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Composition effects on the pH of a hydraulic calcium phosphate cement

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The pH of a hydraulic calcium phosphate cement (HCPC) made of monocalcium phosphate monohydrate ($Ca(H_2PO_4)_2 \cdot H_2O$; MCPM), β-tricalcium phosphate (β-($Ca_3(PO_4)_2$; β-TCP) and water was measured as a function of reaction time and composition at room temperature. During setting, the cement pH varies from very acidic pH values, i.e., 2.5, to almost neutral pH values, i.e., 6. The cement pH profile significantly depends on the initial cement composition. However, all profiles are characterized by a sharp initial decrease of the pH due to the dissolution of MCPM crystals and the precipitation of dicalcium phosphate dihydrate ($CaHPO_4 \cdot 2H_2O$; DCPD) crystals. With an excess of MCPM, the final pH stays low, and its value can be predicted from the initial composition of the cement and solubility data. With an excess of β-TCP, the end pH is close to 5, which is much lower than 5.9, the value predicted by calculation. Results suggest that the difference may be due to the presence of impurities in the cement. Replacing MCPM by phosphoric acid renders the cement paste very acidic for the initial 30 s, but then the pH profile follows that obtained with MCPM. Adding pyrophosphate ions into the cement paste postpones the position of the pH minimum. The delay, which is proportional to the concentration of pyrophosphate ions, is thought to be due to the inhibiting action of pyrophosphate ions on the precipitation of DCPD crystals.

1. Introduction

Recent studies have shown that hydraulic calcium phosphate cements (HCPC) represent highly promising bone substitute materials. HCPC are biocompatible, bioresorbable, and replaced by new bone when implanted *in vivo* [1–7]. Due to their weak mechanical properties, however, HCPC can be used only for the replacement of low-or non-bearing bones.

Amongst the various HCPC, one particular cement is made of a mixture of calcium phosphate monohydrate ($Ca(H_2PO_4)_2 \cdot H_2O$; MCPM), β-tricalcium phosphate (β-$Ca_3(PO_4)_2$; β-TCP) and water [8]:

$$\beta\text{-}Ca_3(PO_4)_2 + Ca(H_2PO_4)_2 \cdot H_2O + 7H_2O \rightarrow 4CaHPO_4 \cdot 2H_2O \qquad (1)$$

The product of the setting reaction, Equation 1, is dicalcium phosphate dihydrate, also abbreviated as DCPD. The chemical formulation of this cement can be simplified by replacing MCPM by a mixture of β-TCP and phosphoric acid (PA) [9]:

$$\beta\text{-}Ca_3(PO_4)_2 + H_3PO_4 + 6H_2O \rightarrow 3CaHPO_4 \cdot 2H_2O \qquad (2)$$

β-TCP/PA-based formulations have several advantages over β-TCP/MCPM-based formulations, these include: (i) easier and faster preparation, (ii) better control of the chemical composition and reactivity, and (iii) improved physico–chemical properties, such as longer setting times, and larger tensile strengths due to higher homogeneity.

So far, animal experiments have only been performed with the β-TCP/MCPM-based cements. The results obtained from dogs [6] and rabbits [7] showed excellent biocompatibility, resorbability and osteoconductivity. However, the cement samples contained a large excess of β-TCP relative to MCPM, which is detrimental to the mechanical properties of the cement [10]. As weak mechanical properties are the main drawback of HCPC, it would be desirable to use the best composition for that purpose, i.e., stoichiometric amounts of β-TCP and MCPM according to Equation 1. Alternatively, it would be interesting to study the β-TCP/PA-based cements with a stoichiometric composition according to Equation 2. However, the use of phosphoric acid might impair the biocompatibility of this formulation, due to low pH values during setting. Therefore, in order to evaluate the importance of composition on the acidity of β-TCP/PA- and β-TCP/MCPM-based cements, the respective pH profiles of the cement samples were measured during and after setting.

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2. Experimental procedures

2.1. Materials

The β-TCP (Bioland, Toulouse, France) had a molar ratio Ca/P of 1.456 ± 0.010, and according to X-ray diffraction (XRD), contained traces of β-calcium pyrophosphate (β-$Ca_2P_2O_7$, β-CCP). The mean particle diameter was 6.86 μm with a specific surface area of $1.64 \pm 0.08\ m^2\,g^{-1}$. The plastic and liquid limits were $0.35 \pm 0.01\ ml\,g^{-1}$ and $0.40 \pm 0.01\ ml\,g^{-1}$, respectively. The MCPM powder was purchased from Aldrich (Art. 30 764-5, lot 12 619-095; Buchs, Switzerland). Even though the powder was sold as the anhydrous form of MCPM, X-ray diffraction (XRD) analysis did not suggest the presence of any phase other than MCPM. Anhydrous tetra-sodium pyrophosphate ($Na_4P_2O_7$ purum, Art. 71 920, lot 326 665/1 1095) and sodium azide (NaN_3 purum, Art. 71 290) were purchased from Fluka (Buchs, Switzerland).

