Hydrogelation of Calcium Metaphosphate Glass

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A calcium phosphate hydrogel with high viscosity was easily derived for a brief period from the reaction of water with the metaphosphate glass powders. ^{31}P MAS-NMR and HPLC spectra showed that the hydrogel has linear and cyclic polyphosphate structures consisting of PO_4 group connected to calcium ions and protons with hydrogen-bonded water molecules.

Calcium phosphate glass-based materials have high potential in use as biomaterials because their chemical composition is near that of hard tissue. $Ca(PO_3)_2$ glass was reported to be nontoxic.[1] We have been studying on reaction of calcium phosphate glasses with some aqueous solutions for applications to biomedical fields. In the present work a hydrogel with high viscosity was observed, for the first time, to be easily formed for a brief period from the reaction of water with the fine-sized powders of $Ca(PO_3)_2$ glass that is a typical condensed phosphate.

A nominal composition of $CaO{\cdot}P_2O_5$ in molar ratio was prepared by melting reagent-grade $CaCO_3$ and H_3PO_4 (85% liquid) under the air in a platinum crucible at 1300 °C for 0.5 h. The melt was poured onto a carbon plate and quenched by pressing with an iron plate. The resulting glass was pulverized using an alumina mortar to below 10 μm in diameter. A mixture of 2 g of the glass powders and 2 mL of distilled water (DW) was placed on a polystyrene dish of 90-mm diameter and 15-mm height. The dish was shielded with a polystyrene cover using vinyl tape for prevention from serious drying and then the sample was held at room temperature for desired period.

Reaction of the glass powders with DW started immediately when they were mixed, and they were completely converted into a transparent gel product with high viscosity after 1–2 days. The gel product was opaque at an early stage, and it became colorless and transparent with time since the glass particles were suggested to be dissolved. It is known that calcium highpolyphosphate solutions with high viscosity (1–100 Pa·s) are prepared by coaservation from mixed solutions of sodium polyphosphate and $CaCl_2$ under appropriate conditions.[2] The product in the present work seems to be similar in terms of composition and viscosity to that of the coaservation. The development of the gel formation, however, is quite different from that of coaservation.

Figure 1 shows ^{31}P magic angle spinning nuclear magnetic resonance (MAS-NMR) spectra of the samples before and after the DW addition to the glass powders.[3] The bonding of the PO_4 tetrahedron is described in terms of Q^n groups, where n is the number of bridging oxygens to neighboring tetrahedra.[4] In the spectrum of the as-prepared glass powders, an isotropic peak with the broad width around –25 ppm for the Q^2 group is seen; the glass consists of long-chain phosphates. In the spectrum after 10 min, Q^0 and Q^1 groups, which are not seen in the spectrum of the glass, are seen with the Q^2 group. This result suggests that the glass is immediately hydrolyzed to break the phosphate chains, resulting in the formation of Q^0 and Q^1 groups. At least three significant signals are observed with the broad peak originated from the glassy state in the Q^2 band of –20 to –28 ppm in the spectra of the specimens after the DW addition. The gel product is suggested to consist of chain phosphates; the peaks in the Q^2 band imply the existence of at least three kinds of middle PO_4 groups.

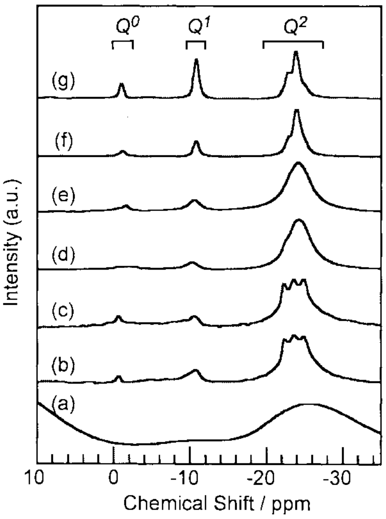

Figure 1. ^{31}P MAS-NMR spectra before and after the DW addition to $CaO{\cdot}P_2O_5$ glass powders. Chemical shifts were measured relative to 85% H_3PO_4. (a) as-prepared glass powders and (b–g) products formed by the DW addition to the glass powders. After the DW addition, the products were left to stand at room temperature for (b) 10 min, (c) 3 h, (d) 6 h, (e) 24 h, (f) 120 h, and (g) 240 h.

The gel products were dissolved in an aqueous solution containing 0.12 M Na_4EDTA which was used as a chelating agent[5] and subsequently high-performance liquid chromatography (HPLC)[6] was used to qualitatively investigate the distribution of phosphate anions in the solutions. HPLC spectra showed that the gel products contain both linear polyphosphates and 3-, 4-, 6- and 8-membered ring phosphates with orthophosphates and pyrophosphates.

