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# Uniaxial quasistatic and dynamic compressive response of foams made from hollow glass microspheres

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ABSTRACT

This study investigates the effects of the size of hollow glass microspheres (20 μm vs. 40 μm) and composition on the energy absorption capacity of the silicate glass foams under both the quasistatic ($\sim 10^{-3}$ s$^{-1}$) and high-strain rate ($\sim 10^{3}$ s$^{-1}$) loading conditions. These measurements revealed that while the size difference of the hollow glass microspheres and the foam composition have negligible effects on the uniaxial quasistatic response, their effects were significant under the dynamic loading conditions. The results suggest that the smaller glass microspheres (20 μm) dominated the dynamic behavior of the glass foams in comparison to the larger glass microspheres (40 μm), leading to a significant increase of the energy absorption capacity of the 20 μm-based glass foams at high-strain rates. Glass foams exhibited energy absorption capacity of about 54 kJ/kg under the dynamic loading that is greater in comparison to that of the typical metallic and syntactic foams.



## 1. Introduction

A key feature of cellular solids is the ability to undergo large strain deformation at a relatively constant stress, making them suitable for usage in automotive bumpers, personal protective gear and armor for the shock wave attenuation and impact energy dissipation [1–6]. Since, primary contribution to the specific energy absorption ($U_m$) capacity of the cellular solids comes from the specific strength of the bulk material and the densification strain, materials with high specific strength are desired to develop cellular solids with superior energy absorption capacity [7]. A specific strength analysis of various materials by Wiest et al. [7], identified silicate glasses as the potential material candidates because of their much higher specific strength in comparison to that of steels, bulk metallic glasses (BMGs), titanium, and aluminum alloys.

Significant progress has been made in the fabrication of ceramic and glass foams by employing one of the following methods. In the replica method, a polymeric sponge is impregnated with a ceramic suspension, followed by organic burnout to produce ceramic foam [8]. In the fugitive phase method, a sacrificial pore former is used to create pores; the pore former is removed following infiltration, leaving a porous structure behind [9]. In the direct foaming method, a gaseous phase is dispersed and stabilized in a liquid, followed by drying and sintering [10]. Other methods such as gelcasting and protein coagulation casting are also commonly utilized for ceramic foam fabrication [11]. A relatively less explored but unique cellular solid fabrication technique is where hollow spheres can be bonded together by applying heat to a cellular network of precursor hollow spheres [12,13]. Wiest et al. [7], recently assembled commercially available hollow borosilicate glass microspheres (also called glass bubbles) to a glass foam by heating the glass bubbles above their glass transition temperature (*Tg*). Uniaxial compression measurements at the quasistatic loading conditions (strain rate range $\approx 10^{-2}$ to $10^{-3}$ s$^{-1}$) revealed that glass foams derived from hollow glass microspheres have energy absorption capacity of about 14 MJ m$^{-3}$ ($\sim$26 kJ kg$^{-1}$), which is comparable to some of the materials with the highest energy-absorbing capacities, such as the AlSi foam and balsa wood [7].

During impact loading scenarios, cellular solids and foams typically deform at strain rates ($\geq 10^{3}$ s$^{-1}$) that are significantly greater than strain rates encountered under quasistatic loading conditions [3–6,14,15]. Investigations on various metallic and polymeric foams as well as on natural cellular solids have revealed that com-

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**Table 1**
Specifications and properties of 3M™ glass microspheres.

| Microspheres types | True density ($kg\,m^{-3}$) | Particle size ($d_{50}$, microns) | Isostatic crush strength (MPa) |
|---|---|---|---|
| K46 | 460 | 40 | 41 |
| iM16K | 460 | 20 | 110 |

pressive deformation responses measured under quasistatic and dynamic loading regimes can be significantly different [3–6,13–15]. Although similar investigations on ceramic and glass foams is still sparse, dense ceramics and glasses are known to exhibit significant rate-sensitivity where mechanical properties such as the fracture strength and hardness increase with loading rate [17–21]. As a result, compressive responses of the foams made from the hollow borosilicate glass microspheres measured under the quasistatic loading conditions [7] may not adequately represent their energy absorption characteristics in the dynamic loading regime. To that end, this work investigates the specific energy absorption capacity and energy absorption efficiency of the glass foams derived from the hollow silicate glass microspheres both at the quasistatic ($\sim 10^{-3}$/s) and high-rate ($\sim 10^{3}$/s) loading regimes. Additionally, this study determines the influence of the size of the constituent hollow glass microspheres on the overall compressive responses of the foams as a function of the composition and strain rate. These investigations are important to reveal the dynamic deformation characteristics of the hollow microspheres-derived glass foams and evaluate their suitability as energy-absorbing materials.

