Advanced Materials Research Vol. 856 (2014) pp 246-250
Online available since 2013/Dec/06 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.856.246

Evaluation of Mechanical Behaviour of Bone Cements by Using Acoustic Emission Technique

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Keywords: Biomaterials, acoustic emission technique, material characterization, mechanical properties.

Abstract. Biomaterials such as acrylic bone cements are widely applied in orthopaedic surgery for the fixation of artificial joints. Therefore, the mechanical behavior of such materials under external stresses is of special interest in order to achieve long-term in vivo performance. Fracture process can be attributed to diverse random microscopic damage modes. As the load increases, new damage modes appear and the existing ones can transition into others depending on the nature of the material. However, limitation exists in detailing the understanding of the micromanage initiation and development, and, consequently, in optimizing biomaterials performance. This paper focuses in the study of the emission of acoustic signals from bone cements in order to monitor the evolution of the internal defects that are believed to dominate in vivo failure.

Introduction

Implant fixation has been achieved with acrylic bone cement for many years. Although this is a successful application overall, limitations have been identified. The bond between the implant and bone cement has been shown to be the most fragile link in the bone/cement/implant construct in femoral components, with failure likely only a short time after implantation [1,2]. In the body, bone cement is subjected to a repetitive loading pattern. Although acrylic cement is reasonably strong in compression, it is a relatively brittle material, making it susceptible to fracture as a result of tensile stresses. Cement fracture and subsequent premature loosening are directly related to the strength of the cement mantle, which acts as an interface between the bone and the prosthetic component, hence it is important to understand the failure process [3]. Although classical fracture mechanics approach has shown remarkable achievement in studying fatigue and integrity of materials, there are some limitations. For example, it fails to detect microcracks generated inside the materials before visible or audible failure. This fact may not be a serious problem in the case of traditional engineering materials such as metals and composites. However it becomes a major problem when the material is sensitive to its fabrication process such as acrylic bone cements used as biomaterials [4,5]. In order to predict the mechanical behavior of a material during its service life, it is important to evaluate its mechanical response under different types of external stresses by studying the initiation and development of cracks and the effects induced by damage and degradation[6]. The acoustic emission (AE) technique is a nondestructive evaluation (NDE) technique that is capable of passively monitoring failure of many types of construct [7,8,9]. It is also a continuous process, avoiding the need to stop and section specimens, making it a time and cost effective alternative to other methods.

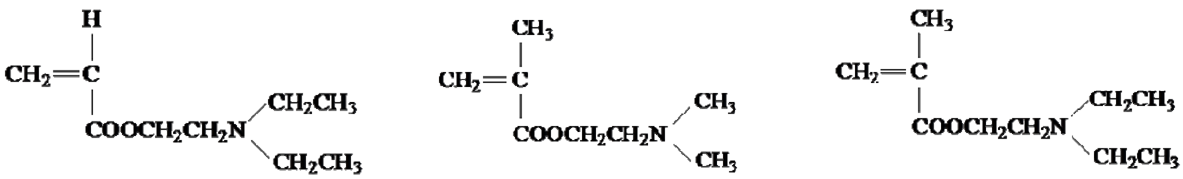
Materials and Methods

Four different bone cement materials were synthesized for mechanical evaluation and labeled according to the type of monomer used and the concentration as displayed in table 1. Specimen preparation and factors such as curing and temperature time are well known to affect the mechanical properties of bone cement. Although all of the specimens were prepared using identical hand mixing techniques and molded into their final shape, such factors changed in function of the formulation. The chemicals structure will depend on the co-monomer used that will form the final polymer matrix. The formulations of the materials are identified as follows: *reference*.- this cement was synthesized by using just the powder and liquid components without any additional co-monomer by solid phase (powder) containing polymethyl methacrylate (89%), benzoyl peroxide (1%), barium sulphate (10%), and the liquid phase containing methyl methacrylate (97.5%) and N,N-dimethyl-p-toluidine (2.5%). *M1*.- This cement contains the same chemical composition as *reference* and an additional monomer in the liquid phase: 2-(diethyl amino) ethyl-acrylate (DEAEA). *M2:* This cement contains the same chemical composition as *reference* and an additional monomer in the liquid phase: 2-(dimethyl amino) ethyl-methacrylate (DMAEM). *M3:* This cement contains the same chemical composition as *reference* and an additional monomer in the liquid phase: 2-(diethyl amino) ethyl-methacrylate (DEAEM). Additional monomer structure are displayed in figure 1.

