

Effect of pyrophosphate ions on the conversion of calcium–lithium–borate glass to hydroxyapatite in aqueous phosphate solution

Hailuo Fu · Mohamed N. Rahaman ·
Delbert E. Day · Wenhai Huang

Received: 16 April 2010 / Accepted: 8 July 2010 / Published online: 1 August 2010
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Abstract The conversion of glass to a hydroxyapatite (HA) material in an aqueous phosphate solution is used as an indication of the bioactive potential of the glass, as well as a low temperature route for preparing biologically useful materials. In this work, the effect of varying concentrations of pyrophosphate ions in the phosphate solution on the conversion of a calcium–lithium–borate glass to HA was investigated. Particles of the glass (150–355 μm) were immersed for up to 28 days in 0.25 M K_2HPO_4 solution containing 0–0.1 M $\text{K}_4\text{P}_2\text{O}_7$. The kinetics of degradation of the glass particles and their conversion to HA were monitored by measuring the weight loss of the particles and the ionic concentration of the solution. The structure and composition of the conversion products were analyzed using X-ray diffraction, scanning electron microscopy, and Fourier transform infrared spectroscopy. For $\text{K}_4\text{P}_2\text{O}_7$ concentrations of up to 0.01 M, the glass particles converted to HA, but the time for complete conversion increased from 2 days (no $\text{K}_4\text{P}_2\text{O}_7$) to 10 days (0.01 M $\text{K}_4\text{P}_2\text{O}_7$). When the $\text{K}_4\text{P}_2\text{O}_7$ concentration was increased to 0.1 M, the product consisted of an amorphous calcium phosphate material, which eventually crystallized to a pyrophosphate product (predominantly $\text{K}_2\text{CaP}_2\text{O}_7$ and $\text{Ca}_2\text{P}_2\text{O}_7$). The consequences of the results for the formation of HA materials and devices by the glass conversion route are discussed.

1 Introduction

Bioactive glasses have attractive properties for biomedical applications [1–3]. When placed in an aqueous phosphate solution, such as the body fluid, bioactive glasses undergo specific surface reactions, leading to the formation of a hydroxyapatite (HA)-type surface layer that is responsible for developing a firm bond with hard and soft tissues [4–6]. The conversion of a bioactive glass (or glass–ceramic) to HA in vitro, when immersed in an aqueous phosphate solution such as a simulated body fluid (SBF), provides a measure of its bioactive potential in vivo [7]. Therefore, it is important to understand the factors that influence the conversion of bioactive glass to HA in vitro.

The conversion of bioactive glass to HA in an aqueous phosphate solution is also of interest because the method can be used as a low temperature route for the formation of biologically useful materials, such as hollow or porous HA microspheres [8–11]. CaO-containing alkali–borate glass with special compositions in the system $\text{Li}_2\text{O–CaO–B}_2\text{O}_3$ or $\text{Na}_2\text{O–CaO–B}_2\text{O}_3$ have been observed to convert rapidly to HA when placed in an aqueous phosphate solution near room temperature, such as the body temperature, 37°C [8, 12]. Porous or hollow HA microspheres prepared by this route have a mesoporous structure of nanosized particles and high surface area (100–200 m^2/g). As such, the glass conversion method provides a novel route for the production of biologically active HA materials and devices for biomedical applications which cannot be obtained by other known methods.

The conversion of silicate and borate bioactive glass to HA in an aqueous phosphate solution has been the subject of several studies [1, 13–16]. It is well established that an initial step in the conversion of silicate bioactive glass

H. Fu · M. N. Rahaman (✉) · D. E. Day
Department of Materials Science and Engineering, and Center
for Bone and Tissue Repair and Regeneration, Missouri
University of Science and Technology, Rolla, MO 65409, USA
e-mail: rahaman@mst.edu

W. Huang
Institute of Bioengineering and Information Technology
Materials, Tongji University, Shanghai 200092, China

(such as 45S5 and 13-93 glass) to HA is the formation of a SiO₂-rich gel layer on the glass surface by ion exchange reactions. Dissolution of Ca²⁺ ions from the glass, their diffusion through the SiO₂-rich layer, and reaction with (PO₄)³⁻ ions from the solution, leads to the precipitation of an amorphous calcium phosphate (ACP) layer on the SiO₂-rich layer, which subsequently converts to HA. The reaction interface moves inward with time. Because of their lower chemical durability, some borate glasses convert faster and more completely to HA than silicate 45S5 or 13-93 glass. The mechanism of converting borate bioactive glass to HA is similar to that for silicate bioactive glass, but without the formation of a SiO₂-rich layer [14, 15].

In addition to factors such as glass composition, reaction temperature, and concentration of the aqueous phosphate solution, the conversion of silicate bioactive glass (13-93) to HA has also been shown to depend on the presence of polyanions in the aqueous phosphate solution [17]. In particular, the conversion rate of 13-93 glass in 0.25 M K₂HPO₄ solution was found to increase linearly with alginic acid concentration in the range 0–1 wt% alginic acid (based on the dry mass of the glass). At a given alginic acid concentration, the conversion rate increased almost six times when compared to that for the reaction without alginic acid. The acceleration of the conversion rate was explained in terms of chelation of the electron donating moieties of alginic acid, such as carboxyls and hydroxyls, to the leached Ca²⁺ from the glass.

