ENHANCED RELIABILITY AND STRENGTH OF CARBONATED Apatite Bone Mineral Substitutes with Organic Reinforcements

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INTRODUCTION: Carbonated apatite materials that resemble the mineral phase of bone have received considerable attention for biomedical applications. When formed at physiological temperature they present significant potential for rapid bone repair, fracture fixation, and augmentation of load bearing hardware. To date, the strength and resistance to fracture of such apatites has been extremely low [1]. This study investigates the mechanical properties and reliability of a representative carbonated apatite bone cement. Strategies to enhance properties, utilizing the addition of such biocompatible organic-phase reinforcements as albumin, bovine serum, gelatin, and soluble and insoluble collagen, are explored and found to dramatically improve mechanical properties. Implications for integrity and reliability are considered for a number of clinical applications.

METHODS: All samples were prepared from a synthetic bone material (SRS®, Norian Corporation, Cupertino, CA) that forms carbonated apatite through a cementitious reaction at physiological temperatures. To examine the effect of organic phase reinforcements, selected volume fractions of albumin, fetal bovine serum, collagen (type I soluble and insoluble), and gelatin were added before the cementitious reaction was initiated. Flexure strength specimens for both control and organic phase reinforced carbonated apatite were prepared in a Delrin mold, with a slightly hexagonal cross section to alleviate the stress concentration effects from rectangular corners (Fig. 1). After setting, the samples were cured in a 37°C phosphate buffered saline. The effect of curing time on mechanical behavior was assessed by removing samples at selected time intervals from the curing environment. To attain flexure strength data, specimens were tested in 4-point bending in a fully articulating fixture. The Weibull statistical method for brittle materials was used to analyze the data and to calculate a Weibull modulus, which provides a measure of the reliability of the material, for each sample set. A higher Weibull modulus indicates a narrower distribution of flaw sizes in the material. Additional fracture toughness and fatigue crack-growth tests were conducted on fracture mechanics samples. Testing was conducted using a high-resolution, electro-servo hydraulic mechanical test system (MTS-810). After testing, fracture surfaces were characterized using SEM.

RESULTS: Characteristic results of the flexure strength measurements are shown in a Weibull plot of fracture probability vs. strength for control and collagen-containing samples in Fig. 2. Strength as well as Weibull modulus tend to increase with organic phase additions. Overall, strength values for the bovine serum samples show the greatest improvement, increasing 67% over the control strength. The collagen-added samples appear to increase in strength with an increase in the amount added. Fracture toughness and fatigue properties were also measured and found to dramatically increase from the low values previously reported [1]. Fractography revealed evidence of toughening through bridging, as seen in Fig. 3.

DISCUSSION: Addition of organic phases have a marked impact on strength and reliability of the bone mineral substitute; they also exhibit typical composite behavior, in contrast to single phase brittle catastrophic failure. Fracture toughness and fatigue resistance are likewise affected. Microstructural examination of these inorganic-organic composite materials reveals a number of toughening mechanisms. Most significant is the bridging of cracks in the apatite by the organic phase additions, which increases material toughness along with strength. Micromechanical models have been developed to account for strengthening and toughening effects. Estimates of fracture toughness from these models show increases over the control. Implications for the behavior of such synthetic bone mineral substitutes in load bearing applications are considered. For example, enhanced resistance to fatigue degradation may lead to significant improvement in long term mechanical reliability of systems that experience cyclic loading. Such improvements in properties of synthetic bone materials will be crucial for future orthopedic applications.

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