Table 1.- Bone cement samples analysed

Concentration	Reference	M1	M2	M3
0%	√			
2%		√	√	√
10%		√	√	√

* M indicates monomer



(a) *DEAEA* (b) *DMAEM* (a) *DEAEM*

Figure 1.- Chemical structure of monomers.

In this research a second monomer is added in the liquid phase. The objective of using monomers that contain amino groups in its chemical structure is because it has been demonstrated that cements elaborated with such monomers achieve major adhesion on their surface by cells responsible of bone generation (osteaoblasts), in other words, biocompatibility of these materials are enhanced. Traditional bone cements formulations are not biocompatible and only remain as inert materials inside the body. Coupons were elaborated having a dog-bone shape with dimensions as shown in figure 2. The samples were loaded in tension mode to progressively higher strain at a cross-head speed of 0.5 mm/min. Acoustic emission sensor were attached to the sample to obtain the signal in order to be related to the damage development and mechanisms of fracture.

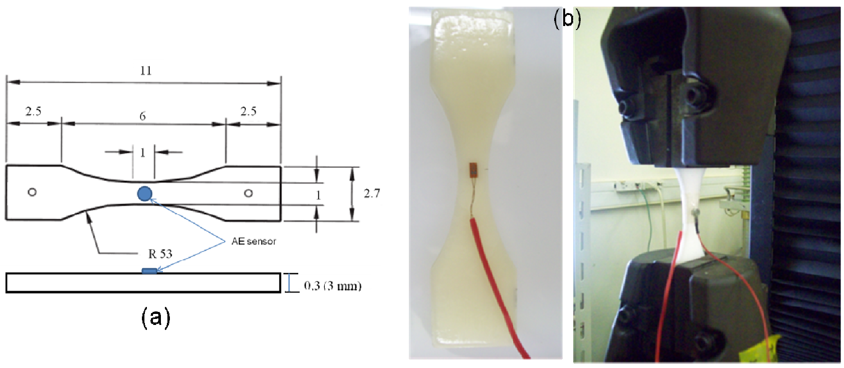


Figure 2.- a) Dog bone shape dimensions, b) longitudinal gauge and attached AE sensor.

Results

Materials synthesized with Monomer 1 (*M1*), shown and improvement as the formulation was augmented. Cement with Monomer 2 (*M2*) exhibited higher maximum stress at lower formulations, and larger displacements at higher formulations. On the other hand, bone cement synthesized with Monomer 3 (*M3*) displayed low dispersed values since it was not observable a marked difference between them; it seems that the formulation does not affect greatly the mechanical properties in tension mode. In comparison with samples with no added monomer (Ref-0%), *M1* displayed lower properties. Also 10% monomer exhibited lower modulus (Table 2).

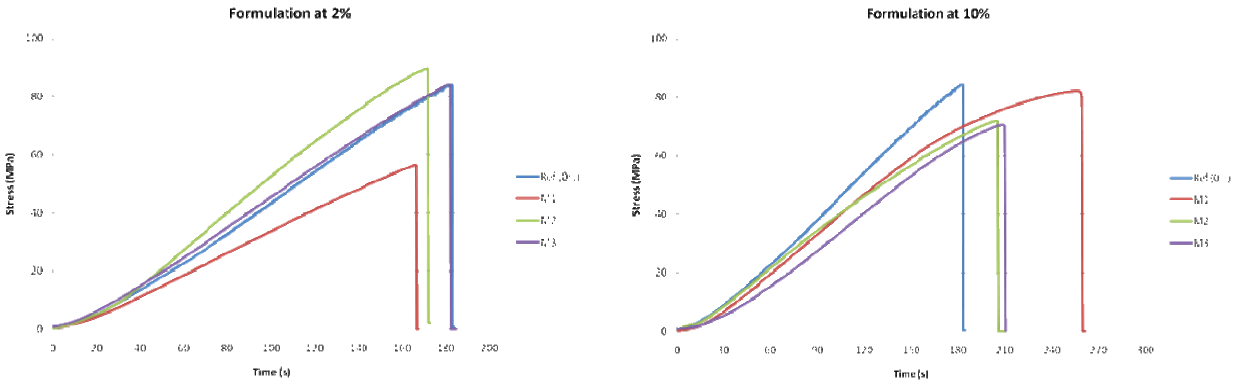


Figure 3.- Stress-time curves in accord to the monomer formulations.

Table 2 presents the Young Modulus values for each bone cement sample formulation. All samples shown similar elastic behavior with low dispersion indicating that resistance is similar for all cases while the others parameters (i.e. maximum stress and strain) are dependant of the formulations and type of monomer as observed in the stress vs. strain curves (Figure 3).

