Preparation, Modification, and Characterization of Acrylic Cements

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ABSTRACT: Acrylic cements with different compositions were prepared by mixing the solid part (composed of poly(methyl methacrylate), PMMA, and benzoyl peroxide, BPO) and the liquid part (composed of methyl methacrylate, MMA, and *N*,*N*-dimethyl-*p*-toluidine, DMPT), modified by addition of hydroxyapatite (HA) and ammonium nitrate (AN) and characterized by measuring thermal and mechanical properties. Three sets of samples were prepared. For B-group, the total amount of solid including HA was constant but the PMMA to HA ratio was varied. For C-group, polymer/monomer ratio was constant and varying amounts of HA was added. For D-group, polymer/monomer ratio was kept constant and AN was added in varying amounts. Effects of these composition changes on the properties of the cement such as setting time, curing temperature, tensile and compression strength, and deformation were examined. For B-group samples, no linear change was observed in thermal (curing temperatures were all quite high) and mechanical (between 27 and 19 MPa for tensile, and 98 and 116 MPa for compression strength) properties upon change of HA content with change in solid/liquid ratio. For C and D-group samples, a continuous decrease in curing temperature from 114 to 101°C and from 94 to 73°C was observed upon increasing HA and AN contents, respectively. Also, a linear relation was observed in compression strength (from 98 to 111 MPa) and in tensile strength (from 27 to 21 MPa) upon HA addition, and in the compression strength (from 103 to 85 MPa) and in the tensile strength (from 22 to 17 MPa) with NA addition. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 99: 3631–3637, 2006

Key words: bone cement; PMMA; hydroxyapatite; HA

INTRODUCTION

Acrylic polymers have been widely used in cement formation for dental and orthopedic applications as filling and fixing agents. In fixations, they act as an intermediary phase between the implant and the bone; transmit the applied force and body weight uniformly to the tissue; and function as a load bearing material. The most commonly used acrylic is poly(methyl methacrylate), PMMA, which is a self-curing polymer with no adhesive properties. Cement preparation is achieved by mixing a solid component (mainly contains PMMA polymer and an initiator e.g., benzoyl peroxide, BPO) and a liquid (mainly contains MMA monomer and an activator e.g., *N*,*N*-dimethyl-*p*-toluidine). Free-radical polymerization of MMA monomer is initiated by a redox system and as the polymerization proceeds the newly formed PMMA matrix surrounds the existing PMMA particles. The reaction is highly exothermic with a total heat of 544 J/g for MMA and causes an increase in temperature (between 67 and 124°C depending on the cement formulation[1]), which may damage the surrounding tissue. These types of drawbacks (local tissue degeneration, shrinkage of the cement during curing, poor cement distribution around the implant, mismatching at the cement-implant interface etc) cause aseptic loosening or breaking of the implant. Therefore, a large number of studies are being carried out on bone cement formulation development to improve their mechanical, thermal, handling, and biocompatibility properties.[2] Effect of various additives including carbon,[3] graphite, aramid,[4] bone particles, polyethylene,[5] PMMA fibers,[6] titanium,[7] chitosan,[8] tricalcium phosphate[9,10] or hydroxyapatite (HA),[11–13] on cement properties are reported in the literature. HA is an osteoconductive calcium phosphate, which naturally exists in bone structure. Introduction of small amounts of homogeneously dispersed HA in cement formulations encourages bone formation and accelerates healing since it strongly integrates into the bone. Besides, existence of HA improves the mechanical properties of the polymeric resin and reduces the polymerization temperature. Lower curing temperatures usually cause an ex-

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TABLE I
Compositions of Acrylic Cement Samples

Sample[a]	Polymer/Monomer (w/w)	PMMA (g)	HA (g)	HA (wt %)	AN (g)	AN (%)
B0	2.00	4.06	—	—	—	—
B1	1.92	3.90	0.16	4	—	—
B2	1.88	3.82	0.24	6	—	—
B3	1.84	3.74	0.32	8	—	—
B4	1.80	3.65	0.41	10	—	—
B5	1.76	3.57	0.49	12	—	—
B6	1.68	3.41	0.65	16	—	—
C0 = B0	2.00	4.06	—	—	—	—
Cl	2.00	4.06	0.32	5	—	—
C2	2.00	4.06	0.53	8	—	—
C3	2.00	4.06	0.68	10	—	—
C4	2.00	4.06	0.83	12		—
D0 = C2	2.00	4.06	0.53	8	0	—
D1	2.00	4.06	0.53	8	0.5	7
D2	2.00	4.06	0.53	8	1.0	13