Inorganic phosphates such as dipotassium phosphate, K₂HPO₄, used for preparing the aqueous phosphate solution in the glass conversion process often contain varying concentrations of other phosphates resulting from incomplete purification. In particular, tetrapotassium pyrophosphate, K₄P₂O₇, is a common ‘impurity’ in commercial K₂HPO₄. Although the specific charge (charge per unit anion group) of the (P₂O₇)⁴⁻ anion is the same as that for the (HPO₄)²⁻ anion, the higher molecular weight could result in preferential adsorption at the reaction interface. This could result in a modification of the rate of formation of HA by the glass conversion method, or in the formation of new phases based on calcium pyrophosphate.

The objective of this work was to study the effect of varying concentrations of K₄P₂O₇ on the conversion of calcium–lithium–borate glass particles to HA in K₂HPO₄ solution (0.25 M). The kinetics of conversion were monitored by measuring the weight loss of the glass particles and the concentration of ions dissolved from the glass into the aqueous phosphate solution. The structure and composition of the solid conversion products were analyzed using X-ray diffraction (XRD), Fourier transform infrared

(FTIR) spectroscopy, and scanning electron microscopy (SEM).

2 Experimental procedure

2.1 Conversion of calcium–lithium–borate glass particles in aqueous phosphate solution

Borate glass, with the composition (wt%): 15CaO, 10.63Li₂O, 74.37 B₂O₃, designated CaLB3-15, was prepared by melting Reagent grade CaCO₃, Li₂CO₃ and H₃BO₃ (Alfa Aesar, Haverhill, MA, USA) in a Pt crucible for 1 h at 1200°C, and quenching the melt between cold stainless steel plates. This glass composition was used because previous work had shown that particles of the glass could be converted rapidly (within 2 days) to a HA-type material in an aqueous phosphate solution [11]. Particles of size 150–355 μm were obtained by grinding the glass in a hardened steel mortar and pestle, and sieving through 45 and 100 mesh sieves. The particles were washed three times with ethanol prior to being used in the conversion reaction.

Conversion of the borate glass particles to HA was studied in 0.25 M K₂HPO₄ solution containing 0–0.1 M K₄P₂O₇ (compositions and reaction times shown in Table 1). The K₂HPO₄ solution was used as the parent solution for the conversion reaction because it had been used previously in several studies [14–16]. The solutions were prepared by dissolving 0.25 mol of K₂HPO₄·3H₂O (99+%; Acros Organics, Morris Plains, NJ, USA) in 1 l distilled water, and then dissolving the required amount of K₄P₂O₇ (98%; Acros Organics). The pH of the as-prepared solutions was 9.0.

In the conversion reaction, 1 g glass particles was placed in a bag consisting of nylon sieve cloth (140 mesh; nominal opening = 106 μm), and immersed in the aqueous phosphate solution. Each bag of particles was placed in a sealed polyethylene bottle containing 100 ml solution and kept at 37°C for up to 28 days (Table 1). After selected immersion times, the particles were removed from the solution, rinsed twice with distilled water, then twice with anhydrous ethanol, and dried at 90°C. For each immersion time, the weight loss was determined from three samples.

Table 1 Composition of K₂HPO₄ solutions with varying K₄P₂O₇ concentration used in these experiments for converting calcium–lithium–borate (CaLB3-15) glass particles to a calcium phosphate material

K ₂ HPO ₄ (M)	0.25	0.25	0.25	0.25
K ₄ P ₂ O ₇ (M)	0	0.001	0.01	0.1
Reaction time (h)	72	96	240	672

The total reaction time for each composition is also shown

2.2 Evaluation of conversion kinetics

Measurement of the weight loss of the borate glass particles as a function of immersion time in the phosphate solution was used to monitor the conversion kinetics of the particles to HA, as described previously [14–16]. The weight loss is defined as $\Delta W/W_0 = (W_0 - W)/W_0$, where W_0 is the initial mass of the particles (prior to immersion) and W is the mass after time t . Since the conversion of the calcium–lithium–borate glass to HA is also accompanied by dissolution of ions such as Li^+ and $(\text{BO}_3)^{3-}$, the concentration of Li and B in the phosphate solution as a function of immersion time was also used to evaluate the conversion process. The concentration of Ca, B, Li and P in the phosphate solution was measured using inductively-coupled plasma optical emission spectrometry (ICP-OES) at a commercial laboratory (Research Analytical Lab, University of Minnesota, St. Paul, MN, USA).

2.3 Characterization of conversion products

The phase composition and microstructure of the solid products of the conversion reaction were analyzed using XRD and SEM. XRD was performed using $\text{Cu K}\alpha$ radiation ($\lambda = 0.15406 \text{ nm}$) at a scan rate of $1.8^\circ/\text{min}$ in the 2θ range $5\text{--}70^\circ$ (D/mas 2550 v; Rigaku; The Woodlands, TX, USA). The conversion product was ground to a powder for the XRD analysis. The microstructure of the external surface of the product was observed using SEM (S-4700; Hitachi, Tokyo, Japan), at an accelerating voltage of 10 kV and working distance of 12 mm. Composition analysis of the conversion product was performed using FTIR spectroscopy (NEXUS 670 FTIR; Thermo Nicolet; Madison, WI, USA) in the wavenumber range $400\text{--}4000 \text{ cm}^{-1}$ (resolution = 8 cm^{-1}). A mass of 2 mg of the product was ground into a powder, mixed with 198 mg KBr, and pressed to form pellets for the FTIR analysis.

