JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 29 (2014) 81–90

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research paper

The effect of composition on mechanical properties of brushite cements☆

Johanna Engstrand, Cecilia Persson, Håkan Engqvist*

Division of Applied Materials Science, Department of Engineering Sciences, Uppsala University, Sweden

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form
20 August 2013
Accepted 25 August 2013
Available online 5 September 2013

Keywords:
Brushite
Calcium phosphate cement
Compressive strength
Porosity
X-ray diffraction
Rietveld analysis

ABSTRACT

Due to a fast setting reaction, good biological properties, and easily available starting materials, there has been extensive research within the field of brushite cements as bone replacing material. However, the fast setting of brushite cement gives them intrinsically low mechanical properties due to the poor crystal compaction during setting. To improve this, many additives such as citric acid, pyrophosphates, and glycolic acid have been added to the cement paste to retard the crystal growth. Furthermore, the incorporation of a filler material could improve the mechanical properties when used in the correct amounts. In this study, the effect of the addition of the two retardants, disodium dihydrogen pyrophosphate and citric acid, together with the addition of β-TCP filler particles, on the mechanical properties of a brushite cement was investigated. The results showed that the addition of low amounts of a filler (up to 10%) can have large effects on the mechanical properties. Furthermore, the addition of citric acid to the liquid phase makes it possible to use lower liquid-to-powder ratios (L/P), which strongly affects the strength of the cements. The maximal compressive strength (41.8 MPa) was found for a composition with a molar ratio of 45:55 between monocalcium phosphate monohydrate and beta-tricalcium phosphate, an L/P of 0.25 ml/g and a citric acid concentration of 0.5 M in the liquid phase.

1. Introduction

Since their introduction some 30 years ago, calcium phosphate cements (CPC) have gained a lot of interest as bone replacement material. However, due to their poor mechanical properties in comparison to the traditionally used acrylic bone cements, most CPCs are used as bone void fillers in orthopedic (Larsson, 2010) or craniofacial applications (Lee et al., 2010; Wolff et al., 2004) where the experienced stresses are limited, or together with external fixations. The main advantage of these cements over the stronger and tougher poly(methyl methacrylate) (PMMA) cements are their chemical resemblance to bone, which makes them highly biocompatible and degradable. PMMA cements may contain toxic residual monomers, they develop heat during curing, and may release non-degradable particles during wear of the cement. This has in later years lead to many available CPC products on the market (Bohner, 2010); however, in order to reduce the use of PMMA, the mechanical properties of CPC need to be improved.

There are mainly two types of CPCs, basic and acidic, with basic cements having precipitated hydroxyapatite (PHA) as

*Correspondence to: Ångströmlab, Lägerhyddsvägen 1, Box 534, 751 21 Uppsala, Sweden. Tel.: +46 18 471 79 46; fax: +46 18 471 35 72.
E-mail address: johanna.engstrand@angstrom.uu.se (J. Engstrand).

1751-6161/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmbbm.2013.08.024

the end product and being the most investigated type of cement up until now (Bohner, 2001). Acidic cements have brushite as the product after reaction and have been known since 1989 when Mirtchi et. al. first published a CPC formulation with beta-tricalcium phosphate (β-TCP) and monocalcium phosphate monohydrate (MCPM) as starting powders (Mirtchi et al., 1989b). Advantages with this type of cements over the already existing PHA cements (Brown and Chow, 1983; Legeros et al., 1982) are their fast setting, albeit sometimes too fast, and the fact that the starting materials are all composed of phases that are easily available and stable at room temperature. Since the original cement had very low mechanical properties (tensile strengths lower than 1 MPa) (Mirtchi et al., 1989b), a lot of research has been carried out towards enhancing the strength. Additives, which retard the crystal growth and hence permit a better crystal compaction, the formation of a material with higher mechanical strength, have been extensively studied. For instance, citric acid (Giocondi et al., 2010; Mariño et al., 2007), different pyrophosphates (Bohner et al., 1996; Marshall and Nancolla, 1969), and glycolic acid (Mariño et al., 2007), have all been suggested to interact with the surface of the growing brushite seed and prevent crystal growth. Furthermore, studies have shown that the combination of more than one growth inhibitor, which act on different crystallization mechanisms or crystallization planes, could further increase the mechanical properties of the cements (Bohner et al., 2000; Giocondi et al., 2010; Mirtchi et al., 1989a). Another approach to improve the mechanical properties is by optimizing the particle size of the starting powders. Since different calcium phosphates have different solubility in water it is important that the particle size ratio between the two constituents is optimal (Kokubo, 2008). The most soluble component, i.e. MCPM, should have slightly larger particles than the less soluble component, i.e. β-TCP; to facilitate a similar dissolution rate between the two powders and thus promote a complete setting. Since the β-TCP particles need to be small to dissolve at a reasonable rate (normally around 10–20 μm), it is more suitable to alter the particle sizes of the larger MCPM, which would lead to larger differences in the mechanical properties. This has been shown by Hofmann et al. (2009), who improved the compressive strength (CS) of a brushite cement with approximately 15 MPa, to 52 MPa, by sieving the MCPM to achieve a good size distribution between the two powders (MCPM particles of sizes 6 times the size of β-TCP and below). Altering the MCPM to β-TCP ratio could further change the mechanical properties after setting (Barralet et al., 2004; Bohner et al., 1997). A slight excess of β-TCP was in one case seen to improve the mechanical properties compared to an equimolar ratio of MCPM and β-TCP (Bohner et al., 1997), and in one case result in lowering of the strength (Barralet et al., 2004). However, an excess of MCPM gave lower strengths under the same conditions (Bohner et al., 1997). Furthermore, a large excess of β-TCP was seen to result in quite poor mechanical properties (Bohner et al., 1997).

