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Preparation of glass ceramic foams for thermal insulation applications from coal fly ash and waste glass

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HIGHLIGHTS

- Glass ceramic foams were prepared by using coal fly ash and waste glass.
- Effects of material ratio and sintering temperature were systematically investigated.
- Energy conservation evaluation was simulated with the software of EnergyPlus.

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ABSTRACT

Glass ceramic foams were prepared by direct foaming method, using coal fly ash and waste glass as the main materials, borax and calcium carbonate as fluxing agent and foaming agent, respectively. The effects of coal fly ash additions, foaming time, heating rate and sintering temperature on the bulk density, porosity, mechanical properties and thermal conductivity were systematically investigated. The optimum parameters to prepare the glass ceramic foams were obtained at 800 °C for 45 min with 40 wt.% coal fly ash, 60 wt.% waste glass, 30 wt.% borax and 0.5 wt.% calcium carbonate. The specimens prepared this way have a low bulk density (as low as 0.46 g/cm^3), exhibiting considerable compressive strength (exceeding 5 MPa) and low thermal conductivity (about 0.36 (W/m K)). The energy saving effect using glass ceramic foams was evaluated by EnergyPlus software, indicating that the prepared glass ceramic foams show good energy conservation effect for building thermal insulation materials. The preparation of glass ceramic foams using solid wastes may provide a promising way to prepare thermal insulation material, considering the advantages in both economic and environmental aspects.

1. Introduction

Glass ceramic foams, which are porous heat-insulating and soundproof materials, have attracted great interest and have been applied in many areas such as building, chemistry and defense fields [1]. Glass ceramic foams have excellent properties such as low density, low thermal conductivity, incombustibility, etc. Furthermore, they show better thermal insulation and weatherability properties compared to organic thermal insulation materials, especially polymeric foams which may cause serious problems related to the fire hazard, short life, environmental toxicity and adhesive incompatibility [2]. Currently, numerous technologies have been developed to produce glass ceramic foams, such as replica, sacrificial template and direct foaming methods [3], etc, with different kinds of solid waste used as the raw materials, like waste glass and fly ash [4–7], metallurgical slag [8–10], municipal solid waste [11], polishing porcelain stoneware tile residue [12], etc. Among them, the most straightforward and widely used way is direct foaming, namely, sintering a mixture of raw materials and a small amount of additives, which is also the method employed in the present investigation. These additives commonly referred to as pore-foaming agents, which generate porosity by emitting gas frothing the glass ceramic melt during reaction at elevated temperatures [7]. Meanwhile, the pore size and structure of glass ceramic foams can be significantly influenced by the concentration and the type of the pore-foaming agent [13].

Coal fly ash is the by-product of coal combustion produced in power stations [14]. As is known to all, China's energy structure is dominated by coal. With the rapid economic development, more

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than one billion tonnes of coal are burned annually to meet the increasing electricity demand. Consequently, the annual coal fly ash generation continues growing and is anticipated to reach 580 million tonnes by 2015 [15]. However, only parts of the enormous waste residue are utilized, primarily in cement industry and building materials field. The residual coal fly ash is generally disposed in ponds or landfill without any treatment, which not only occupies vast land but also results in serious environmental pollution. For example, potentially toxic substances in coal fly ash could leach into soils and groundwater and accumulate in the food chain [16].

Waste glass is another enormous solid waste derived from glass manufacture process and municipal solid waste. To be specific, waste glass accounts for 15–30% of glass production and for 4% of municipal solid waste [17], with millions tonnes of waste glass generated in China each year. Although it has been used in the manufacturing of the original glassware, the proportion of waste glass added in the process is limited by risks of contamination and degradation of quality. Further, the disposal of waste glass is therefore an urgent issue and the production of glass ceramic foams from waste glass has been proposed [18,19].

Considering both fly ash and waste glass contain large amount of SiO_2, Al_2O_3 and CaO [20], which is similar to the components of glass ceramic foams, our research was therefore motivated, with coal fly ash and waste glass as the raw materials. Meanwhile, borax and calcium carbonate were used as fluxing agent and foaming agent, respectively.

Macroscopic properties, such as the bulk density, porosity, compressive strength and thermal conductivity of the foams are tested in detail. At last, a building energy simulation software (EnergyPlus) was used to evaluate the energy saving effect of the glass ceramic foams and the possibility of using the material as a thermal insulation material for buildings.