2.2. Experiments

All the pH measurements were performed at 24 ± 1 °C with a pH meter, Corning model 240. The pH electrode (Inlab 423, N°52 000 124; Mettler Toledo, Urdorf, Switzerland) was regularly calibrated with buffer solutions prepared with buffer concentrated solutions (pH = 4: batch 0055.0022; pH = 7: batch 0045.0032; Metrohm Ltd, Herisau, Switzerland).

To avoid hardening, the pH of the cement paste was measured in slurries containing a liquid to solid ratio of ten. Experiments were performed either with the β-TCP/MCPM-based formulations, or with the β-TCP/PA-based formulations. In the β-TCP/MCPM-based formulations, the pH of a slurry of β-TCP and MCPM was measured as a function of time in 20 ml of deionized water. The compositions of the samples were: x g β-TCP, (2 − x) g MCPM, where $0.0 \leq x \leq 1.8$ g. The β-TCP powder was introduced into the 20 ml of deionized water at time $t = 0$. The liquid was agitated by means of a magnetic stirrer bar spinning at 350 r.p.m. The pH was measured as a function of time until a practically constant pH was reached.

Similar experiments were performed on the β-TCP/PA-based cements. As pyrophosphate ions are commonly used to increase the setting time of β-TCP/MCPM-based cements or β-TCP/PA-based cements [10, 11]. The effect of four different pyrophosphate concentrations on the pH of both the β-TCP/MCPM-based cements and the β-TCP/PA-based cements was also measured.

In order to get an idea about the equilibrium pH of the cement paste after hardening, cement samples were incubated in deionized water, and the pH of the solution was measured for up to three weeks. In one sample series, the solution was replaced by fresh deionized water, and the pH followed during three additional weeks. The samples were made of x g β-TCP, (2 − x) g MCPM and 2 ml deionized water ($0.4 \leq x \leq 1.8$ g). The paste obtained by mixing the latter compounds for 30 s was filled into a syringe whose tip had been cut. After setting, the samples were dipped into 5 ml of deionized water, and the pH was measured at regular time intervals. One series of samples was incubated in a 0.02wt % sodium azide solution to exclude any artifacts from potential bacterial contamination. At the end of the incubation time, the samples were dried in air and their diametral tensile strength measured.

2.3. Characterization

XRD patterns of the filtered slurries and the hardened cement samples were obtained with a Siemens Kristalloflex 805 diffractometer, using CuK_α, Ni-filtered radiation, at an angular sweeping rate of $0.01°(2\theta)\,s^{-1}$. The diametral tensile strength [12] of the cement samples was measured at a strain rate of $0.5\ mm\,min^{-1}$ with an Instron 8562 testing machine.

3. Results and discussion

3.1. Slurries

Large differences in the pH profiles of β-TCP/MCPM slurries can be observed depending on the relative amounts of β-TCP and MCPM (Fig. 1). With an excess of MCPM ($x < 1.10$ g), the pH continuously decreases until a plateau value is reached. With an excess of β-TCP ($x > 1.10$ g), the pH also decreases, but then increases at an increasingly small rate. The shape of the pH profiles should be determined by the occurrence of the three following setting reactions:

(a) Dissolution of MCPM

$$Ca(H_2PO_4)_2 \cdot H_2O \rightarrow Ca^{2+} + 2H_2PO_4 + H_2O \quad (3)$$

(b) Dissolution of β-TCP

$$Ca_3(PO_4)_2 + 4H^+ \rightarrow 3Ca^{2+} + 2H_2PO_4^- \quad (4)$$

(c) Precipitation of DCPD

$$Ca^{2+} + H_2PO_4^- + H_2O \rightarrow CaHPO_4 \cdot 2H_2O + H^+ \quad (5)$$

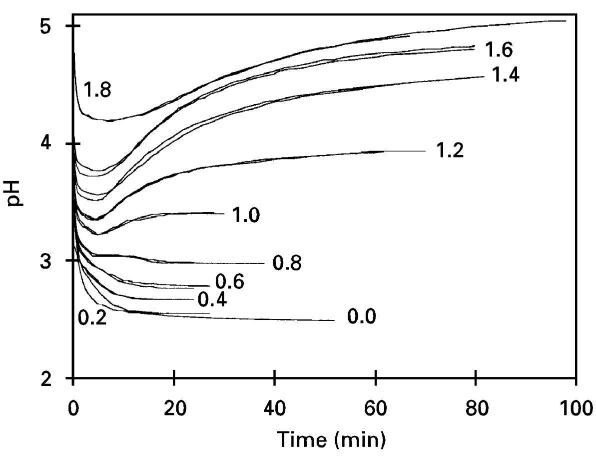

Figure 1 pH profiles of slurries composed of x g β-TCP, (2 − x) g MCPM and 20 ml of deionized water ($0.0\ g \leq x \leq 1.8$ g). Two pH curves of each composition are shown except for x = 0.2 g ($n = 1$) and x = 0.0 g ($n = 1$).

