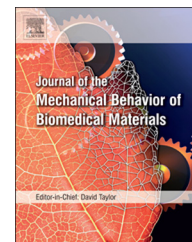


Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

Compressive fatigue and fracture toughness behavior of injectable, settable bone cements



Andrew J. Harmata^{a,b,1}, Sasidhar Uppuganti^{b,d,2}, Mathilde Granke^{b,d,2},
 Scott A. Guelcher^{a,b,c,1}, Jeffry S. Nyman^{b,c,d,e,*,2}

^aDepartment of Chemical and Biomolecular Engineering, Vanderbilt University, Nashville, TN, USA^bCenter for Bone Biology, Vanderbilt University Medical Center, Nashville, TN, USA^cDepartment of Biomedical Engineering, Vanderbilt University, Nashville, TN, USA^dDepartment of Orthopaedic Surgery and Rehabilitation, Vanderbilt University Medical Center, Nashville, TN, USA^eDepartment of Veterans Affairs, Tennessee Valley Healthcare System, Nashville, TN 37212, USA

ARTICLE INFO

Article history:

Received 27 January 2015

Received in revised form

23 July 2015

Accepted 27 July 2015

Available online 1 August 2015

Keywords:

Synthetic bone graft

Polyurethane composite

45S5 bioactive glass

Fatigue

Fracture toughness

Calcium phosphate bone cement

ABSTRACT

Bone grafts used to repair weight-bearing tibial plateau fractures often experience cyclic loading, and there is a need for bone graft substitutes that prevent failure of fixation and subsequent morbidity. However, the specific mechanical properties required for resorbable grafts to optimize structural compatibility with native bone have yet to be established. While quasi-static tests are utilized to assess weight-bearing ability, compressive strength alone is a poor indicator of in vivo performance. In the present study, we investigated the effects of interfacial bonding on material properties under conditions that re-capitulate the cyclic loading associated with weight-bearing fractures. Dynamic compressive fatigue properties of polyurethane (PUR) composites made with either unmodified (U-) or polycaprolactone surface-modified (PCL-) 45S5 bioactive glass (BG) particles were compared to a commercially available calcium sulfate and phosphate-based (CaS/P) bone cement at physiologically relevant stresses (5–30 MPa). Fatigue resistance of PCL-BG/polymer composite was superior to that of the U-BG/polymer composite and the CaS/P cement at higher stress levels for each of the fatigue failure criteria, related to modulus, creep, and maximum displacement, and was comparable to human trabecular bone. Steady state creep and damage accumulation occurred during the fatigue life of the PCL-BG/polymer and CaS/P cement, whereas creep of U-BG/polymer primarily occurred at a low number of loading cycles. From crack propagation testing, fracture toughness or resistance to crack

Abbreviations: LTI, lysine triisocyanate; BG, 45S5 bioactive glass; CaS/P, calcium sulfate and phosphate-based bone cement; PCL-BG/PUR, poly(ϵ -caprolactone) surface-modified BG and polyurethane composite; U-BG/PUR, un-modified BG and polyurethane composite; $\sigma_{\max}$, maximum stress level applied; c_k , overall creep strain (relative to initial strain); d_m , maximum displacement; K_{init} , critical stress intensity required to initiate cracks

*Corresponding author at: Department of Orthopaedic Surgery and Rehabilitation, Vanderbilt University Medical Center, Nashville, TN, USA. Tel.: +1 615 936 6296.

E-mail addresses: Andrew.J.Harmata@Vanderbilt.edu (A.J. Harmata), Sasidhar.Uppuganti@Vanderbilt.edu (S. Uppuganti), Mathilde.Granke@Vanderbilt.edu (M. Granke), Scott.Guelcher@Vanderbilt.edu (S.A. Guelcher), Jeffry.S.Nyman@Vanderbilt.edu (J.S. Nyman).

¹107 Olin Hall, 2400 Highland Ave, Nashville, TN 37235, USA.

²1215 21st Ave. S., Suite 4200, Nashville, TN 37232, USA.

<http://dx.doi.org/10.1016/j.jmbbm.2015.07.027>

1751-6161/Published by Elsevier Ltd.

growth was significantly higher for the PCL–BG composite than for the other materials. Finally, the fatigue and fracture toughness properties were intermediate between those of trabecular and cortical bone. These findings highlight the potential of PCL–BG/polyurethane composites as weight-bearing bone grafts.

Published by Elsevier Ltd.

