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Evaluation of thermal protective performance of basalt fiber nonwoven fabrics

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Abstract Thermal insulation and fire protection have been a point of interest and discussion for several decades. Due to its excellent performances, basalt fiber has been widely used in the fields of thermal insulation and fire protection. The morphological structure and thermal stability of continuous basalt fiber were analysed using CH-2 projection microscope, scanning electron microscope (SEM) and thermogravimetry (TG). In order to evaluate the thermal radiation protective performance when exposed to fire environment, the spectral reflectances of nonwoven fabrics with different thicknesses were evaluated by ultraviolet-visible-near infrared (UV–Vis–NIR) spectrophotometer analysis. The jointly analysis of TG and UV–Vis–NIR spectrophotometer revealed that the basalt fiber exhibits good thermal stability, and the nonwoven fabrics present excellent thermal protective performance.

Keywords Basalt fiber · Morphological structure · Nonwoven fabric · Thermal protective performance · Thermal stability

Introduction

Each year, fires cause about 300,000 deaths in the world and most of these occur at home. Residential fires comprise 75% of fires in the United States and burns are the fourth leading cause of unintentional injury related to deaths [1]. Fire fighters are generally subjected to a variety of hazard conditions, such as flash fire and intense heat flux. Fire fighters can be burned by radiant energy that is produced by a fire and localized flame contact exposure. The most common exposure is to low level radiant heat flux over prolonged periods of time. So the development of long term durability fire protective and thermal insulating clothing has been a matter of public attention.

In the past few years, basalt fiber spun from melted basalt rock has gained mass production in China [2]. Due to its excellent performances, basalt fiber has been widely used in the fields of heat insulation [3, 4]. However, there has been little study on the thermal properties and thermal protective performance of fabrics made of basalt fiber when exposure to environments of intense heat fluxes such as flash fire.

So the present article focuses on the structure and thermal property of basalt fiber, by presenting a comparative analysis with glass fiber, using CH-2 projection microscope, scanning electron microscope (SEM), and thermogravimetry (TG). In order to obtain the thermal radiation protective performance when exposed to fire environment, the thermal protective performances of nonwoven fabrics with different thicknesses were evaluated by ultraviolet-visible-near infrared (UV–Vis–NIR) spectrophotometer analysis.

Experimental

Materials

Basalt fiber and glass fiber were obtained from Zhejiang GBF Basalt Fiber Co., LTD., and Deqing Guotai Fireproof

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Table 1 Basic properties of basalt and glass fiber

Property	Basalt fiber	Glass fiber
Diameter/µm	13	10
Density/g/cm^3	2.65	2.53–2.60
Softening temperature/ °C	840	960

Table 2 Technical index of basalt fiber nonwoven fabrics

Sample	Thickness/mm	Weight/g m^{-2}
A	3	302.4
B	4	415.2
C	6	500.8
D	8	750.6

& Insulation Materials Factory, respectively. The nonwoven fabrics made of basalt fiber were also purchased from Zhejiang GBF Basalt Fiber Co., LTD. The basic properties of basalt fiber, glass fiber and nonwoven fabrics made of basalt fiber are presented in Tables 1 and 2.

Methods

Morphological structure analysis of basalt fiber was performed on an Olympus CH-2 projection microscope and a DXS-10 ACKT scanning electron microscope produced by Shanghai Tianjing Electron Optics Technology Co., LTD.

TG is a technique, which measures the mass change of a sample as a function of temperature in the scanning mode or as a function of time in the isothermal mode [5]. The thermogravimetry analysis of basalt fiber and glass fiber were performed with a TG 209 F1 Iris device of Netzsch, which allows simultaneous detection of mass changes and heat effect of decomposition for samples [6]. Alumina crucibles were served as reference and sample cells. The 5–10 mg of samples were subjected to a rising temperature regime over the range of ambient to 900 °C at a heating rate of 20 K min^{-1} in the presence of air. From the analysis of TG curves, the onset temperature of the decomposition (T_o, °C), the temperature at which the mass loss is maximal (T_i, °C), and the terminal temperature of the decomposition (T_t, °C) of the two fibers were determined. The study was performed under a dry air atmosphere with a flow rate 20 mL min^{-1}.

The radiative properties of fabrics, such as reflectance, transmittance, and emittance, are important indexes related to thermal protective performance of fabrics. Optical reflectance and transmittance spectra of nonwoven fabrics made of basalt fiber were measured using an UV–Vis–NIR spectrophotometer (Hitachi, U-4100) over the wavelengths ranging from 250 to 2600 nm. The experiment was performed with a scan speed of 10 nm s^{-1}.