2. Experimental procedure

2.1. Raw materials

Coal fly ash (below 200 meshes) was obtained from a thermal power plant at Shuozhou city, Shanxi Province, China and waste glass (200 meshes) was gathered from waste sheet glass. Waste glass can provide sufficient amorphous phase, which is necessary for good heating insulation performance [21]. Chemical compositions (wt.%) of these two raw materials were analyzed by X-ray fluorescence (XRF) and shown in Table 1. Borax ($Na_2B_4O_7{\cdot}10H_2O$) was added as fluxing agent to lower the softening temperature of mixture [22]. Calcium carbonate was chosen as foaming agent, which can decompose at around 800 °C and the CO_2 gas generated by calcium carbonate will be besieged by the softened glass phase, resulting in a porous structure in the samples.

The crystalline phases were identified using X-ray diffraction (XRD), and the XRD patterns of coal fly ash and waste glass are shown in Fig. 1. The major crystalline phases in coal fly ash are anhydrite, quartz and mullite. The existence of anhydrite is owing to the in-furnace desulphurization process.

2.2. Sample preparation

In all samples, 30 wt.% of borax and 0.5 wt.% of calcium carbonate were added in the raw materials respectively. Coal fly ash and waste glass were mixed in different proportions, and the samples were named as B35, B40, B45, B50 and B55, respectively. Raw materials compositions and chemical compositions of samples were shown in Tables 2 and 3, respectively. The raw material mixtures were homogenized in porcelain jars with a planetary ball mill for 10 h. Finally, the batches were prepared by uniaxial dry-pressing into disks with a diameter of 22 mm, thickness of 10 mm, using a pressure of 10 MPa.

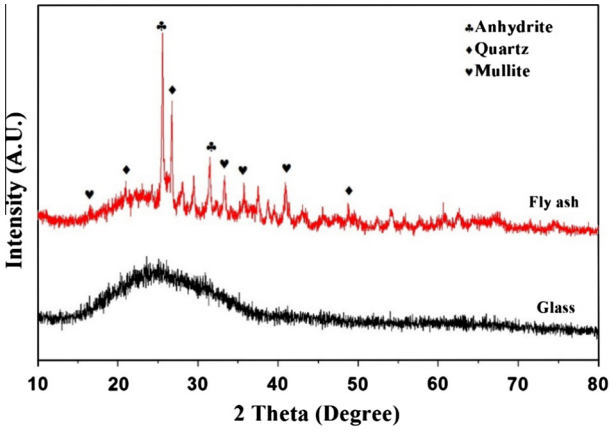

Fig. 1. XRD patterns of the coal fly ash and waste glass.

Table 2
Raw materials compositions (wt.%) of samples.

Sample	Coal fly ash	Waste glass	Borax	Calcium carbonate
B35	35	65	30	0.5
B40	40	60	30	0.5
B45	45	55	30	0.5
B50	50	50	30	0.5
B55	55	45	30	0.5

The obtained green samples were heated to 450 °C for 30 min in a muffle furnace with air atmosphere to remove residue water and prevent the samples from rupturing caused by the uneven thermal distribution [10]. Subsequently, the samples were heated to 600–900 °C for 45 min with a heating rate of 20 °C/min, then cooled down to room temperature with a natural cooling rate.

2.3. Characterization techniques

The total porosity was calculated from the following equation:

$$\%\text{Porosity} = (1 - \text{bulk density}/\text{powder density}) \times 100 \quad (1)$$

In Eq. (1), the bulk density and powder density of materials were measured by Archimedes method and pycnometer method (50 ml capacity), respectively.

The specimens for compressive strength test were cut using a hacksaw and refined with SiC abrasive paper to form disks of Φ20 mm × 7 mm. The compressive strength of the foams was measured using a universal testing machine (Suns Shenzhen, China) with a crosshead speed of 2 mm/min. Scanning electron microscope (SEM, S-4800, Hitachi) was used to analyze the size and morphology of pores. The crystalline phases in the raw materials and prepared foams were investigated by X-ray diffraction using Rigaku D/max 2550PC X-ray (CuKα, scanning rate: 8°/min, scanning range: 10–80°). Finally, thermal analysis was conducted with a thermal analyzer (DRL-III, Instrument and meter Co., Xiangtan, China), adopting the heat flux technique.

3. Results and discussion

3.1. Effect of coal fly ash content

Fig. 2 shows the evolution of compressive strength, bulk density and porosity with the different coal fly ash content for samples sintered at 800 °C. In addition, the typical surface appearance of glass ceramic foams can be seen from the inserted images in Fig. 2(a). Apart from sample B35, it can be seen that both the density and compressive strength increase while the porosity decreases with

Table 1
The chemical compositions (wt.%) of coal fly ash and waste glass.

Raw materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	P_2O_5	LOI
Coal fly ash	35.42	39.40	2.63	10.04	1.85	0.14	0.40	1.19	4.62	0.217	4.09
Waste glass	66.55	1.55	0.26	8.71	4.55	17.26	0.55	0.027	0.281	0.022	0.24