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## Single-phase bone cement based on dicalcium phosphate dihydrate powder and sodium silicate solution

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### ABSTRACT

Bone cement, based on dicalcium phosphate dihydrate as initial powder and sodium polysilicate solution as hardening liquid, was developed. The apatite phase started to form 3–4 h after the cement preparation. The kinetics of phase transformations during the hardening process was investigated, applying the energy dispersive X-ray diffraction (EDXRD) technique for real time studies. The Fourier transform infrared (FTIR) spectroscopical, scanning electron microscopy (SEM) morphological studies and compressive strength test were carried out.

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### 1. Introduction

Calcium phosphate cements (CPC) are of great interest as biomaterials for bone replacement that are capable of rapid setting to a hard mass, biocompatible and gradually replaced by the new bone *in vivo* [1]. There are two major groups of CPC, classified by the end-product, which is either dicalcium phosphate dihydrate (DCPD) ( $\text{pH} \leq 4.2$ ) or poorly crystalline apatite (otherwise, non-stoichiometric calcium deficient hydroxyapatite (CDHA)) ( $\text{pH} > 4.2$ ) [2]. Apatite cements are more frequently studied, likely, due to the fact that they set at a pH value closer to the physiological environment. However, being the resorbability *in vivo* an important requirement to CPC, DCPD based cements are more suitable for this scope, since they are better resorbed than the apatite cements under physiological conditions [3]. Although, it was reviewed in [3] that too much DCPD in the end-product is detrimental for biocompatibility. When large quantities of DCPD occasionally were formed after the hardening reaction, a certain degree of tissue inflammation during the first weeks of *in vivo* implantation was reported [4]. Further investigations indicated that the inflammation could be due to the partial transformation of DCPD into CDHA with the release of the orthophosphoric acid during the long follow up period [5].

It is well known that the DCPD cement preparation is based classically on the interaction of tricalcium phosphate with monocalcium phosphate monohydrate, resulting in DCPD [6]. The second type of the setting reaction might be defined as hydrolysis of a metastable calcium orthophosphate in aqueous media and might be called the single-phase cement. Various CPC made of amorphous calcium phosphates or tricalcium phosphate or tetracalcium phosphate and an aqueous solution are the typical examples, the majority of them being re-crystallized into CDHA during setting [3]. In the case of DCPD as a starting reagent, there is little knowledge. In particular, just the hydrolysis of DCPD powder in water and in 1 M  $\text{Na}_2\text{HPO}_4$  solution was investigated [7,8].

Therefore, the purpose of this work was to obtain the single-phase bone cement, starting from simple initial reagents, such as DCPD and the sodium polysilicate hardening liquid (SPL) and to study the hardening process.

### 2. Experimental

#### 2.1. Materials

The procedure followed to synthesize the flat plate-shaped DCPD crystals as initial powder consisted in the preparation of two solutions, as described in [9]. A commercial glass with a nominal composition of 20 mol%  $\text{Na}_2\text{O}$  and 80 mol%  $\text{SiO}_2$  was used as a hardening liquid phase. It was manufactured by the conventional melting-quenching of a powder mixture of the  $\text{Na}_2\text{CO}_3$  and  $\text{SiO}_2$  reagent-

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grade chemicals. Afterwards, a sodium silicate solution ( $\text{Na}_2\text{O}-\text{SiO}_2-\text{H}_2\text{O}$  system) with  $\text{pH}=9.5$ , water content of about 50–60%, and with an as-batched silicate modulus of 3 was prepared and used as the hardening liquid phase.

CPC powder and hardening liquid were mixed in a powder-to-liquid ratio  $P/L=1:1(\text{g:g})$  in a glass mortar for 60 s.

## 2.2. Characterization

The setting times of the prepared cement pastes were evaluated using the tip (1 mm diameter) of a Vicat needle with a 400 g load (ISO standard 1566).

The pH value was measured after 1 h of soaking time in distilled water using a Hanna Instruments HI 8314 pH meter (HANNA).

The EDXRD method was applied to follow in real time the structural modifications taking place upon cements hardening, by collecting sequences of diffraction patterns up to 120 h. The EDXRD measurements were performed by a non commercial apparatus [10].

SEM apparatus (TESCAN VEGAII), working in the secondary and backscattered electron modes, was used for morphological studies of the cements, the observation time was up to 120 h.

