JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 29 (2014) 451–461

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

Modification of acrylic bone cement with mesoporous silica nanoparticles: Effects on mechanical, fatigue and absorption properties

Josh Slane[a,*], Juan Vivanco[b,e], Jill Meyer[d], Heidi-Lynn Ploeg[b], Matthew Squire[c]

[a]Materials Science Program, University of Wisconsin-Madison, Madison, WI 53706, United States
[b]Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, WI 53706, United States
[c]Department of Orthopedics and Rehabilitation, University of Wisconsin-Madison, Madison, WI 53706, United States
[d]Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, United States
[e]Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibañez, Viña del Mar, Chile

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form
1 October 2013
Accepted 7 October 2013
Available online 24 October 2013

Keywords:
Acrylic bone cement
Fatigue
Fracture toughness
Mesoporous silica
Implant fixation

ABSTRACT

Polymethyl methacrylate bone cement is the most common and successful method used to anchor orthopedic implants to bone, as evidenced by data from long-term national joint registries. Despite these successes, mechanical failure of the cement mantle can result in premature failure of an implant which has lead to the development of a variety of techniques aimed at enhancing the mechanical properties of the cement, such as the addition of particulate or fiber reinforcements. This technique however has not transitioned into clinical practice, likely due to problems relating to interfacial particle/matrix adhesion and high cement stiffness. Mesoporous silica nanoparticles (MSNs) are a class of materials that have received little attention as polymer reinforcements despite their potential ability to overcome these challenges. Therefore, the objective of the present study was to investigate the use of mesoporous silica nanoparticles (MSNs) as a reinforcement material within acrylic bone cement. Three different MSN loading ratios (0.5%, 2% and 5% (wt/wt)) were incorporated into a commercially available bone cement and the resulting impact on the cement's static mechanical properties, fatigue life and absorption/elution properties were quantified. The flexural modulus and compressive strength and modulus tended to increase with higher MSN concentration. Conversely, the flexural strength, fracture toughness and work to fracture all significantly decreased with increasing MSN content. The fatigue properties were found to be highly influenced by MSNs, with substantial detrimental effects seen with high MSN loadings. The incorporation of 5% MSNs significantly increased cement's hydration degree and elution percentage. The obtained results suggest that the interfacial adhesion strength between the nanoparticles and the polymer matrix was poor, leading to a decrease in the flexural and fatigue properties, or that adequate dispersion of the MSNs was not achieved. These findings could potentially be mitigated in future work by chemically modifying the mesoporous silica with functional groups.

*Correspondence to: 1513 University Ave, room 3046 Madison, WI 53706 United States Tel.: +1 608 263 6692.
E-mail address: jaslane@wisc.edu (J. Slane).

1751-6161/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmbbm.2013.10.008

1. Introduction

Acrylic bone cement is the material most commonly used to affix orthopaedic implants to bone and is the gold standard for implant fixation, as indicated by results from long-term national joint databases (Hailer et al., 2010). In essence, bone cement acts as a grout by filling in the voids that are left between the implant and the patient's bone, thus creating a mechanical interlock. The two primary roles of bone cement are to provide immediate fixation of the implant to the bone and to distribute forces from the implant to the surrounding bone. In order to adequately perform these functions, bone cement must be compatible with the host tissue as well as possess sufficient strength to withstand the large and repetative magnitudes of load/stress to which it is exposed (Lee, 2005). The mechanical properties of bone cement, therefore, play a pivotal role in the long term outcome of a cemented joint arthroplasty (Dunne, 2008).

The primary cause of failure in cemented joint replacements is aseptic loosening of the components (Hailer et al., 2010), which can arise from mechanical failure of the cement mantle surrounding the implant (Jeffers et al., 2007). As a result, a wide variety of techniques have been developed with the aim of improving the material properties of bone cement such as modifying the initiation chemistry (Hasenwinkel et al., 2002), reducing porosity with vacuum mixing devices (Dunne et al., 2003; Lewis, 1999) and adding reinforement fibers/particles. With respect to the use of reinforcements, numerous types of materials have been used in various loading ratios including nanosized radiopacifiers (Gomoll et al., 2008), graphene oxide (Goncalves et al., 2012), zirconia (Kane et al., 2010), titanium fibers (Kotha et al., 2006), variable diameter fibers (Zhou et al., 2009) and multiwalled carbon nanotubes (Marrs et al., 2006; Ormsby et al., 2012), along with others. Generally, the use of these materials has resulted in cement compositions with several improved in vitro properties but they have not transitioned into clinical use, likely attributable to issues regarding interfacial adhesion between the reinforcemnt and cement matrix, poor rheological properties, high cement stiffness and biocompatability (Lennon, 2008).