Table 2.- Young's Modulus (E) for bone cements in tension.

	0%-*Ref*	2%	10%
0%	2.3		
M1		1.9	1.8
M2		2.3	1
M3		2.2	1.9

E values are given in GPa

Figure 4 shows the relationship between the stress-time curves with the acoustic emission signals during tensile test for samples with added monomer 1 and 2. It is important to point out that, independently of the monomer used in the sample, all of them exhibited suddenly fracture with no previous distinctive damage. AE waves were strongly identified mainly at the end very near to the fracture point. *M1*-10% samples exhibited a slightly higher maximum stress and elongation than *M1*-2% but similar Young's modulus.

AE signals were detected after 110 s in each case being higher at 10%. On the other hand *M2*-10% showed a decrement in maximum stress values than M2-2% but similar strain. AE signals were detected around 110 s but in 10% samples an increment of energy related to a main crack formation is found around 140 s. 10% sample displayed a clearly non linear behavior suffering higher plastic behavior in which AE signals are detected a little bit earlier during the plateau previous to fracture indicating the appearance of damage.

Stress-time curves for *M3* bone cement are represented in figure 5. Mechanical parameters at 2% and 10% are similar, however, acoustic emission signals were found to be higher at 10%. It seems that these bone cements behaved like brittle materials allowing the AE waves to be noticed by the sensors from an early stage of deformation. AE analysis for samples labeled as "0%-reference" is also presented in figure 5. Signals related to main damage are not easily identified. Small energy signals are recorded at the middle of the test after about 50 s that may be related to micro-interfacial flaws between solid components of the cement such as $BaSO_4$ and the matrix (PMMA). It is at the end of the test just second s before total fracture when AE signal are detected with higher amount of energy, obviously related to the total rupture of the sample.

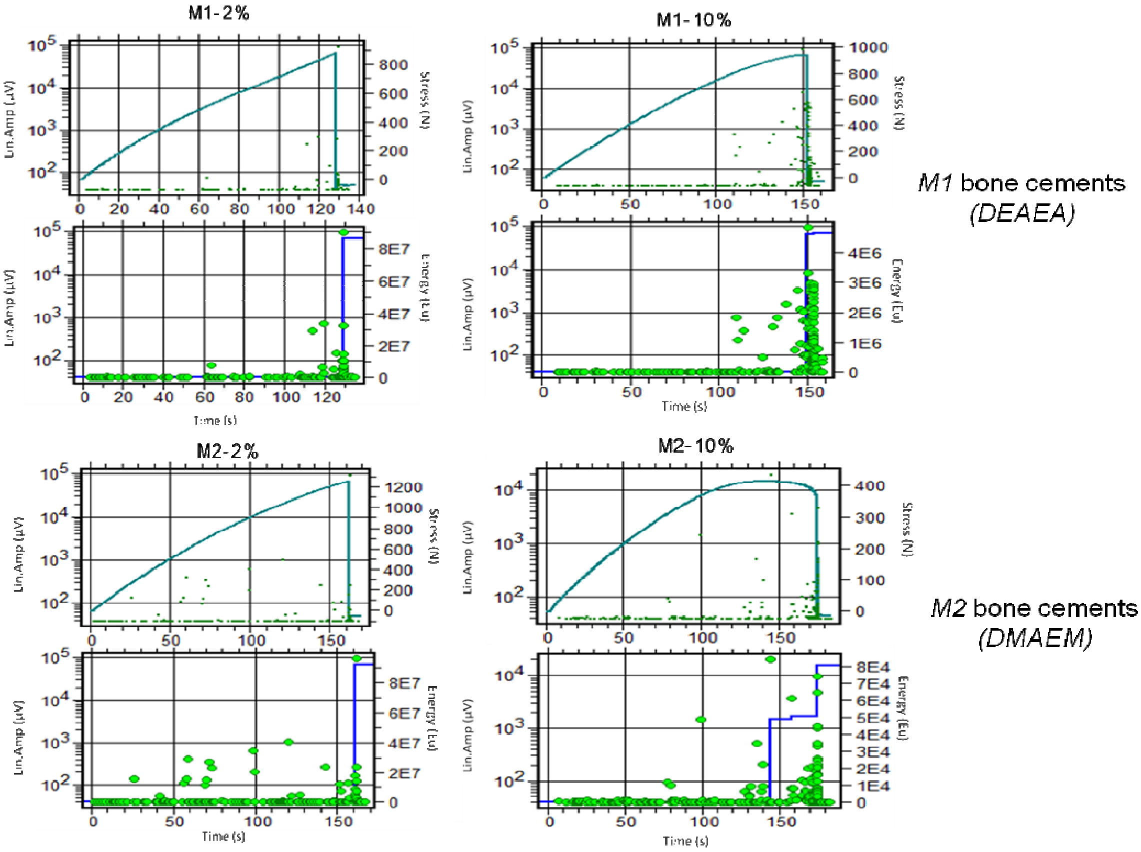


Figure 4.- AE signal analysis for M1 and M2 bone cements.