FTIR spectroscopy (Perkin Elmer) analysis was performed after mixing 1 mg of sample powders with 300 mg of KBr powder in an agate mortar, followed by compacting those into a thin pellet in a stainless steel die.

The compressive strength (Instron 4082) was evaluated in accordance with the ISO standard 9917E.

## 3. Results and discussion

CPC powder-to-liquid ratio  $P/L=1:1(\text{g:g})$  was found after several trial routine procedures. At this ratio the setting time of the cement paste was measured to be about 15 min and  $\text{pH}$  – equal to 8.2. Afterwards, the pH value was gradually decreased and reached 7.8 after 5 days. These properties are considered to be suitable for the clinical applications [1,3].

For a deeper insight, the kinetics of phase development during the hardening process was investigated by the EDXRD (Fig. 1). As can be seen, several intense peaks were registered, attributable to

the crystalline contribution of the DCPD phase (JCPDS (# 9-0077)). In the inset of Fig. 1, a comparison between the diffraction spectra, collected after 10 min and after 120 h, is shown. A general decrease of the overall diffracted intensity can be observed due to the decrease of the background intensity related to the evaporation of the liquid component of the paste. Some other changes can be also noted: the (202) reflection at  $q=2.52(\text{\AA}^{-1})$  undergoes to a significant decrease, which can be quantified as  $-85\%$ , while a new reflection appears at  $q=3.15(\text{\AA}^{-1})$ . It appears 3–4 h after the beginning of the process and reaches its maximum intensity after about 10 h. This new reflection can be attributed both to hydroxyapatite (HA) (JCPDS (# 9-0432)).

The EDXRD results are in agreement with the ones obtained by FTIR spectroscopy. In Fig. 2(A), the representative FTIR spectra are shown with the overall observation time up to 24 h. At the beginning, the DCPD [11] only was registered in the spectra. After 2 h, the peaks corresponding to the phosphate group vibrations ( $1350$  and  $870\text{ cm}^{-1}$ ) are shifted about  $5-10\text{ cm}^{-1}$  to the shorter wavelengths. This could be an indication of the bonds strengthening in DCPD. Some changes in the DCPD peak profile and intensities at  $1650$ ,  $1350$ ,  $980$  and  $870\text{ cm}^{-1}$  and absence sharp bands over the range of  $3050$  to  $3570\text{ cm}^{-1}$  were registered. After 4 h, the phosphate bands at  $469$ ,  $450$ ,  $434$  and  $418\text{ cm}^{-1}$  (Fig. 2(B)) were appeared. All these changes are indicated the apatite formation [8].

To better understand what kind of structural changes take places during the hardening process, an accurate quantitative analysis of the diffraction spectra was performed. For this purpose, the (150) reflection at  $q=2.34(\text{\AA}^{-1})$  was chosen. The relative area trend for the (150) peak (A), the grain size (B) and the compressive strength time evolution (C) are shown in Fig. 3. Comparing these three curves a similar trend can be noticed. Particularly, as regards the (150) diffraction peak and the compressive strength time evolution. In both cases, an initial increase is registered, then the values decrease until a minimum, which is reached after 10–15 h. Afterwards, a new increase takes place, and the maximum value is reached after about 25 h. Then both values decrease, and a plateau is attained after about 30 h. Finally, a new decrease takes place, and the final minimum values are reached after 60 h of the hardening process. Dash vertical lines in Fig. 3 evidence the maximum (25 h) and the final minimum