The beginning of the pH profile is probably mainly determined by the dissolution of the fast-dissolving MCPM crystals, provoking a sharp pH decrease. However, since the pH decrease is faster with 1.8 g MCPM and 0.2 g β-TCP than with 2 g MCPM (Fig. 1), the precipitation of DCPD crystals must also proceed. Afterwards, the pH profiles tend to an equilibrium value which depends on the starting composition. Two cases can be distinguished. First, with an excess of MCPM (x < 1.10 g), the final pH is determined by the composition of the slurry, i.e., a mixture of DCPD crystals and an acidic solution as indicated by XRD (Table I). Using solubility- and equilibrium-data given in reference [13], the equilibrium pH can be calculated (Appendix). The results are very close to those observed at the end of the curves shown in Figs 1 and 2. Second, with an excess of β-TCP (x > 1.10 g), the final pH is determined by the equilibrium between DCPD crystals and remnants of β-TCP particles (Table I), which should correspond to a pH of about 5.9 (Fig. 3). However, no satisfactory agreement was obtained between experimental and calculated values (Fig. 2). The reason for this will be discussed in section 3.2.

TABLE I Crystalline phases present in the β-TCP/MCPM-based slurries according to XRD analysis. Prior to XRD, the β-TCP/MCPM-based slurries were filtered, rinsed with deionized water, and dried in air. When a phase is present in the cement sample, the intensity of one of the main XRD peaks is given and expressed in counts per second. The XRD peaks used for each phase are: β-TCP: $d = 0.288$ nm (JCPDS file 9-169; Intensity: 100%), MCPM: $d = 0.388$ nm (9-347; 100%), DCPD: $d = 0.424$ nm (9-77; 100%), DCP: $d = 0.296$ nm (9-80; 100%), β-CPP: $d = 0.331$ nm (33-297; 36%)

Initial composition		Phases observed by XRD				
β-TCP	MCPM	β-TCP	MCPM	DCPD (counts s^{-1})	DCP	β-CPP
0.40	1.60	151[a]	0	3706	97	0
0.80	1.20	1208[a]	0	16 834	0	294
1.00	1.00	504[a]	0	7184	0	82
1.20	0.80	1008	0	6221	0	81
1.60	0.40	7973	0	8099	0	232

[a] Diffraction peak at $d = 0.321$ nm (I = 55%).

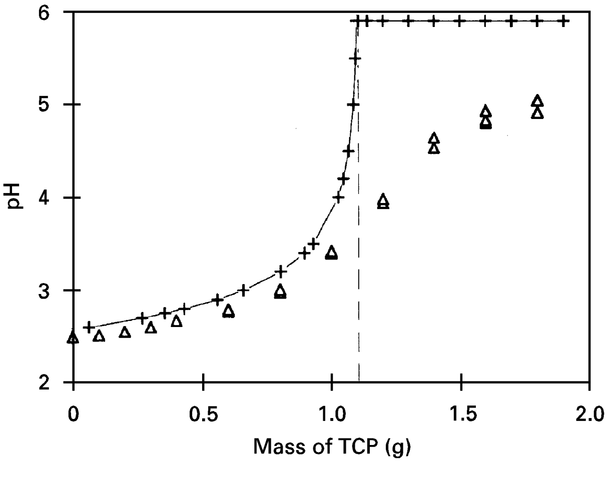

Figure 2 Comparison between (Δ) the pH measured at the end of the curves in Fig. 1 and (+) the pH calculated from the initial cement composition and solubility data. Sample composition: x g β-TCP, (2 − x) g MCPM and 20 ml of deionized water (0.0 g ≤ x ≤ 1.8 g). The dashed line corresponds to the stoichiometric amount according to Equation 1.

