J Mater Sci: Mater Med (2007) 18:1883–1888
DOI 10.1007/s10856-007-3026-5

Poly(acrylic acid) modified calcium phosphate cements: the effect of the composition of the cement powder and of the molecular weight and concentration of the polymeric acid

A. O. Majekodunmi · S. Deb

Received: 1 November 2005 / Accepted: 5 May 2006 / Published online: 24 May 2007

Abstract Polymer modified calcium phosphate cements made with cement powders of varying tetracalcium phosphate [TTCP] content were prepared using two different molecular weight fractions of poly(acrylic acid) at four different concentrations. The ratio of the precursors (TTCP:DCPA) in the cement powder was found to influence the initial setting which decreased with increasing concentration of TTCP in the powder phase. It was also observed that cements derived from the higher molecular weight containing PAA yielded significantly ($P < 0.05$) shorter initial setting time (Ti) than cements containing the lower molecular weight, poly(acrylic acid) [GE7 PAA] The effect of the varying the TTCP content in the three different cement types PCPC-A, PCPC-B and PCPC-C showed that the trends of the compressive strength were specific to the concentration and molecular weight of the poly (acrylic acid). A 20% concentration of Glascol-E7 with a cement powder composed of an equimolar ratio of precursors (PCPC-B) resulted in optimal compressive strength within the range investigated. The TTCP content of the cement powder could also be varied to improve the diametral tensile strengths of the cements; the specific effects however, were again governed by both the concentration and molecular weight of the constituent poly (acrylic acid). The influence of TTCP on both the initial setting time and diametral tensile strength was related to the Ca^{2+} ion concentration, which determined the rate and amount of cross-linking in the cement.

Introduction

One of the most extensively studied calcium phosphate cement (CPC), consisting of tetracalcium phosphate/dicalcium phosphate anhydrous (TTCP/DCPA), was developed by Brown and Chow [1]. These cements are excellent candidates for use as bone repair substitutes, due to among other reasons, their excellent tissue response and osteoconductivity. However, these materials have a number of drawbacks, principally, poor mechanical properties, rapid decay when the unset cement comes in contact with an aqueous environment, long setting times and high solubility during setting [2–5]. Over the years many efforts have been made to improve the properties of these cements by eliminating these drawbacks. One approach investigated in the literature involves the addition of water-soluble polymers [6–8] including polyelectrolytes and their co-polymers [9] polymeric drugs for reinforcement and drug delivery [8, 10] and natural polymers including chitosan derivatives [2, 11, 12].

The addition of poly(acrylic acid), a water soluble polymer to a CPC would be expected to result in a reaction akin to the setting reaction in glass-ionomer cements, which would remedy some of the problems associated with high solubility in the initial stages of setting. In addition the basicity of TTCP is also expected to result in a rapid setting reaction via the neutralisation reaction, which in turn would result in crosslinking of the polymers. The embedding of a CPC in a polymeric matrix is expected to yield cements with improved handling, setting and mechanical properties. In a previous study [3] eported the influence of the addition of poly(acrylic acid) on water setting CPCs and the influence of the molecular weight and concentration of the poly(acrylic acid) on the setting kinetics and mechanical properties. In the present study the composition

A. O. Majekodunmi · S. Deb (✉)
Department of Dental Biomaterials, GKT Dental Institute, Floor 17, Guy's Tower, London Bridge, London SE1 9RT, UK
e-mail: sanjukta.deb@kcl.ac.uk

of the cement powder has been varied and the effect of the molecular weight and concentration of the poly(acrylic acid) has been related to the composition with a view to formulate cements with optimum properties.

Materials and methods

Tetracalcium phosphate powder (TTCP)

The TTCP precursor was formed by a solid-state reaction between calcium carbonate and calcium hydrogen orthophosphate anhydrous. Equimolar amounts of both precursors were weighed separately and mixed together thoroughly, prior to transfer to an alumina crucible and firing at a temperature of 1450 °C for 4 h. X-ray diffraction analyses of the reaction product confirmed that the methodology was sufficient to produce phase pure TTCP. The TTCP was then hand ground using a pestle and mortar and sieved periodically in order to obtain particles 45–75 μm in size analysed using a Malvern Particle size analazyer.