[a] BPO, 45 mg; DMPT, 18 μL in all samples.

tension of the dough time, without affecting the curing time.[14–19] Related to mechanical properties, there are controversial results reported in literature. It was observed that, depending on the amount, size, and surface properties of the HA particles, addition can cause either an increase or a decrease in the mechanical strength of the bone cement.[20] The objective of the present work is to prepare acrylic cements in various compositions by using ground and sieved PMMA powder, modify them by adding HA or AN, and to investigate the setting, thermal, and mechanical properties of the prepared compositions.

EXPERIMENTAL

Materials

The solid component of cement consisted of poly(methyl methacrylate) (PMMA; Sigma-Aldrich Chemie, Germany) with an average molecular weight of 120.000 and initiator benzoyl peroxide (BPO; Sigma-Aldrich Chemie, Germany).

PMMA particles were ground by using water-cooled analytical mill (Tekmar®, Janke and Kunkel GMBH Co. KG) and were sieved before use.

The liquid component was a mixture of methyl methacrylate (MMA) (Merck A.G., Germany) and the accelerator *N*,*N*-dimethyl-*p*-toluidine (DMPT; Sigma-Aldrich Chemie, Germany).

Hydroxyapatite was a product of Riedel-de Haën A.G., Germany, and was sieved before use.

Ammonium nitrate (purity > 99%) was obtained from Acros Organics, USA and were used as received.

The average particle size and size distribution curves for PMMA and HA particles were obtained by a particle size analyzer (Malvern™ Mastersizer, Malvern Instruments Ltd, UK).

Methods

Specimen preparation

Bone cement samples were prepared by mixing various amounts of solid (contains PMMA, HA, NA, and BPO) and liquid components (contains MMA and DMPT) as given in Table I. The constituents were taken out of the refrigerator and stored at room temperature for at least 1 h before mixing, to achieve thermal equilibrium. For preparation of cement samples, weighed amounts of constitutes of the solid part was placed in a container, the liquid ingredients were added and mixed using a spatula until the powder was fully wetted. The mixing was continued for 1–3 min with a mixing rate of 2–4 cycles per second, and when the dough had enough viscosity to handle, it was shaped to the desired form by molding. All samples were prepared at room temperature (about 23–25°C). After preparation, test specimens were soaked in saline solution for 24 h in a temperature-controlled water bath at (37 ± 1)°C, to simulate the body conditions.

In B samples, amounts of monomer, initiator, and accelerator were kept constant (MMA = 2.03 g, BPO = 45 mg, and DMPT = 18 μL), while the amount of solid part (PMMA + HA) was constant (Total = 4.06 g) but PMMA/HA ratio was varied, resulting in a change in polymer/monomer ratio. In C samples, polymer/monomer ratio was kept constant at 2.0 w/w but HA was added to the powder part in varying amounts. In D samples, ammonium nitrate was added in different amounts to the composition selected as the optimum from C group samples (C2) by considering all handling, mechanical, and thermal properties.

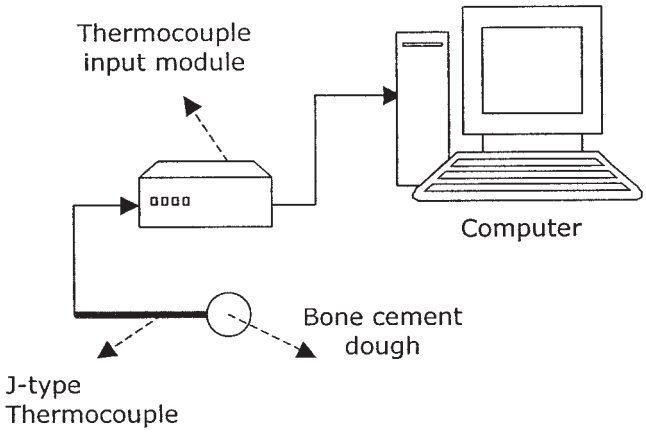

Figure 1 Temperature measurement setup.

