Novel calcium phosphate composite bone cement: strength and bonding properties

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A new high-strength cement prepared from calcium phosphate and calcium aluminate has been developed and was evaluated for potential use in bone and joint repair applications. Cement specimens were aged under simulated physiological conditions. The compressive strength of the cement was determined at time intervals 1 h after setting up to 52 weeks. A compressive strength of 111.6 $\pm$ 12.9 MPa was measured at 4 weeks, with the cement attaining 64% of this maximum strength within 4 h of preparation. Compressive strength greater than 90 MPa was maintained up to 52 weeks.

The strength of the cement–prosthesis interface was studied using a pull-out test. Polished, 316L stainless steel rods were implanted in canine cadaver femurs to simulate a cemented hip prosthesis. At 4, 24 h, and 60 days post implantation, the force required to displace the rod was measured. Mean interfacial shear strengths of 1.17 $\pm$ 0.25, 1.11 $\pm$ 0.21, and 1.11 $\pm$ 0.32 MPa were observed at respective time-periods.

1. Introduction

Poly(methyl-methacrylate) (PMMA) cements are widely used in orthopedic repair and joint replacement surgery despite well-documented shortcomings including the exothermic setting reaction, lack of direct bonding at the cement–bone interface, cement breakdown over time, and effect of cement particulate debris.

In recent years, much research has focused on the development of calcium phosphate cements. Hydroxyapatite and β-tricalcium phosphate have been found to have favorable tissue responses. The interface between bone and these ceramics occurs without the formation of an intermediary, soft tissue layer [1, 2]. Present calcium phosphate cements are generally brittle and have poor mechanical properties. Although efforts continue to improve this class of cement, present mechanical properties are too low for load-bearing applications [3, 4].

A novel cement for orthopedic applications has been developed [5] and is referred to as OC-cement. This cement is modeled after a calcium phosphate-spinel osteoceramic composite that has tissue bonding cellular response [6–8]. In OC-cement, calcium phosphate is incorporated for biological activity while calcium aluminate provides high, enduring strength. The result is a hydraulic cement wherein setting may be controlled through the use of additives.

The objective of the present study was to evaluate the crushing strength of OC-cement over time when stored under simulated physiological conditions and to measure the shear strength of the cement–prosthesis bond.

2. Materials and methods

2.1. Cement preparation

In previous work, cements with a range of calcium phosphate to calcium aluminate ratios were prepared and evaluated for enduring strength [9]. From these results, a composition of β-tricalcium phosphate (33 wt %, Fluka Chemicals, Neu-Ulm, Switzerland) and calcium aluminate (66 wt %) was selected for use. Powders were mixed together until uniform. Calcium aluminate with a molar ratio of calcium to alumina of approximately 0.82 : 1.00 was used. This cement contained mainly CA, CA_2, with small amounts of $C_{12}A_7$ and alumina, where $C = CaO$ and $A = Al_2O_3$. Calcium chloride solution prepared from calcium chloride hexahydrate (Fisher Scientific, Fairlawn, NJ) and de-ionized water was used to control the setting properties. The solid to liquid ratio was maximized while allowing for adequate flow of the

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cement paste. The dry components were combined with hydration solution, mixed for one minute to form a paste, and vibration was applied with a hand massager for 45 s at high speed to aid in mixing and removal of entrapped air. The cement paste was then placed in the appropriate test mold during a working period of approximately 6 min. The setting time was temperature dependent and ranged from 12–13.5 min at 37 °C.

2.2. Temperature rise during setting

Approximately 50 g of OC-cement paste (equivalent in volume to 25 g of PMMA bone cement) was prepared and placed in an insulated mold. A type K thermocouple was embedded in the center of the cement mass and the temperature was recorded during the setting of the cement.