Dicalcium phosphate anhydrous (DCPA)

The DCPA precursor, obtained commercially (Fisher) was sieved to obtain particles less than 45 μm in size and then mechanically comminuted by ball milling. The DCPA was milled using alumina reinforced porcelain jars with zirconia grinding media in an ethanol medium for 40 h. Particle size analysis using a Malvern instruments Mastersizer showed that this grinding duration and methodology were sufficient to comminute the DCPA to a mean particle size of 5 μm.

Cement formulation

Three different cement precursors were prepared by mixing various ratios of the respective precursors shown in Table 1. The cement liquid, poly(acrylic acid) was composed of various w\v concentrations of two different molecular weight poly(acrylic acids) fractions, Glascol-E7 and Glascol-E9 (Table 2). Both PAAs were supplied as aqueous solutions and were diluted with distilled water where necessary to obtain 25%, 20%, 15% and 10% w/v solutions. Cement pastes were made by mixing the powder to liquid phases at P/L ratio of 2.5 for 30s in a porcelain pestle and mortar. After mixing the pastes were either characterised in terms of initial(Ti) and final setting time (Tf), or packed into moulds prior to mechanical strength testing.

Table 1 Compositions of polymer modified CPC powders

Powder name	Composition (Range of particle size)
PCPC-A	80 w/w % TTCP (45–75 μm) 20 w/w % DCPA (5 μm)
PCPC-B	73 w/w % TTCP (45–75 μm) 27 w/w % DCPA (5 μm)
PCPC-C	65 w/w % TTCP (45–75 μm) 35 w/w % DCPA (5 μm)

Table 2 Compositions of polymer modified CPC powders

Poly(acrylic) acid	pH	Solid content in stock solutions	[a]Viscosity at 25 °C	[a]Molecular weight
Glascol-E9 (G-E9)	1.5	25%	200 mPa s	100,000
Glascol-E7 (G-E7)	1.5	25%	50 mPa s	30,000

[a] Data supplied by manufacturer

Initial and final setting time

Initial (Ti) and final (Tf) setting times were determined at room temperature and humidity using the standard Gilmore needle test (American National Standards Institute/ American Dental Association Specification No. 61 for zinc polycarboxylate cement)[14].

Compressive and diametral tensile tests

For these tests the cement pastes were packed into stainless steel split moulds pre-treated with a silicone releasing agent (nominal height of 12 mm, inside diameter of 6 mm respectively) and allowed to cure in their moulds at 50% humidity and a temperature of 37 °C for 4 h. Once incubation had been completed the specimens were removed from their moulds and immersed in distilled water for 16 h prior to mechanical testing. All mechanical tests were conducted in ambient laboratory air, using a servo hydraulically driven universal testing machine (Model:Instron 1193) at a crosshead speed of 1 mm/min.

Statistical analysis

ANOVA was used to test the level of significance for determining the trends of the initial and final setting time. Student *T*-tests were performed on both the diametral tensile and compressive strength data to derive any influence of cement powder composition on mechanical properties.

Results

Initial and final setting times

The ratio of the precursors (TTCP:DCPA) in the cement powder was found to influence the initial setting time but not the final setting time. Ti decreased with an increasing concentration of TTCP in the powder phase. A comparison of the Ti of the three different cements PCPC-A, PCPC-B and PCPC-C using the two different molecular weight poly (acrylic acid), G-E9 and G-E7 respectively, showed that the cements derived from the higher molecular weight PAA yielded significantly ($P < 0.05$) shorter Ti (Table 3) and Tf (Table 4) than their G-E7 containing counterparts. A relationship between Ti and concentration was apparent in the cements containing the G-E7 additive. A 20 w/v% concentration typically resulted in a Ti longer than the corresponding cements made with both higher and lower concentrations (Tables 5 and 6).

Compressive strength

The mean compressive strengths of the different cement formulations are shown in Fig. 1. The effect of the varying the TTCP content in the three different cement types PCPC-A, PCPC-B and PCPC-C showed that the trends of the compressive strength were specific to the concentration and molecular weight of the poly (acrylic acid). It was observed that when mixed with a 20% concentration of Glascol-E7 (Fig. 2), a cement powder composed of an equimolar ratio of precursors (PCPC-B) resulted in optimal compressive strength within the range investigated.

