Hydrothermal Synthesis of Hydroxyapatite from Calcium Sulfate Hemihydrate

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Abstract

Commercial grade calcium sulfate hemihydrate ($CaSO_4 \cdot 0.5H_2O$, or plaster of paris, PoP) an economically feasible and abundant precursor has been used in ($Ca_{10}(PO_4)_6(OH)_2$, HAp) synthesis. The synthesis was realized by reacting solid PoP precursor with 1M of $(NH_4)_2HPO_4$ aqueous solution, at ambient and mild hydrothermal conditions (2 ± 0.2 atm and 120 °C). The effect of reaction temperature and pressure on PoP to HAp conversion efficiencies and reaction kinetics has been reported. The formation of HAp at a reaction temperature lower than 50 °C occurs at very limited extend; at 25 °C HAp formation starts after 7 days. Extending the reaction time for low temperature reactions improves the HAp formation efficiency, meanwhile this also promotes precipitation of another calcium phosphate- $CaHPO_4 \cdot 2H_2O$ together with HAp. At a reaction temperature of 90 °C HAp formation completes in 6 hours. Hydrothermal reaction conditions on the other hand significantly enhances reaction kinetics, where the transformation to HAp starts in 15 min and finalizes only in 90 min. Hydrothermal reaction also hampers the formation of secondary phases, most likely originating from the impurities of low grade PoP precursor. The scanning electron microscopy analyses showed that HAp crystals are preferentially growing on the reactant PoP powders in a reticulated need-like morphology, suggesting a dissolution and repreciptation mechanism for HAp formation. The findings showed that HAp synthesis can be accomplished by using a single and relatively cheap solid precursor under technological relevant hydrothermal conditions. Such synthesis routes can be practically expanded for making phase pure HAp powders in industrial scale.

Keywords: Calcium phosphates, calcium sulfate, hydroxyapatite, powder synthesis, hydrothermal synthesis.

1. Introduction

Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$, HAp) is the main constituent of hard tissues. It has gained considerable attraction due to its excellent osteoconductive and osteointegration properties, allowing synthetic HAp to be used widely in clinical surgery and biomedical applications. In general, synthetic HAp powders are synthesized by precipitation [1-3], hydrolysis [4-6], sol-gel method [7], solid state reactions [8]. Some common problems for these synthesis techniques are, long reaction times, agglomeration, uncontrolled particle size and non-stoichiometric products. However, hydrothermal methods combine moderate temperatures with high pressures and they offer good control on morphology and chemical stoichiometry [9-13].

In this study calcium sulfate hemihydrate ($CaSO_4 \cdot 0.5H_2O$, or plaster of paris, PoP) has been used in HAp synthesis via mild hydrothermal conditions. Previously, several studies have been employed to produce HAp from calcium sulfate sources using phosphate solutions [14-16]. Almost all of these studies, complete conversion to HAp was achieved; however, the reaction times can prolong from 4 hours up to 15 days, which makes them unfeasible for industrial scale bulk production.

The main objective of present study was to investigate the conversion kinetics of commercial grade PoP into HAp by treating with 1 M of $(NH_4)_2HPO_4$ solution under hydrothermal conditions (2 atm, 120 °C). The kinetics was compared to those achieved under ambient conditions (1 atm, 25 °C, 50 °C, 90 °C). The analytical characterization performed by x-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses showed that under hydrothermal conditions, PoP was completely transformed into HAp in 90 min. As-synthesized hydrothermal reaction product was calcium deficient of moderate crystallinity. The thermal stability studies of the HAp product showed that the crystallinity can be further improved by calcination treatments lower than 600 °C.
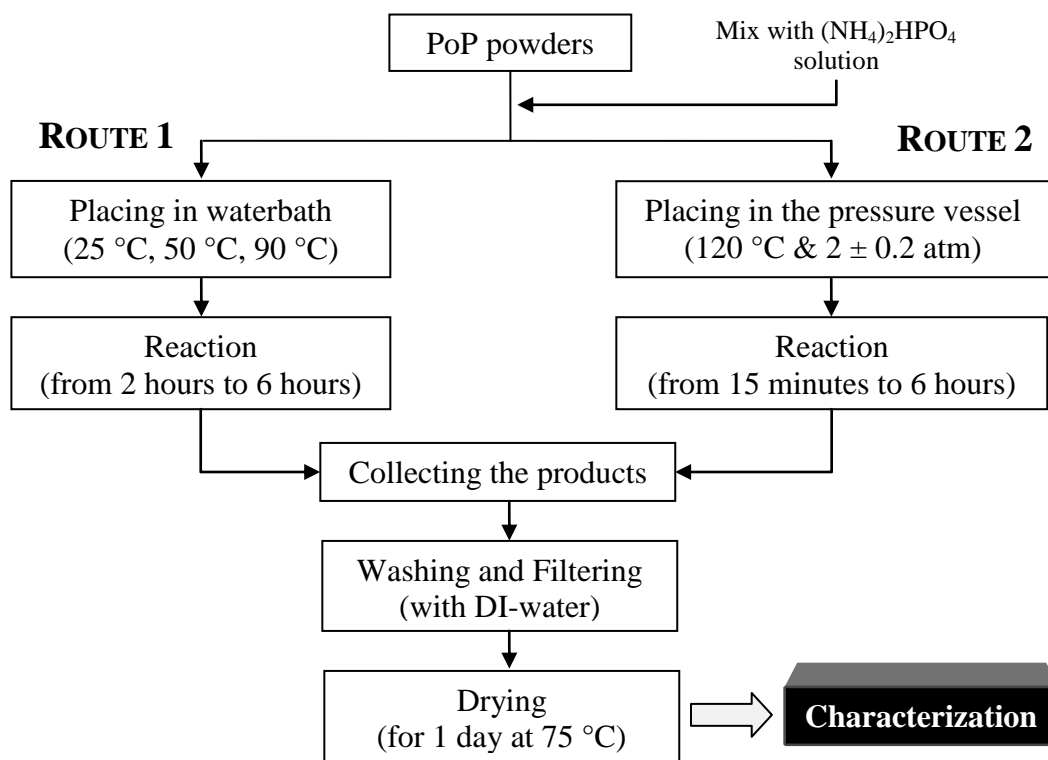

