Journal of Alloys and Compounds 747 (2018) 408–415

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Optimal conditions and significant factors for fabrication of soda lime glass foam from industrial waste using nano AlN

Emad Mohamed M. Ewais [a, *], Mohammed A.A. Attia [b], Ahmed A.M. El-Amir [a], Ahmed M.H. Elshenway [a], Thomas Fend [c]

[a] Refractory & Ceramic Materials Division (RCMD), Central Metallurgical R&D Institute (CMRDI), P.O. Box 87 Helwan, 11421 Cairo, Egypt
[b] Mechanical Engineering Department, Faculty of Engineering at Helwan, Helwan University, Cairo, Egypt
[c] German Aerospace Center (DLR), Cologne, Germany

ARTICLE INFO

Article history:
Received 6 December 2017
Received in revised form
27 February 2018
Accepted 4 March 2018
Available online 6 March 2018

Keywords:
Float glass waste
Aluminum nitride
Glass foam
Sintering
Mechanical properties
Recycling

ABSTRACT

In the present work, based on the environmental issues and on the properties of glass foams, the foaming behavior of the float glass waste (soda-lime glass waste) generated from a lapping machine was systematically investigated at temperatures between 850 and 950 °C using different percentages of nano aluminum nitride (2.5–7.5 wt%) as a foaming agent. Physical properties, compressive strength, the hot wire method, SEM and X-ray diffractometry were used to characterize foams and evaluate the foaming ability and the sintering process. The foaming process was found to depend on the initial batch composition and the sintering temperature. Bulk density of the obtained products is less than 0.5 g cm^{-3}. The cold compressive strength of the foams ranged between 0.65 and 2.48 MPa and the thermal conductivity between 0.09 and 0.106 W m^{-1}K^{-1}. Both cold crushing strength and thermal conductivity increased with increasing foam density. The obtained results are promising and the present technology is cost-effective and suitable for the large scale production of a wide range of porous glass-ceramics that have appropriate properties to be used for various structural applications.

1. Introduction

The glass manufacturing industry provides products critical to a wide range of applications, including (i) container glass for consumer products, (ii) flat glass for automotive and buildings, (iii) fiberglass for thermal insulation, roofing, and reinforced composite materials, and (iv) specialty glass such as liquid crystal displays, optical communication, and lighting, to name a few [1]. Container glass represents more than 65% of the mass of glass produced worldwide [2]. The scope and importance of the glass manufacturing industry are underscored by the following statistical facts: it employs about 150,000 people; approximately 22 million tons of glass is melted each year; and it has around $23,215,000,000 market value in the US. During the past two decades, business competition and economic challenges have forced glass manufacturers worldwide to increase productivity and product quality. They have also faced ever more stringent regulations for combustion-generated pollutant emissions [3–5].

The main types of glass, according to their physico-chemical composition, are: soda-lime glass, lead crystal and crystal glass, borosilicate glass and electric glass, also called E glass. The first three categories account for more than 95% of all glass produced [6]. The physico-chemical compositions of the most frequent glass types are summarized in Table 1. Soda-lime-silica glass, also known as soda-lime glass, is the most common type of glass used for containers, lighting devices, and windows for buildings and automotive applications [7,8].

Annually, millions of tons of glass are produced as solid waste. This waste can be contaminated with high percentage of pretty fine metallic and non-metallic fragments as well as with organic substances. The cost involved in the removal of these impurities is relatively high. The foam glass industry is not sensitive to impurities in the recycle glass. It is therefore considered to play an important role in future glass recycling [6–8].

Glasses foams, also referred to as cellular glasses, have been commercially available since the 1930's [9]. They are promising materials due to their specific properties such as low density, low thermal conductivity, thermal stability, high surface area, good

* Corresponding author.
E-mail address: dr_ewais@hotmail.com (E.M.M. Ewais).

https://doi.org/10.1016/j.jallcom.2018.03.039
0925-8388/

Table 1
Major components of soda-lime glass, lead crystal glass, borosilicate glass, and E glass [6–8].

	Soda-lime glass	Lead crystal glass	Borosilicate glass	E glass
Silicon dioxide (SiO_2)	71–75%	54–65%	70–80%	52–56%
Boron trioxide (B_2O_3)			7–15%	0–10%
Lead oxide (PbO)		25–30%		
Soda (Na_2O)	12–16%	13–15%	4–8%	0–2%
Potassium oxide (K_2O)				
Lime (CaO)	10–15%			16–25%
Alumina (Al_2O_3)			7%	12–16%

impact behavior, high permeability and exhibit good machining ability and high water resistance. These types of foamed glasses have a number of desirable characteristics that make them attractive for technological applications, such as catalyst supports, filters for molten metals and hot gases, thermal insulators, refractory linings and implants and building materials [9–12]. The pores of these foams can also be controlled to become impermeable to water in liquid or vapor form and this character can be considered as an additional property and give the foams exceptional compressive strength, and energy-saving characteristics if they can resist the temperature [9,13].