To the authors' knowledge the combined effect of varying these parameters has not yet been studied. The purpose of this study was therefore to investigate the effect on the mechanical properties when four different factors were simultaneously altered, (1) the liquid-to-powder (L/P) ratio, (2) the MCPM-to-β-TCP ratio, (3) the relative concentrations of sodium pyrophosphate (SPP) and citric acid, and (4) the MCPM particle size by using MCPM from two different suppliers, containing different particle sizes. The ranges for the different factors were chosen based on the results from the previously published studies mentioned above. First, the L/P should be as low as possible, but still high enough to achieve a paste. Second, the MCPM content should be below 50 mol%, but not too low, as low amounts was found to give a reduction in strength (Bohner et al., 1997). And third, concerning the liquid phase of the cement, citric acid concentrations of both 0.5 and 0.8 M have previously showed good mechanical properties (Barralet et al., 2004), whilst higher concentrations might result in poor wet strengths (Mariño et al., 2007). Compression testing was chosen as the method to measure the strength since it is the most commonly used method for both acidic (Hofmann et al., 2009; Tamimi et al., 2008) and basic (Barralet et al., 2003b; Gbureck et al., 2005; Montufar et al., 2013) CPCs, facilitating comparisons with previous studies. Both CS and porosity were investigated for all compositions; furthermore, X-ray diffraction and Rietveld analysis were used for phase identification in some of the compositions.

2. Materials and methods

2.1. *Cement preparation*

The powders used were β-tricalcium phosphate (β-TCP, >96%, Sigma-Aldrich, Germany), two different monocalcium phosphate monohydrate (MCPM, >97%, Alfa Aesar, Germany and >98%, Scharlau, Spain), and sodium pyrophosphate (SPP, >99%, Sigma-Aldrich, Germany). The average particle size of the β-TCP was 13.6 (±0.10) μm, as measured by dynamic light scattering. The MCPM particle sizes were measured by sieving the powder and weighing the fractions. The MCPM powder from Alfa Aesar had 90 wt% >200 μm, while Scharlau had 90 wt% <200 μm. From here on, the MCPM powders will be denoted “MCPM L” (large) and “MCPM S” (small) for MCPM from Alfa Aesar and Scharlau, respectively.

First, SPP was added in 1 wt% to β-TCP and MCPM separately, and respective powder mixtures were blended thoroughly for 30 min using a TURBULA® T2F (Willy A. Bachofen AG, Switzerland). Second, the MCPM and β-TCP, containing SPP, were mixed thoroughly for 30 min in MCPM-to-β-TCP ratios from 50:50 mol% to 30:70 mol%. The powder was mixed with water or citric acid (0.5 M or 0.8 M) in liquid-to-powder ratios (L/P) of 0.25 or 0.35 ml/g. These values were chosen since the cements mixed with water needed a higher L/P to be fully injectable through a syringe with an outlet diameter of 1.90 mm compared to the powders mixed with citric acid. The compositions prepared from each MCPM are presented in Table 1. The paste was molded in rubber-molds with dimensions of ⌀ 6 × height 13 mm. The samples were then immersed in 40 mL of phosphate buffered saline (PBS, 0.01 M phosphate buffer, 0.0027 M potassium chloride and 0.137 M sodium chloride, pH 7.4, Sigma-Aldrich, Germany) at 37 °C for 24 h after which they were removed from the molds.