phosphate–alginate), Phos–Alg_2, Phos–Alg_3, and Phos–Alg_4 respectively.

2.3. Thermal and structural characterization techniques

TGA were conducted under air in a TA Instrument Q500 apparatus with a 10 °C/min ramp between 25 and 1000 °C. X-ray diffraction patterns of the samples were obtained at room temperature on a Bruker AXS D-8 diffractometer using Cu-Kα radiation in Bragg–Brentano geometry (9–20). Fourier transform infrared spectra of samples in KBr pellets were measured on a Bruker Vector 22 spectrometer. Scanning electron microscopy pictures were recorded on a FEI Quanta 200 microscope after carbon metallization.

3. Results and discussion

In order to conduct this study, we investigated several parameters, especially the concentration of phosphate precursor and the drying temperature, that influence the nucleation and growth of the inorganic matrix and obviously the hybrid material by afterwards. Thus, the concentration of the precursor of the phosphate plays an important role in the appearance of the prepared hybrid xerogels. Fig. 1 shows pictures taken by a digital camera and SEM at low magnification of the as synthesized hybrid xerogel microspheres (Phos–Alg_1 and Phos–Alg_2), micro-lentils (Phos–Alg_3) and granulated powder (Phos–Alg_4). This change in the external shape can be explained by the increase of the concentration of HPO₄²⁻ ligand which occupies the space in the alginate chains and subsequently distorts the spherical shape of the droplet.

The XRD patterns have been used to investigate the phases in our hybrid xerogels at different phosphate concentrations. Fig. 2 shows diagrams of the samples such as Phos–Alg_1, Phos–Alg_2, Phos–Alg_3 and Phos–Alg_4 corresponding to (NH₄)₂HPO₄ concentrations: 0.1 M, 0.3 M, 0.5 M and 1 M respectively. The Phos–Alg_1 is poorly crystalline maybe because the amount of phosphates is poor, but has a pure brushite phase or dicalcium phosphate dihydrate with monoclinic crystal structure (JCPDS 4-013-3344). Brushite crystallized in the monoclinic system (space group P2₁) with the crystallographic parameters a = 6.239 Å, b = 15.180 Å, c = 5.812 Å, α = γ = 90° and
The intensity of the diffraction peaks indicates that the sample Phos–Alg_2 is well crystallized. This is made up of a brushite phase with trace amount of monetite or dicalcium phosphate with triclinic crystal (JCPDS 4-009-4184). The Phos–Alg_3 represents a coexistence of both phases which is confirmed by the high intensity of diffraction peaks of the monetite (020) facet and brushite (200) facet. Finally, the Phos–Alg_4 sample is composed predominantly of the monetite phase. Monetite crystallized in the triclinic system (space group \( P\alpha \)) with the crystallographic parameters: \( a = 6.91 \text{ Å} \), \( b = 6.998 \text{ Å} \), \( c = 6.627 \text{ Å} \), \( \alpha = 96.34^\circ \), \( \beta = 91.67^\circ \) and \( \gamma = 76.18^\circ \).

The oversaturation of alginate matrix by phosphate leads to a high percentage of the monetite phase in Phos–Alg_4. High concentrations of phosphate source favor monetite formation (Fig. S3). This can be explained by increased steric hindrance exerted on the alginate fibers by ligand \( \text{HPO}_4^{2−} \), which will reduce necessary space for keeping the structural water. We have also studied the influence of the drying temperature on samples: Phos–Alg_2 and Phos–Alg_3. The analysis of these bio-composites dried at 100 °C overnight by XRD shows that we have a total selectivity to synthesis monetite (Fig. 3). This can be explained by the conversion of brushite phase into monetite, which is simply due to the dehydration of brushite (removal of water molecules from the structure). Thus we can get simply the monetite phase by increasing the drying temperature. It’s also noteworthy that the use of other sources of \( \text{HPO}_4^{2−} \) ligand gives similar results. The semi-qualitative analysis by energy dispersive spectroscopy (EDAX) was carried out, when taking SEM photographs (Fig. S4). The study allowed us to demonstrate the presence of the chemical elements that constitute calcium phosphates: i) phosphorus, ii) oxygen, and ii) calcium. The data from semi-qualitative analysis give us an idea as to the composition of xerogels prepared in terms of molar ratio \( \text{Ca}/\text{P} \). The results of the \( \text{Ca}/\text{P} \) ratio are in the range of: 1.12, 0.94, 0.97 and 1.24 for Phos–Alg_1, Phos–Alg_2, Phos–Alg_3 and Phos–Alg_4 respectively. These values are consistent with the molar ratio of brushite and monétite \( \text{Ca}/\text{P} = 1 \) reported in the literature.

The crystal unit cell contains four motifs of \( \text{CaHPO}_4 \cdot 2\text{H}_2\text{O} \) and the structure is shown in Fig. 4. The latter shows that the crystals are composed of brushite corrugated sheets of composition \( \text{CaHPO}_4 \) arranged in parallel to each other, normal to the axis \( b \) and linked together by a double layer of water molecules. In the same way, Fig. 5 gives a projection of monetite viewed along the \( b \)-axis. This projection shows the spatial
distribution and the unit cell of monetite illustrating the sequence of PO₄ units and the location of calcium ions within the framework.