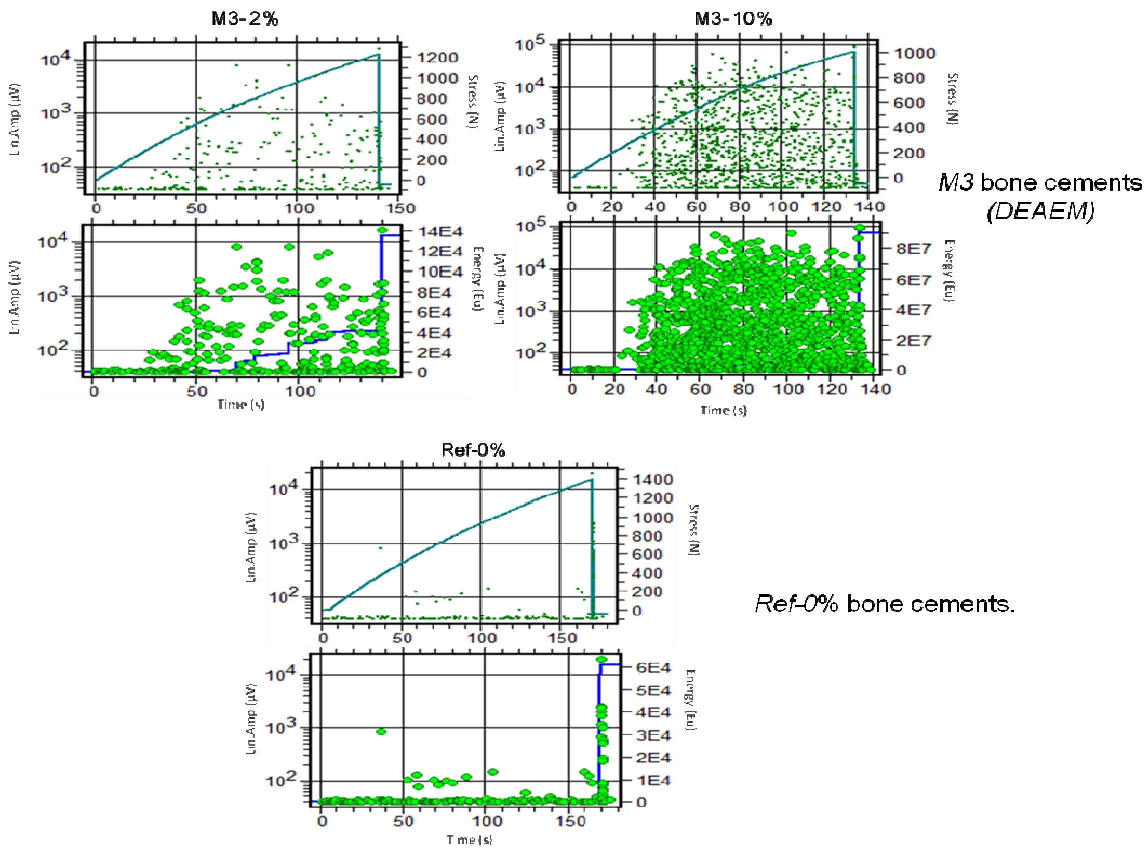


Figure 5.- AE signal analysis for M3 and Ref-0% bone cements.

Conclusions.

Bone cement materials tested in tension mode showed similar resistance (*E*), however elongation seems to be affected by the type of monomer and concentration exhibiting better values at 10%. Tenacity is also enhanced with formulations of 10% for all three types of added monomer. As a result, it is possible to resume that higher concentrations of monomer will improve the absorbing energy capabilities and the biocompatibility. Acoustic Emission signals were detected in higher amount when the material was prepared with 10% of monomer indicating that failure events appeared in superior quantity. Since this formulation stand more tenacity, failure generated at higher stresses were identified as subsequent interfacial failure between the PMMA matrix and the barium sulfate (BaSO4) agglomerates.

Acknowledgments.

The authors are grateful to the Mexican Council for Science and Technology (CONACYT) for the provision of grant 60204/ CM0042.

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Material Science and Engineering Technology II
10.4028/www.scientific.net/AMR.856

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