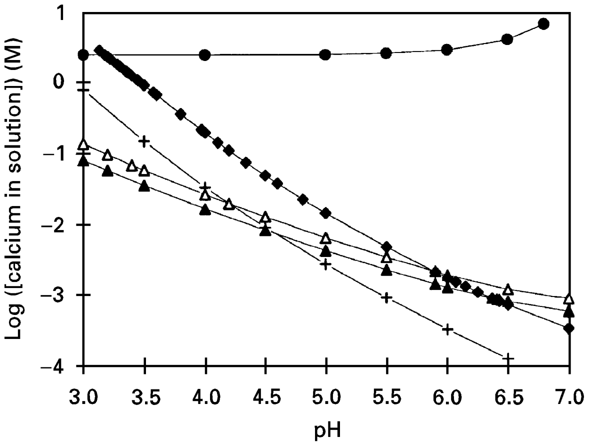

Figure 3 Solubility isotherms of (Δ) DCPD, (▲) DCP, (◆) β-TCP, (+) HAp and (●) MCPM in the system $Ca(OH)_2/H_3PO_4/H_2O$ at 25 °C. The total amount of calcium ions in solution is represented as a function of pH.

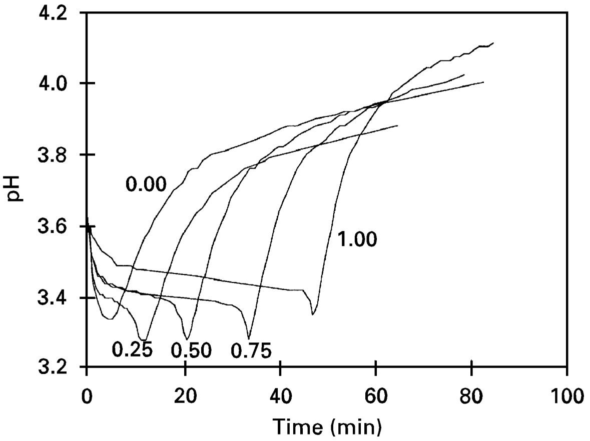

Figure 4 Effect of pyrophosphate ions on the pH profile of slurries composed of 1.2 g β-TCP, 0.8 g MCPM and 20 ml of pyrophosphate solution (concentrations: 0.25, 0.50, 0.75 and 1.00 mM).

The presence of pyrophosphate ions in the slurries significantly modifies the pH profiles (Fig. 4): the larger the concentration, the longer the time needed to reach a pH minimum. However, the first part of the pH profiles is unaffected by the presence of pyrophosphate ions. Since pyrophosphate ions inhibit the growth of DCPD crystals by adsorbing onto the active sites of the DCPD crystal surfaces [14, 15], these results suggest that the pyrophosphate ions separate the pH changes resulting from the reactions shown in Equations 3 and 5. The initial pH drop would be due to the dissolution of MCPM crystals, whilst the sharp pH minimum observed at longer times would be caused by the main precipitation of DCPD crystals. This sharp minimum would occur when all the pyrophosphate ions were adsorbed onto the DCPD surface. Therefore, the larger the pyrophosphate concentration, the longer the time needed to reach the sharp pH minimum (Figs 4 and 5).

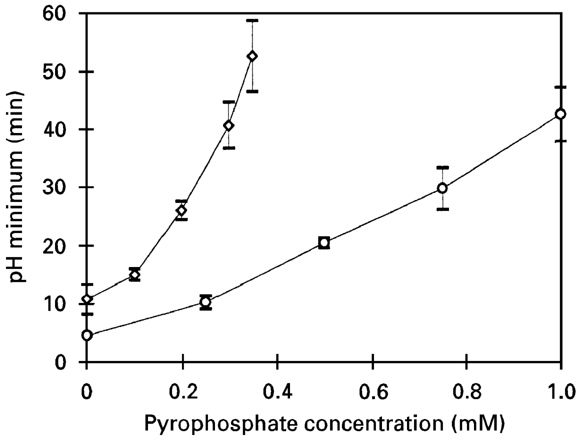

Figure 5 Effect of pyrophosphate ions on the position of the pH profile minimum. Each point corresponds to an average of three measurements. The error of the mean is given at a 95% confidence level. (○) β-TCP/MCPM/water mixtures. (◇) β-TCP/PA/water mixtures.

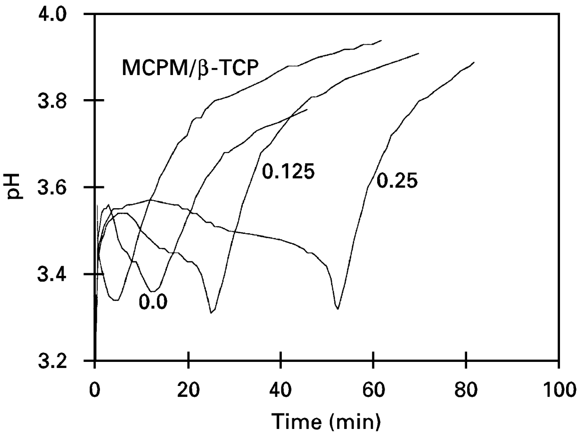

Figure 6 Effect of pyrophosphate ions on the pH profile of slurries composed of 1.2 g β-TCP and 20 ml of a 0.171 M phosphoric acid solution. Pyrophosphate concentration: 0 mM, 0.125 mM and 0.250 mM. The line labelled "MCPM/β-TCP" corresponds to a mixture of 1.2 g β-TCP and 0.8 g MCPM.