The molecular weight of the constituent poly (acrylic acid) did not markedly influence the compressive strength of the cements (Fig. 1). The values obtained for formulations derived from either the G-E9 or G-E7 was comparable. The concentration of the PAA additive however was an important factor and cements made with a 20% concentration of either PAA exhibited higher compressive strengths to corresponding formulations made with 25% and 15% concentrations, whereas cements made with a 10% concentration had significantly lower compressive strengths than those made with all the other concentrations investigated.

Diametral tensile strength

At higher concentrations of PAA, 25% and 20% (Figs. 4, 5), DTS was positively correlated with the TTCP content of the cement powder, whereas at lower concentrations 15% and 10% (Figs. 4, 5) the correlation was found to be negative. Unlike compressive strength, the diametral tensile strength of the cements (Fig. 3) was influenced by the molecular weight of the constituent poly (acrylic acid). Cements made using the higher molecular weight PAA (G-E9) exhibited significantly higher values of DTS in comparison to the lower molecular weight PAA (G-E7) containing cements. The concentration of the PAA was also found to influence the DTS, 20% and 15% concentrations tended to result in cements with diametral tensile strengths significantly higher than those made with both 25% and 10% concentrations (Figs. 4, 5). Tables 5, 6

Table 3 Initial setting times for cements made with varying TTCP contents and concentrations of the G-E9 PAA

	Initial setting time in minutes [SE]		
	Cement powder		
Cement liquid (w/v)	PCPC-A	PCPC-B	PCPC-C
25% G E9	2.5 [0.5]	3.5 [0.5]	3.5 [0.5]
20% G E9	2.0 [0.5]	3.0 [0.5]	3.0 [0.3]
15% G E9	1.7 [0.3]	1.7 [0.3]	2.3 [0.3]
10% G E9	2.0 [0.3]	1.5 [0.5]	2.0 [0.3]

Table 4 Initial setting time for cements made with varying TTCP contents and concentrations of the G-E7 PAA

	Initial setting time in minutes [SE]		
	Cement powder		
Cement liquid	PCPC-A	PCPC-B	PCPC-C
25% G E7	6.0 [0.3]	7.5 [0.5]	7.5 [0.5]
20% G E7	8.5 [0.5]	9.0 [0.2]	11.0 [2.0]
15% G E7	4.3 [0.3]	4.0 [0.3]	11.0 [2.0]
10% G E7	3.0 [0.3]	3.0 [0.3]	3.5 [0.5]

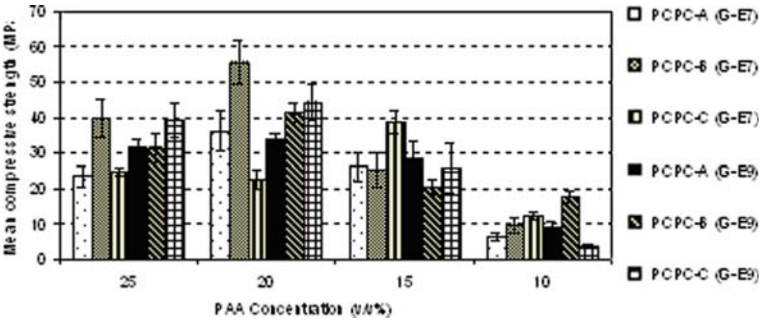
Table 5 Final setting time for cements made with varying TTCP contents and concentrations of the G-E9 PAA

	Final setting time in minutes		
	Cement powder		
Cement liquid	PCPC-A	PCPC-B	PCPC-C
25% G E9	8.0 [4.0]	9.0 [4.0]	8.5 [3.5]
20% G E9	8.5 [4.0]	8.5 [4.5]	7.5 [3.1]
15% G E9	8.7 [2.5]	8.3 [3.2]	10.0 [2.5]
10% G E9	12.5 [5.5]	9.5 [4.5]	10.0 [3.5]

Table 6 Final setting time for cements made with varying TTCP contents and concentrations of the G-E7 PAA