1. Introduction

Tibial plateau fractures involve a weight-bearing joint and often have depressed portions that require extensive open reduction and internal fixation approaches along with subchondral grafting to maintain articular congruence. Bone grafts utilized in the clinical management of these fractures are subjected to repetitive, dynamic physiological loading from everyday activities, such as sitting, standing, and walking (Ramakrishna et al., 2001). Anatomic reduction and maintenance of the joint is important for both bone healing and articular regeneration, since lack of articular congruence after fractures increases the likelihood of osteoarthritis (Anderson et al., 2011). While the use of calcium phosphate cements (CPCs) mitigates the loss of reduction compared to autograft (Simpson and Keating, 2004), CPCs are contraindicated for filling bone voids that are intrinsic to the stability of the bony structure. Consequently, direct reduction of tibial plateau fractures requires stable internal fixation, which is associated with high rates of complications, such as non-union and loss of reduction (Schatzker et al., 1976; Young and Barrack, 1994; Papagelopoulos et al., 2006; Hall et al., 2009; Musahl et al., 2009). Injectable grafts with bone-like mechanical properties could potentially reduce the amount of internal fixation required and/or allow earlier weight-bearing. Considering that failure of fixation often results in re-hospitalization and an increased risk of poor outcomes (Bosse et al., 2002), there is a compelling clinical need for weight-bearing bone grafts that prevent failure of fixation and subsequent morbidity.

The criteria for non-resorbable cements designed to maintain the stability of the bony structure have been extensively investigated (Gilbert et al., 1995; Lewis, 2006). Fatigue failure is a predominant in vivo failure mode of non-resorbable bone cements used in hip replacements, such as poly(methyl methacrylate) (PMMA) (Ramakrishna et al., 2001). Despite the recognized need for resorbable grafts for repair of weight-bearing bone defects (Rezwan et al., 2006), the specific mechanical properties required for these materials to optimize structural compatibility with native bone have yet to be established (Ramakrishna et al., 2001; Johnson and Herschler, 2011). Tensile strength, fracture toughness, and fatigue life have been suggested as key mechanical properties that should be assessed and optimized (Gisep et al., 2004; Bohner, 2010; Johnson and Herschler, 2011). While quasi-static load-to-failure tests in compressive mode are frequently utilized to assess whether a material is “weight-bearing” (Johnson and Herschler, 2011), compressive strength alone is a poor indicator of in vivo performance, since physiologic loads typically include shear components and are cyclic (Gisep et al., 2004; Bohner, 2010). Thus, there is a gap between the methods by

which materials are tested and the mechanical environment they encounter post-implantation in vivo due to cyclic loading (Bohner, 2010).

Reporting only the mean quasi-static strength is often misleading, considering that materials fail under cyclic loads that are below the reported strength of the material (Bohner, 2010; Krause and Mathis, 1988). Nonetheless, properties such as fatigue life or fracture toughness are infrequently reported for CPCs or polymer/ceramic composites (Latour and Black, 1993; Morgan et al., 1997; Gisep et al., 2004; Johnson and Herschler, 2011; Slane et al., 2014). Brittle materials are susceptible to micro-cracking when subjected to repetitive subcritical loading, as is often applied in dynamic fatigue (Morgan et al., 1997; Kessler et al., 2003; Tilbrook et al., 2005; Pinter et al., 2006). Micro-crack growth or general damage accumulation can lead to a degradation of material properties that is difficult to detect because it often forms internally within the microstructure. Thus, we considered the assessment of initial fracture toughness and fatigue life at physiologically relevant loads to be a more stringent test (compared to quasi-static methods) of the ability of a bone graft to sustain in vivo service loads over time (Morgan et al., 1997; Gisep et al., 2004; Lewis, 2006; Bohner, 2010).

We recently reported that surface-modification of 45S5 bioactive glass (BG) particles via surface-initiated polymerization of ϵ -caprolactone significantly increased the initial quasi-static compressive and torsional strength of resorbable lysine-derived polyurethane (PUR) polymer/BG composites to levels exceeding that of human trabecular bone (Harmata et al., 2014). In the present study, we investigated the effects of interfacial bonding on material properties under conditions that re-capitulate the cyclic loading associated with tibial plateau and other weight-bearing fractures (Gisep et al., 2004; Bohner, 2010). We evaluated the initial cyclic compressive fatigue properties of PUR polymer/BG composites when subjected to physiological (5–15 MPa) (Ramakrishna et al., 2001; ASTM, 2010) or supra-physiological (15–30 MPa) loads. Experimental composites were compared to a commercially available, resorbable, and biphasic CPC (CaS/P), which has been reported to support rapid remodeling and an early return to weight-bearing activities when used to reconstruct bone voids following intra-lesional curettage of primary benign bone tumors (Evaniew et al., 2013). Furthermore, the selected biphasic CPC has similar compressive properties to those of monophasic apatitic cements (Dumas et al., 2012, 2014). The fatigue life (N_f) was determined for three independent definitions of failure, which were chosen to represent three potential mechanisms of clinical failure, including accumulation of internal micro-crack defects, plastic deformation, and subsidence. In order to evaluate the ability of the

Download English Version:

<https://daneshyari.com/en/article/810571>

Download Persian Version:

<https://daneshyari.com/article/810571>

[Daneshyari.com](https://daneshyari.com)