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Lightweight and high-strength glass foams prepared by a novel green spheres hollowing technique

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Abstract

Lightweight and high-strength glass foams were fabricated from recycled glass powder by a novel green spheres hollowing technique. Utilizing green spheres could tailor the microstructure features and properties of the foams and reduce the sintering temperatures to 680–800 °C. The foaming process of the sample consists of six consecutive stages. The obtained glass foams show uniform structure and small cell size, with apparent density, porosity, thermal conductivity and compressive strength values of 0.129–0.229 g/cm^3, 91–95%, 0.055–0.077 W/m K and 0.85–5.92 MPa, respectively. In comparison to glass foams prepared via traditional methods, the obtained glass foams have exceptionally high mechanical strengths. The green spheres hollowing technique is a general, energy-saving and easy scale-up approach for the fabrication of inorganic foams.

Keywords: A. Sintering; B. Microstructure-final; C. Mechanical properties; D. Glass; Foaming process

1. Introduction

Glass foams have been produced since 1930s, when many patents were granted in the same period [1,2]. Glass foams are characterized as lightweight, compression-resistant, thermally insulating, sound absorbing, nonflammable, and water- and steam-resistant. Due to their unique properties, glass foams have comprehensive applications in many areas such as acoustic and thermal insulation materials, catalyst supports, lightweight aggregate material in concrete and biomedical implants [3–8]. Generally, the microstructure of glass foams determines their properties and usefulness. And the microstructure has great dependence on the fabrication process. While considerable progress has been made on the fabrication of glass foams, currently available methods still have important limitations.

There are two industrial processes for the fabrication of glass foams. The first industrial process is to introduce fluids (e.g. air, CO_2 and water vapor) directly into the molten raw materials dating back to 1930s. However, high costs of the process have constituted a key disadvantage because of the high energy-consuming for preparing glass melts. It is substituted by a sintering approach which is applied at much lower temperatures than those for blowing. The most convenient viscosity range for optimizing the foaming process is 10^5–10^3 Pa s, which corresponds to the temperature range 800–1000 °C for a typical soda-lime glass composition [3]. Nowadays the main industrial process is to sinter glass powders admixed with suitable blowing agents. The blowing agents are classified as neutralizers (e.g. $CaCO_3$, $MgCO_3$ and Na_2CO_3) [9,10] and redox agents (e.g. C, SiC and organic compounds) [11,12]. Traditionally, the glass powder is mechanically mixed thoroughly with blowing agent to obtain a uniform raw material before heating. However, the mechanically mixed process leads to the inhomogeneity of the raw material, resulting in uneven pore structure. On the other hand, the

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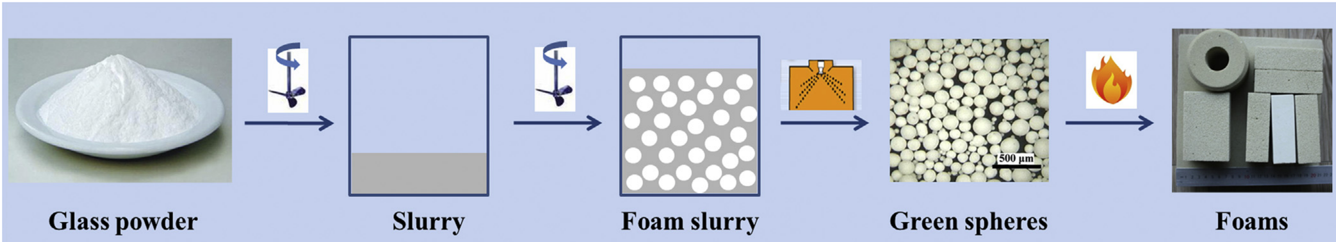

Fig. 1. Illustration of the preparation process of glass foams.

granular blowing agent is responsible for big voids of the foams and the deterioration of mechanical properties. Besides, the foaming temperature is still very high (above 800 °C in general case), which contributes to the high cost of the products.

