Si-TCP Synthesized from “Mg-free” Reagents Employed as Calcium Phosphate Cement

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The influence of silicon doping on calcium phosphate cement were explored in this work. \(\alpha\)-TCP and Si-\(\alpha\)-TCP were prepared by solid state reaction employing “Mg-free” CaHPO\(_4\), CaCO\(_3\), and CaSiO\(_3\) as precursors. It was possible to obtain TCP powders with low contents of \(\beta\) phase as contaminant. Cement liquid phase was an aqueous solution containing 2.5 wt. (%) of Na\(_2\)HPO\(_4\) and 1.5 wt. (%) of citric acid. The liquid-to-powder ratio was 0.6 mL.g\(^{-1}\). Chemical, physical and mechanical properties of the cement samples were determined by means of XRD, FTIR, XRF, compressive strength and SEM. The calcium phosphate cements obtained achieved satisfactory properties; however, Si-\(\alpha\)-TCP presented a decrease on the rate of setting reaction.

**Keywords:** calcium phosphate cements, Si-doped calcium phosphates, bioceramics

1. Introduction

The need for new biomaterials which could improve life quality of people who suffer from oldness diseases or who have any bone tissue injury due to accidents and diseases like obesity and cancer are resulting in a growing number of researches. In this context, the development of new orthopedics biomaterials based on calcium phosphate compounds is relevant once they present excellent bioactivity and biocompatibility due to its chemical composition similar to the mineral part of bone and teeth\(^1\)-\(^3\).

Silicon substitution into some phosphorous sites of calcium phosphate bioceramics is a promising approach to develop new biomaterials for orthopedics applications due to the increased bioactivity and cell differentiation on the material’s surface which could be promoted by the presence of this element\(^4\)-\(^11\). Therefore, silicon doped \(\alpha\)-tricalcium phosphate (Si-\(\alpha\)-TCP), is attracting the attention of researchers since its employment as bone cement could be of great interest. Nevertheless, it is still not well stabilized if the enhanced biological properties of the silicon doped calcium phosphates compounds is due to the presence of silicon itself or it is because of its influence on the chemical properties of the material\(^12\)-\(^14\).

Moreover, silicon is known to stabilize the \(\alpha\)-tricalcium phosphate, \(\alpha\)-TCP, structure and to promote its formation at lower temperatures\(^15\)-\(^17\) leading to a cost reduction of its processing. It is well known that the synthesis of a pure \(\alpha\)-TCP is not an easy task since all process conditions can change its final properties, or even inhibit its formation. The most limiting factor is the quality of the starting reagents which may preclude the formation of \(\alpha\)-TCP at temperatures as high as 1600 °C\(^10\),\(^13\). Therefore, the reproducibility of \(\alpha\)-TCP synthesis becomes very difficult and, in some cases, impossible. In a previous work, our group has developed simple synthetic methods to synthesize high purity reagents to eliminate the most important impurity: magnesium, which is an established stabilizer element of \(\beta\)-tricalcium phosphate, \(\beta\)-TCP\(^8\). It has been discovered that the standardization of the reagents properties guaranteed the reproducibility of \(\alpha\)-TCP manufacturing process and the formation of a high purity \(\alpha\)-TCP and Si-\(\alpha\)-TCP. Thus, the major objective of this study is to investigate the influence of Si on the chemical, physical and mechanical properties of the calcium phosphate cement.

2. Material and Methods

2.1. TCP precursors and TCP powders synthesis

“Mg-free” CaHPO\(_4\), and CaCO\(_3\) were synthesized by aqueous solution precipitation in the presence of ethylenediamine tetracetic acid (EDTA). CaSiO\(_3\) were synthesized by solid state reaction of “Mg-free” CaCO\(_3\) and electronic grade SiO\(_2\), which was kindly provided by the Photonic Materials Laboratory-UNICAMP, Brazil\(^16\).

Afterwards, two tricalcium phosphate powders, \(\alpha\)-TCP and Si-\(\alpha\)-TCP, were synthesized by solid state reaction. The syntheses parameters are displayed in Table 1. For \(\alpha\)-TCP, a stoichiometric mixture of CaO (\(<0.02\) wt. (\% of Mg)) and CaHPO\(_4\) (\(<0.0001\) wt. (\% of Mg)) was fired at 1300 °C. Meanwhile, Si-\(\alpha\)-TCP was obtained by adding 2 wt. (%) of CaSiO\(_3\) (\(<0.0001\) wt. (\% of Mg)) to the mixture of CaHPO\(_4\) and CaCO\(_3\). The firing temperature was 1250°C. For both
the sample in known proportions. The standard employed was Al₂O₃ and β-TCP diffraction line used was (214).

Chemical composition of the samples were evaluated by means of fourier transformed infrared spectroscopy. Samples were diluted in KBr and analyzed in a Perkin Elmer 1600 FT-IR spectrometer with a scanning range from 450 to 4000 cm⁻¹ and resolution of 2 cm⁻¹.