	Final setting time in minutes		
	Cement powder		
Cement liquid	PCPC-A	PCPC-B	PCPC-C
25% G E7	18.5 [5.1]	20.5 [7.5]	22.5 [9.5]
20% G E7	25.5 [10]	25.0 [7.4]	32.0 [12]
15% G E7	17.0 [8.7]	22.0 [10]	19.5 [9.5]
10% G E7	14.5 [4.7]	14.5 [4.7]	20.0 [10]

Fig. 1 Effect of cement composition on mean compressive strength



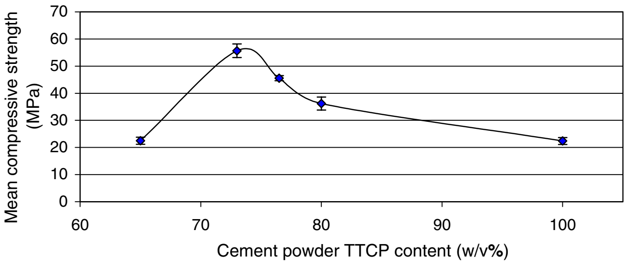


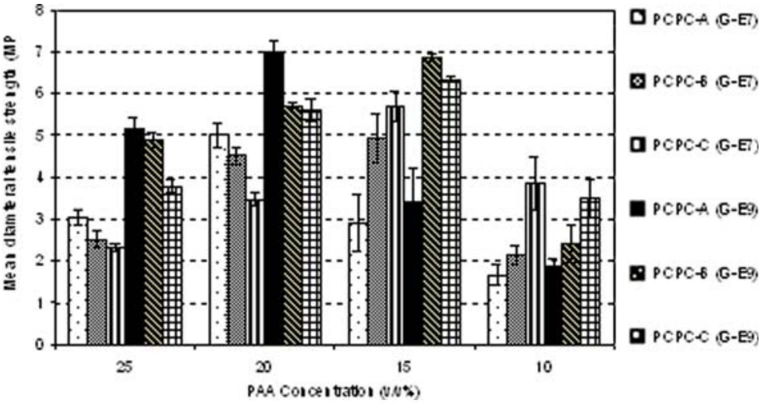
Fig. 2 The influence of the TTCP content of the cement powder on the properties of a PCPC made with a 20% (v/v) solution of G-E7

Discussion

The cement forming reaction in the presence of PAA differs from that occurs in the water setting CPC. In PCPC's, both neutralisation and chelation occur, the neutralisation process occurs via the dissociation of the H^+ ions from the PAA subunits, which in turn react with the basic TTCP thus enhancing the dissolution of TTCP. As a result Ca^{2+} ions then participate in a crosslinking reaction, resulting in the bridging of acrylic acid subunits [13]. The ratio of the precursors in the cement powder, thus has a marked influence on the initial cement forming reaction and its kinetics. The higher the concentration of TTCP, the higher is the concentration of Ca^{2+} ions and thus, greater the collision frequency of the interaction with the polycarboxylate anions. The effect of the ratio of the precursors in the cement powder is not apparent from final setting time (Tf) as the mobility of the Ca^{2+} ions is severely restricted at this stage due to extensive chelation. The effect of the molecular weight of the PAA present in the liquid component is likely to have influenced the Ti and Tf, by virtue of the reinforcement that can be provided by the elongated chains of the polymeric matrix. As the Gillmore apparatus uses resistance to deformation as a means to determine setting times, formulations containing the G-E9 PAA would appear to set more rapidly than those containing G-E7, even though in terms of reaction kinetics both were at comparable points in the setting reaction. This hypothesis is supported by the observations of investigators working with the glass ionomer cement [15, 16] in which a similar influence of molecular weight has been reported.