2.3. Strength testing

Specimens, 12 mm diameter × 16 mm height, were prepared for compressive strength testing. Following preparation, the cement paste was placed in a methacrylate mold and allowed to set in a water bath maintained at 37 °C. Approximately 20 min after setting, the specimens were removed from the molds and placed in lactated Ringer's solution (Abbott Laboratories, North Chicago, IL). Specimens were stored at 37 °C until tested. Testing was performed at times 1 h after setting to 52 weeks. The force required for failure was measured using an Instron 4202 universal testing machine (Instron Corp., Canton, MA) equipped with a 50 kN load cell and the cross-head speed was set at 1 mm/min. The compressive strength was calculated by dividing the maximum force by the cross-sectional area. The mean compressive strength is reported for each time $(n \geq 9)$.

The tensile strength of the cement was measured using a diametral tensile test with the same Instron settings as used for compressive strength testing. Specimens approximately 12 mm diameter × 4.8 mm in height were prepared and stored as described above for compressive testing. The mean diametral strength was determined at 1 day and 1 week $(n = 10)$. Diametral tensile strength was calculated as: $\text{force}_{\max}/(\pi * t * d/_2)$, where t is the thickness and d is the diameter of the cement disc.

2.4. Pull-out strength

The strength of the cement-prosthesis interface was studied using a pull-out test. Canine cadaver femurs were prepared to receive a 6 mm post of 316L stainless steel to simulate cement anchoring of the femoral component of a hip replacement.

Metal posts, 6 mm diameter × 100 mm length, were machined from medical grade 316L stainless steel. Care was taken not to scratch or mar the surface. Prior to testing, posts were washed in a mixture of mild detergent and water, placed in an ultrasonic cleaner for 5 min, rinsed with de-ionized water and dried. The surface roughness of the posts was measured using a Dektak IIA profilometer (Veeco, S.A., Plainview, NY). A typical scan is displayed in Fig. 1. The average surface roughness was determined by a sample of 15 posts with three measurements collected per post. The mean surface

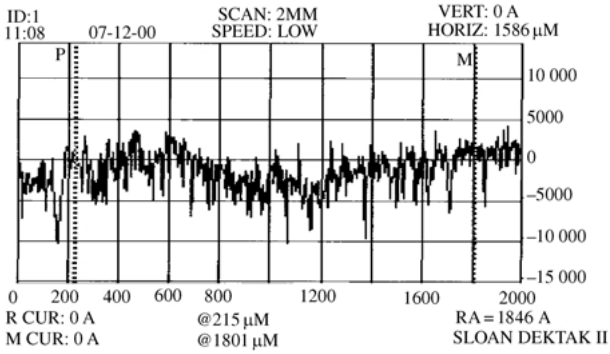

Figure 1 Typical surface roughness graph.

roughness was found to be 2322 ± 388 Å. Before using the posts for pull-out testing, the bottom surface of the post was coated in paraffin wax to act as a release agent.

Femurs from mixed breed canines were collected. After the soft tissue was removed, the femurs were wrapped in towels moistened with saline solution. Femurs were stored at − 20 °C until the time of specimen preparation when they were thawed under normal laboratory conditions. The head of the femur was removed, the medullary canal was reamed with a 9 mm drill, rinsed with water, and drained. Next, the femurs were centered in a testing fixture and potted with Plaster of Paris to secure each specimen. Once the plaster had hardened and the specimen had cooled to 37 °C, the cement and post were inserted and centered. OC-cement was prepared as previously described. Palacos®R PMMA bone cement (Smith & Nephew Richards Inc., Memphis, TN) was used as a control. The manufacturer's instructions were followed for the preparation of PMMA cement. The liquid component was added to the cement powder and mixed in a bowl. After preparing the given cement, it was loaded into the medullary canal of the femur, and a stainless steel post was inserted into the cement and centered (Fig. 2). After the cement had set, test specimens were stored at 37 °C until the time of testing. The cement was kept moist by irrigation with lactated Ringer's solution after setting until testing.

