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Preparation, structure and solubility of $Ca_2KNa(PO_4)_2$

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Materials based on calcium alkali orthophosphate using for filling bone defects have been fabricated by means of solid state reaction method. The starting materials were selected from chemical reagents: $CaHPO_4{\cdot}2H_2O$, $CaCO_3$, Na_2CO_3, K_2CO_3 and H_3PO_4(85%). After these materials were mixed stoichiometrically and dried at 200°C for 2 hours, the mixture was sintered in air at high temperature for 2 hours. The samples were characterized by X-ray diffraction. The results showed that the new materials contained only one crystal phase: $Ca_2KNa(PO_4)_2$, whether the sintering temperature was 1350 degrees C or higher if the material was designed as $Ca_2KNa(PO_4)_2$. Furthermore, the solubility was tested and it revealed that these materials containing $Ca_2KNa(PO_4)_2$ had higher solubility than α-TCP.

1. Introduction

Hard tissues in the human body are composites, consisting of a mixture of 22wt% organic matrix of which 90–96wt% is collagen and 69wt% inorganic phase of which the major subphase consists of submicroscopic crystals of an apatite of calcium and phosphate, resembling hydroxyapatite in its crystal structure ($Ca_{10}(PO_4)_6(OH)_2$) [1]. So calcium hydroxyapatite (HAp) and tricalcium phosphate (TCP) are commonly used calcium phosphate ceramics for bone replacement due to their excellent biocompatibility [1–4]. Porous HAp and β-TCP implants have been widely used in various fields (orthopaedics, maxillofacial, etc.) and demonstrated bone in-growth into the open pores on the surface of the implant [5–7]. Dense HAp and β-TCP implants become surrounded by mature fibrous tissue with a variable amount of new bone formation [8]. However, the poor mechanical properties of these ceramics limit the scope of their clinic applications, and the difficulties to shape make it difficult to directly use as heavy load-bearing bone implants, but they can be used to fill bone defects directly [8]. Experiments shown that calcium phosphate ceramics can enhance bone growth and can be biodegradated and absorbed slowly [8–10]. Sodium and/or potassium phosphate can be added in the calcium phosphate ceramics to improve their biodegradability [11], and cell cultures exhibit that materials containing $Ca_2KNa(PO_4)_2$ have favored osteoblast growth [12]. So calcium alkali orthophosphate, $Ca_2KNa(PO_4)_2$, is one of the most promising materials used as bone filler to heal bone defects.

The objectives of the present work were to prepare pure calcium alkali orthophosphate suitable for clinic application filling bone gaps and to study the effects of sintering temperature on the structure and cooling manner on the solubility of $Ca_2KNa(PO_4)_2$.

2. Materials and methods

2.1. Preparation of the samples

The solubility of calcium phosphate is different with that of alkali metal phosphates, it is impossible to synthesize calcium alkali orthophosphate from aqueous medium by co-precipitation, the method to prepare $Ca_2KNa(PO_4)_2$ may be solid-state reaction. Almost all calcium phosphates have high melting point. The melting point of tricalcium phosphate (TCP) is about 1670°C, the adding of alkali metal phosphate to TCP may decrease the melting point of the mixture, which makes it possible to manufacture calcium alkali orthophosphate at relatively lower temperature. The platinum crucible must be used as the container to melt the mixture because the alkali metal phosphate can corrupt the alumina crucible though it can be used at high temperature.

The starting materials for manufacturing calcium alkali orthophosphate were selected from chemical reagents that were analytical purity. They were $CaHPO_4 \cdot 2H_2O$, $CaCO_3$, Na_2CO_3, K_2CO_3, and H_3PO_4 (85%). These materials were mixed in stoichiometrical amount and dried at 200°C for 2 hours, then, the mixture was milled in an alumina roller for about 2 hours

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TABLE I Preparation condition of samples

Sample name	Formula	Sintering temp.	Cooling manner
R6-18	$Ca_2KNa(PO_4)_2$	1550°C	Quenched in air
R7-13	$Ca_2KNa(PO_4)_2$	1550°C	Cooled in furnace
R8-15	$Ca_2KNa(PO_4)_2$	1550°C	Cooled in furnace
Alpha-TCP	$Ca_3(PO_4)_2$	1300°C	Quenched in air

to mix uniformly. The blended powder was separated into several portions. The mixture was then heated in Pt crucible in dry atmosphere from room temperature to desired different high temperature that is from 1350 °C to 1550°C at a rate of 5°C/min, and sintered at the high temperature for 2 hours. To get crystallized compounds, the melts were cooled at the rate of about 3°C/min in the furnace (such as sample R7-13 and R8-15); otherwise, to obtain material containing more glassy phase, the melts were quenched in air (as sample R6-18). The result materials were removed out from platinum crucible and crushed into pieces. For chemical analyses of the composition and powder X-ray diffraction measurements of the structure, the materials were milled to powder smaller than 18 μm. For the solubility tests, the granule particles of 300–500 μm were selected after the materials were crushed freshly. The preparation conditions of all the used samples are listed in Table I.