The influence of PAA concentration relates to the viscosity of the cement liquid. High viscosities, found at high concentrations, result in poor precursor dissolution and the reduced mobility of Ca^{2+} ions; as the concentration of the G-E9 PAA is decreased, the extent of both processes increases thereby shortening the setting time. The relationship between the concentration of the G-E7 PAA and Ti is more complicated. In this situation the setting reaction is due to the interaction of two competing processes. As noted

Fig. 3 Effect of cement composition on diametral tensile strength



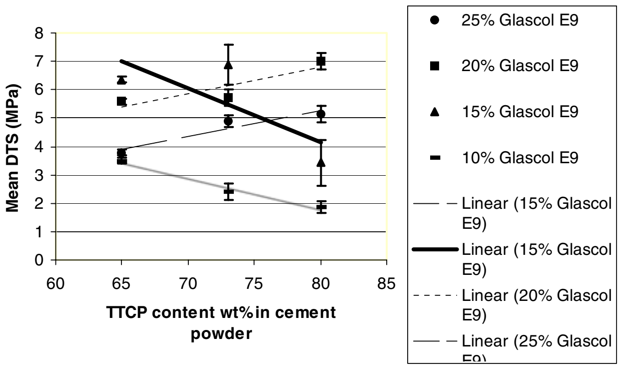


Fig. 4 The effect of cement powder TTCP content on the diametral tensile strength of cements made with different concentrations of the Glascol-E9 PAA

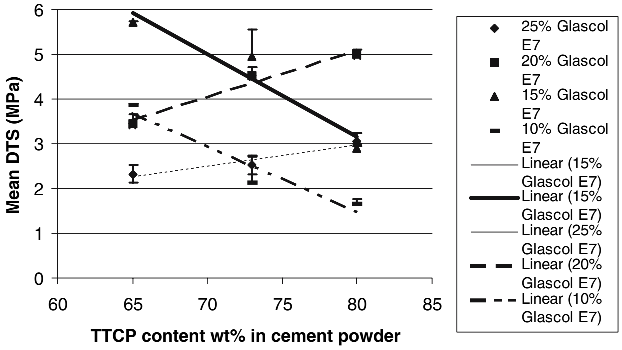


Fig. 5 The effect of cement powder TTCP content on the diametral tensile strength of cements made with different concentrations of the Glascol-E7 PAA

earlier, as the concentration of the PAA increases the viscosity of the liquid phase increases, inhibiting dissolution and the movement of ions, however it also results in an increased number of available polymer chains, which can increase the rate of reaction via an increase in collision frequency. The increased Ti at a 20% concentration of G-E7, relative to other concentrations, is suggestive of a concentration at which viscosity is neither low enough nor collision frequency high enough to result in a fast setting reaction. These results in a cement with a Ti longer than cements made with both higher and lower poly (acrylic acid) concentrations.

From the results of the mechanical testing it was apparent that the UCS was influenced and positively correlated to the composition of the cement powder up to a critical point, after which there was a decrease. It is likely that, a concentration greater than 73% of TTCP caused excessive crosslinking.

The improved mechanical properties of cements made with intermediate concentrations of the PAA can be explained as follows. As noted earlier, precursor dissolution is limited by the viscosity of the solution at higher PAA concentrations (25%), which may be responsible for the encapsulation of some TTCP particles within the insoluble product. Other authors have reported the encapsulation of particles [6, 17], which results in a reduction in the amount of Ca^{2+} available for crosslinking, which in turn reduces the mechanical strength. At lower concentrations (10–15%), although the proportion of Ca^{2+} ions released would increase, the availability of polymer chains for crosslinking and chain entanglement would be reduced, resulting in inferior mechanical properties. It is thus likely that at intermediate PAA concentrations the amount of crosslinks formed were limited neither by the proportion of available Ca^{2+} ions, nor by the proportion of polymer chains. This would have increased the incidence of crosslinking increasing compressive strength.

The differing effects of cement powder composition on diametral tensile strength at high and low PAA concentrations can be explained by reptation processes. A student T-test confirmed that at 25% and 20% concentrations of both G-E7 and G-E9, the diametral tensile strength of cements made with PCPC-A (80 w/w % TTCP) were significantly greater than those made with (PCPC-C) (65 w/w % TTCP). However at 15% and 10% concentrations of both PAA solutions, the diametral tensile strengths of cements made with PCPC-A were significantly less than that those made with PCPC-C. The differing effects of cement composition at high and low poly(acrylic acid) concentrations relates to the effect of crosslinking on reptation. The positive correlation between cement powder TTCP content and DTS at high PAA concentrations was due to the formation of ionic crosslinks between the polymer chains, increasing both pullout strength and effective molecular weight [15]. At low concentrations (15% and 10%) as a result of a lower proportion of polycarboxylate ions, more crosslinks can be formed on individual polymer chains than at higher concentrations. Increased crosslinking on individual polymer chains increases chain pullout strength, which can result in increases in mechanical strength up to a critical point, after which crosslinking is termed excessive and leads to a decrease in mechanical properties. It is thus likely that the concentration of Ca^{2+} ions in PCPC-A resulted in excessive crosslinking at low PAA concentrations (15% and 10%) but not at higher ones (25% and 20%).