Figure 1. Experimental procedure for synthesis of HAp from PoP powders.

2. Materials

Commercial grade plaster of paris ($CaSO_4 \cdot 0.15H_2O$, PoP, Knauf) are used for starting material to synthesize HAp powders. The average particle size of the PoP powders was around 55 μm. Di-ammonium hydrogen phosphate (($NH_4)_2HPO_4$, 99.0%) obtained from Merck employed in preparing the aqueous reactant solution.

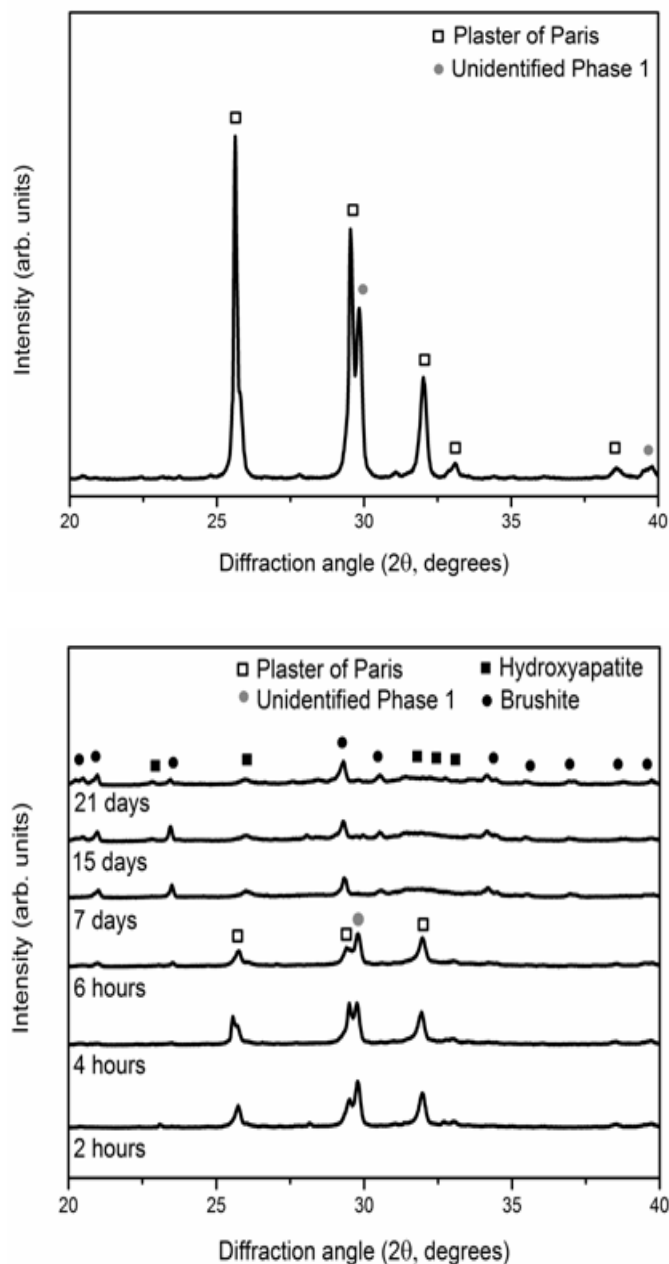**Figure 2.** XRD diffractograms of unreacted PoP (top) and the product of reaction of PoP with 1 M