2.2. Chemical analysis of composition

The chemical composition of the material was determined after the mixture was sintered. The starting materials were analyzed too. The CaO content was determined by EDTA complexometric titration, the P_2O_5 content was measured by phosphomolybdic acid–quinoline gravimetric method. Sodium and potassium oxides were analyzed by flame atomic absorption spectroscopy (FAAS; WFX-1C, Beijing second optical instrument manufacturer, Beijing, China).

2.3. X-ray diffraction measurements

The structure of the material was characterized by powder X-ray diffraction (XRD, D–S X-ray diffractometer, Rigaku, Japan) at room temperature, using Cu K_α radiation (wavelength: 0.154178 nm) at 40 kV and 40 mA. The 2θ angles were swept from 20°C to 70°C at a rate of 0.02°C/sec.

2.4. Determination of solubility

The granule fraction of the material with the size of 300–500 μm was used to determine the solubility. 1.00 gram of sample was put into a 500 ml triangle flask with 250 ml pH7.4 buffer solution, the solution in the flask was kept to 37 ± 1°C in water bath. Having been dipped for 24 hours, the solution was analyzed to determining the solubility. Calcium, sodium, and potassium cations concentration were measured by FAAS. The phosphate was determined by phosphomolybdic blue spectrophotometric method.

TABLE II The composition of the prepared samples

Sample	CaO wt%	P_2O_5 wt%	Na_2O wt%	K_2O wt%	Ca/P
$Ca_2KNa(PO_4)_2^*$	33.76	42.73	9.33	14.18	1.00
R6-18	35.53	42.97	8.55	12.26	1.05
R7-13	34.88	42.96	8.79	11.76	1.03
R8-15	34.10	42.57	9.23	13.25	1.01

*Theoretical formula, the oxide contents were calculated from the formula.

3. Results and discussion

3.1. Chemical composition of the materials

The material to be prepared was designed as $Ca_2KNa(PO_4)_2$. The starting materials were mixed in stoichiometric amount and sintered with the method described before in 2.1. These samples were produced at different time and batches in one furnace, but sintered at same high temperature of 1550°C, the cooling manner were different, as listed in Table I. The determined and theoretical composition of the material was shown in Table II. It is clear that there are differences between theoretical (designed) and tested contents, which may be caused by the analytical errors. The composition of synthetic $Ca_2KNa(PO_4)_2$ was matched with the chemical formula.

3.2. The effect of sintering temperature on the structure

To investigate the structure of the synthetic compound, $Ca_2KNa(PO_4)_2$, powder X-ray diffraction was used, as described in 2.3. The X-ray diffraction patters of sample R6-18, R7-13 and R8-15 are shown in Fig. 1. To understand how the sintering temperature effect the structure of synthetic $Ca_2KNa(PO_4)_2$, four samples with the same starting mixture were sintered at different temperature: 1350, 1400, 1500, 1550°C, and cooled in the furnace, and were investigated by XRD (Fig. 2).

It was shown from Fig. 1 that the XRD patters of samples R6-18 and R7-13 were much similar, this indicated that the main crystal phase of the two samples had the same structure. The background of the XRD of R6-18 was higher than that of R7-13, especially in lower 2θ angle, this meant that R6-18 had more amorphous phase than sample R7-13. The background of XRD pattern of R8-15 was much lower, and some weak peaks were not detected or very weak, this meant that

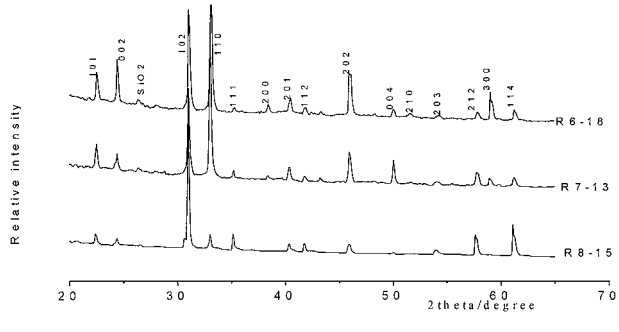

Figure 1 X-ray diffraction patterns of $Ca_2KNa(PO_4)_2$ prepared at 1550°C: R6-18 was quenched in air, R7-13 and R8-15 were slowly cooled in furnace.