Pull-out tests were conducted on specimens of each cement type at 4, 24 h, and 60 days after preparation $(n \geq 7)$. Specimens were randomly assigned a testing time of 4 or 24 h. Due to complications in aging femurs

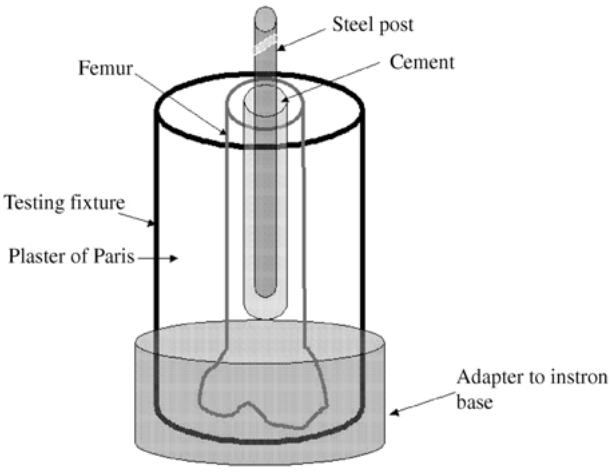

Figure 2 Drawing of pull-out test fixture and specimen.

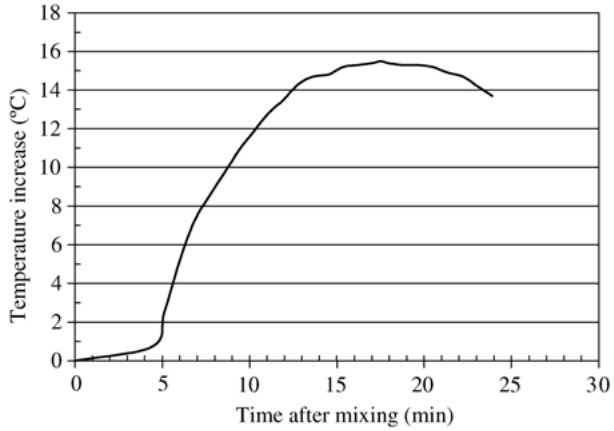

Figure 3 Temperature rise during setting of OC-cement.

under test conditions longer than 24 h, rigid, textured, plastic tubing was used to simulate femurs for the specimens tested at 60 days. After the designated time, the potted specimens were placed in the testing fixture and attached to the Instron machine. The rate of displacement for the crosshead was 1 mm/min. The maximum tensile force to displace the prosthesis and method of failure were recorded for each specimen. The interfacial shear area was calculated as: $L\ \pi\ d$, where $L =$ length of the rod embedded in cement and $d =$ diameter of the rod. Since the bottom surface of the post was coated with wax, its effect was negligible and the interfacial shear strength was determined by dividing the maximum force by the interfacial shear area.

2.5. Statistical analysis

Means and standard deviation are presented for the experimental data. The Student's *t*-test was used to assess whether the observed differences between the means of different groups were statistically significant.

3. Results

3.1. Temperature rise during setting

A maximum temperature increase of 15.5 °C was observed during the setting of OC-cement (Fig. 3). When the starting temperature of the materials and the laboratory was 22 °C, a maximum temperature of 37.5 °C was reached during setting.

3.2. Strength

The compressive strength of the cement was measured for OC-cement at 1, 4, 12, 24, 48 h, 5 days, 1, 4, 8, 16, 32, and 52 weeks. Mean compressive strengths were 30.34, 71.26, 77.94, 74.73, 66.16, 92.27, 105.91, 111.56, 101.20, 111.75, 99.71, and 92.00 MPa, respectively, as shown in Fig. 4. Although a small, temporary decease in strength was observed at 48 h, the general trend in strength increased up to 4 weeks. The mean compressive strength at 52 weeks was 82% of the maximum strength that was measured at 4 weeks.

Values for mean diametral tensile strength were 7.02 ± 0.79 and 11.34 ± 1.3 MPa at 24 h and 1 week, respectively. This is approximately $^{1}/_{10}$ of the compressive strength for the same time-periods and is typical for ceramic materials.