Phosphorus in the middle groups near the end groups in the linear phosphates is influenced more strongly by the coordination of ions such as protons and/or calcium ions than that in the cyclic phosphates or that distant from the end groups. The NMR peak of –24.9 ppm (denoted by peak Q^2-A), which appears at the highest magnetic field in the Q^2 peaks, may have originated from the ring or linear polyphosphates. Ions coordinated to the PO_4 group are suggested to be protons and calcium ions. The NMR peak of –22.3 ppm (denoted by peak Q^2-B),

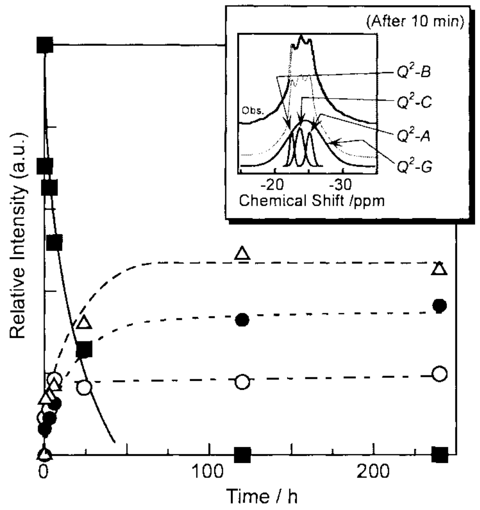

Figure 2. Relative area intensities of the Q^2 peaks in the ^{31}P MAS-NMR spectra as a function of time after the DW addition. The Q^2 band was deconvoluted into four peaks as shown by an example in the insert. The observed spectrum after 10 min and the deconvoluted result are shown. (○) Q^2-*A*, (●) Q^2-*B*, (△) Q^2-*C*, and (■) Q^2-*G*.

which appears at the lowest magnetic field in the Q^2 band, is suggested to originate from the short-chains connected to protons having high electronegativity. The peak of –23.5 ppm (denoted by peak Q^2-*C*) would be due to the short-chains connected to calcium ions that have smaller electronegativity than protons.

As shown in the insert (an example) in Figure 2, the Q^2 band in the spectra were deconvoluted into four Gaussian component peaks, that is, Q^2-*A*, Q^2-*B*, Q^2-*C* and Q^2-*G* due to the residual glassy phase. Figure 2 shows the relationship between the relative area intensities of four Q^2 peaks and time after the DW addition. Judging from the Q^2-*G* plots, the glass powders would be completely dissolved within 2 days. The Q^2-*A*, Q^2-*B* and Q^2-*C* peaks, which are observed in the spectra of the samples immediately after the DW addition (10 min–3 h), are very sharp. Asymmetric Q^1 bands in the spectra also suggest the existence of phosphorus in the end groups influenced by protons and calcium ions. These peaks in the Q^2 and Q^1 bands are suggested to be due to phosphate chains dissolved into DW. Fwhms of the peaks after 6–24 h are slightly larger in comparison with those after 10 min–3 h. The increase in the fwhms is supposed to originate from the gel formation. In the spectra after 24 – 240 h, increase in the relative intensities of the Q^2-*B* and Q^2-*C* peaks in the Q^2 band and also increase in intensities of the Q^1 and Q^0 groups are observed. This result means that the polyphosphates are hydrolyzed to form short-chain phosphates and orthophosphates.

When $Ca(PO_3)_2$ glass particles are placed in contact with water, the surface of the particles is rapidly hydrolyzed to break the long-chain phosphate structure, resulting in the dissolution of a variety of phosphate groups such as the linear phosphates, cyclic phosphates and orthophosphate in water. As a result, the activity of protons in the water increases. A calcium metaphosphate glass has a long-chain phosphate structure and nonbridging oxygens (NBOs). Calcium ions serve as ionic cross-links between the NBOs of two different chains.[7] Protons break the cross-links, resulting in connection to the NBOs, and the calcium ions are bound to the phosphate chains by chelation. Subsequently, water molecules are hydrogen-bonded around the protons connected to the NBOs. The gel products are suggested to be clusters consisting of such hydrated phosphate chains.

Thus far, calcium metaphosphate glass has been reported to be dissolved slowly into water.[8] However, when the fine-sized glass particles are contacted with water, the gelation reaction starts immediately, resulting in formation of calcium polyphosphates with high viscosity. The present letter describes the first work concerning a phosphate hydrogel converted from the glass. Since glasses can be allowed some latitude in the choice of compositions, various phosphate gels could easily be prepared. The calcium phosphate gels in the present work may be available to new applications to biomedical fields such as bone cements. Further work is in progress to investigate the effective additives for the setting of the hydrogels.

References and Notes

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3 Spectra were recorded using a Varian Unity-400 NMR spectrometer, operating at 161.906 MHz. MAS spinning speed of ~7 kHz, delay time of 10 s, and pulse length of 8.8 µs were used. Spinning speed was varied to resolve isotropic peaks from the spinning side bands.

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6 A JASCO Model 851AS liquid chromatograph with a solvent programmer was used for the separation of the phosphates. Eluents with different concentration gradients of KCl containing Na_4EDTA (5% to KCl) were fed in the chromatographic column by means of a solvent programmer with a flow rate of 1 mL/min. A sample solution (10 µL) was added to the column with the aid of a loop injection valve and the chromatographic run was started. The solvent delivery system is programmed to linearly increase the molarity of the KCl concentration from 0.252 to 0.302 over a 10-min time interval after flowing the eluent containing 0.252 M KCl for 20 min, from 0.302 to 0.351 over the subsequent 60 min, and from 0.351 to 0.45 over the successive 50 min. The retention time for different phosphates on the column was calibrated by injecting solutions consisting of known phosphate groups obtained by dissolving crystalline phosphate compounds such as K_3PO_4, $Na_4P_2O_7$, $Na_5P_3O_{10}$, $[C(NH_2)_3]P_4O_{13}$, $(NaPO_3)_3$, $(NaPO_3)_4$, $(NaPO_3)_6$, and $(NaPO_3)_8$. Each of the phosphate compounds contributes only one phosphate anion.

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