($NH_4)_2HPO_4$ solution at 25 °C under ambient conditions. (bottom)

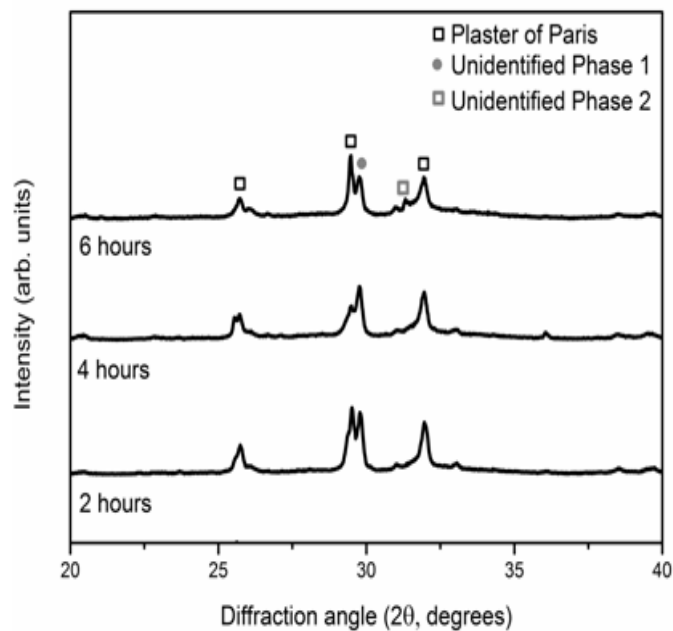**Figure 3.** XRD diffractograms for the product of reaction of PoP with 1 M ($NH_4)_2HPO_4$ solution at 50°C under ambient conditions.
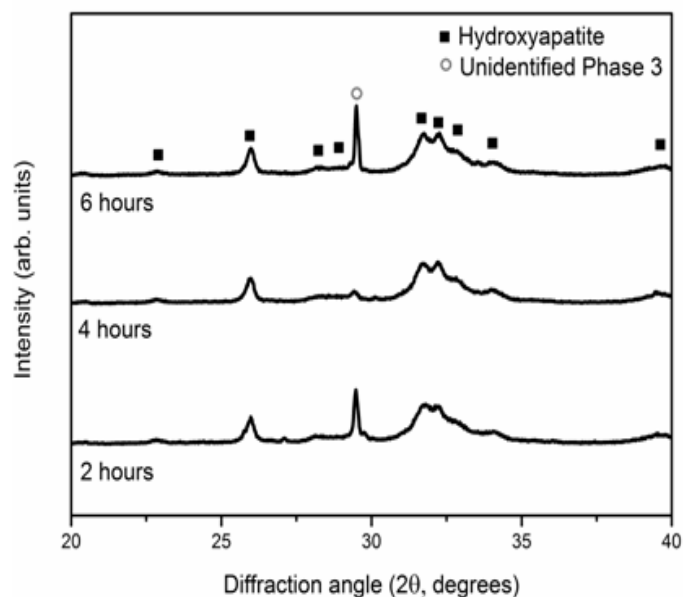