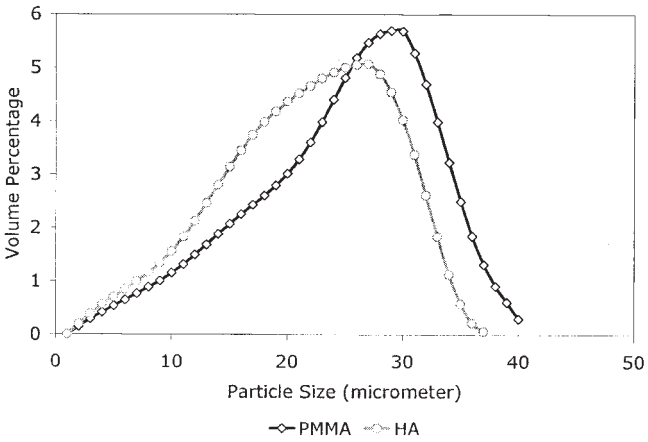

Figure 3 Particle size distributions of PMMA and HA.

Measurement of thermal properties

Thermal properties of the samples were measured by using a J-type thermocouple. The probe was placed at the center of the spherical bone cement dough (which has a radius of ~10 mm) after 5 min mixing. The temperature changes during curing were recorded for 1200 s at a rate of 1 data per second, by using a data acquisition software package in a Thermocouple Input Module (SuperLogics, USA) (Fig. 1). Measurements were achieved under atmospheric conditions for B and C samples, and in saline for D samples. From the resultant T versus t graph (Fig. 2), setting time and maximum curing temperatures were determined.

The dough time was determined as the time at which the bone cement mixtures no longer adhere to the surgical glove in hand, and the setting time was taken as the time when the exothermic temperature rose to the midpoint between the ambient and maximum temperatures.[1]

Characterization and mechanical properties

Tensile and compressive properties of the samples were determined at room temperature by using a mechanical test instrument (LLoyd® LRX 5K, LLoyd Instruments Limited, Fareham, Hampshire, UK). All experiments were carried out with standard specimens, according to ASTM F 451. For tensile tests, dog-bone shape samples in the sizes of $3 \times 1 \times 0.5$ cm^3 were prepared and the tests were carried out at room temperature with a cross-head speed of 1 mm/min. For each set of composition, 6–8 samples were analyzed. All the samples were prepared using the same method to eliminate the influence of preparation technique on the mechanical properties. In compression tests, cylindrical samples (diameter 6 mm and length 12 mm) were prepared and tested with the speed of 25 mm/min at room temperature. For each set of composition, 10–14 samples were tested. Fracture surfaces of both tensile and compressive test specimens were examined with scanning electron microscopy (SEM) (JEOL, JSM-6400, NORAN Instruments, Tokyo, Japan) to determine the nature of the break and to study the differences between the formulations.

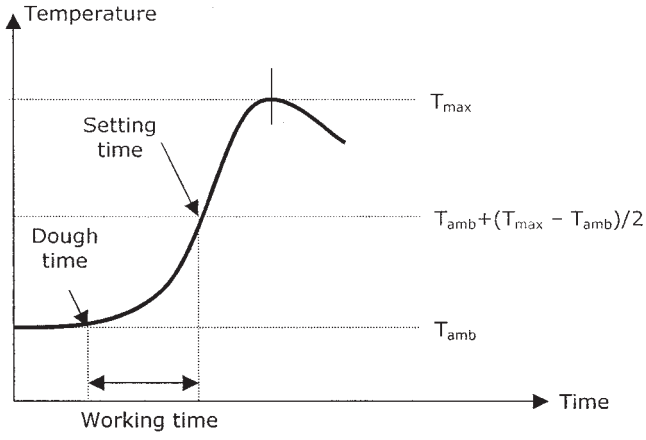

Figure 2 Time-temperature graph of curing cement.

RESULTS

Particle size and dough properties

Average diameters (volume mean diameter) of the PMMA and HA were found to be quite close to each other, 29.52 and 23.63 μm, respectively, (Fig. 3). The dough samples prepared using these powders were homogeneous, opaque with white color, and demonstrated proper consistency.

Thermal properties

Temperature measurement results

Setting time and curing temperature of bone cement is affected by polymer-to-monomer ratio, composition of the powder phase, and the presence of a chain transfer agent. Another important factor that affects the curing

TABLE II
Curing Temperatures and Setting Times of Cement Samples

Sample	T_{max} (°C)	Setting time (s)
B0	114	164
B1	111	142
B2	111	140
B3	112	159
B4	114	150
B5	112	181
B6	113	162
C0 = B0	114	164
C1	111	108
C2	103	96
C3	101	109
C4	NA	NA
D0[a] = C2	94	154
D1[a]	79	150
D2[a]	73	141

[a] Measured in saline solution.

temperature is the particle size of the PMMA powder. Average particle size of PMMA used in this study was constant, 29.52 μm. In general, very small particles with sizes less than 20 μm may dissolve completely in the liquid MMA monomer, leading to a decrease in the amount of PMMA particles that absorb the heat produced during the polymerization process. On the other hand, particles with sizes greater than 100 μm may cause inhomogeneity in the matrix due to insufficient wetting. Use of similar size PMMA and HA yielded a homogeneous distribution with a smooth texture.