Generally, these properties are achieved by having a large number of small, evenly sized bubbles, with thin walls in-between. As the product is made of glass it is naturally inert in most environments with respect to biological, thermal, chemical and environmental degradation.

Various processing routes have been proposed for ceramics foams, including foaming agent, polymeric sponge, or space holder method [14]. There are quite few studies on the production of foams from recycling glass, but new approaches have been recently proposed [15]. The present work aims at providing the optimal conditions and significant factors for fabrication of soda lime glass foam from industrial waste using nano AlN as a foaming agent.

2. Materials and experimental procedures

2.1. Foam glass preparation

The present study involves the fabrication of a foamed glass product from industrial glass waste using nano-AlN powder as foaming agent. Experiments were performed using soda lime glass, which has the composition listed in Table 2. After removing impurities, industrial glass waste was crushed, using a crushing machine, and dry milled using a planetary ball mill (weight ratio of glass/porcelain balls = 1/2). The speed of the mill was 350 rpm and the time was 1.30 h. The glass was separated by screening into fractions with grain size in the range of 38–300 μm. The foaming agent used was nano AlN powder, with an average grain size less than 4000 nm. The measured surface area (BET) of AlN powder is 697.2 m^2/kg.

Table 2
Composition of Soda lime glass used in the experiments.

Compound	Composition (Wt.%)
SiO_2	71.6
Na_2O	13.5
CaO	9
MgO	3.87
Al_2O_3	0.97
K_2O	0.42
SO_3	0.19
Fe_2O_3	0.13
Other	0.32

Different batches from soda lime glass and nano AlN powders (2.5, 5 and 7.5 wt %) were dry mixed and placed in stainless steel forms. The latter ones have been coated on the bottom part with alumina powder to facilitate separation from the mould. The mixture was compacted by light cold pressing before being subjected to the heating treatment. The mixed glass and foaming agent were placed in moulds and passed through a furnace where the mixture is heated and maintained at a foaming temperature and then cooled or annealed to produce foamed glass blocks. A nonreactive gas having desired isolative properties was introduced during heating to sweep air away from the mixture. The foamed glass blocks were then removed from the moulds and cut and ground to a selected size and finish.

The effect of the dwell temperature T_D as well as the foaming agent amount on the product characteristics were investigated by performing all the experiments under normal atmosphere condition, at constant values of dwell time t_D (30 min) and heating rate (5 °C/min) to achieve the T_D value. After foaming, the specimens were slowly cooled to room temperature.

2.2. Characterization

Both structure and properties of materials were characterized to obtain quantitative structure-property relationships [16,17]. The bulk density (ρ_{pg}) was determined by measuring the weight (W) and the volume (V) of the produced foams, where $\rho_{pg} = W/V$. The relative density (RD) was estimated by $RD = \rho_{pg}/\rho_{dg}$, where ρ_{dg} is the bulk density of the glass without pores ($\rho = 3.2\ g/cm^3$). The porosity (ε) was calculated by $\varepsilon = (1\text{-}RD)$. Cellularity (ppi-number) has been determined with simply counting the number of pores being cut by a straight line on a mircrograph after [18]. The morphology of foam glass was observed through a field emission scanning electron microscopy (SEM, Quanta 200, FEI, Holland). Phase analysis of the glass foam was done by advanced X-ray powder diffraction using a Brukur advanced X-ray diffractometer model (Bruker axes D8 Advance, Germany) with Cu kα radiation ($\lambda = 1.5406$ Å) and a secondary monochromator in the 2θ range from 5° to 70°.

The cold crushing strength of the foamed specimens was carried out by placing each specimen of ~50 mm diameter between two parallel plates of stainless steel. The edges of each traction surface were chamfered using 600 grit SiC paper before testing. The load was slowly applied at a rate of 1.3 mm/min using the universal testing machine (SHIMADZU Corporation made in Japan-model UH-F1000KNCapacity 20–1000 kN). The alignment of the specimens in the load blocks was ensured. Five different samples from each composition were tested. The maximum load of the first plateau of the stress-strain plots divided by the cross sectional area was considered as the compressive strength [19]. CCS was calculated according to the following formula: $CCS = W/A\ (kg/cm^2)$ where W is the maximum load (N) and A is the cross section area of the specimen (cm^2).

Thermal conductivity is considered as a "volume averaged