Figure 4. XRD diffractograms for the product of reaction of PoP with 1 M ($NH_4)_2HPO_4$ solution at 90 °C under ambient conditions.
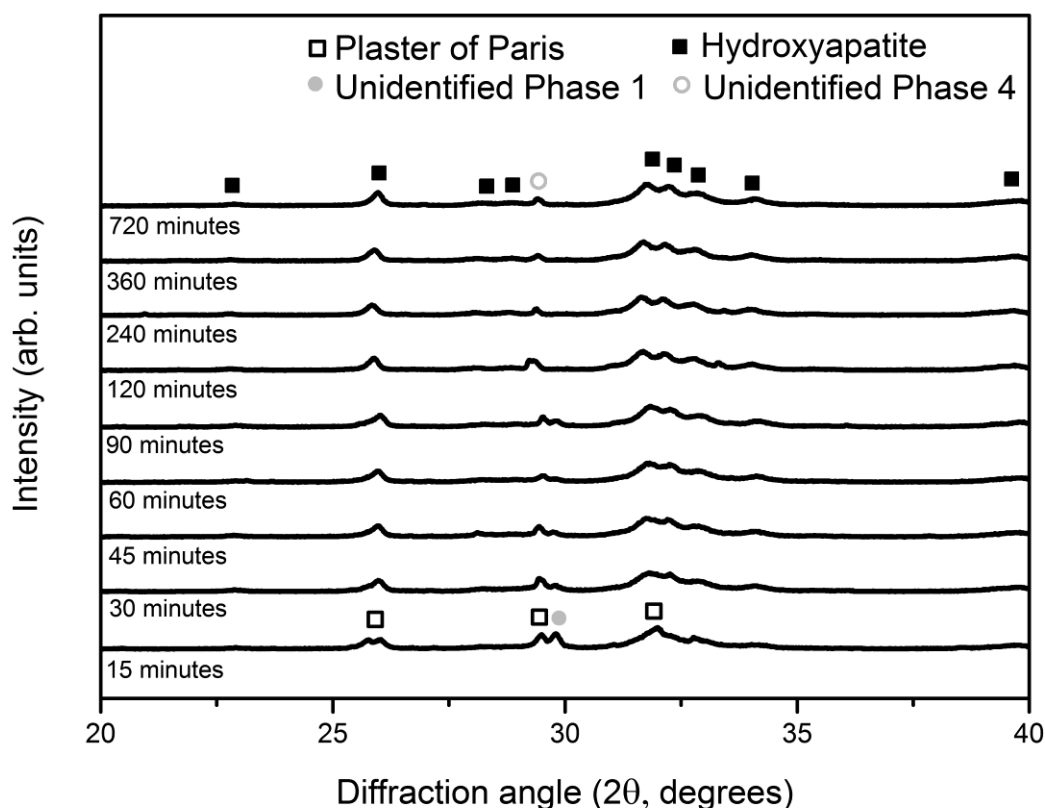
Figure 5. XRD diffractograms for the hydrothermal reaction product between PoP and 1 M of $(NH_4)_2HPO_4$ solution.

2.1. Synthesis of HAp

HAp synthesis from PoP powders was achieved by two routes. The flowchart in Figure 1 shows the details for conversion of PoP powders to HAp. In *Route-1*, HAp was synthesized in powder form under ambient conditions at 25 °C, 50 °C and 90 °C to investigate the effect of temperature on reaction kinetics. This reaction conversion was achieved according to the reaction below:

$$10CaSO_4 \cdot 0.15H_2O + 6(NH_4)_2HPO_4 \longrightarrow Ca_{10}(PO_4)_6(OH)_2 + 6(NH_4)_2SO_4 + 4H_2SO_4 + 1.4H_2O$$
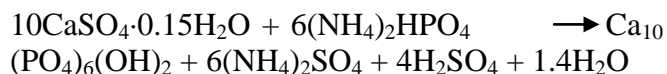
Typically, 4 g of PoP was mixed with the 40 mL 1M of $(NH_4)_2HPO_4$ solution in a high density polyethylene (HDPE) container floated in the water bath at the reaction temperature. The reaction time varied from 15 min to 6 h. For the reaction at 25 C, prolonged reaction times up to 21 days have been also performed. In *Route-2,* HAp was produced using a hydrothermal vessel to examine the effect of pressure on the conversion kinetics of PoP powders to HAp. Again 4 g of PoP powders was mixed with 40 mL of $(NH_4)_2HPO_4$ solution in HDPE bottle. Then, the bottle was put inside the pressure vessel operating at 2 ± 0.2 atm and 120 °C. The reaction time varied from 15 min to 6 h. For both routes, at the end of reaction period, the solid products were washed with DI-water and filtered to eliminate any water soluble remains. After washing, the solid residue was put in open air drying oven operating at 75 °C for 1 day.

2.2. Characterization

X-ray diffraction (XRD) analyses were employed for the phase analysis of the starting PoP powder and the reaction products. The analyses were performed by a Rigaku Ultima