Powders stoichiometry was determined by quantitative X ray fluorescence (MagIX Super Q Version 3.0 X-ray fluorescence spectrometer, Philips, The Netherlands). Samples were weighed at 0.3000 g, mixed with 5.5 g of spectral grade Li₂B₄O₇, and melted in a Pt/Au crucible and formed into disks in a special controlled furnace Perl’X3 (Philips, The Netherlands). Calibration curves were prepared using certified composition standards of natural and synthetic calcium phosphates and calcium silicates. Finally, BET specific surface area and particle size distribution were determined using a Micromeritics ASAP 2010 and a Malvern Mastersizer S, respectively.

Cement setting times were determined using the ASTM-C266-04 standard. Cement samples compressive strength after each time of setting were determined using a MTS, Test Star II with a 10 kN cell attached and a compression velocity of 1 mm/min. The fracture surface was gold coated (BAL-TEC, SCD 050) and its morphology was analyzed on a scanning electron microscope (JEOL, JXA-840A).

3. Results

For both samples it was possible to obtain TCP powders in its α-TCP form as can be observed on XRD diffractograms of Figure 1. The contents of β-TCP were very low: 8 and 4 wt. (%) for α-TCP and Si-α-TCP, respectively. Powders stoichiometry is displayed on Table 2, Ca/P and Ca/P+Si ratios were 1.50 and 1.46, respectively.

| Sample  | CaSiO₃ (wt. (%)) | Mg (wt. (%)) | T (°C) | Heating rate (°C/min) | Dwell time (hours) |
|---------|------------------|--------------|--------|-----------------------|-------------------|
| α-TCP   | 0                | 0.0059       | 1300   | 10                    | 6                 |
| Si-TCP  | 2                | 0.0058       | 1250   |                       |                   |

Figure 1. XRD patterns of powders and cement samples. Cement samples: after 24 hours at 100% of relative moisture (α-TCP-c0 and Si-TCP-c0), 1 day in Ringer (α-TCP-c1 and Si-TCP-c1) and 7 days in Ringer (α-TCP-c7 and Si-TCP-c7). β-TCP weight content are 4 wt. (%) for Si-TCP and 8 wt. (%) for α-TCP. Legend: α = α-TCP and β = β-TCP and * = apatite.
The effectiveness of the solid state reaction employed was also elucidated by FTIR analysis since the absorption bands present on both spectrums (Figure 2) are characteristic of $\alpha$-TCP as displayed on Table 3.

Moreover, both TCP powders have very similar BET specific surface area (0.8030 ± 0.0125 and 0.6930 ± 0.0033 m$^2$/g for $\alpha$-TCP and for Si-TCP, respectively) and particle size distribution after 48 hours of ball milling. The mean particle diameter was 9.61 ± 0.14 µm for $\alpha$-TCP and 10.68 ± 0.08 µm for Si-TCP. This results are resumed on Table 2.

Cement setting times are displayed on Table 4. For both cements the values obtained using the Gilmore Needles were higher when compared to the values reported on the literature.

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As can be observed on XRD patterns of Figure 1 $\alpha$-TCP and Si-$\alpha$-TCP setting reaction occurs by the dissolution of TCP phase and the precipitation of apatite crystals once these are the only crystalline phases observed during the role process. Indeed, as displayed on the FTIR spectrums of Figure 3 the apatite phase formed are calcium deficient hydroxyapatite (CDHA, Ca$_9$(HPO$_4$)$_6$(PO$_4$)$_2$OH) since their characteristics absorption bands (Table 5) are present in both spectrums. Moreover, it is possible to verify that both cements lead to an apatite phase which is also carbonated due to the CO$_3^{2–}$ characteristics bands at 850 to 900 and at 1350 to 1600 cm$^{-1}$ (highlighted with a “*” on Figure 3).

Cement’s mechanical strength evolution with time of SBF immersion can be observed on Figure 4. It is verified that Si-$\alpha$-TCP resulted on lower values of compressive strength after 7 days of immersion. Moreover, during the first day of immersion, Si-$\alpha$-TCP did not achieve any mechanical resistance while $\alpha$-TCP achieved values around 5 MPa.

Cements fracture surface after 7 days of immersion can be observed on Figure 5. Silicon doping has resulted on smaller apatite crystals with morphology much similar to the biological apatite.