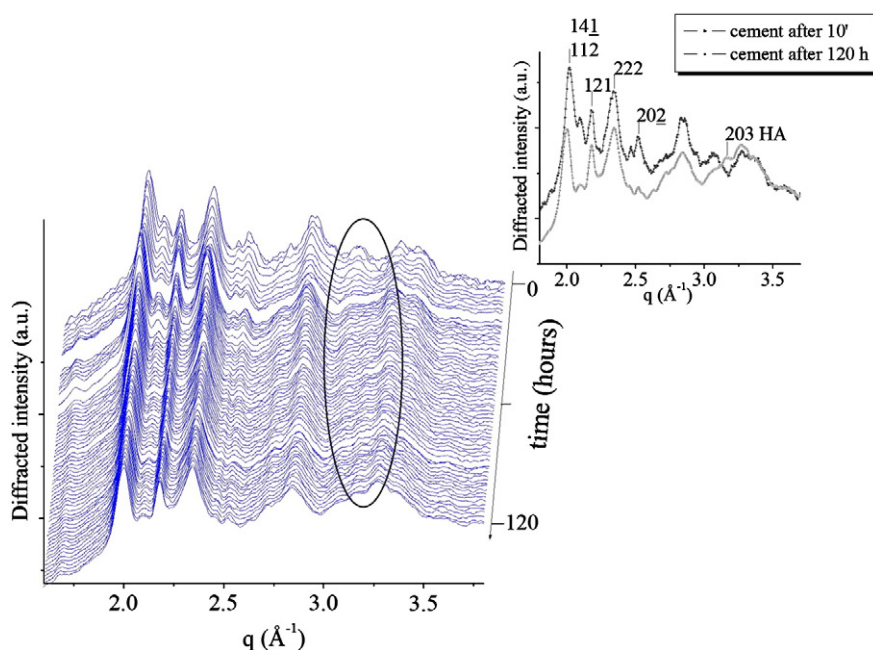


Fig. 1. EDXRD patterns plotted as a function of scattering parameter and of hardening time. In the inset, the spectra collected after 10 min (black triangles) and after 120 h (gray circles), are shown.

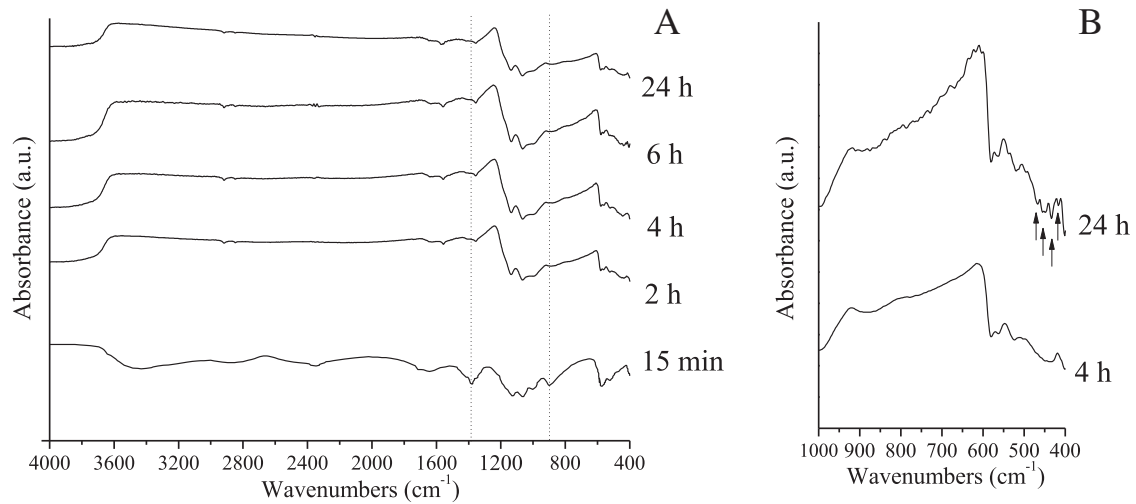


Fig. 2. FTIR spectra, collected upon DCPD cement paste with the overall observation time of 24 h (A) and the spectra collected after 4 and 24 h (B).

(60 h). For the grain size, first, a fast increase from  $13.5 \pm 1.0$  to  $18 \pm 1.0$  nm takes place. Afterwards, a decrease, down to a minimum of 14 nm reached after 32 h, is registered. After that, a new increase takes place up to the final value of about 16.5 nm. The variation (initial vs final value) of grain size corresponds to +3 nm.