3.3. Cement–prosthesis bonding strength

During pull-out testing, failure occurred at the cement–prosthesis interface for all specimens. Macroscopic evaluation of specimens that had been cut longitudinally showed good filling and close contact of the cement with the post. Mean interfacial shear strengths for the OC-cement–prosthesis were 1.18 ± 0.27, 1.11 ± 0.21 and 1.18 ± 0.34 MPa at 4, 24 h, and 60 days, respectively; PMMA-prosthesis results at corresponding times were 1.45 ± 0.70, 1.18 ± 0.66 and 1.48 ± 0.92 MPa (Fig. 5). The differences in means for the OC-cement and PMMA interfaces at each time-period were not found to be statistically significant ($p < 0.05$). The mean interfacial shear strengths for the OC-cement and PMMA interfaces did not change significantly during the test period.

Force vs. displacement was recorded during testing. Typical plots are shown in Figs. 6 and 7. The initial portion of the graphs typically indicated a gradual increase in load as the fixture and specimen became firmly seated. This was followed by a linear segment that rapidly increased in load until failure. Failure was sometimes accompanied by an audible ''pop.'' Following failure, there was a dramatic reduction in

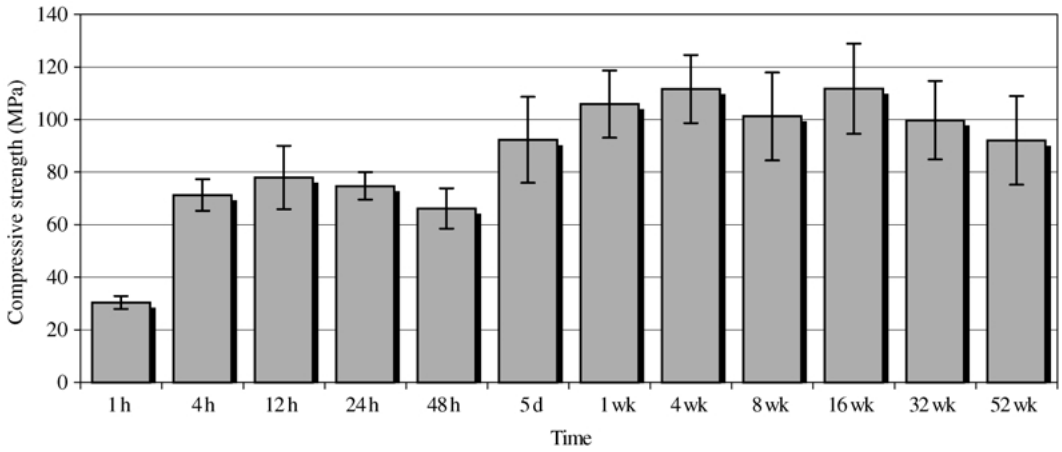

Figure 4 Compressive strength of OC-cement over time (mean ± standard deviation).

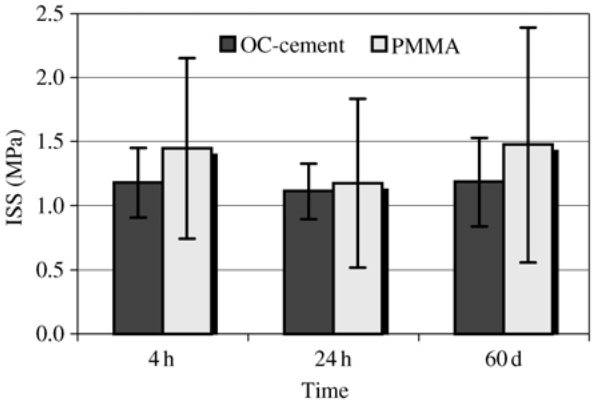

Figure 5 Interfacial shear strength of cement–prosthesis bond (mean ± standard deviation).