3 Results

3.1 Structure and composition of conversion products

XRD patterns of the starting glass (CaLB3-15) and the products formed by reacting the glass particles in 0.25 M K_2HPO_4 solution with varying concentration of $\text{K}_4\text{P}_2\text{O}_7$ at 37°C and $\text{pH} = 9.0$ are shown in Fig. 1. The starting glass had a diffraction pattern with no identifiable peaks, typical of an amorphous glass. (A small peak at $\sim 13^\circ 2\theta$ is due to the instrument). For the conversion products formed by reacting the glass particles in the K_2HPO_4 solution (without $\text{K}_4\text{P}_2\text{O}_7$) and in the K_2HPO_4 solution containing 0.001 M and 0.01 M $\text{K}_4\text{P}_2\text{O}_7$, the XRD patterns showed diffraction

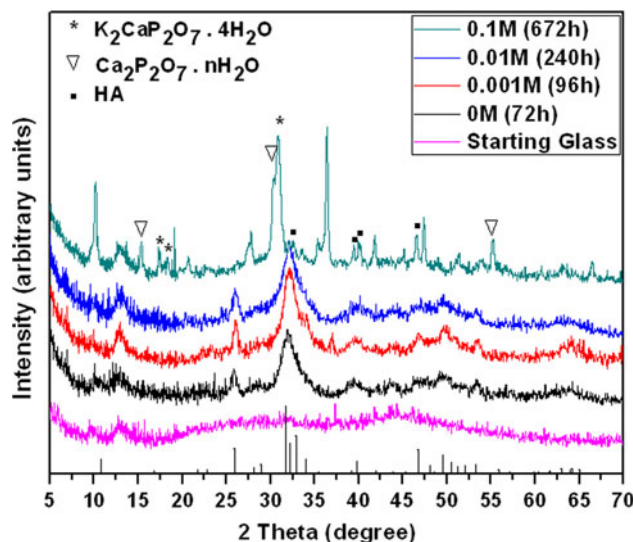


Fig. 1 XRD patterns of the starting calcium–lithium–borate (CaLB3-15) glass particles and the products formed after converting the glass particles for the times shown in 0.25 M K_2HPO_4 solution containing 0, 0.001, 0.01, and 0.1 M $\text{K}_4\text{P}_2\text{O}_7$. For comparison, the pattern for a reference hydroxyapatite (JCPDS 72-1243) is also shown

peaks corresponding to those of a reference HA (JCPDS 72-1243). The peaks in the XRD patterns appeared to be broad, which might indicate that the conversion products were poorly crystallized, or consisted of nanometer-sized crystals, or a combination of both.

In comparison, the product formed when the glass particles were reacted in the K_2HPO_4 solution containing 0.1 M $\text{K}_4\text{P}_2\text{O}_7$ had a markedly different XRD pattern (Fig. 1). The major peaks corresponded to those of a dipotassium calcium pyrophosphate, $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and a calcium pyrophosphate, $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$. Only minor peaks corresponding to HA were identified in the XRD pattern, indicating little formation of HA. The XRD pattern showed the presence of additional phases that could not be clearly identified.

FTIR spectra of the conversion products formed when the glass particles were reacted in the K_2HPO_4 solution (without $\text{K}_4\text{P}_2\text{O}_7$) and in the K_2HPO_4 solution containing 0.001 M and 0.01 M $\text{K}_4\text{P}_2\text{O}_7$ are shown in Fig. 2. The most dominant resonances were the phosphate ν_3 resonance, centered at $\sim 1040 \text{ cm}^{-1}$, and the phosphate ν_4 resonance, with peaks at ~ 605 and 560 cm^{-1} , which are associated with HA [18, 19]. These FTIR spectra provided further evidence that the products formed by reacting the glass particles in these three solutions consisted of HA. Additional resonances in the spectra of these conversion products included a weak shoulder at $\sim 962 \text{ cm}^{-1}$ corresponding to the phosphate ν_1 resonance [20], and a resonance at $\sim 878 \text{ cm}^{-1}$ corresponding to the vibrations of CO_3^{2-} ions substituting for PO_4^{3-} ions in the HA lattice [20].

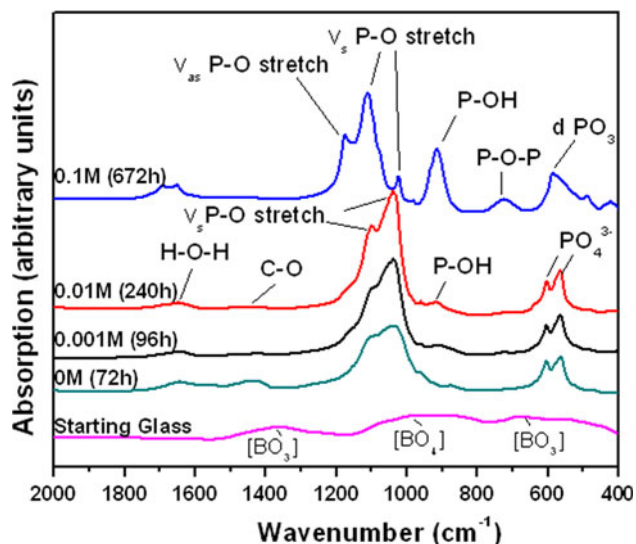


Fig. 2 FTIR spectra of the starting calcium–lithium–borate (CaLB3-15) glass particles and the products formed after converting the glass particles for the times shown in 0.25 M K₂HPO₄ solution containing 0, 0.001, 0.01, and 0.1 M K₄P₂O₇. The main resonances in the spectra are shown