D/MAX2200/PC X-Ray Diffractometer. CuKα radiation was used as an X-ray source at 40 kV. The scan speed was 2°/min. The samples were scanned over from 20º to 40º in 2θ. The morphology of the PoP powder and the reaction products were examined by scanning electron microscopy (SEM) SEM analyses were performed by using a JEOL JSM-6400 Electron Microscope, equipped with a Noran System 6 X-ray Microanalysis System and Semafore Digitizer. Samples were coated by Au-Pd alloy by an Anatech Hummle VII sputter coating device.
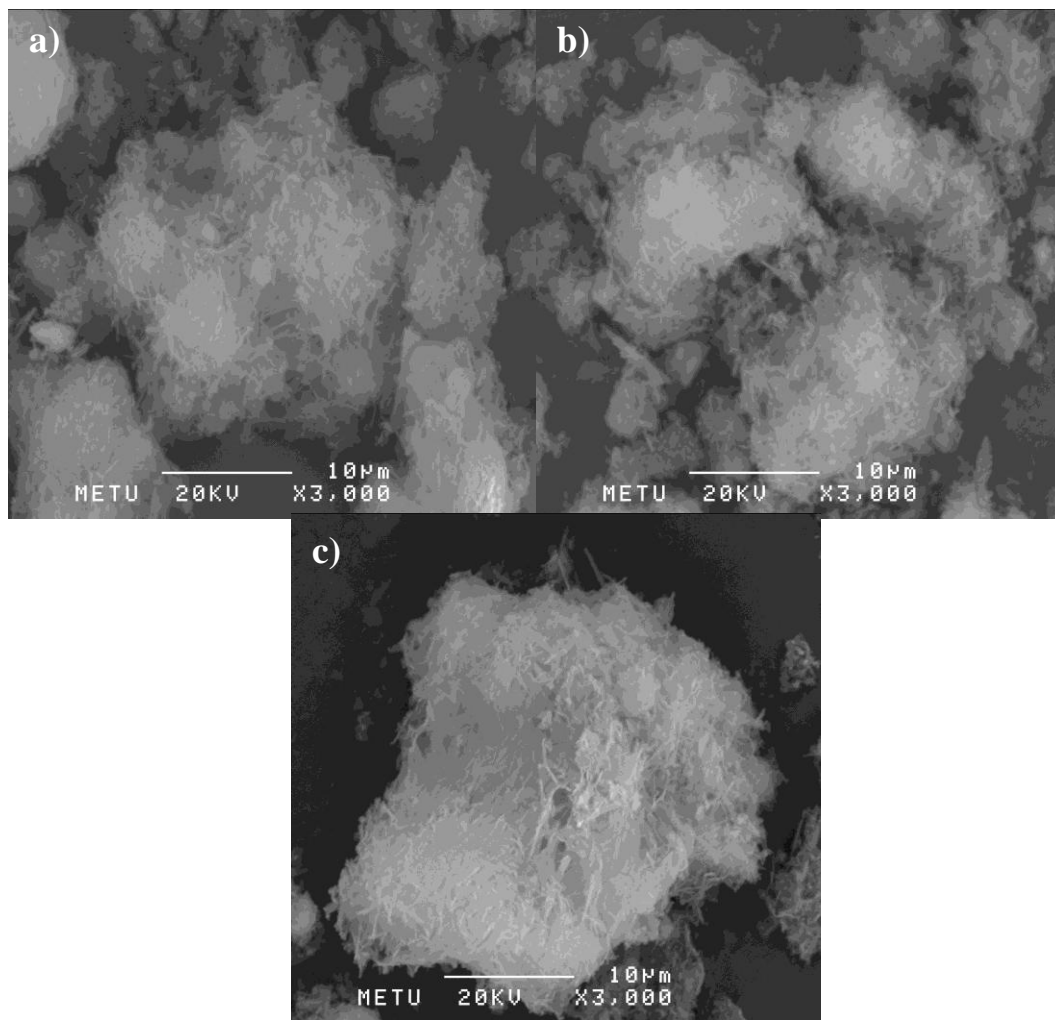

Figure 6. SEM micrographs of HAp products obtained under hydrothermal conditions after reaction with 1 M $(NH_4)_2HPO_4$ solution for a) 2 hours, b) 4 hours and c) 6 hours.

3. Results and Discussion

Figure 2 shows the XRD diffractograms for unreacted PoP sample and the product obtained according to Route-1 for the reaction of PoP with 1M $(NH_4)_2HPO_4$ solution at 25 °C up to 21 days. Up to 6 hours no significant change occurs and the initial PoP powder stays as it is. Only some unidentified phase (labeled as *Unidentified Phase 1*) from the calcium sulfate source seems to be eliminated during initial periods of the reaction. After 7 days, the reactants mostly converted into brushite $CaHPO_4 \cdot 2H_2O$ (JCPDS card no. 09-077). In addition, small amounts of HAp (JCPDS card no. 09-432) was formed after 7 days, as revealed by broad peaks at round 2θ of 31°-33°

which are characteristic to HAp. The XRD diffractograms in Figure 3 show the reaction products formed at 50 °C up to 6 hours. This set of data is comparable with the XRD patterns of the products formed at 25 °C, and no HAp or some other calcium phosphate phase develops up to 6 h. On the other hand, the reaction products of the 90 °C-reaction was distinctly different as shown by the XRD diffractograms in Figure 4. The reaction seems to be more complete compared those reactions performed at 25 °C and 50 °C, as the characteristic HAp diffraction peaks ($2\theta \approx 31°$ - $33°$) can be more clearly observed even after 2 h. As the reaction period was extended from 2 h to 6 h, the HAp product becomes more crystalline and peaks becomes more distinct. The extra phases originating from PoP source have been also detected, however the detailed investigation and identification of these unknown has been considered trivial within general scope of the present work.