The replacement of MCPM by phosphoric acid in the β-TCP/MCPM-based slurries only modifies the initial part of the pH curve (Fig. 6). The pH profile is shifted by a time determined by the occurrence of the first pH maximum. Since this maximum is reached in less than a minute, the replacement of MCPM by phosphoric acid does not fundamentally change the behaviour of the cement. The pH minimum related to the precipitation of DCPD occurs after 10.8 ± 2.6 min for β-TCP/PA-based slurries as compared to 4.5 ± 0.2 min for β-TCP/MCPM-based slurries. This delay cannot be explained by a higher acidity of the solution as, in terms of reactivity, the amount of phosphoric acid used can react with the same amount of β-TCP as 0.8 g of MCPM according to Equations 1 and 2. This suggests that β-TCP/PA-based cements should have longer setting times than β-TCP/MCPM-based cements as previously observed [10]. Moreover, the effect of pyrophosphate ions is stronger in the β-TCP/PA/water system than in the β-TCP/MCPM/water system (Fig. 5). As a short setting time represents a drawback for practical use, cements made of β-TCP/PA/water mixtures may be preferable.

3.2. Incubated cement samples

The pH values measured after incubating cement samples for three weeks are similar to those measured in slurries (Fig. 7). With an excess of MCPM, the pH values are close to those calculated from the initial cement composition assuming an equilibrium between DCPD crystals and a solution (Fig. 7). With an excess of β-TCP, the pH values are not constant, and lie well below the predicted pH. Despite similarities between slurries and incubated cement samples, differences appear in the final composition of samples prepared with an excess of MCPM. These cements contain small amounts of MCPM which may have appeared while drying the cement samples at the end of the three-week incubation period (Table II). The cements also contain rather large amounts of anhydrous dicalcium phosphate ($CaHPO_4$; DCP). The XRD signal of DCP crystals is roughly proportional to the excess of MCPM (Fig. 8). The DCP crystals may have formed either during the drying of the cement samples or during incubation. In the latter case, their presence may have modified the equilibrium pH. However, since the equilibrium DCP/solution is very close to that of DCPD/solution, the change would not be extensive (Fig. 7). DCP crystals were previously found in cements made of β-TCP/PA/water mixtures containing an excess of phosphoric acid [8]. It was attributed to the recrystallization of DCPD into DCP. This recrystallization resulted in a deterioration of the strength of each individual DCPD crystal, and thus lowered the macroscopic strength of the cements (Fig. 9). The maximum in the tensile strength occurs around the equimolar point between β-TCP and MCPM in accordance with previous findings [8].

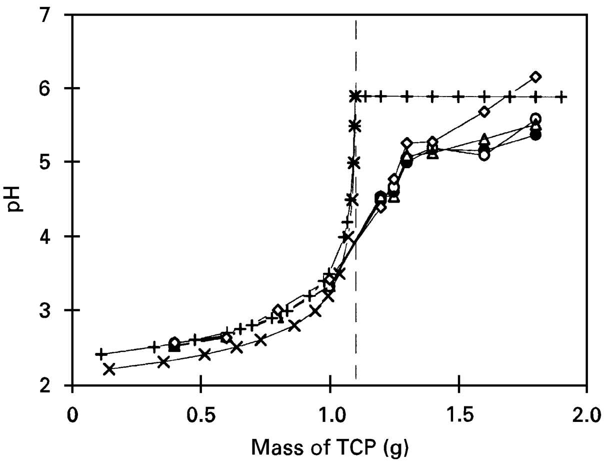

Figure 7 Effect of composition and time on the pH of the incubated solution in contact with cement samples made of x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (0.4 g ≤ x ≤ 1.8 g). The pH was measured after (◇) 1 h, (△) one day, (●) one week and (○) three weeks. The pH was calculated from the initial cement composition and solubility data assuming the presence of (+) DCPD or (×) DCP in the hardened cement. The dashed line corresponds to the stoichiometric amount according to Equation 1.