## 2. Experimental

### 2.1. Materials and fabrication

In the current work, foams were fabricated from two types of hollow soda-lime-borosilicate glass microspheres (K46 and iM16K) obtained from 3M™ (St. Paul, MN). While the both types of microspheres have same material composition and true density ($460\,kg\,m^{-3}$), their average diameters and crush strengths differ significantly (K46: 40 μm and 41 MPa and iM16K: 20 μm and 110 MPa), Table 1. Scanning electron micrographs of the as-received K46 and iM16K microspheres (Fig. 1) show that the microspheres were almost intact and have good spherical shape. It can be seen that the K46 not only contains larger microspheres (Fig. 1 and Table 1) and has a wider size distribution compared to the iM16K. In the current work, glass foams were fabricated from: (i) the K46 microspheres, (ii) the iM16K microspheres, and (iii) a 50-50 mixture (by wt.%) of the K46 and iM16K (hereinafter referred as K46-iM16K). For each composition, glass microspheres were packed in a fused silica ($SiO_2$) tube (ID – 9 mm) with one end sealed and a small plug of quartz wool securing the bubbles at the opposite end [7]. The silica tube was placed in a furnace and densified under vacuum. Samples were heated from room temperature to 843 °C at a heating rate of 5 °C/min, held for 30 min, and followed by cooling to the room temperature. After the heat treatment, the cellular solid was removed from the tube and average diameter of the porous glass cylinders was measured approximately 8 mm. Densities of the glass foams were estimated by measuring the sample dimensions and mass. To investigate the progressive microstructural developments, a study was conducted where the K46 glass microspheres were heated at 843 °C for different durations (5, 10, 15, 20, 25 and 30 min), cooled to room temperature, and microstructures of the glass foams for each conditions were investigated using a scanning electron microscope (SEM). Microstructures of the iM16K and K46-iM16K foams (processed at 843 °C for 30 min) were also investigated using an SEM.

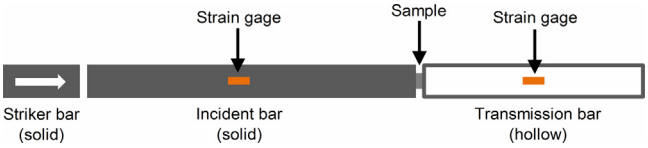


**Fig. 2.** Schematic of a modified split Hopkinson pressure bar (SHPB) set up for testing foams.

### 2.2. Quasistatic and dynamic compression tests

To investigate the rate-sensitivity of the processed glass foams, uniaxial compression experiments were conducted both at low- ($\sim 10^{-3}$/s) and high-strain rates ($\sim 10^{3}$/s). It should be noted that compression tests were conducted only for the K46, iM16K and K46-iM16K foams processed at 843 °C for 30 min. To avoid premature structural collapse of the porous solids during the compression tests, all the compression experiments were conducted on the thin cylindrical disks of $l/d$ ratios in the range of 0.13–0.17. However, average specimen thickness was still ~35–70 times greater than the average microsphere diameter (depending on the microsphere type), thus large enough to ensure that the specimen behavior is representative of the bulk material. Quasistatic compression experiments were conducted using a screw driven mechanical testing machine at a displacement rate of 0.5 mm/min. For the high-strain rate compression experiments, a modified split Hopkinson pressure bar (SHPB) set up was employed that is suitable for testing low strength and low impedance materials such as foams [21]. Fig. 2 shows a schematic of a modified SHPB set up that consists of a solid striker bar (of length 330.2 mm and diameter 12.7 mm), a solid incident bar (of length 1397 mm and diameter 12.7 mm), and a hollow transmission bar (of length 914.4 mm, outer diameter 12.7 mm and inner diameter 9.48 mm), all made out of high-strength aluminum (Al) alloy. At the specimen-transmission bar interface, an Al alloy end cap was press fitted into the hollow tube to support the specimen. Upon impact by the striker bar, a compressive stress pulse is produced in the incident bar, travels through the bar and loads the sample in compression. A part of the pulse is transmit-

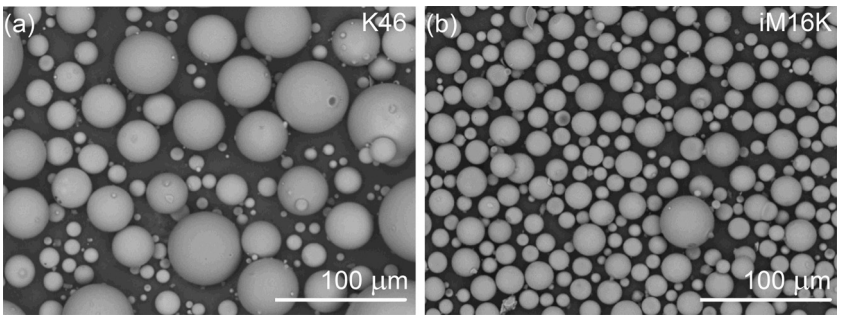


**Fig. 1.** SEM micrographs of the as-received hollow glass microspheres: (a) K46 and (b) iM16K.