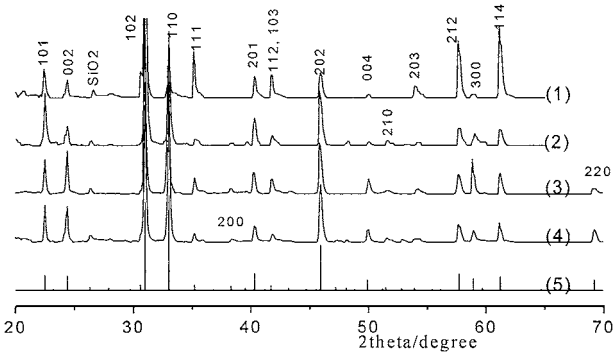

Figure 2 Powder XRD patterns of $Ca_2KNa(PO_4)_2$ samples prepared at different Temp. and cooled in furnace: (1), 1550°C (R8-15); (2), 1500°C; (3), 1400°C; (4), 1350°C; and (5), the XRD pattern of $Ca_2KNa(PO_4)_2$ reported by G. Berger [11].

sample R8-15 was high crystallized, and the crystal orientation was notable. From the XRD patterns, the plane indices and the lattice parameters of the hexagonal crystal phase of $Ca_2KNa(PO_4)_2$ were calculated, as shown in Fig. 1, and $a = 0.5432$ nm, $c = 0.7308$ nm. From Fig. 2, it was shown that all peaks of the XRD patterns of the four materials were in same positions one-to-one and were similar to the XRD patterns of $Ca_2KNa(PO_4)_2$ described by G. Berger [11], while the peaks relative intensities were changing, so that the lattice structures of the main crystal phase of the 4 samples were similar to one another. The crystal structure was calculated as a hexagonal space lattice, and the plane indices were shown in Fig. 2. Micro amount impurity SiO_2 existed in the samples came from the reactant and agate mortar. The background for XRD pattern of sample $Ca_2KNa(PO_4)_2$ made at higher temperature was flat, otherwise, if the sintered temperature was lower, say 1350°C, the background would changed to more rough. This meant that $Ca_2KNa(PO_4)_2$ materials had more crystal phase if the synthetic temperature was high, and contained more amorphous phase if the temperature was lower. This could be explained to the formation of poorly crystallized $Ca_2KNa(PO_4)_2$ when it crystallized spontaneously and directly from the melt at lower temperature. If the melt at higher temperature crystallized, there was enough time to produce perfect crystalline. The diffraction intensities of planes (002), (004), and (200), (300) were decreasing with the sintering temperature increasing, this could be explained by the selected orientation of crystal grains.

There were no other phases of calcium and phosphate compounds, such as $Ca_2P_2O_7$, CaO, $Ca_3(PO_4)_2$ and $CaKPO_4$ or $CaNaPO_4$ in the resulted materials, no XRD peaks of these materials' could be defined in the patterns, so the material contains only one crystal phase of $Ca_2KNa(PO_4)_2$ that was not listed in the JCPDS-index. Even at the lower temperature, for example, 1350°C, the crystal phase of the prepared material was the single phase of $Ca_2KNa(PO_4)_2$.

The melting point of potassium-sodium carbonate is about 850°C, if the temperature is higher than the melting point, the melted alkali metal carbonate can reacted with calcium phosphate, and this can be observed from the XRD pattern as shown in Fig. 2. The synthesis process can be explained by the following reaction:

$$CaHPO_4 \cdot 2H_2O \rightarrow CaHPO_4 + 2H_2O \uparrow \quad (1)$$

$$2CaHPO_4 \rightarrow Ca_2P_2O_7 + H_2O \uparrow \quad (2)$$

$$Ca_2P_2O_7 + 1/2Na_2CO_3 + 1/2K_2CO_3 \rightarrow Ca_2NaK(PO_4)_2 + CO_2 \uparrow \quad (3)$$

Reaction (1) takes place at about 120°C, reaction (2) occurs when temperature is above 400°C. Calcium pyrophosphate ($Ca_2P_2O_7$) melts approximately at 1360°C, the potassium and sodium phosphates melt at this temperature also, the melting points of the mixture is about 1340°C. So if the starting mixture is heated to 1350°C or over, the reactants and the resultant are melted simultaneously and the reaction (3) will carry out easily. Therefore the proper temperature for fabrication of $Ca_2KNa(PO_4)_2$ is about 1400°C.