In addition, several novel techniques have been developed to prepare glass foams. Lightweight ceramics with porosity in the range 76–92% (apparent densities in the range 0.208–0.566 g/cm^3) of theoretical were fabricated by sintering hollow glass spheres [13]. Nevertheless, the high production costs of using hollow glass spheres as raw material can be the fatal flaw for industrial production. Ji et al. demonstrated a facile green chemistry route for the fabrication of high-performance porous silica foams by recycling solid glass wastes [14]. The apparent density of glass foams is greater than 0.20 g/cm^3, but this route has not been widely used at present. In recent years, the tendency towards fewer heat-treatments, use of abundant resources or recycled materials and reduction of costs will be enhanced for the fabrication of foam materials [15–17]. Hence, an energy-saving, low-cost and easy scale-up approach for fabricating lightweight and high-strength glass foams from recycled glass powder is highly desirable.

In this paper, we report a novel technique to prepare lightweight and high-strength glass foams using green spheres as raw material. The green spheres are produced by a spray drying technique from an aqueous suspension with recycled glass powder, dispersants, binders and foaming agents. The foaming process of lightweight glass foams prepared by a green spheres hollowing technique was investigated. The role of green spheres during the foaming process was discussed. In addition, the microstructures and properties of the obtained materials were measured.

2. Experimental procedure

2.1. Preparation [18,19]

Fig. 1 shows the preparation process of glass foams. Firstly, a slurry containing water, waste glass powder, polyvinyl alcohol (0.5 wt%, based on deionized water) and sodium hexametaphosphate (0.2 wt%, based on glass powder) as dispersant was prepared. The slurry was ball-milled for 10 h to obtain a homogeneous slurry with a solid loading of 50 wt%. Propyl gallate (1.0 wt%, based on glass powder) was added to the slurry as foaming agent. A foam slurry was prepared with vigorous stirring. The foam density is 0.74 g/cm^3 and the foam expansion is ∼2. The foam slurry was introduced into a centrifugal atomization equipment to atomize it into slurry droplets which were fed into a drying chamber at 240 °C. Green spheres were collected after drying, with packing density and size distribution values of 0.60 g/cm^3 and 40–200 μm, respectively. Polyvinyl alcohol, sodium hexametaphosphate and propyl gallate were purchased from Sinopharm Chemical Reagent Co., Ltd., Shanghai, China.

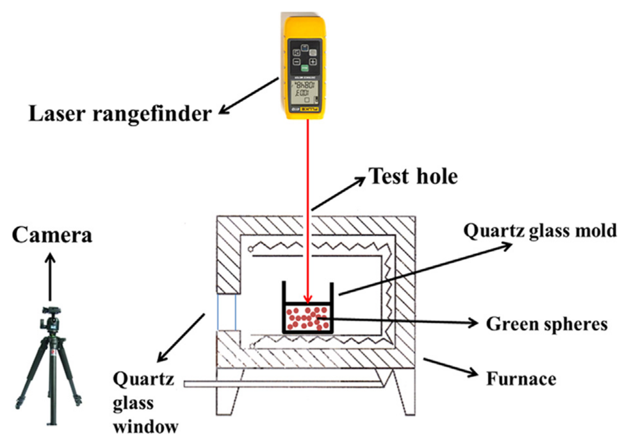

Fig. 2. Schematic diagram of experimental facility for investigating the foaming process.

The green spheres with good fluidity were poured into ceramic molds with different dimensions (70 mm × 70 mm × 70 mm, 300 mm × 300 mm × 60 mm). The inner surfaces of the mold were coated with a thin layer of kaolin to ensure a smooth demolding. The foaming was performed in a muffle furnace between 680 °C and 800 °C and held for 120 min, with a heating rate of 3 °C/min. The samples were cooled in the furnace to room temperature and cut into various test sample dimensions.

2.2. Investigation of foaming process

In order to investigate the foaming process of the sample, a box-type furnace was upgraded as seen in Fig. 2. A transparent quartz glass mold (30 mm in diameter and 80 mm in height) and a transparent quartz glass window (100 mm × 100 mm) were used in order to take photographs of the sample during the foaming process. A laser rangefinder over the furnace was used to measure the distance between the sample and the laser rangefinder in real time. Before heating the sample, the height of sample (h_0) and the initial distance between the sample and the laser rangefinder (H_0) were measured. The linear