With B samples, no substantial decrease in curing temperature was achieved by addition of HA (Table II). This can be explained to result from the combined effects of two opposing factors. In these samples, polymer-to-monomer ratio decreased as the content of HA increased. Although addition of HA is expected to decrease the curing temperature, the increase in the fraction of MMA caused the opposite effect and increased the curing temperature. These two factors compensated the effect of each other, and therefore, no relation between curing temperature and HA content could be observed.

For C samples, where the polymer/monomer ratio was kept constant and HA was additional, a clear change was observed in the curing temperature (Table II). C0 had the maximum curing temperature (114°C) and this value decreased to 101°C with introduction of 10% HA. Further addition of HA increased viscosity, created difficulty in workability, and caused inhomogeneity in the cement structure. Therefore, a curing temperature could not be obtained for C4 sample. C2 was chosen as the optimum composition after considering its handling, mechanical, and thermal properties.

For D samples, ammonium nitrate, which has an endothermic dissolution, was added into the formulation to decrease the curing temperature. As expected, addition of ammonium nitrate decreased the curing temperature from 94 to 73°C (Table II). Although the formulations were same for D0 and C2 samples, the differences in the observed values are caused by immersion of D0 samples into an aqueous medium during measurements.

When setting times were examined, it was observed that while the polymer/monomer ratio was kept constant and HA was added, setting time decreased from 164 to 109 s (in C0 and C3); when the amount of HA was kept constant and AN was added, the setting time decreased from 154 to 141 s (for D0 and D2), respectively.

TABLE III
Mechanical Properties of Cement Samples

		Tensile properties		Compressive properties	
Cement sample	HA (%; w/w)	σ_T (MPa)	E_T (GPa)	σ_C (MPa)	E_C (GPa)
B0	0	27.49 ± 5.02	0.38 ± 0.06	98.57 ± 3.12	0.63 ± 0.02
B1	4	20.71 ± 3.08	0.42 ± 0.03	95.35 ± 4.60	0.61 ± 0.03
B2	6	23.00 ± 4.00	0.49 ± 0.06	99.93 ± 3.48	0.64 ± 0.01
B3	8	24.02 ± 1.16	0.42 ± 0.05	120.66 ± 3.92	0.66 ± 0.02
B4	10	24.28 ± 3.36	0.44 ± 0.02	104.15 ± 3.26	0.67 ± 0.01
B5	12	24.59 ± 2.36	0.46 ± 0.03	119.12 ± 4.66	0.68 ± 0.02
B6	16	19.14 ± 4.11	0.45 ± 0.01	116.63 ± 4.46	0.67 ± 0.02
C0 = B0	0	27.49 ± 5.02	0.38 ± 0.06	98.57 ± 3.12	0.63 ± 0.02
Cl	5	24.90 ± 1.38	0.41 ± 0.05	96.08 ± 5.40	0.64 ± 0.01
C2	8	22.86 ± 3.09	0.43 ± 0.03	103.68 ± 5.00	0.68 ± 0.03
C3	10	21.75 ± 3.93	0.44 ± 0.03	105.26 ± 4.73	0.68 ± 0.01
C4	12	21.17 ± 1.77	0.51 ± 0.02	110.96 ± 2.79	0.66 ± 0.02
D0 = C2	8	22.86 ± 3.09	0.43 ± 0.03	103.68 ± 5.00	0.68 ± 0.03
Dl	8	18.29 ± 2.23	0.45 ± 0.02	95.99 ± 1.86	0.64 ± 0.01
D2	8	17.65 ± 2.17	0.41 ± 0.05	86.73 ± 2.73	0.61 ± 0.01