Fig. 6 shows the FT-IR spectra of the hybrid composite beads. The absorptions observed at 1421 cm⁻¹ in all samples are due to the symmetric and asymmetric stretching modes of the COO⁻ bands from the carboxylate groups [48,49]. The spectra of Phos–Alg. 1, Phos–Alg. 2, and Phos–Alg. 3 exhibit similar bands. Brushite is characterized by the O–H stretching modes of the crystallization water and also for alginate matrix, with two peak doublets, respectively, 3550 and 3466 cm⁻¹ [48]. The H–O–H bending gives rise to absorption at 1651 cm⁻¹ [50]. The main IR bands characterizing the PO₄ group can be detected at 1128, 1059 and 998, and 1012 cm⁻¹, due to PO stretching modes of the PO₄ fragment [50]. Weaker sharp bands at 1210 and 871, and 875 cm⁻¹ are due, respectively, to the P–O–H stretching mode and the P–OH bending mode [51]. Bands at frequencies 521, 590, and 650 cm⁻¹ are assigned mainly to PO deformation modes of the tetrahedral PO₄ group [52]. The FTIR also identifies the functional groups of C-monetite sample [53], water vibrations at 3550 and 3466 cm⁻¹ are not seen in the spectrum of samples “d” corresponding to Phos–Alg..4.

Morphologies of the hybrid bio-composites are shown in Fig. 7. These show that the morphology of the crystals prepared by this route is very much dependent on the precursor concentration. Fig. 7a shows the SEM image of Phos–Alg..1, where the inorganic matrix is the brushite crystal prepared with 0.1 M of the (NH₄)₂HPO₄ solution. The morphology of the crystal is small plate-like and needle-like structures with a heterogeneous size. Fig. 7b presents the SEM image of Phos–Alg..2, where the inorganic matrix is a mixture of the brushite and monetite crystals prepared with 0.3 M. This image consists of heterogeneous shapes like the first sample. In contrast, the platelet arrangement shown in Fig. 7c, which was prepared with 0.5 M concentration of HPO₄²⁻ ligand, gives rise to this single morphology with homogeneous dimensions, even though we have two phases. Generally, for the first three samples (a), (b) and (c), the morphology consists of merged platelets forming irregular chunky materials with various dimensions (a), (b) and (c). The fast rate of nucleation and crystal growth as a result of the high precursor concentration led to better defined plate-like structures corresponding to the predominant brushite crystals [54]. Finer spherical-like monetite particles are formed when we have increased the source concentration of HPO₄²⁻ ligand (1 M). The morphology of monetite crystals is similar to snowball flowers with a size at around 2 µm (Fig. 7d).

The thermal behavior of these dried beads was investigated by thermogravimetric analysis. The curves (Fig. 8a, b, c and d) showed different profiles characterized by different ranges of thermal degradation. These thermograms (a, b, c, d) showed continuous weight loss in the range of 25–330 °C and 330–750 °C. The first weight loss at ca. 200 °C can be assigned to the loss of absorbed water that can lead to conversion of DCPD to DCP [54] and also the conversion of DCP to calcium pyrophosphate (Ca₃P₂O₇ (CCP)) [53,55]. These observations were confirmed by the analysis of inorganic materials recovered after calcination at 750 °C by XRD and FTIR (Figs. 9 and 10). The weight loss shown by the curve (a) at 750 °C is around 4% and can be explained by thermal degradation of amorphous carbon. The total weight loss was found to be around 55%, 37%, 27% and 19% as shown in Fig. 8 (a, b, c and d) respectively, these results prove that increasing the amount of phosphate in an alginate gel matrix leads to decrease of the mass loss directly causing the formation of β-TCP and CCP.

From a mechanistic point of view, the fact that the mixture of the phosphate source with alginate gives rise to a homogeneous gel, suggests an interaction between the biopolymer and the HPO₄²⁻. The stability and homogeneity of this gel can be explained by the possible interactions between the HPO₄²⁻ ligand and the carboxylate group of the alginate. This physical bonding translates to mixtures that are rich in electronic pairs showing higher reactivity and mineralization potential to be transformed into hybrid hydrogel materials. When the mixture of alginate and phosphate source meets the solution of Ca²⁺, divalent ions, interchain cross-linking occurs as a result of calcium coordination with pliers formed by two phosphorylated GG blocks as the “egg-box” model [56–58]. In addition, the nucleation and the growth of brushite and monetite can be due to interactions between inorganic minerals and alginate chains in the biopolymer. These observations are in agreement with those reported by M. Rajkumar [29].

4. Conclusions

In summary, a new type of hybrid materials was obtained via a straightforward synthetic route with alginate biopolymer as organic matrix and phosphate source ions with calcium ions. All the synthesis has been carried out at room temperature; thus greatly expanding the applicability of the method for the preparation of materials loaded with thermally unstable substances. Four hybrid beads were prepared with different inorganic filler contents. Structure and physicochemical characterization of these hybrid phosphates were evaluated by FT-IR,
Fig. 7. SEM micrographs of hybrid xerogels: Phos–Alg_1 (a), Phos–Alg_2 (b), Phos–Al_3 (c) and Phos–Alg_4 (d).

Fig. 8. Thermogravimetric curves for hybrid xerogels: Phos–Alg_1 (a), Phos–Alg_2 (b), Phos–Al_3 (c) and Phos–Alg_4 (d).

Fig. 9. XRD patterns of calcined beads at 750 °C.
XRD, SEM and TGA. Experimental results for all hybrid materials indicated that the phosphate source concentration is a predominant factor for the sequential nucleation and growth and also the crystalline selectivity. The structural characterization results suggested that the particles formed into the biopolymeric matrix are brushlike and/or monometallate. Moreover, the observation of particle morphology by TEM proved that the shape changes according to the concentration of phosphate. The thermal behavior of these materials depends on the amount of water physisorbed, or structural, and the phosphate concentration. Characterization of the recovered phosphates after heat treatment reveals the formation of a mixture of several types of calcium phosphate. Studies of the applications of these materials are underway in our laboratory.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.msec.2013.11.012.

References