In comparison, the FTIR spectrum of the product formed in the K₂HPO₄ solution containing 0.1 M K₄P₂O₇ was markedly different from those described above. The asymmetric and symmetric terminal stretching vibrations of PO₂ groups usually occur in the region 1250–980 cm⁻¹ [21–23]. The intense band observed at 1175 cm⁻¹ is attributed to the asymmetric P–O stretching, while the symmetric P–O stretching is located at 1109 and 1024 cm⁻¹. The P–OH vibrations are observed at 916 cm⁻¹ and 487 cm⁻¹. The resonance observed at 723 cm⁻¹ is attributed to symmetric P–O–P bridge vibration, while the resonance centered at ~580 cm⁻¹ might be produced by the phosphate ν₄ and asymmetric δ PO₃ vibration. Taken together, the FTIR spectrum showed that the product formed in K₂HPO₄ solution with 0.1 M K₄P₂O₇ contained the function groups P₂O₇⁴⁻, HP₂O₇³⁻ and PO₄³⁻, indicating the presence of a pyrophosphate, as well as a phosphate.

3.2 Reaction kinetics

Data for the weight loss, $\Delta W/W_0$, of the glass particles as a function of immersion time in the K₂HPO₄ solution with or without K₄P₂O₇ are shown in Fig. 3. The average weight loss and deviation for each immersion time were determined from three samples under the same conditions. In the K₂HPO₄ solution without K₄P₂O₇, the weight loss increased rapidly with immersion time, reaching a steady, limiting value of 63% after 48 h. The presence of 0.001 M K₄P₂O₇ in the K₂HPO₄ resulted in a small decrease in the

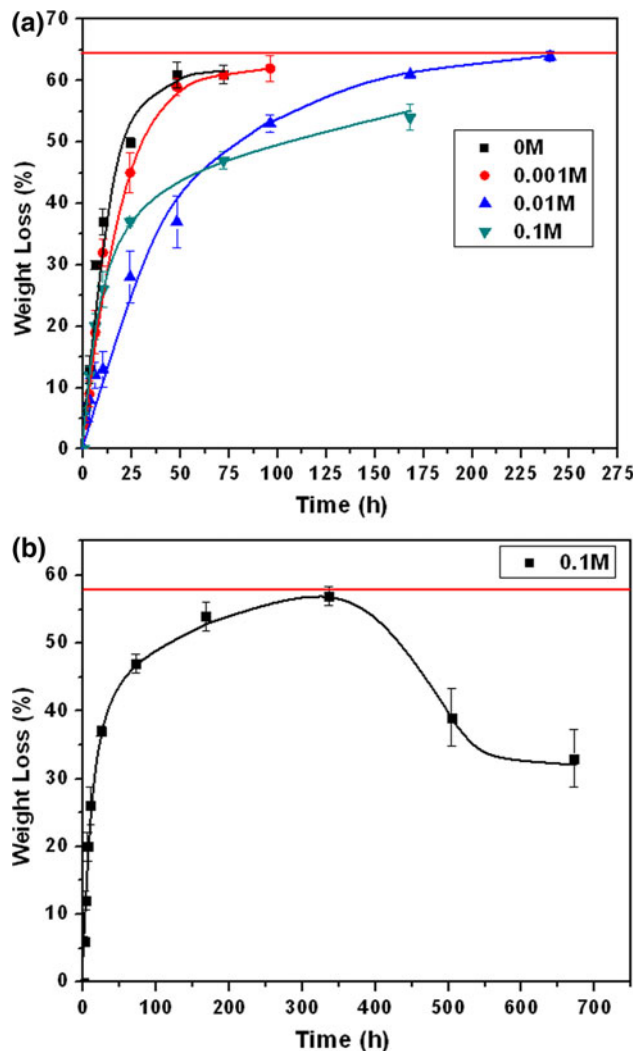


Fig. 3 **a** Weight loss of calcium–lithium–borate (CaLB3-15) glass particles during conversion in 0.25 M K₂HPO₄ solution containing 0, 0.001, 0.01, and 0.1 M K₄P₂O₇. **b** Weight loss curve for the glass particles during conversion in 0.25 M K₂HPO₄ solution containing 0.1 M K₄P₂O₇, showing a maximum, followed by a decrease at longer times

$\Delta W/W_0$ value at a given immersion time, so the weight loss curve was shifted slightly to longer immersion times. For the glass particles reacted in the K₂HPO₄ solution containing 0.01 M K₄P₂O₇, the weight loss data showed a marked decrease at any immersion time, when compared to the data for particles reacted in K₂HPO₄ solution without K₄P₂O₇. The weight loss reached the same final limiting value (63%), but only after 200–250 h.

