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Fabrication of adiabatic foam by sodium silicate with glass fiber as supporting body

Ye Li [a], Xudong Cheng [a,b], Wei Cao [a], Lunlun Gong [a], Ruifang Zhang [a], Heping Zhang [a,b,*]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230027, PR China
[b] Collaborative Innovation Center for Urban Public Safety, Anhui Province, PR China

HIGHLIGHTS

- Fabrication of adiabatic foam using sodium silicate and glass fiber.
- Thermal conductivity is about 0.0454–0.0459 W/m K.
- Density is about 74–80 kg/m^3 and compression strength is about 0.42–0.46 MPa.
- Thermal conductivity is more sensitive to glass fiber content.

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ABSTRACT

Fabrication of adiabatic foam by sodium silicate with glass fiber as supporting body was researched in this paper. The variation of the thermal conductivity, density, and compression strength with the sintering temperature, modulus of sodium silicate and glass fiber content were characterized. The results show that through sintering at 450 °C with 3.3 modulus of sodium silicate and less than 0.67 wt.% content of glass fiber, the adiabatic foam with 0.0454–0.0459 W/m K of thermal conductivity, 74–80 kg/m^3 of density, and 0.42–0.46 MPa of compression strength can be obtained. Therefore, this adiabatic foam has a large potential of thermal insulation application.

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1. Introduction

In recent years, several serious fire accidents occurred in China due to the use of organic thermal insulation materials. Therefore, inorganic thermal insulation materials received widespread attention. At present, rock wool [1], thermal insulation mortar [2], expanded perlite board [3] and glass foams [4] are the main inorganic thermal insulation productions in the exterior wall thermal insulation market though they do not obtain a good market share. Some disadvantages limit their application, including complex process, high sintering temperature, and low strength. Therefore, it is necessary to find a new inorganic thermal insulation material with excellent performance, simple preparation technology and widely used.

In previous investigations, Kluth [5] produced a kind of water glass foam based on alkali metal silicates. It becomes a candidate of potential heat insulation material, called adiabatic foam, due to its outstanding thermal insulation performance, low cost and energy consumption. But the low compression strength limits its application for heat insulation. Shi [6] improved the strength of this material using the foam slurry with sodium silicate and azodicarbonamide reaction. But the thermal conductivity and density were higher than those of the products in the market. Therefore, how to improve the compression strength of the adiabatic foam while maintaining the thermal conductivity at a low value becomes our research focus.

Introducing enhancers is a commonly used method to improve the mechanical properties of the productions. Fiber as one reinforcing material is widely used to fabricate composite material. Zhao et al. [7] reinforced isotactic polypropylene by PA6 and Kevlar fiber and studied the structure, mechanical properties and crystallization and melting behavior. Wu et al. [8] modified PBO fiber, Kevlar fiber and carbon fiber by Acid Treatments to produce

* Corresponding author at: State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230027, PR China.
E-mail address: zhanghp@ustc.edu.cn (H. Zhang).

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Composites. Karout et al. [9] improved the shaping and mechanical reinforcement of silica aerogel biocatalysts with ceramic fiber felts. Reinforced methyl silicon resin composites were fabricated by Wang et al. using heat-treated quartz fiber [10]. Iba et al. [11] researched the fabrication, optical and mechanical properties of the glass fiber-reinforced epoxy matrix composite. Moreover, nanofiber reinforced aerogel was also synthesized [12].

In this paper, we chose a burn resistant glass fiber as the supporting body to fabricate the adiabatic foam. The effects of the sintering temperature, modulus of sodium silicate and glass fiber content on the performance of the products were studied in detail.

2. Experiment

Sodium silicate (industrial-grade, Shanghai, China) was used as the raw material to fabricate the adiabatic foam. Sodium hydroxide (Cp, Shanghai, China) was added to adjust the modulus of sodium silicate from 3.55 to 3.0 (the modulus of sodium silicate indicates the SiO_2/Na_2O molar ratio in sodium silicate). 0, 0.5, 0.67, 0.83 and 1.0 wt.% contents of glass fiber (Guangdong, China) were added to increase the strength of the samples. The chemical compositions of glass fiber listed in Table 1 were determined by X-ray fluorescence spectroscopy (XRF-1800, SHIMADU, Japan). 300 g of sodium silicate was weighed in a beaker with different contents of sodium hydroxide. The mixer was stirred using a direct driven motor at a speed of 500 rpm to produce stable solution. Subsequently, the solution was poured into a mould within the glass fiber prepared and sintered in the muffle furnace at an optimum temperature for 30 min with 5 °C/min of heating rate. Fig. 1 shows the photos of the mould, glass fiber and sintered sample.

The information about various chemical bonds was studied using Fourier Transform Infrared Spectroscopy (FT-IR) (Nicolet 8700, Thermo Fisher Scientific, USA). For this purpose, the samples were ground into refined powders, mixed with KBr and pressed to form a sample pellet for the FTIR measurements. The density was determined simply by quality divided volume ($\rho = m/v$). And the thermal conductivity of the samples was measured by DRE-2C thermal conductivity tester (China), a hot-disk thermal analyzer, adopting the transient plane source technique. During the measurement, the hot disk sensor was placed between the two samples, the surfaces of which should be smooth. The dimension of the two specimens was $8 \times 8 \times 4$ cm to ensure that they can completely cover the sensor. The microstructure of the sintered samples was observed on fresh fracture surfaces by SEM (JSM-6490LV, Japan). The pore size distribution was obtained by analyzing SEM micrographs using an image analyzer (Nano measurer, China) with a total of at least 200 pores being counted on each image. Compressive strength was measured using a universal testing machine (E3000K8953, Instron Co., USA) with a crosshead speed of 0.05 mm/min. The dimension of the test piece was $20 \times 20 \times 20$ mm. The cross-sectional area of the sample and the maximum failure load were used to calculate the fracture stress.