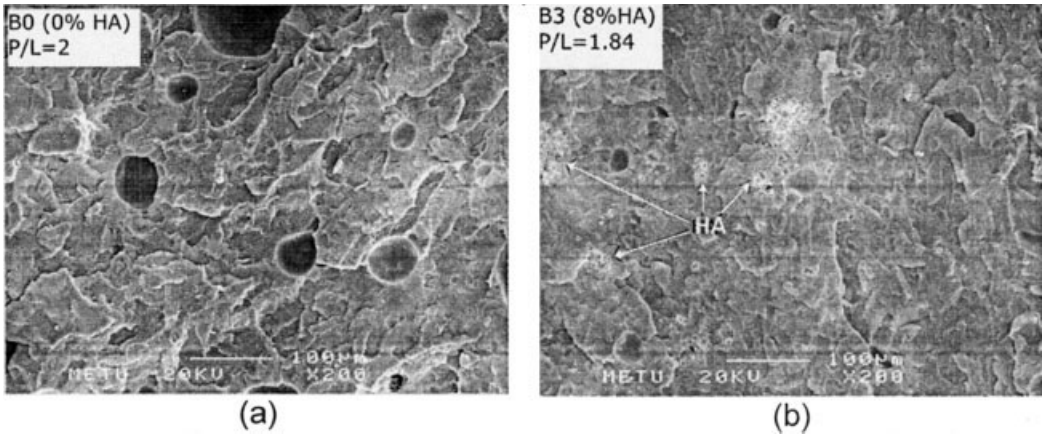

Figure 4 Fracture surfaces of acrylic cements: (a) B0 and (b) B3.

Mechanical test results

The average values of tensile strength (σ_T), compressive strength (σ_C), elastic moduli of tension (E_T) and compression (E_C) of the cement samples are given in Table III. For B samples, PMMA cement containing no HA (B0) demonstrated the maximum tensile strength value (~27 MPa) among all the HA containing formulations (samples B1–B6). Presence of HA caused a change in σ_T values, but there was no direct proportionality between the results and the HA content. In compression experiments, B3 sample demonstrated the maximum compressive strength (σ_C), ~121 MPa. Neither the compression nor the tensile strengths demonstrated a direct relation with HA content. Compression strength values were much higher than those of tension since HA particles behave as load carriers against the compressive forces but act as stress risers against tensile forces and produce mechanically weak areas adjacent to the PMMA matrix. On the other hand, the absence of a linear relation between the results and the HA content can be explained by variation of polymer-to-monomer ratio in these B-group formulations. Similar absence of proportionality was also observed for elastic moduli values of tension and compression, which varied in the range of 0.38–0.49 GPa, and 0.61–0.68 GPa, respectively.

In the preparation of the C-group samples, the polymer-to-monomer ratio was kept constant and HA was added by increasing amounts. In this group, a parallel increase in the compression strength (from 98 to 110 MPa), and a decrease in tensile strength (from 27 to 21 MPa) with HA content was observed. The decrease in tensile strength can be explained as follows. During the setting and cooling stage of PMMA, it will shrink and entrap HA particles producing a circumferential stress around them (called as Hoop Stress).[17,20] The weak bonding area produced between these two phases may cause a decrease in tensile strength. On the other hand, a parallel increase in elastic modulus values of tension (from 0.38 to 0.51 GPa), and compression (from 0.63 to 0.68 GPa) were observed upon increasing HA content.

In the samples prepared with the addition of ammonium nitrate (D0–D2), a decrease in both tensile and compressive strength values were observed. As it can be seen in Table III, D0 has a high ultimate tensile strength value (~23 MPa). The reduction in the strength may be explained with the increase in porosity or increase in the inhomogeneity upon introduction of AN because AN dissolves and leaves behind voids. Therefore, ultimate compressive strengths of D1 and D2 were significantly smaller than D0 ($P < 0.05$). Likewise, compressive elastic modulus decreased significantly ($P < 0.05$) from 0.68 GPa (D0) to 0.61 GPa (D2) by addition of 1.0 g ammonium nitrate, and the cement became more ductile.

SEM results

The fracture surfaces were analyzed by SEM after the tension and compression experiments. Pores observed in the cured bone cement could be formed by entrapment of air during mixing and monomer vaporization

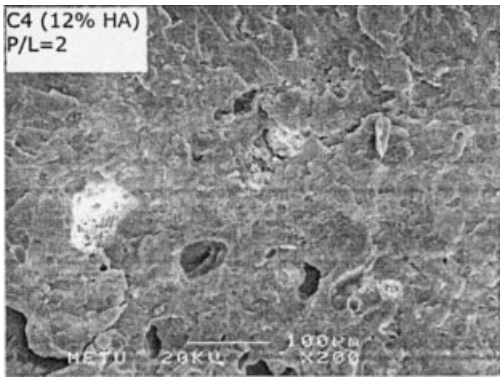

Figure 5 Fracture surface of C4 acrylic cements.

