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Recycling of waste amber glass and porcine bone into fast sintered and high strength glass foams

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ABSTRACT

Waste amber glass is primarily disposed into landfills, and only small proportions are reused or remelted. Recycling waste amber glass reduces the quantity of disposal and minimizes the potential environmental impact on landfill sites. This study adopts the fast sintering method and the concept of recycled materials in fabricating high strength glass foams: ceramic green body composed of pulverized waste amber glass and pork bone is sintered at 850 °C for 600 s. Prepared glass foam samples were thermally, structurally, and mechanically characterized to investigate the processing–property relationships. Particularly, high flexural strength values between 16.71 ± 1.73 and 29.69 ± 3.23 MPa were reported for glass foams prepared in this study. High strength glass foams prepared in present work is promising as a component in a variety of advanced structural and energy material systems, given their unique properties including heat insulation, sound absorption, and shock-wave absorption.

1. Introduction

Amber glass has been widely used as containers or bottles for protection from the deteriorating effect of light, such as beverages, pharmaceutical products and chemicals (Mosch, 1998). The most common amber glass compositions includes: iron oxides, carbon, sodium sulfate, calcium oxide, sodium oxide and silica. Notably, amber glass has several adsorption bands in the visible, helping to minimize the contained products (eg.pills, beers and chemicals) from direct interaction with light (Morsi et al., 2015; Mosch, 1998). Large quantities of amber glass are being produced daily to meet the needs of such containers; therefore, recycling and managing of waste amber glass has become an emerging environmental problem.

Only a small portion of waste amber glass is recycled through re-melting, while the remainder is typically disposed into landfills (Shayan and Xu, 2004). The amount of waste glass disposed into landfills was approximately 4.5% of the total municipal solid waste disposed in United States in 2013 (total disposed municipal waste is 186 million tons) (EPA, 2013). However, the amount of glass that can be disposed of in landfills is restricted due to environmental and social concerns (Burnley, 2001). Legislation acts have been continuously passed and enacted in U.S Congress since 1899 calling to lower the environmental impact and risk of depositing municipal wastes in landfills (Sharma and Lewis, 1994). Additionally, waste management [eg.recycling of waste glass into new or optimizing established materials systems (Nature, 2002)] efficiently lowers the percentage of waste glass stored in landfills. In recent years, world-wide environmental concerns have led to an increase recycling of various waste materials including amber glass (Arulrajah et al., 2015). One critical question posed is how the concept of waste management or recycled materials improves the environmental performance of businesses manufacturing, supplying, recycling and recovering waste amber glasses. Nevertheless, waste amber glass is potentially valuable source of major oxides, such as SiO_2 and CaO (Mosch, 1998), which are common in glass. Thus, development of environment-friendly recycles for waste amber glass is urgently required to settle those environmental and social concerns.

One common recycling method is to mix the glass into concrete (Akai et al., 2005), but sodium in the recycled glass often results in deleterious effects on the mechanical properties of the concrete (Akai et al., 2005; Johnston, 1974; Polley et al., 1998). Therefore, only glasses with relatively low sodium concentrations are suitable for this method of utilization of waste glasses. Another suggested method, as described by Chen et al. (2006), transforms common borosilicate glasses into porous silica by a process of heat treatment and hydrofluoric etch. Porous silica produced by this method can be

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applied to various aspects of commercial (Chen et al., 2004) or research use (Minakuchi et al., 1996, 1997). However, this method requires the glass to be or capable of being turned into phase separated glass. Cost-efficiency and further environmental impact of this recycling method is poor since the etching process creates large amount of waste (Chen et al., 2006). Common amber glasses are neither phase separated nor sodium free; thus, both of the above processes are not ideal methods. One potential way of recycling amber glasses is through the processing of glass foams (Andreola et al., 2007; Bernardo and Albertini, 2006; Bernardo et al., 2005, 2007; Ducman and Kovačević, 1997; Guo et al., 2010a, 2010b; Hicks et al., 2005; König et al., 2014; Ponsot et al., 2015). Glass foams hold a significant advantage of much lower processing temperature comparing to other re-vitrification processes of waste glass due to the intensive fluxing ability of glass matrix [eg.typical sintering temperature of foam glass is below 1000 °C (Andreola et al., 2007; Bernardo et al., 2005; Chen et al., 2012; Ducman and Kovačević, 1997; Guo et al., 2010a, 2010b; König et al., 2014; Llaudis et al., 2009)]. Relatively low processing temperature of glass foam is highly favorable to both economic and environmental perspectives of recycling waste glass. Lower processing temperature of glass or ceramic product is crucial given the ceramic industry consumes 8.9% of the world's total energy production (Gong et al., 2015). Most of energy input into the ceramic/glass industry is mainly consumed by generation of heat for sintering or melting anticipated final product (eg.glass, ceramics, crystals or etc.) (Gong et al., 2015). Thus, the glass foaming process holds the potential to be an environment-friendly and cost-efficient way of recycling and managing the waste amber glass.