Results and discussion

Morphological structures of basalt fiber

The longitudinal and cross-sectional shapes by CH-2 projection microscope for basalt fiber were shown in Fig. 1a and b, respectively. Figure 1c reveals the longitudinal shapes of basalt fiber observed by scanning electron microscope.

Observed from the micrographs, the cross-section of the fiber is circular and the surface is smooth. The morphological structure might be attributed to the spinning process of the fiber. Basalt fiber is spun from solidified lava poured out of the volcanoes in a single step process melting and extrusion process [7, 8]. In the spinning process, basalt rocks are crushed, melted and spun through a platinum alloy set-holes of bushing. Before cooling and solidification, the surface area of melt would shrink into minimum cylindrical shape due to the effect of surface tension. Slow cooling leads to more or less complete crystallization, to an assembly of minerals. When solidified, the melt will keep the shape and form into fibers. The spinning procedure causes the forming of very long crystallites which are very highly oriented in the longitudinal axis of the fiber.

Thermal analysis of fiber

Since the basalt fiber, like glass fiber, is also a kind of aluminosilicate fiber composed of many oxides. So in order to evaluate the thermal stability of basalt fiber, the thermal analysis was pursued by presenting a comparative analysis with glass fiber. The TG curves at a heating rate of 20 K min^{-1} for basalt fiber and glass fiber studied are given in Fig. 2. As indicated by Fig. 2, the process appears to be in a single-step mode. A mass loss at low temperatures due to water desorption in the samples is not significantly observed. In the initial stage, where the temperature range is below 200 °C,with the increase of temperature the mass remains nearly constant. However, the mass loss occurs in the temperature range of 200–350 °C. In this stage, the mass loss is very fast and significant. It is clearly observed that the fibers resemble in the thermal behavior, but basalt fiber has better thermal stability than glass fiber.

Table 3 shows the related parameters of thermal decomposition of the fibers from analysis of TG curves. The onset temperature of the basalt thermal decomposition process is about 40 °C higher than that of glass fiber. This behaviour could be related to the crystallinity degree as well as the orientation of basalt samples obtained by the