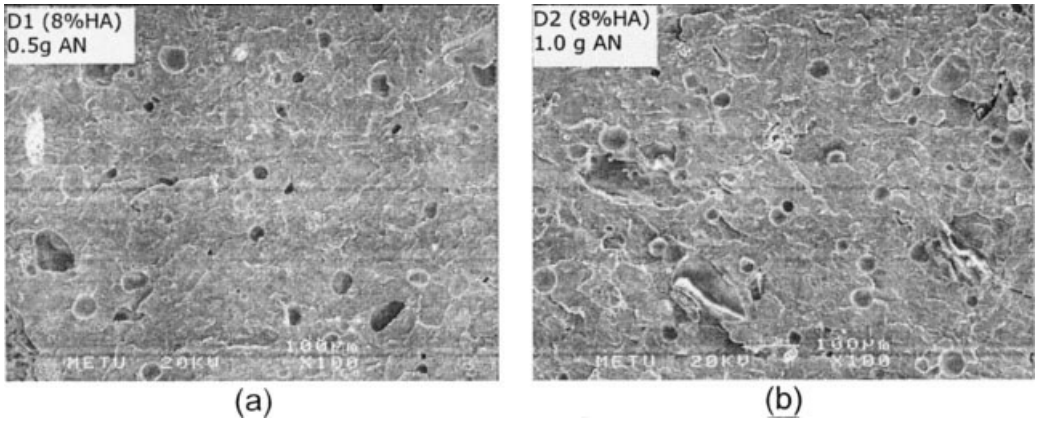

Figure 6 Fracture surfaces of acrylic cements: (a) D1 and (b) D2.

during polymerization. Since the strength of bone cement negatively correlated with the presence of air inclusions, porosity was one of the important parameters in the mechanical properties.

For B samples, it was observed that, the pore size and quantity at the fracture surface decreased with increasing HA content (Fig. 4).

Since polymerization of MMA is an exothermic reaction, presence of HA may cause a drop in the curing temperature by absorption of heat. Therefore, the decrease in temperature leads to less evaporation and to matrices with lower porosity. It was also observed that, HA particles were well embedded in the bone cement and allowed the compression stresses to be distributed evenly in the matrix. In a similar fashion, for C samples, the fracture surfaces revealed a lower porosity upon the addition of HA; compare C4 (Fig. 5) with C0 (Fig. 4(a)).

D samples contained AN, a water soluble inorganic salt, and in saline solution, it is expected to dissolve and create pores. Fracture surfaces of AN-containing samples (Fig. 6) demonstrated higher number of pores than the C samples.

CONCLUSION

In this study, acrylic cement samples were prepared by using mainly PMMA powder and MMA monomer and various amounts of HA and AN. For B group samples, where solid-to-liquid ratio was constant and the polymer-to-monomer ratio was not, thermal and mechanical properties did not demonstrate a parallel change to the amount of HA added. For C group samples, where polymer-to-monomer ratio was constant, the amount of added HA led to a parallel change in the values of thermal and mechanical properties. For D group samples, an inorganic salt, ammonium nitrate (AN), which has an endothermic dissolution enthalpy, was added to decrease the curing temperature. It was observed that AN has a strong effect on curing temperature of the acrylic bone cements. It decreased the curing temperature while keeping the mechanical properties in an acceptable range.

However, the use of ammonium nitrate might raise concern about the final biocompatibility of the bone cement developed in this study. The literature about the toxicity of ammonium nitrate gives the oral LD50 dose for rats as 2.217 g/kg[21] and as 4.820 g/kg[22] in two different reports. Meanwhile, the total amount of AN in a typical package of bone cement of 30 g is about 4 g, yielding a dose of 0.057 g/kg (4 g/70 kg) for an average human assuming all the AN dissolved instantaneously. This is 38 or 84 times lower than that of the LD50 dose for rats, and we believe that this dose is safe while keeping in mind the species difference. Before further testing, however, an *in vitro* test on biocompatibility of this bone cement would be appropriate.

We, therefore, conclude that the formulation developed in this study has a significant potential for use as a bone cement in further applications because of the lower setting temperature and lower risk of tissue damage.

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