3.3. The solubility of $Ca_2KNa(PO_4)_2$

For testing the solubility of $Ca_2KNa(PO_4)_2$ two samples were used, one was cooled in the heated furnace after shut off the electronic power (R8-15), the other was air quenched. The samples' solubility in 24 hours in pH7.4 buffer solution at 37°C were 190, 57 and 72 mg/L for R6-18, R8-15, and alpha-TCP respectively.

The solubility of R6-18 was much higher than that of R8-15 and α-TCP. That means the cooling manner had great influence on the solubility. The poorly and glassily crystallized material (R6-18) developed when the melt cooled in air made it more easy to dissolve, the perfect crystalline (R8-15) formed from the melt spontaneously and slowly when the melt was cooled slowly in the furnace showed decrease of the solubility.

Investigations of the dissolution process revealed that the material did not dissolve stoichiometrically. At the different time during the solubility test, a 5.00 ml solution was picked up and the fresh 5.00 ml buffer solution was added to the bulk to maintain the solution volume. Then the concentrations of Ca^{2+}, Na^+ and K^+ ions were determined and shown in Fig. 3.

It was shown in Fig. 3 that the concentrations of Na^+ and K^+ ions increased with time, but the concentration of Ca^{2+} ion increased in the beginning 12 hours and decreased later. This phenomenon is different with that reported by Dr. Berger [11]. $Ca_2KNa(PO_4)_2$ might

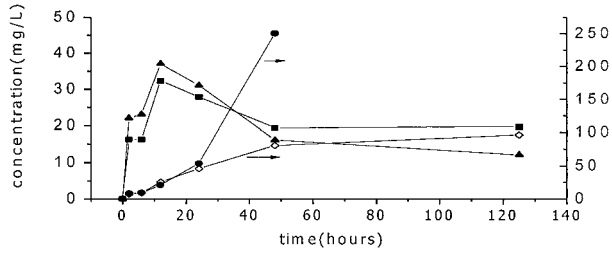

Figure 3 The relationship between ion concentration and time during dissolution: the concentration of Ca^{2+} (▲), Na^+(●) and K^+(◇) ions in the solution of R6-18; and the concentration of Ca^{2+} (■) ion in the solution of α-TCP.

be solved stoichiometrically at the beginning of the dissolution process, but with the time prolonged, the concentrations of Ca^{2+} and PO_4^{3-} ion increased to a great amount so that it made the solution saturated for HAp, calcium ion concentration would decrease with the increasing concentration of phosphate ion. With the dissolving of $Ca_2KNa(PO_4)_2$, the solution became more basic, pH > 7. Because HAp is the least soluble calcium phosphate compound in a wide range of pHs from approximately 4.2 to 14, thus, within this range, all other calcium phosphates will have the tendency to dissolve and precipitate as HAp [13, 14]. This phenomenon has been illustrated by Monma [15] who reported that alpha-TCP converted to HAp in hot water. $Ca_2KNa(PO_4)_2$ and α-TCP may have the same phenomenon, they are dissolved easily at the beginning, but the concentration of Ca^{2+} and PO_4^{3-} would be controlled by the Ksp of HAp, which would induce the decrease of $[Ca^{2+}]$ with the increase of $[PO_4^{3-}]$. The dissolution and precipitation process may be describe as the following reactions:

$$Ca_2KNa(PO_4)_2 \rightarrow 2Ca^{+2} + K^+ + Na^+ + 2PO_4^{3-}$$

$$PO_4^3 + H_2O \leftrightarrow HPO_4^{2-} + OH^-$$

$$10Ca^{2+} + 6PO_4^{3-} + 2OH^- \leftrightarrow Ca_{10}(PO_4)_6(OH)_2$$

4. Conclusion

Calcium potassium sodium orthophosphate could be fabricated by sintering a mixture consisting of a stoichiometric molar rate of 4:1:1 of $CaHPO_4$, Na_2CO_3 and K_2CO_3 at high temperature of 1400°C. X-ray powder diffraction characterized that the resultant was the single phase of $Ca_2NaK(PO_4)_2$. This material had higher solubility than α-TCP if the melt was quenched in air. The dissolution process was interesting because it was not a stoichiometrical course, the concentration of alkali metal phosphate was increasing with the time but calcium ion concentration increased to maximum and then decreased with the time. The dissolving process may be controlled by equilibrium of the dynamic dissolution of $Ca_2KNa(PO_4)_2$ with the precipitation of HAp, because HAp is the least soluble calcium phosphate in a wide range pHs of 4.2 to 14, $Ca_2KNa(PO_4)_2$ may be dissolved and changed to HAp deposition. This may be the cause why we got different results with that reported by Dr. G. Berger [11]. The virtual dissolution kinetics, the hydration process of $Ca_2KNa(PO_4)_2$ in water may be worth investigated deeply in future.

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