Glass foams can be widely used as building and construction materials given their unique properties including: lightweight, heat insulation, sound absorption, and moisture and fire retardation (Guo et al., 2010a, 2010b). Foam glass can be used for construction applications (eg.interior and exterior wall of infrastructure), given that failures can be reduced by its lightweight while critical structure strength can be maximized by its shock wave adsorption properties (Guo et al., 2010a, 2010b). These unique properties of foam glasses are primarily due to a developed porous structure, produced at elevated temperatures. The porous structure of foam glasses is typically achieved through sintering of the glass matrix with addition of foam agents, which release gaseous species at designated sintering temperatures. Examples of common foaming agents include carbides (Guo et al., 2010a), alkali-carbonates (Chen et al., 2012; Fernandes et al., 2009; König et al., 2014), and other industrial grade chemicals (Chen et al., 2009; Llaudis et al., 2009). In some cases producing foam glass is not always cost effective due to the expense of the foaming agents (Kingery et al., 1976). Therefore, a cheap, obtainable and simple foaming agent for amber glass-based foams is of particular need and interest. Additionally, a typical heat treatment (sintering, holding, cooling) schedule of glass foam is well above 30 min, and the cost of manufacturing glass foam can limit the application of glass foams.

In this study, high strength foam glasses were successfully fast sintered (~600 s) using only waste materials: pulverized amber beer bottles and pork bone as the matrix and foaming agent, respectively. Porcine bone was chosen as the foaming agent given that porcine bone is well considered to be a non-recyclable waste in food industry (Jayathilakan et al., 2012) and was never reported to be used as a functional component in material systems to the authors' best knowledge. However, recycling of bone minerals by combining them into material systems is not limited to porcine bones (e.g. other animal bones from food industry). Resultant glass foams were characterized structurally and mechanically to investigate the processing-property relationships of glass foams. Recycle end product developed by this study would probably give a feasible solution to the environmental problems of the glass as well as food industry, and can be potentially utilized as a novel approach upon cleaner production of glass foam.

2. Materials and methods

2.1. Processing

Commercially available amber beer bottle glass and dried porcine bones were used as the glass and foaming agent components respectively. X-ray photoelectron spectroscopy (XPS) was performed on air-fractured glass pieces to ensure the glass used is lead-free. Amber glass cullet was pulverized into fine particles with a Gyro Mill (Glen-Creston Ltd., UK). Pulverized glass powders were ultrasonically cleaned in acetone for 10 min, and then dried in vacuum at 90 °C. Porcine bone was slow cooked at approximately 90 °C, dried at 90 °C, pulverized in a ball mill, sieved through 100 mesh, and soaked in acetone for 24 h to remove any organic compound. The glass and bone powders were then combined, by weight, to form the following compositional batches: 97%-3%, 95%-5%, 93%-7%, and 80%-20%. The amount of foaming agent added to the glass is typically in the range of 1wt% to 20 wt% (König et al., 2014; Scheffler and Colombo, 2006). In order to investigate the effect of excess bone addition on the mechanical and structural property of resultant glass foam, 20 wt% of bone was added to the glass matrix. The powders were then mixed with an agate mortar and pestle and pressed into pellets with a half-inch stainless steel die. A uniaxial pressure of 30 MPa was used for all samples. The pellets were then placed in an electrical furnace and heated at 850 °C for 600 s (König et al., 2014). As-sintered pellets were cooled in an oven for 1 h.

2.2. Thermal analysis

Differential thermal analysis (DTA) was performed on all as-prepared powder mixtures (prior to pellet preparation and heating) using a SQT-Q600 DTA/TGA (TA Instrument, USA) over a temperature range of room temperature to 1000 °C. A heating rate of 10 K/min was used in all measurements.

2.3. Mechanical strength

Three-point loading bending tests were performed using 10 mm × 4 mm × 3 mm specimens cut from glass foam pellets. Specimens were prepared by grinding of pressed pellets (loading sides down) to 1200 grade (2.5 μm sized polishing particles) with SiC grinding paper. Grinding and polishing of the test bars avoids the uncertainties of specimen dimension in calculations of the flexural strength, and minimizes the possible surface defects caused by machining of the specimens. The flexural strength was measured at a cross-head rate speed of 2 mm/min, using an 8874 axial-torsion fatigue testing system (Instron, USA). The flexural strength (σ) was measured on 10 test bars for each series of sample, and calculated using geometric loading area. Standard error of flexural strength is as follows as follows:

$$\sigma_{error} = \frac{\sqrt{\left(\sigma_1 - \sigma_{average}\right)^2 + \cdots + \left(\sigma_n - \sigma_{average}\right)^2}}{n}$$

where n is the number of sample tested, and σ is the flexural strength.