### Table 2. BET specific surface area, Ca/P or Ca/(P + Si) ratios and particle size distribution.

| Sample   | BET (m$^2$.g$^{-1}$) | Ca/P or Ca/(P + Si) | $d_{10}$ (µm) | 10% < d < 90% (µm) |
|----------|----------------------|---------------------|---------------|---------------------|
| $\alpha$-TCP | 0.8030 ± 0.0125 | 1.50 | 9.61 ± 0.14 | 1.08 ± 0.02-20.42 ± 0.29 |
| Si-TCP   | 0.6930 ± 0.0033 | 1.46 | 10.68 ± 0.08 | 1.51 ± 0.01-20.33 ± 0.18 |

### Table 3. FTIR absorption bands of $\alpha$-TCP.

| Absorption | Bond | Wavenumber [cm$^{-1}$] |
|------------|------|------------------------|
| $\nu_1$    | P-O  | 963                    |
| $\nu_2$    | OPO  | 462                    |
| $\nu_3$    | P-O  | 1084                   |
| $\nu_4$    | OPO  | 597                    |

### Table 4. Setting times of cement samples. $T_t$ = initial setting time and $T_f$ = final setting time.

| Sample   | $T_t$ [min] | $T_f$ [min] |
|----------|-------------|-------------|
| Si-TCP   | 30          | 120         |
| $\alpha$-TCP | 15          | 43          |

### Figure 2. FTIR spectrum of TCP powders.

### Figure 3. FTIR spectrum of cement samples after 7 days of setting, Si-TCP-c7 and $\alpha$-TCP-c7. “*” represents CO$_3^{2–}$ absorbance bands.

### Figure 4. Cement fracture surface after 7 days of immersion can be observed on Figure 5. Silicon doping has resulted on smaller apatite crystals with morphology much similar to the biological apatite.

### 4. Discussion

The lower content of $\beta$-TCP on Si-$\alpha$-TCP confirms the efficiency of Silicon in stabilizing the $\alpha$-TCP phase by lowering the $\beta \rightarrow \alpha$ phase transformation temperature once the powder doped with Silicon resulted on purer $\alpha$-TCP (4 wt. (%)) of $\beta$-TCP at a lower sintering temperature.
work were sintered for longer times it would be expected a reduction on \( \beta \rightarrow \alpha \) conversion. Samples purity were also confirmed after Ca/P and Ca/P + Si ratios determination since their values are very close to the theoretical ones of TCP (\( \alpha \) and \( \beta \) phases) compounds, 1.50.

During cement preparation, it was determined larger values of setting time. In a first moment, this fact can be explained by the high liquid-to-powder ratio employed 0.60 mL\cdot g\(^{-1}\) against 0.32-0.34 mL\cdot g\(^{-1}\) normally used for conventional \( \alpha \)-TCP cement\(^8,20,21,25\); however, this huge amount of liquid was necessary to guarantee the cement moldability. Moreover, the addition of citric acid to cement’s liquid phases has also contributed to the high setting times since this compound increases the TCP particles’ wettability and cement paste fluidity caused by a deflocculation on the TCP powder which also leads to a lower rate of setting reaction\(^26\).

It is important to emphasize that without citric acid addition the liquid-to-powder ratio needed was higher than 1.0 mL\cdot g\(^{-1}\).

Furthermore, by comparing XRD patterns of Figure 1 it is possible to infer that Silicon induces a reduction on the rate of setting reaction. In the first 24 hours, as it was expected, \( \alpha \)-TCP (\( \alpha \)-TCP-c0) started to solubilize together with CDHA precipitation. Surprisingly, for Si-TCP the setting reaction seems not to occur on the first 48 hours (Si-TCP-c0 and Si-TCP-c1) since only \( \alpha \)-TCP diffraction lines are observed on the XRD patterns. Finally, after 168 hours, for \( \alpha \)-TCP cement the TCP \( \rightarrow \) CDHA conversion has finished while Si-TCP cement still have some TCP without reacting. The difference on TCP reactivity is responsible for the lower compressive strength achieved by Si-TCP cement, as displayed on the boxplot chart of Figure 4. At initial times Si-TCP did not have any mechanical resistance while \( \alpha \)-TCP reached a higher compressive strength (p < 0.05).

The difference on TCP reactivity is responsible for the lower compressive strength achieved by Si-TCP cement, as displayed on the boxplot chart of Figure 4. At initial times samples “Si-TCP-c0” and “Si-TCP-c1” did not present any mechanical resistance while sample “\( \alpha \)-TCP-c0” reached 5.6 ± 0.9 MPa. As TCP \( \rightarrow \) CDHA conversion evolves samples’ compressive strength enhances reaching after 168 hours 21.5 ± 2.4 and 14.8 ± 2.6 MPa for \( \alpha \)-TCP-c7 and Si-TCP-c7, respectively.

Nevertheless, it is important to observe that even though the mechanical resistance for Si-TCP cement after 168 hour is lower than for \( \alpha \)-TCP cement, this material had not reached the 100\% TCP \( \rightarrow \) CDHA conversion, thus, it is expected that its maximum mechanical resistance became higher after all Si-TCP is converted into CDHA.

### 5. Conclusions

\( \alpha \)-\( \alpha \)-TCP was synthesized by a simple solid state reaction in which it was employed “Mg-free” reagents leading to lower sintering temperatures for both Si doped and non-doped \( \alpha \)-TCP. Moreover, calcium phosphate cements obtained employing these TCP powders achieved satisfactory properties; however, Silicon has induced a decrease on the setting reaction velocity.

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