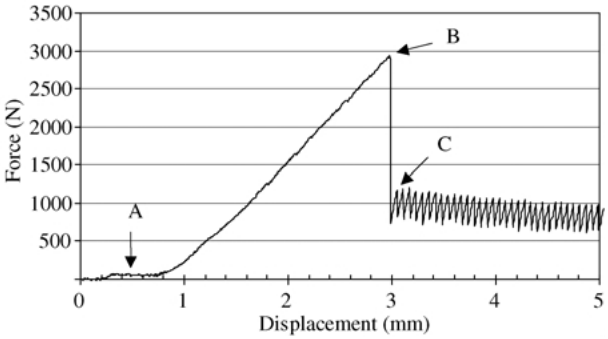

Figure 6 Typical force vs. displacement chart of pull-out test specimen exhibiting ''slip-stick'' behavior after failure: (A) tightening of testing fixture and specimen, (B) maximum load at failure, and (C) residual load after failure.

load to a new level referred to as the residual load. This residual load continued to decline until the post was completely withdrawn. These were the general features of most plots. For most specimens, the shape of the plot following failure was saw-toothed as in Fig. 6, indicating ''slip-stick'' detachment after initial failure, or smooth as in Fig. 7 with a gradual reduction in load after failure. The assorted sizes of femurs used in this study led to variations in the embedded length of the posts. Therefore, the interfacial shear strength, which is normalized for differences in surface area, was used to compare specimens.

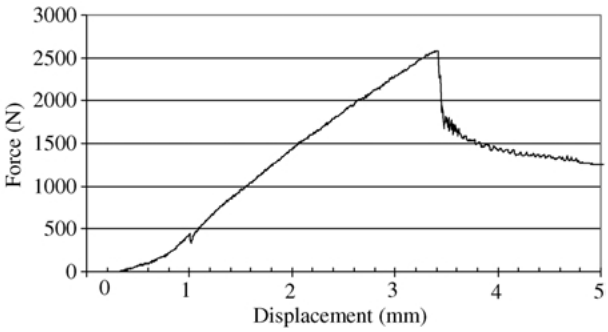

Figure 7 Typical force vs. displacement chart of pull-out test specimen with smooth decrease in load after failure.

4. Discussion

Compressive strength of OC-cement was found to increase over the first 4 weeks of the testing period. Within 4 h of preparation, OC-cement achieves strengths of approximately 70 MPa. The changes in strength over time are due to the continued hydration of calcium aluminate and conversion of the hydrated calcium aluminate phases. The mixing technique and experience of the processor are thought to affect the resulting strength. Although the values for compressive strength of OC-cement are comparable with values for commercial PMMA bone cement, the tensile strength is approximately $^1/_3$ to $^1/_2$ values reported for PMMA [10]. In the future, it may be possible to further improve the strength properties of OC-cement by decreasing porosity through techniques such as vacuum mixing.

The mean values for interfacial shear strength of OC-cement did not change over the 60-day test period. The values obtained for the PMMA-prosthesis interfacial shear strength at 60 days were greater than anticipated. Other researchers have reported high initial shear strength for the PMMA-prosthesis interface when stored under dry conditions [11], but a decrease was found after 18 h submersion in saline, [12] and values decreased to 0 MPa when test specimens were aged for 60 days in saline at 37 °C [13]. Even for the dry interface, a range of values has been given in the literature. Some authors have tried to explain these variations based on shrinkage of the PMMA cement that results from polymerization [13–15]. The temperature gradient between the inner and outer surface of the PMMA cement can influence whether polymerization begins at the inner surface leading to shrinkage onto the prosthesis or at the outer surface inducing shrinkage of the cement away from the prosthesis.

It is concluded that the OC-cement has a relatively small temperature rise during setting, achieves and maintains high compressive strength *in vitro*, has similar bonding strength to the prosthesis as PMMA, and may show potential for orthopedic applications. Work continues in the development this cement, study of the cement's properties, and evaluation of tissue response.

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