The XRD diffractograms in Figure 5 show the effect of pressure on conversion of PoP to HAp. Under hydrothermal conditions the conversion to HAp starts in 15 min, which is considerably shorter than the conversion reaction at ambient conditions, and HAp is revealed by the broad characteristic peaks at $2\theta \approx 31°$ - $33°$. In 30 min, more HAp is produced and some PoP remained unreacted. PoP was still present up to 90 min reaction; however, after 2 hours, the reaction seems to be complete to some extent. As reaction time increases, crystallinity of the HAp phase also enhances, but the crystallinity of HAp phase was still at moderate degree. Additionally, the extra phase (labeled as *Unidentified Phase 1*) converts into some other phase (labeled as *Unidentified Phase 3*) as reaction time increases. The intensity of the extra phase apparently reduces with time; however it is impossible to say that it can be eliminated at longer reaction times due to the uncertain behavior of these phases. The new unidentified extra phase also does not match with any standard JCPDS card.

The SEM micrographs in Figure 6 show the morphological details of the starting PoP powders together with HAp products obtained by hydrothermal reaction produced using 1 M of $(NH_4)_2HPO_4$ solution. This figure shows the micrograph of HAp produced after 2 h, 4 h and 6 h reactions. According to this figure, the morphology of the particles has changed compared to their initial appearance shown in Figure 6a. The new form resembles the general prismatic structure of the α-hemihydrate; however, the surface of these prismatic particles is covered with HAp crystals. It is impossible to predict the chemical composition of the interior side (core) of the particles; however the XRD data has shown that almost complete conversion to HAp has occurred in all cases. Newly formed HAp on the surface of the PoP particles has needle-like morphology with an approximate crystal size of 1 μm to 8 μm. The details of this morphological change can be more clearly seen by the SEM micrograph in Figure 7. It is possible to clearly observe the reticulated needle-like crystals of HAp with a primary particle size of $20 - 30$ μm.
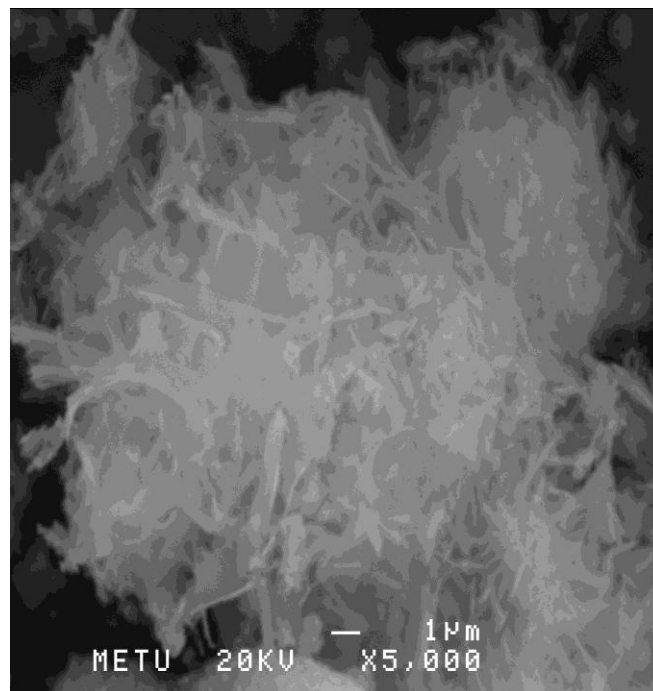