The weight loss curve for the particles immersed in K₂HPO₄ solution with 0.1 M K₄P₂O₇ showed a markedly different behavior (Fig. 3a, b). The weight loss first increased with immersion time, reaching a maximum value of 57% after an immersion time of 300–350 h, but then decreased at longer immersion times. After an immersion

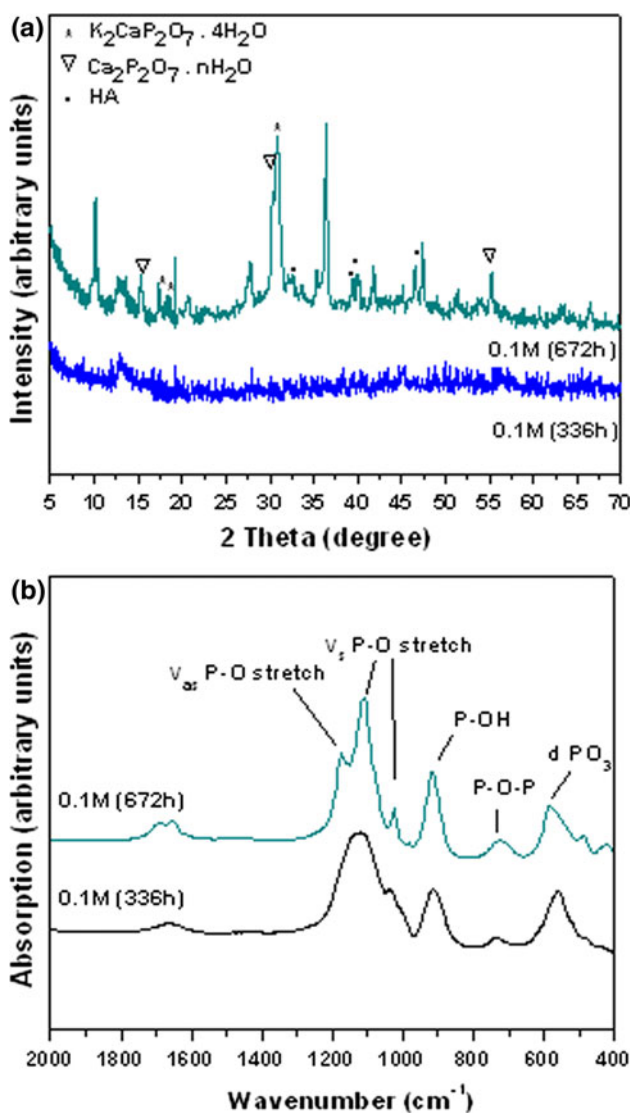


Fig. 4 (a) XRD patterns and (b) FTIR spectra of the products formed by converting calcium–lithium–borate (CaLB3-15) glass particles in 0.25 M K_2HPO_4 solution containing 0.1 M $K_4P_2O_7$ for 14 days (336 h) and for 28 days (672 h)

time of 672 h when the experiment was terminated, the final weight loss was 39%. According to XRD analysis, the product formed by reacting the particles for 336 h, corresponding to approximately the maximum on the weight loss curve, was amorphous (Fig. 4a). (A small peak at $\sim 13^\circ 2\theta$, as indicated earlier, is due to the instrument.) The FTIR spectrum of the amorphous product also showed differences from that of the final product, particularly in the wavenumber range 1000–1200 cm^{-1} (Fig. 4b).

Table 2 shows data for the concentration of B, Ca, Li, and P in the K_2HPO_4 solution (with or without $K_4P_2O_7$) after different immersion times. For the K_2HPO_4 solution containing 0–0.01 M $K_4P_2O_7$, the concentration of B and Li showed trends similar to those described earlier for the

Table 2 Concentration of B, Ca, Li, and P in 0.25 M K_2HPO_4 solution containing 0, 0.001, 0.01, and 0.1 M $K_4P_2O_7$ after immersion of calcium–lithium–borate (CaLB3-15) glass particles for the times shown

	B (mg/l)	Ca (mg/l)	Li (mg/l)	P (mg/l)	Theoretical concentration of P (mg/l)
0 M $K_4P_2O_7$					
0 h	1.3	<0.7	<0.1	7381	7750
1 h	227	2.4	47.2	7335	
1 day	2169	1.2	414	7280	
3 days	2339	<0.7	427	6746	
0.001 M $K_4P_2O_7$					
0 h	1.7	0.8	<0.1	7438	7810
1 h	205	1.7	35.9	7337	
1 day	2081	2.4	421	6972	
4 days	2400	0.8	434	6802	
0.01 M $K_4P_2O_7$					
0 h	3.8	1.2	<0.1	8300	8370
1 h	190	5.4	39.2	8105	
1 day	1148	16.3	234	7990	
10 days	2275	2.5	427	7570	
0.1 M $K_4P_2O_7$					
0 h	1.5	1.3	<0.1	13677	13950
1 h	207	37.7	41.4	13431	
1 day	1600	70.5	322	12958	
14 days	2313	75.1	419	12658	
28 days	2325	3.7	420	11847	
Theoretical composition (in starting glass)	2310	1070	494	0	

weight loss data. With increasing $K_4P_2O_7$ concentration, the B and Li concentration decreased at a given immersion time, indicating a reduction in the degradation of the glass due to the presence of increasing $K_4P_2O_7$ concentration in this range. However, when the $K_4P_2O_7$ was increased to 0.1 M, this trend of decreasing B and Li concentrations at any given immersion time was not observed. Instead, the concentrations of B and Li at earlier emersion times (e.g., 1 day or earlier) showed an increase over those for the K_2HPO_4 solution containing 0.01 M $K_4P_2O_7$. When the experiments were terminated after 3–28 days, presumably after completion of the conversion reaction, the B concentration in the solution was similar to the theoretical value (taken as the amount in the nominal composition of the starting glass), whereas the Li concentration was slightly less than the theoretical value. The Li/B atomic ratio in the final solution was in the range 0.180–0.188 for all four solutions.