TABLE II Crystalline phases present in β-TCP/MCPM-based cement samples incubated in 5 ml of water for 3 weeks according to XRD analysis. When a phase is present in the cement sample, the intensity of one of the main XRD peaks is given and expressed in counts per second. The XRD peaks used for each phase are: β-TCP: $d = 0.288$ nm (JCPDS file: 9-169; Intensity: 100%), MCPM: $d = 0.388$ nm (9-347; 100%), DCPD: $d = 0.424$ nm (9-77; 100%), DCP: $d = 0.296$ nm (9-80; 100%), β-CPP: $d = 0.331$ nm (33-297; 36%)

Initial composition		Phases observed by XRD				
β-TCP	MCPM	β-TCP	MCPM	DCPD	DCP	β-CPP
				(counts s^{-1})		
0.40	1.60	562^a	600	724	3204	0
0.60	1.40	199^a	259	1653	5812	0
0.80	1.20	247^a	276	3568	4787	0
1.00	1.00	227^a	227	7255	3221	0
1.20	0.80	1107	0	11 844	0	173
1.25	0.75	1681	0	10 652	0	130
1.40	0.60	2560	0	9005	0	173
1.60	0.40	4955	0	3500	0	210

^{a} Diffraction peak at $d = 0.321$ nm (9-169; 55%).

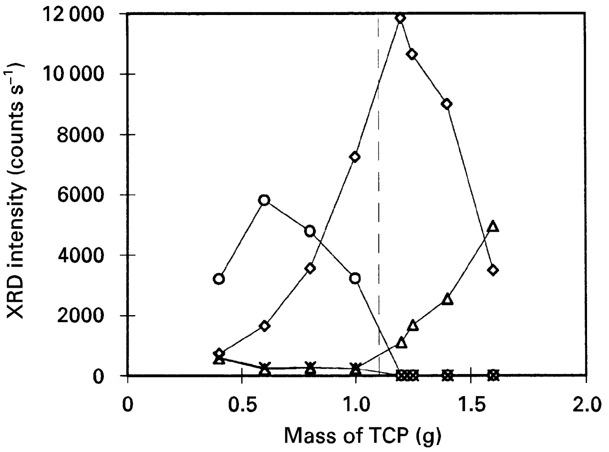

Figure 8 Effect of initial cement composition on the final cement composition according to the XRD results. The height of the peaks given in Table II are reported for the following crystalline phases: (◇) DCPD, (△) β-TCP, (○) DCP and (×) MCPM. Cements composition: x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (0.4 g ≤ x ≤ 1.8 g). The dashed line corresponds to the stoichiometric amount according to Equation 1.

The solutions in contact with cement samples prepared with an excess of β-TCP were after the three-week incubation more acidic than expected from solubility calculations (Fig. 7). Several explanations may be proposed. First, the equilibrium between β-TCP and a solution cannot be precisely defined. β-TCP is thermodynamically stable only at high temperatures and hence cannot be precipitated from a solution at atmospheric pressure and temperature. Therefore, the surfaces of the β-TCP particles are probably coated with another calcium phosphate which could have a pH-dependent stoichiometry and hence solubility. For example, previous results suggest that the dissolution of β-TCP in acidic solution ($3.6 < \text{pH} < 5.3$) is controlled by an interfacial layer of hydroxyapatite ($Ca_5(PO_4)_3OH$; HAp) [10, 16]. Moreover, several calcium phosphates such as HAp, DCPD and octocalcium phosphate ($Ca_4H(PO_4)_3 \cdot 2.5H_2O$; OCP) are less soluble than β-TCP below pH 5.9 [13]. Second, the low pH values might be caused by bacterial contamination. To examine this hypothesis, a series of samples were incubated in a 0.02wt % solution of sodium azide. After 1 h, the pH of the incubated solutions were half a unit higher than without sodium azide. However, this difference virtually disappeared after three weeks (Fig. 10). This suggests that the pH measured in deionized water was not influenced by any bacterial contamination. Finally, the end pH could be modified by the presence of impurities in the starting calcium phosphate powders. To test this idea, the incubation solution was replaced after three weeks, and the pH measured for the three following weeks. As shown in Fig. 11, the pH values were much higher than before and induced very close to 5.9.