An analogous complex long-time crystallization behavior, accompanied by a remarkable and concordant modulation of the diffracted intensity and the compressive strength, was registered in our earlier work [12]. Generally, the hydration process of calcium

orthophosphate cements undergoes five periods: initiation, induction, acceleration, deceleration and termination period [3]. It was suggested in [13] that the presence of a crystal seed can increase the compressive strength, while authors [14] believe that crystal seeding reduces the compressive strength. The results obtained in the work [15], by means of the AC impedance spectroscopy, allowed to clarify the mechanism of hydration. At the initial stages, the presence of crystals can accelerate the hydration reaction, increasing the compressive strength. At the later stages, the presence of seeds decreases

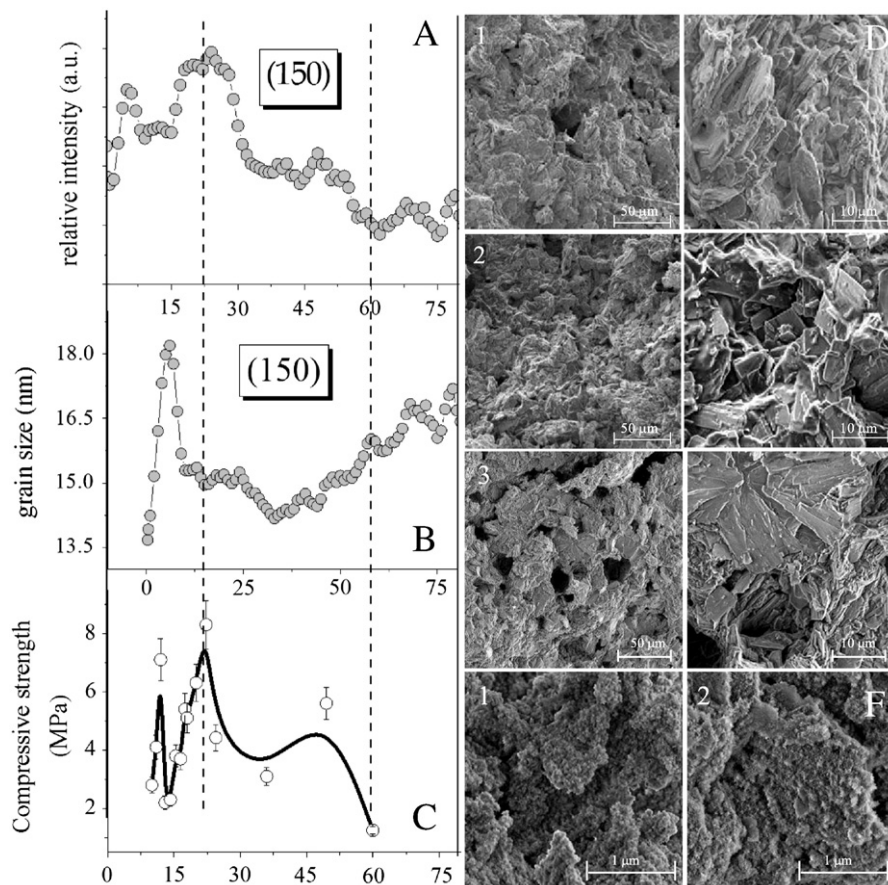


Fig. 3. Time evolution: (A)—the (150) reflection intensity, (B)—grain size, (C)—compressive strength, (D)—SEM micrographs after: (1)—15 min, (2)—10 h and (3)—36 h (1000 and 5000 magnifications) and (E)—after: (1)—10 h and (2)—36 h (30000 magnifications) of cement hardening.

the compressive strength due to the influence of metastable small particles produced by fast reaction. In our case, this phenomenon is probably repeated several times upon the hydration processes and therefore the process is more complex as it was presented before.

The obtained SEM results support the mechanism of CPC hydration discussed above (Fig. 3(D)). Large plate-like DCPD particles of about 10  $\mu\text{m}$  in length and amorphous part with a high portion of SPL are visible (Fig. 3(D1)). After about 10 h, finer plate-like DCPD particles were formed (Fig. 3(D2)). Further, DCPD particles became thinner and their average length became less than 10  $\mu\text{m}$ . After about 36 h, the microstructure of the cement became markedly different. The formation of large pore-like channels with the dimensions from 20 to 50  $\mu\text{m}$  was observed, in which the needle-like DCPD particles are cross-linked (Fig. 3(D3)), as the result of the apatite formation (Fig. 3(F1–2)).

#### 4. Conclusions

The hardening process of the new cement prepared by mixing DCPD powder with SPL was studied. The investigated cement is characterized by quite simple composition, setting time of about 15 min and pH equal to 8.2. The apatite phase started to form at 3–4 h after the cement preparation. The hardening process is complex and it is included several stages.

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