Figure 7. The detailed SEM micrograph of the HAp product obtained under hydrothermal conditions after reaction with 1 M $(NH_4)_2HPO_4$ solution for 4 hours.
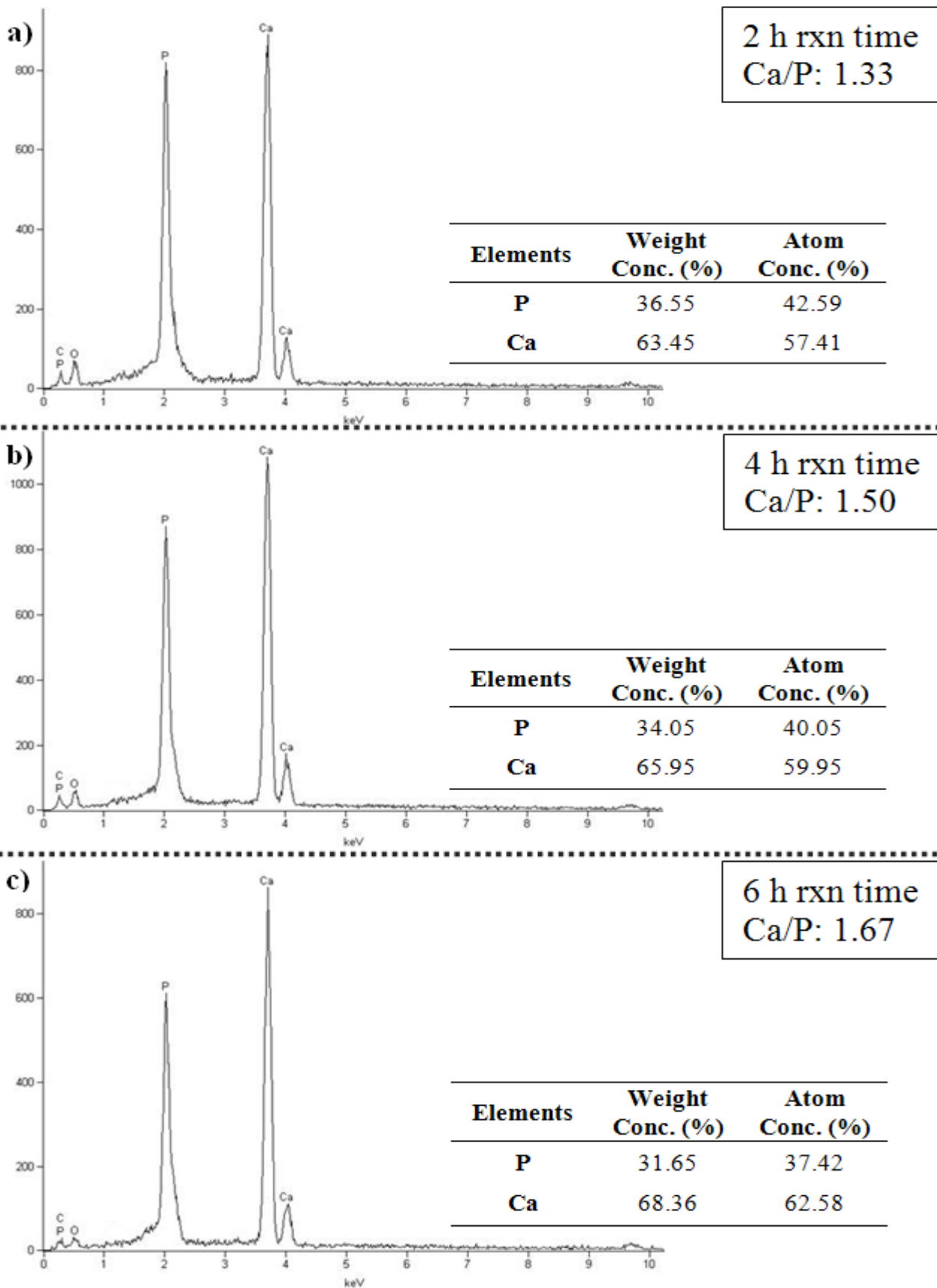
Figure 8. EDS spectra for HAp products obtained under hydrothermal conditions after reaction with 1 M $(NH_4)_2HPO_4$ solution for a) 2 hours, b) 4 hours and c) 6 hours.