The effect of incubation time on the pH values is very limited except for cement samples containing a large excess of β-TCP, i.e., at least 1.6 g β-TCP (Fig. 7). With 1.6 g β-TCP, the pH continuously decreased finally reaching a value lower than that obtained with 1.4 g β-TCP (Fig. 12). With 1.8 g β-TCP, the pH dropped for about 10 days and then

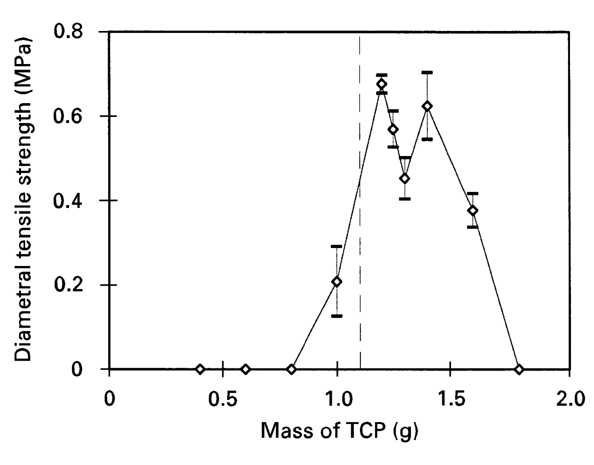

Figure 9 Effect of initial cement composition on the diametral tensile strength of the hardened cement samples after three weeks of ageing. Cements composition: x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (0.4 g ≤ x ≤ 1.8 g). The dashed line corresponds to the stoichiometric amount according to Equation 1. The error of the mean is given at a 95% confidence interval.

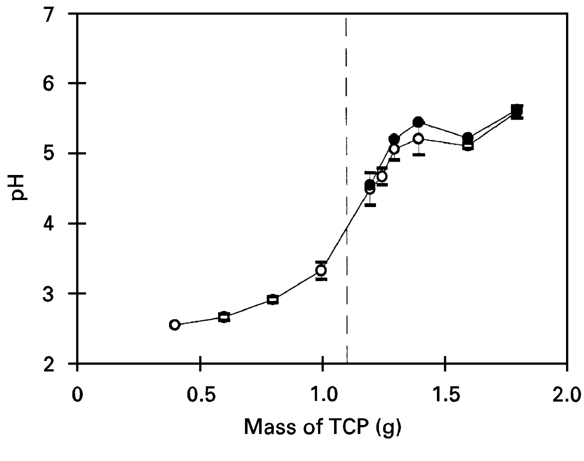

Figure 10 Effect of sodium azide on the pH of cements made of x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (0.4 g ≤ x ≤ 1.8 g). (○) without sodium azide ($n = 3$ or 5); (●) with sodium azide ($n = 1$). The error of the mean is given at a 95% confidence interval. The dashed line corresponds to the stoichiometric amount according to Equation 1.

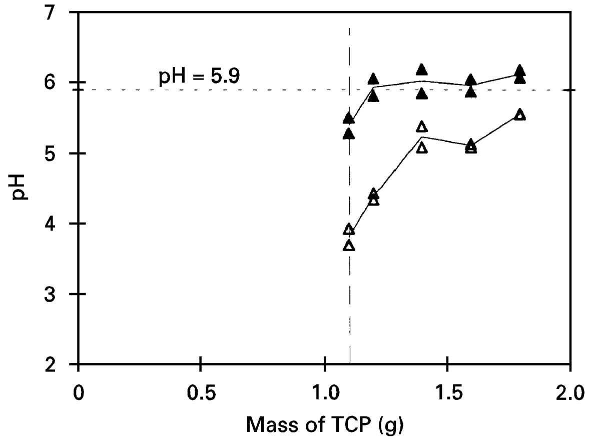

Figure 11 Effect of a change of the ageing medium on the equilibrium pH. Cements made of x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (0.4 g ≤ x ≤ 1.8 g) (△) before and (▲) after changing the incubating solution. The long dashed line corresponds to the stoichiometric amount according to Equation 1.

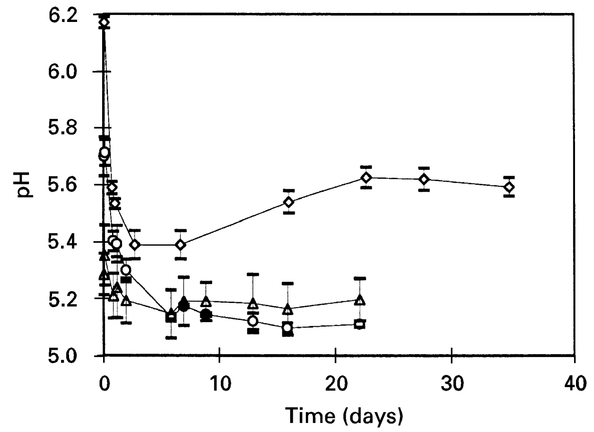

Figure 12 Effect of incubation time on the pH of a solution in contact with a cement sample made of x g β-TCP, (2 − x) g MCPM and 2 ml of deionized water (x = 1.8 g (◇), 1.6 g (○) and 1.4 g (△)).

increased. These effects were significant and reproducible. The reason for these changes is not yet known and requires further investigation. However, it could be related to the previously described interfacial phenomena.