Based on the low concentration of Ca in the K_2HPO_4 solution containing 0 or 0.001 M $K_4P_2O_7$, it appeared that

almost all the Ca^{2+} ions released from the glass reacted rapidly with the phosphate ions of the solution to precipitate a HA-type material. However, as the $\text{K}_4\text{P}_2\text{O}_7$ increased to 0.01 and 0.1 M, the concentration of Ca^{2+} remaining in solution, while low, increased with increasing $\text{K}_4\text{P}_2\text{O}_7$ concentration, indicating that all the Ca^{2+} ions did not react rapidly with the phosphate ions from the solution to precipitate a calcium phosphate material. The concentration of P in each of the four solutions decreased with increasing immersion time of the glass particles, indicating a continuous consumption of the phosphate ions from the solution in the formation of the calcium phosphate material.

3.3 Microstructure of reaction product

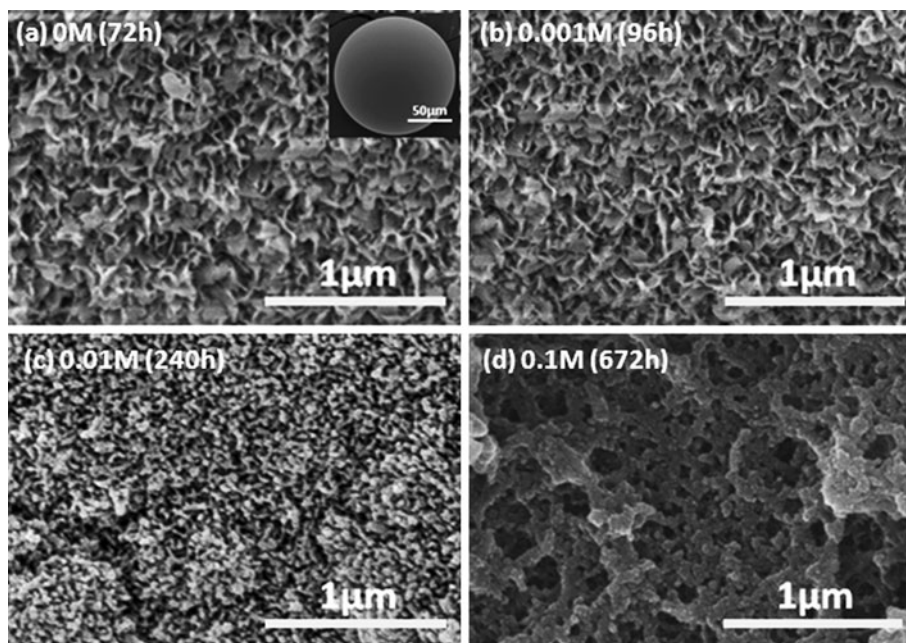
SEM images (Fig. 5) of the surfaces of the converted particles showed marked changes in the microstructure when compared to that of the starting glass particles. In general, the smooth surface typical of a dense glass changed to a porous particulate surface after conversion in the phosphate solution. After conversion in K_2HPO_4 solution containing 0 or 0.001 M $\text{K}_4\text{P}_2\text{O}_7$, the surface of the product consisted of fine, plate-like (or needle-like) particles (Fig. 5a, b), typical of HA precipitated from solution [10]. An increase of the $\text{K}_4\text{P}_2\text{O}_7$ concentration to 0.01 M resulted in a more equiaxial particle shape (Fig. 5c). The product formed in K_2HPO_4 solution containing 0.1 M $\text{K}_4\text{P}_2\text{O}_7$ had a microstructure (Fig. 5d) consisting of more rounded particles, which was markedly different from that of the HA-type material formed in the K_2HPO_4 solution without $\text{K}_4\text{P}_2\text{O}_7$ (Fig. 5a).

4 Discussion

The results show that the presence of pyrophosphate ($\text{P}_2\text{O}_7^{4-}$) ions in an aqueous phosphate solution (0.25 M K_2HPO_4) has a marked effect on the degradation of a calcium–lithium–borate glass and its conversion to a HA-type material. The degradation and conversion also appear to show a marked difference in behavior when the $\text{K}_4\text{P}_2\text{O}_7$ concentration in the K_2HPO_4 solution increases above 0.01–0.1 M. When the $\text{K}_4\text{P}_2\text{O}_7$ concentration is 0.01 M or lower, the degradation and conversion rate decreases with increasing $\text{K}_4\text{P}_2\text{O}_7$ concentration, and according to XRD and FTIR, the conversion product consists of a HA-type material (Figs. 1, 2). On the other hand, for a $\text{K}_4\text{P}_2\text{O}_7$ concentration of 0.1 M, the degradation rate shows a different trend (Fig. 3), and, according to XRD and FTIR, the product does not consist predominantly of a HA-type material (Figs. 1, 2). Instead, the product consists predominantly of a pyrophosphate material consisting of $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$, with only little HA.