Mesoporous silica nanoparticles (MSNs) are a class of inorganic materials that have only received slight attention as reinforcement agents in polymers (Zhang et al., 2010). These particles are honeycomb-like in structure and exhibit controllable pore sizes (2–50 nm), high surface areas (e.g. 1000 m^2/g), high pore volumes (e.g. 1 cm^3/g) and homogeneous nano-level structures (Izquierdo-Barba et al., 2008). The highly porous nature of MSNs suggests that mechanical interlocking between the particle and the polymer matrix can occur, forming a strong adhesion which could mitigate interfacial adhesion problems typically observed with other types of reinforcement materials. Additionally, the high surface area inherent to MSNs could lead to an efficient stress transfer mechanism, thus increasing the strength of the MSN/polymer composite (Fu et al., 2008). Studies conducted by Zhang et al. (2009, 2010) observed an increase in the tensile properties and storage modulus of poly(methyl methacrylate) modified with mesoporous silica foams. Likewise, work performed by Samuel et al. (2009) found significant enhancement of the static mechanical properties of a dental resin augmented with high loadings of MSNs. Despite the potential benefits of mesoporous silica however, their use as a reinforcement material within acrylic bone cement has not been explored.

In addition to aseptic loosening, failure of joint replacements can occur as the result of periprosthetic joint infection (PJI), which has a prevalence rate of 1–3% for hip and knee implants (Parvizi et al., 2012). PJI is one of the most devastating complications following arthroplasty, causing significant physical and emotional pain to the patient in addition to high treatment costs which can exceed $100,000 (Gutowski, 2013). As a result, antibiotics are often incorporated into bone cement in order to act as a prophylactic measure against infection. Shen et al. (2011) used MSNs in an acrylic bone cement not for mechanical reinforcement but rather as a drug delivery mechanism to release gentamicin . This highlights another potential benefit of MSN use in bone cement; the highly porous nature of the particles can create a diffusion network that would allow fluid to penetrate into the cement and release water soluble drugs trapped within the polymer matrix.

Sub-micron sized particles tend to group together as a result of weak forces between them (e.g. Van der Waals or electrostatic), forming agglomerates with overall dimensions much larger than an individual particle (Taurozzi et al., 2011). These particle agglomerates can lead to the development of stress concentration sites that act as failure initiation sites (Ormsby et al., 2010a). Therefore, regardless of the type of reinforcement material used within bone cement, one of the most important aspects that must be considered is the technique used to incorporate the material into the polymer. Many processes have been developed to uniformly disperse nanoparticles into polymers including emulsion polymerization, high-temperature shear mixing and colloid milling, however, these techniques may not be applicable to bone cement since it would be difficult to implement them in a clinical setting. Ultrasonic homogenization is a viable alternative that is both easy to implement and effective. Several recent studies conducted by Ormsby et al. (2010a, 2012) utilized ultrasound to disperse carbon nanotubes within the monomer component of the cement prior to mixing and achieved encouraging results.

The aim of this study was to investigate the effect of mesoporous silica nanoparticle reinforcement on the mechanical and physical properties of acrylic bone cement used for orthopedic applications. A commercially available acrylic bone cement was modified with various loading ratios of MSNs using an easy to implement ultrasonic dispersion technique. The static mechanical properties (flexural, compressive and fracture toughness), fatigue performance and water absorption/elution properties of the resulting cement compositions were then determined.

2. Material and methods

2.1. Materials

A commercially available antibiotic-loaded acrylic bone cement was used as received for all testing (Palacos *R*+G, Heraeus Medical GmbH, Wehrheim, Germany). This cement