3. Results and discussion

3.1. FTIR analysis

Fig. 2 displays the IR spectra of sodium silicate, glass fiber and the sample fabricated by them at 450 °C. For all the three samples, there are significant absorption peaks at 3420 cm^{-1} and 1649 cm^{-1}, corresponding to the stretching vibration and bending vibration of the —OH groups [13], respectively. However, there is a strong decrease of peak intensities for glass fiber and the sintered sample. This is because that these bands are mainly induced by water of imbibition and physically adsorbed water, which decreased during the sintering process. And the two peaks still existing may be attributed to the free Si—OH groups and the water left [14]. The peaks at 447 cm^{-1}, 755 cm^{-1} and 1007 cm^{-1} can be seen for all the samples, which should be attributed to the stretching vibration and bending vibration of the Si—O bonds [15,16]. Moreover, there are an increase of peak intensity at 755 cm^{-1} and a right shift at 1007 cm^{-1} for the sintering sample. This indicates that more Si-O bonds were produced. The peaks at 611 cm^{-1} and 1444 cm^{-1} just exist in the sodium silicate and sintered sample. The former can be ascribed to the stretching vibration of Al—O bonds [17], which comes from the impurities in the sodium silicate solution, and the latter is the result of the reaction of CO_2 and sodium silicate [14]. The peaks at 1387 cm^{-1} and 1505 cm^{-1} in glass fiber can be ascribed to the organic coating, which disappear for the sample sintered at 450 °C. Besides, there are obvious peak intensities at 2860 cm^{-1} and 2942 cm^{-1} for glass fiber and sintered sample, which may be attributed to C—H asymmetric stretching modes [14], but this needs to be investigated further.

Table 1
Elemental analysis of glass fiber using the XRF technique.

Glass fiber	MgO	Al_2O_3	SiO_2	Na_2O	CaO	Others	Ignition loss
wt.%	2.80	3.03	43.41	6.77	9.32	1.64	33.03

3.2. Physical properties

Fig. 3 shows the effect of sintering temperature on the thermal conductivity, density, and compression strength. All of the samples were fabricated with 0.67 wt.% content of glass fiber and 3.55 modulus of sodium silicate. In general, the foaming capacity increases with the increase of the sintering temperature. Therefore, 400, 450, and 500 °C were chosen as the final sintering temperature to fabricate the adiabatic foam. Based on the results in Fig. 3, the samples have the optimal performance, including 0.0544 W/m K of thermal conductivity, 117 kg/m^3 of density and 0.6 MPa of compression strength. As the sintering temperature increases from 400 to 450 °C, the foaming capacity increases, resulting in a decrease of density. And then both of thermal conductivity and compression decrease. However, further increasing temperature to 500 °C does not contribute to improve the performance of the samples. It is considered that higher content of SiO_2, which comes from the glass fiber, enters into the sodium silicate solution and promotes the solidification process. The denser network structure of SiO_2 causes the enhancement of substrate itself, resulting in the increase of thermal conductivity, density and compression strength [18,19].

Fig. 4 shows the thermal conductivity, density and compression strength of the samples vary with different modulus of sodium silicate as the samples are sintered at 450 °C. It can be observed that when the modulus of sodium silicate increases from 3.0 to 3.55, all of the thermal conductivity, density and compression strength decrease first and then increase. In the sodium silicate solution, a variety of silicic ions exist, including orthosilicic $\left(SiO_4^{4-},\ HSiO_4^{3-},\ H_2SiO_4^{2-},\ H_3SiO_4^{-},\ H_4SiO_4\right)$ or metasilicic species $(SiO_3^{2-},\ HSiO_3^{-},\ H_2SiO_3)$ [20]. They can form the structural network due to a progressive condensation of hydroxo groups bound to silicon-oxygen tetrahedra [14,21,22]. And then the silicon-oxygen tetrahedra gathers mutually to produce colloid, which reduces the foaming capacity. Moreover, more of polymeric silicates are present in the sodium silicate solutions at higher modulus of sodium silicate [23], resulting in the more obvious inhibitory effect. Therefore, the samples with high modulus of sodium silicate have higher density, thermal conductivity and compression strength. However, for the sodium silicate solution with low modulus, it is easier for SiO_2 in the glass fiber to dissolve, resulting in the increase of the viscosity. Thus the foaming capacity also decreases at low modulus of the sodium silicate. Based on the above two reasons, the adiabatic foam with 0.0459 W/m K of thermal conductivity, 80 kg/m^3 of density, and 0.46 MPa of compression strength can be obtained at 3.3 modulus of sodium silicate.

The effect of glass fiber content on the thermal conductivity, density and compression strength is shown in Fig. 5 for the samples sintered at 450 °C with 3.3 modulus of the sodium silicate. It is obvious that all of the thermal conductivity, density and compression strength increase with the glass fiber content increasing from 0 to 1.0 wt.%. And the three curves are divided into two stages at 0.67 wt.% glass fiber content, respectively. This indicates that when the added glass fiber content exceeds 0.67 wt.%, excess

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