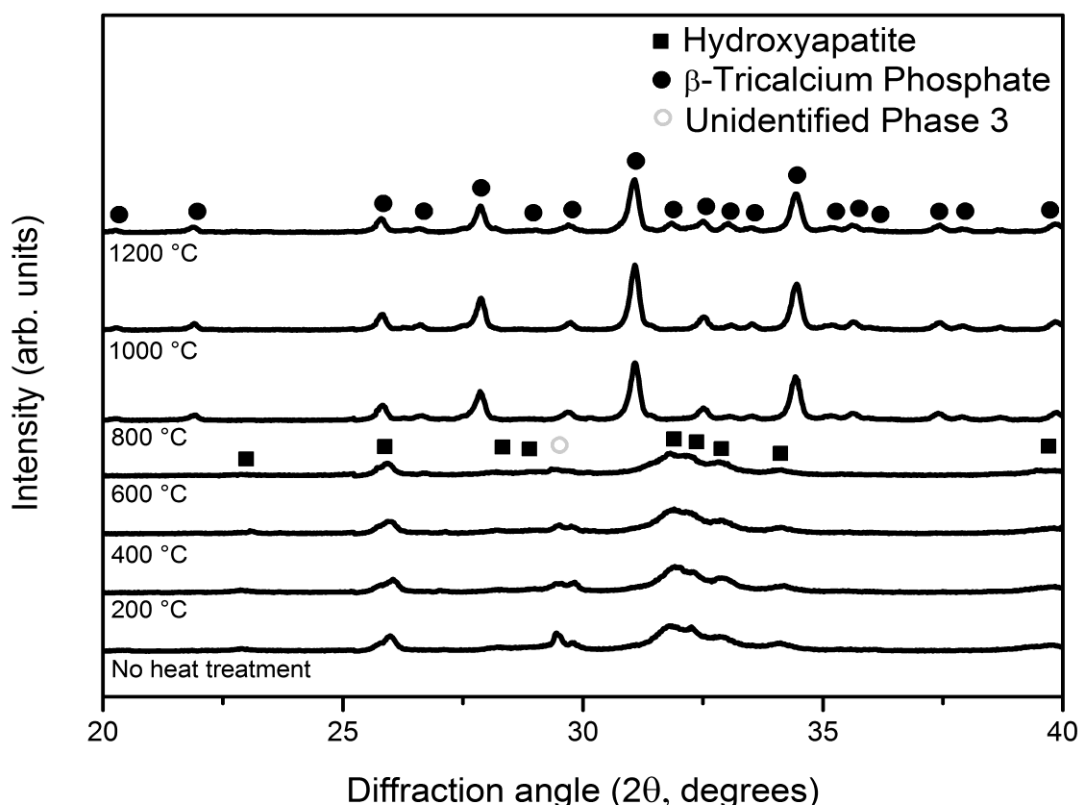**Figure 9.** XRD diffractograms HAp product obtained under hydrothermal conditions after reaction with 1 M $(NH_4)_2HPO_4$ solution for 30 minutes after heat treatment at different temperatures.

Additionally, the EDS spectra of the produced HAp powders shown in Figure 8 give some insights about the chemical nature of the reaction products obtained by hydrothermal conditions. According to the EDS spectra, Ca/P ratio increases from 1.33 to 1.67 while the reaction time increases from 2 h to 6 h. Even though, exact chemical composition analyses based solely on EDS data are questionable, these data, at least, show qualitatively that the reaction products forming in early stages are calcium-deficient. However, after prolonged and efficient reaction with $(NH_4)_2HPO_4$ solution, stoichiometric $Ca_{10}(PO_4)_6(OH_2)$ with Ca/P ratio of 1.67 can be produced with the hydrothermal reactions.

In order to identify the exact chemical identity of the HAp product, HAp powders, synthesized for 30 min under hydrothermal conditions, were heat treated from 200 °C to 1200 °C for 2 h and thermal stability of HAp powders is experimented. After the heat treatment operation, the samples

were air cooled to room temperature (25 °C) and the resultant chemical phases were identified by XRD analyses. The phase changes upon heating of HAp can be related to the chemistry and stoichiometry of the HAp, i.e Ca/P atomic ratio, with the help of the thermodynamic data provided by CaO-P_2O_5 phase diagram [17].

The XRD diffractograms in Figure 9 show the phase changes for the HAp products obtained by 30-min upon heating up to 1200 °C.The HAp product was found to be stable up to 600 °C. Beyond 800 °C HAp converts into β-tricalcium phosphate (β-TCP). While the heat treatment temperature increases, the crystallinity of the β-TCP phase increases. Additionally, the extra phase (labeled as *Unidentified Phase 4*) seems to be eliminated after the heat treatment operation at 800 °C. The formation of β-TCP shows that the products have Ca/P ratio between 1.50 and 1.67 which means the products are calcium deficient.

HAp with exact stoichiometric Ca/P ratio of 1.67 should be stable up to 1550 °C which incongruently melts at this temperature [17]. This finding correlate with EDS data, again revealing a Ca/P ratio smaller than 1.67 for the HAp products forming in the early stages of hydrothermal reaction. In fact this is quite rational, as excess amount of phosphate reactant was in all experiments. This was done in order to achieve complete wetting of the PoP powders. Therefore, the resulting HAp was found to be Ca-deficient as suggested earlier by EDS analyses and proven by the qualitative evaluations performed by thermal stability studies.

4. Conclusions

PoP can be converted to HAp by reacting with aqueous phosphate solution both in ambient and mild hydrothermal conditions. However, hydrothermal condition offers several advantages both in terms of reaction kinetics and also in regard to the crystal nature and purity of the reaction product. At ambient conditions HAp formation completes in longer than 21 days and at around 6 h, at 25 °C and 90°C, respectively. At hydrothermal conditions achieved in the present study, i.e. at 2 ± 0.2 atm and 120 °C, this only takes about 90 min. Besides the need for prolonged reaction times another problem associated with ambient reaction conditions is the formation of additional calcium phosphates with HAp product.

Acknowledgment

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