4. Conclusion

Large variations of pH values occur during and after cement setting. Rather low pH values are measured during setting for all cement formulations (around 3). In cements made with an excess of MCPM, the pH values remain very low (2 to 3). However, in cements made with an excess of β-TCP, the pH values increase rapidly to reach moderately acidic pH values (≈5). Knowing the initial and the final composition of the cements, their equilibrium pH value can be calculated from solubility data. The agreement between measured and calculated values is excellent for cements made with an excess of MCPM. However, the value calculated for cements made with an excess of β-TCP is too high, i.e., 5.9. The difference between measured and calculated values is not produced by bacterial contamination. Results suggest that the presence of impurities in the incubating solution may be responsible for this difference, although it should be noted that interfacial phenomena could also be involved.

Cement samples made with an excess of MCPM contain large amounts of DCP. The presence of DCP, due to the recrystallization of DCPD into DCP, is associated with a large decrease of the diametral tensile strength of the cements. At the same time, low tensile strengths are observed in cements made with a large excess of β-TCP. This demonstrates the importance of the initial cement composition on the final cement composition. A small excess of β-TCP in the initial cement composition is thus desirable.

The replacement of MCPM by phosphoric acid does not fundamentally change the pH time course. The pH values are in the same range, but the pH minimum is postponed. This delay is in accordance with previous results showing that β-TCP/PA-based cements have longer setting times than β-TCP/MCPM-based cements.

The addition of pyrophosphate ions into the cement slurries leads to an increase in the time needed to reach the minimum in the pH time course. This pH minimum is associated with the main precipitation of DCPD crystals. The effect of pyrophosphate ions on β-TCP/PA-based cements is larger than on β-TCP/MCPM-based cements. As a short setting time represents a drawback for practical use, cements made of β-TCP/PA/water mixtures may be preferable over β-TCP/MCPM-based cements.

Acknowledgements

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Appendix

The equilibrium pH of a volume, *V*, of deionized water in contact with a mass, *m*, of cement containing an excess of MCPM can be determined from the initial cement composition and solubility data. The detail of the calculation is given hereafter for DCPD. The same method applies for anhydrous dicalcium phosphate ($CaHPO_4$; DCP). In this appendix, it is assumed that the hardened cement sample contains only DCPD when prepared with an excess of MCPM. According to the LeChatelier principle the amount of calcium and phosphate ions remain constant before and after reaction:

$$n_{\mathrm{Ca,MCPM}} + n_{\mathrm{Ca,TCP}} = n_{\mathrm{Ca,DCPD}} + n_{\mathrm{Ca,Sol}} \quad \text{(A6)}$$

$$n_{\mathrm{P,MCPM}} + n_{\mathrm{P,TCP}} = n_{\mathrm{P,DCPD}} + n_{\mathrm{P,Sol}} \quad \text{(A7)}$$

where n_{Ca} and n_{P} are the molar amounts of Ca and P in MCPM, β-TCP, DCPD and the solution.

Knowing the cement composition, the left terms of Equations A6 and A7 are known. Also, by definition:

$$n_{\mathrm{Ca,DCPD}} = n_{\mathrm{P,DCPD}} \qquad \text{(A8)}$$

The incubation solution must be in equilibrium with the cement. In other words, the amount of Ca and P in the solution are related to the solubility isotherm of DCPD according to:

$$n_{\mathrm{Ca,Sol}} = [\mathrm{Ca}]_{\mathrm{tot}} V \qquad \text{(A9)}$$

$$n_{\mathrm{P,Sol}} = [\mathrm{P}]_{\mathrm{tot}} V \qquad \text{(A10)}$$

where $[\mathrm{Ca}]_{\mathrm{tot}}$ and $[\mathrm{P}]_{\mathrm{tot}}$ are the total concentrations of Ca and P dissolved in the solution [13]. Both concentrations depend on the pH according to the DCPD solubility isotherm.

$$[\mathrm{Ca}]_{\mathrm{tot}} = f(\mathrm{pH}) \qquad \text{(A11)}$$

$$[\mathrm{P}]_{\mathrm{tot}} = g(\mathrm{pH}) \qquad \text{(A12)}$$

Using Equations A6–A12, the 7 unknowns ($n_{\mathrm{Ca,DCPD}}$, $n_{\mathrm{P,DCPD}}$, $n_{\mathrm{Ca,Sol}}$, $n_{\mathrm{P,Sol}}$, $[\mathrm{Ca}]_{\mathrm{tot}}$, $[\mathrm{P}]_{\mathrm{tot}}$, pH) can be easily determined, in particular, the pH corresponding to the starting cement composition.

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