Chain pullout or reptation processes were also responsible for the influence of molecular weight on diametral tensile strength. Unlike compressive strength, molecular weight within the range investigated was observed to influence diametral tensile strength. The influence of *Mw* on DTS was due to the entanglement of the polymer chains in the cement matrix and the reduction in crack propagation during failure as a result of chain pullout. As the molecular weight of the polymer chain increased the amount of energy that could be dissipated during crack growth increased, increasing mechanical strength.

Conclusions

Several factors influence the properties of the polymer modified CPCs. The composition of the powder formulation was found to alter the setting times and strengths of the PCPC cements. However, the specific effects was also dependent on the molecular weight and concentration of the poly(acrylic acid).

Acknowledgement The authors would like to thank EPSRC (Engineering & Physical Research Council, UK) for a research studentship to Dr Majekodunmi.

References

1. W. C. Brown, L. C. Chow, In edited by P. W. Brown, *Cements Research Progress* (Westerville: American Ceramics Society, 1986), pp. 352–379
2. A. CHERNG, S. TAKAGI and L. C. CHOW, *J. Biomed. Mater. Res.* **35** (1997) 273
3. Y. MIYAMOTO, K. ISHIKAWA and M. TAKECHI et al., *Biomaterials* **17**(14) (1996) 1429
4. M. TAKECHI, Y. MIYAMOTO and K. ISHIKAWA, et al., *J. Biomed. Mater. Res.* **39**(2) (1998) 308
5. Y. MIYAMOTO, K. ISHIKAWA and M. TAKECHI, et al., *J. Biomed. Mater. Res.* **48**(1) (1999) 36
6. Y. MATSUYA, J. M. ANTONUCCI, S. MATSUYA, S. TAKAGI and L. C. CHOW, *Dent. Mater.* **12**(1) (1996) 2
7. Y. MATSUYA, S. MATSUYA, J. M. ANTONUCCI, S. TAKAGI, L. C. CHOW and A. AKAMINE, *Biomaterials* **20**(7) (1999) 691
8. M. TAKECHI, Y. MIYAMOTO and K. ISHIKAWA, et al., *Biomaterials* **19**(22) (1998) 2057
9. K. MIYAZAKI, T. HORIBE, J. M. ANTONUCCI, S. TAKAGI and L. C. CHOW, *Dent. Mater.* **9**(1) (1993) 46
10. M. P. GINEBRA, A. RILLIARD, E. FERNANDEZ, C. ELVIRA, J. SAN ROMAN and J. A. PLANELL, *J. Biomed. Mater. Res.* **57**(1) (2001) 113
11. L. LEROUX, Z. HATIM, M. FRECHE and J. L. LACOUT, *Bone* **25** (Supplement 1) (1999) 31S
12. X. WANG, J. MA, Y. WANG and B. HE, *Biomaterials* **22**(16) (2001) 2247
13. A. O. MAJEKODUNMI, J. W. NICHOLSON and S. DEB, *J. Mater. Sci.: Mater. Med.* **14**(9) (2003) 747
14. ANSIAD Specification No. 61 for zinc polycarboxylate cement. *J. Am. Dent. Assoc.* **101** (1980) 669
15. R. W. HILL A. D. WILSON and C. P. WARRENS, *J. Mater. Sci.* **24** (1989) 363
16. A. D. WILSON, R. G. HILL, C. P. WARRENS and B. G. LEWIS, *J. Dent. Res.* **68**(2) (1989) 89
17. K. MIYAZAKI, T. HORIBE, J. M. ANTONUCCI, S. TAKAGI and L. C. CHOW, *Dent. Mater.* **9**(1) (1993) 41