Based on the results of previous work [8, 14], it is generally understood that upon immersion of a calcium–lithium–borate glass (e.g., CaLB3-15) in an aqueous phosphate solution (e.g., K_2HPO_4), Li and B dissolve to form Li^+ and BO_3^{3-} ions in the solution. At the same time, Ca^{2+} ions from the glass react with $(\text{PO}_4)^{3-}$ ions from the solution to precipitate HA. ICP-OES data for the concentration of Li, B, and Ca in the phosphate solution (Table 2), coupled with the weight loss data for the glass particles (Fig. 3), are in general agreement with this degradation and conversion mechanism.

Fig. 5 SEM images of the surface of the products formed by converting calcium–lithium–borate (CaLB3-15) glass particles in 0.25 M K_2HPO_4 solution containing (a) 0 M, (b) 0.001 M, (c) 0.01 M, and (d) 0.1 M $\text{K}_4\text{P}_2\text{O}_7$ for the times shown. The inset in (a) shows an SEM image of the unreacted glass surface



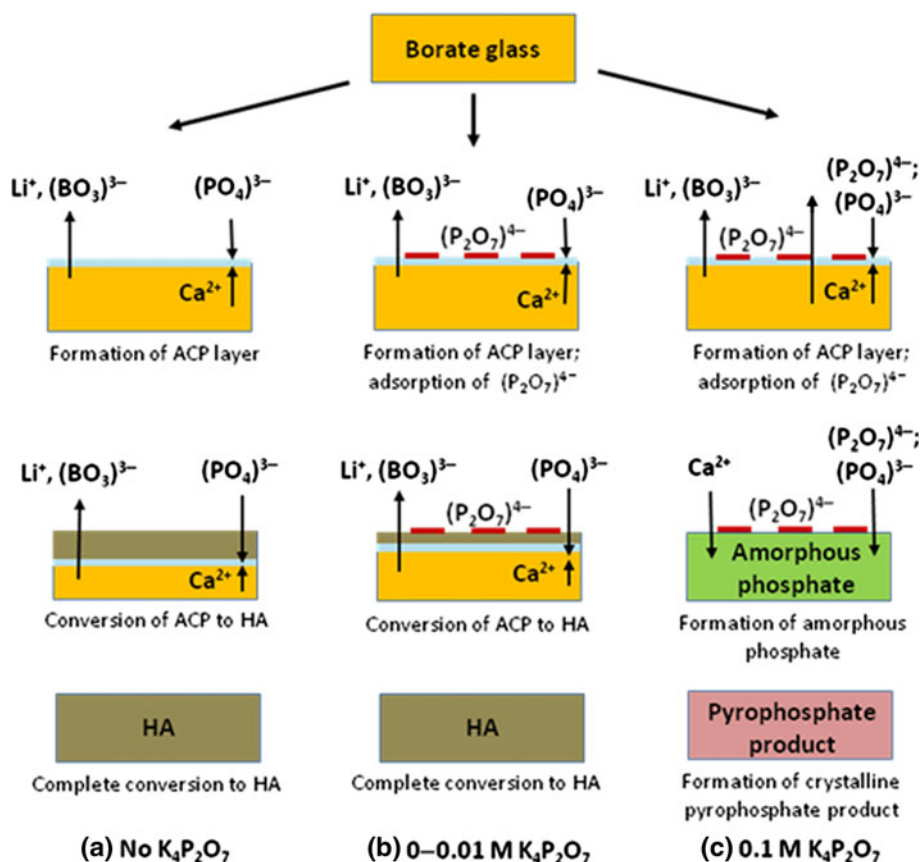
Upon addition of 0.001 M and 0.01 M $K_4P_2O_7$ to the K_2HPO_4 solution, XRD and FTIR analyses show that a HA-type product is still formed. However, the ICP-OES and weight loss data show that both the degradation of the glass particles (Table 2) and the conversion to HA (Fig. 3) are markedly reduced with increasing $K_4P_2O_7$ concentration. The time for complete conversion of the particles increases from ~ 2 days (no $K_4P_2O_7$) to ~ 10 days (0.01 M $K_4P_2O_7$). Assuming that all the CaO from the glass reacts with phosphate ions from the solution to form HA, then the theoretical weight loss is 73%. Figure 3 shows that the final, limiting weight loss of the particles in the K_2HPO_4 solution containing 0–0.01 M $K_4P_2O_7$ is 64%. As discussed previously [9], formation of a substituted hydroxyapatite, such as the substitution of Ca^{2+} with K^+ or $(PO_4)^{3-}$ with $(CO_3)^{2-}$ could account for a deviation from the theoretical value.

At lower $K_4P_2O_7$ concentrations (0–0.01 M), a possible explanation for the reduction in degradation rate and conversion to HA is preferential adsorption of $(P_2O_7)^{4-}$ to the surface of the particles because of their larger molecular weight, when compared to $(HPO_4)^{2-}$ ions. Upon immersion of the borate glass particles into the K_2HPO_4 solution, a calcium phosphate surface layer is presumably formed rapidly [18, 24]. Pyrophosphate ions such as $(P_2O_7)^{4-}$ and

$(HP_2O_7)^{3-}$ have been reported to adsorb readily on the surfaces of HA crystals [25] and to chelate with positively charged ions such as Ca^{2+} [26]. In the present work, adsorption of pyrophosphate ions and chelation with the positively charged network modifiers Li^+ and Ca^{2+} could lead to a reduction in the degradation of the glass. The adsorption of pyrophosphate ions could also lead to a reduction in the nucleation and growth of HA-type material, resulting in a reduction in the conversion to a HA-type material, as observed (Fig. 3). For each system, the Ca content of the solution (Table 2) reaches its highest value at intermediate immersion times, then it decreases at longer times. However, the Ca concentration in the solution is far smaller than the Ca content of the starting glass, indicating the Ca is essentially precipitated as a HA-type material on the particles or chelated with the $(P_2O_7)^{4-}$ ions on surface of the particles.

For the highest $K_4P_2O_7$ concentration (0.1 M) in the K_2HPO_4 solution, the weight loss data (Fig. 3b) and the concentrations of B and Li in the solution (Table 2) show approximately similar trends up to an immersion time of 14 days: they increase with immersion time and reach their maximum values within 14 days. At longer times, the weight loss decreases, whereas the B and Li concentrations essentially show no further change. Essentially all the Li

Fig. 6 Schematic diagrams showing the main steps in the conversion of CaLB3-15 glass in K_2HPO_4 solution (0.25 M) containing (a) no $K_4P_2O_7$; (b) 0–0.01 M $K_4P_2O_7$; and (c) 0.1 M $K_4P_2O_7$



and B has dissolved out of the glass particles within 14 days. On the other hand, the Ca and P concentrations decrease markedly between 14 and 28 days, which indicate the precipitation of these two ions from the solution. As outlined earlier, according to XRD, the product formed after 14 days is amorphous (Fig. 4a), whereas it is crystalline after 28 days, consisting predominantly of $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$. A possible explanation for the behavior at this higher $\text{K}_4\text{P}_2\text{O}_7$ concentration (0.1 M) is that the glass first degrades and converts to an ACP material within the first 14 days of immersion. Calcium ions are chelated with pyrophosphate (P_2O_7)⁴⁻ ions adsorbed on the surface of the particles and in solution. Subsequently, precipitation from solution coupled with crystallization of the ACP material leads to a decrease in the weight loss and the formation of a product consisting predominantly of $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$. XRD showed the presence of additional phases that could not be clearly identified, indicating that the final product consisted of a fairly complex mixture of phases.

A schematic diagram illustrating the proposed mechanism for the conversion of the calcium–lithium–borate glass in K_2HPO_4 solution containing varying concentrations of pyrophosphate (P_2O_7)⁴⁻ ions is shown in Fig. 6. In the K_2HPO_4 solution with no $\text{K}_4\text{P}_2\text{O}_7$, degradation of the glass, coupled with reaction between Ca^{2+} and $(\text{PO}_4)^{3-}$ ions leads to the formation of a HA-type material, as described previously [8, 14]. With the small additions of $\text{K}_4\text{P}_2\text{O}_7$ (0.01 M or smaller) to the K_2HPO_4 solution, adsorption of (P_2O_7)⁴⁻ ions (and possibly (HP_2O_7)³⁻ to the surface coupled with chelation of Ca^{2+} ions leads to a reduction in the degradation rate of the glass and its conversion to a HA-type material. However, with higher $\text{K}_4\text{P}_2\text{O}_7$ addition (0.1 M) to the K_2HPO_4 solution, an ACP material is formed which eventually converts to a crystalline pyrophosphate, consisting predominantly of $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$.

The present results have important consequences for the use of bioactive glass in biomedical applications. Firstly, the addition of pyrophosphate ions to an aqueous phosphate solution could provide a method for controlling the degradation rate of a bioactive glass and its conversion to a HA-type material, particularly for borate glass, which has a low durability. Secondly, the presence of pyrophosphate ions in an aqueous phosphate solution should be avoided when the efficient and complete conversion of a bioactive glass to a HA-type device is required.

5 Conclusions

The conversion of calcium–lithium–borate glass particles (150–355 μm) to a HA-type material in an aqueous

phosphate solution (0.25 M K_2HPO_4) was markedly influenced by the concentration of pyrophosphate (P_2O_7)⁴⁻ ions in the solution. In the K_2HPO_4 solution containing 0–0.01 M $\text{K}_4\text{P}_2\text{O}_7$, while the conversion rate to HA decreased with increasing $\text{K}_4\text{P}_2\text{O}_7$ concentration, XRD and FTIR showed that the fully converted particles consisted of an HA-type product. At higher $\text{K}_4\text{P}_2\text{O}_7$ concentration (0.1 M), the conversion rate of the particles also decreased, but the product did not consist of an HA-type material. Instead, the product consisted predominantly of an ACP material which eventually crystallized to a pyrophosphate product, consisting predominantly of $\text{K}_2\text{CaP}_2\text{O}_7 \cdot 4\text{H}_2\text{O}$ and $\text{Ca}_2\text{P}_2\text{O}_7 \cdot n\text{H}_2\text{O}$. The results show the potential of pyrophosphate ions for influencing the conversion of a bioactive glass to HA in an aqueous phosphate solution, as well as the ability to produce a calcium pyrophosphate product predominantly by reacting a calcium–lithium–borate glass in a phosphate solution containing a sufficient concentration of pyrophosphate ions.

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