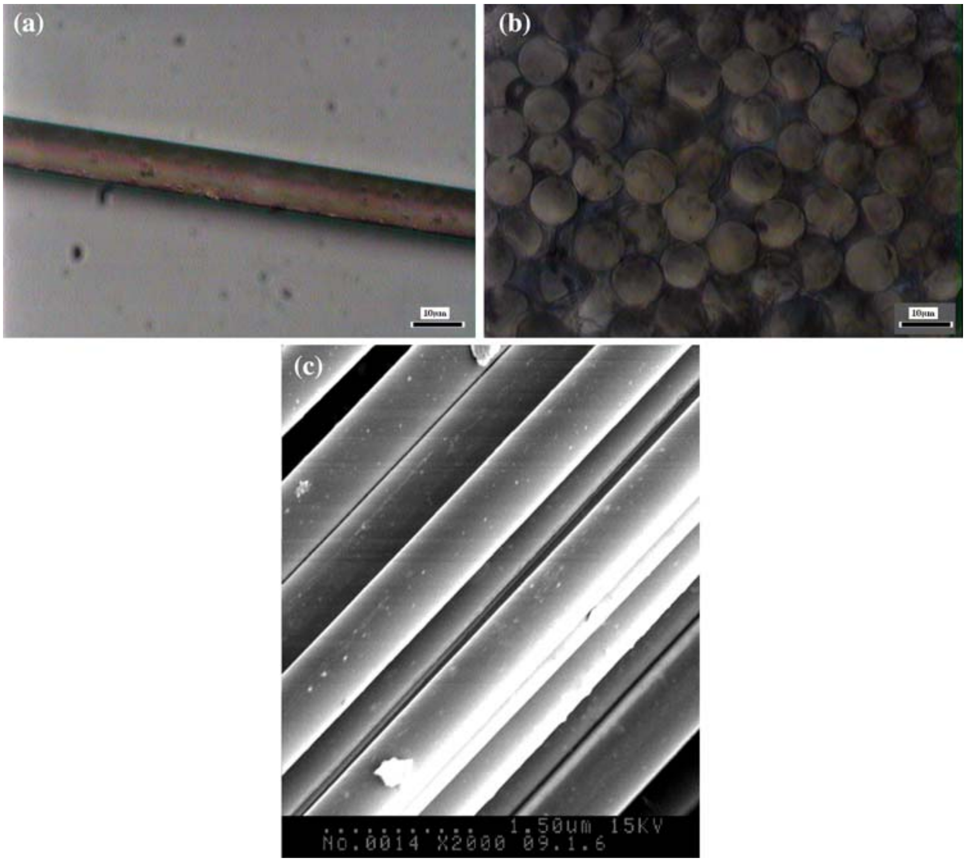

Fig. 1 Micrographs of basalt fiber. **a** longitudinal, magnification: ×400. **b** cross-sectional, magnification: ×400. **c** SEM micrographs of longitudinal shape

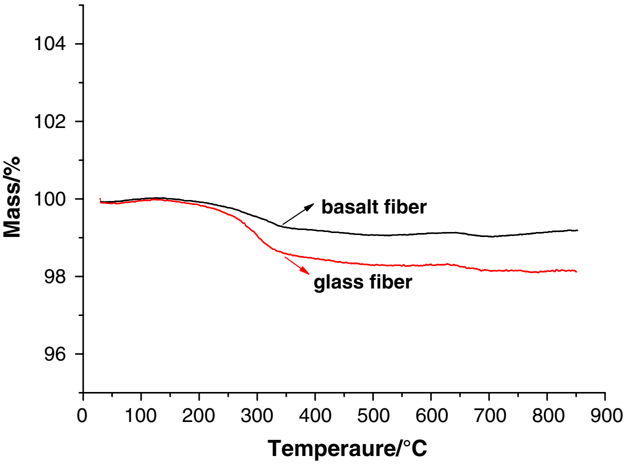

Fig. 2 TG curves for three samples

Table 3 Characteristic parameter of thermal decomposition of basalt fiber and glass fiber obtained from TG curves

Sample	T_o/ °C	T_i/ °C	T_t/ °C	Original mass/mg	Loss of mass/%
Basalt fiber	204.9	324.1	795.7	8.67	0.74
Glass fiber	163.3	300.8	850.3	7.74	1.76

T_o the onset temperature of the decomposition, T_i the temperature at which the mass loss is maximal, T_t the terminal temperature of the decomposition

spinning process, as increases in either property are associated with increases in their thermal resistance [9]. The main mass loss is produced in the 200–350 °C temperature range (>70%) as a consequence of the decomposition process of certain chemical composition of the fibers. From 350 °C on, the mass loss continues but with a low gradient. The onset temperature of decomposition is 204.9 °C for basalt fiber, and 163.6 °C in the case of glass fiber. The temperature at which the mass loss is maximal is 324.1 and 300.8 °C for basalt and glass fiber, respectively. The mass loss of the fibers were both very small, 0.74% and 1.76% for basalt and glass fiber, respectively, which is also related to the good thermal stability of chemical composition, the crystallinity degree and the orientation of the fibers.

Observed from the TG curves and the data such as T_o, mass loss, etc., both of the basalt fiber and the glass fiber are stable during the TG process, but the basalt fiber is more stable.

Thermal radiative performance of nonwoven fabrics

The reflectance characteristics

Spectral reflectance results of four kinds of nonwoven fabrics are presented in Fig. 3. It is obvious that the reflectance curves of different fabrics vary a little throughout the full range of wavelengths from 250 to 2600 nm. Especially, there is almost none difference between the fabrics of 6 and 8 mm thickness. The reflectance curves exhibit a gradually increasing characteristic. All of the fabrics have high reflectance, up to 38% or even more in NIR wavebands, as are shown in Table 4. As is known, the radiative properties, such as reflectance, transmittance, and emittance of single layer structures and multilayer structures largely depend on the direction and wavelength of incident radiation. They are also affected by thin-film coatings and surface roughness [10]. The little discrepancies among the fabrics are largely due to the similar surface conditions.

The transmittance characteristics

Spectral transmittance results of four kinds of nonwoven fabrics are shown in Fig. 4. The results reveal that there are obvious differences among the four fabrics. All of the spectral transmittance curves present an increasing characteristic. The nonwoven fabric with the smallest thickness has the largest transmittance, while the nonwoven fabric with the largest thickness has the smallest transmittance. This reveals that the transmittance of the nonwoven fabrics largely depends on the thickness of fabrics. However, the average transmittance of the fabric with a thickness of 4 mm, 4.7%, is far below that of the fabric with a thickness of 3 mm in the NIR waveband, 10.1%.

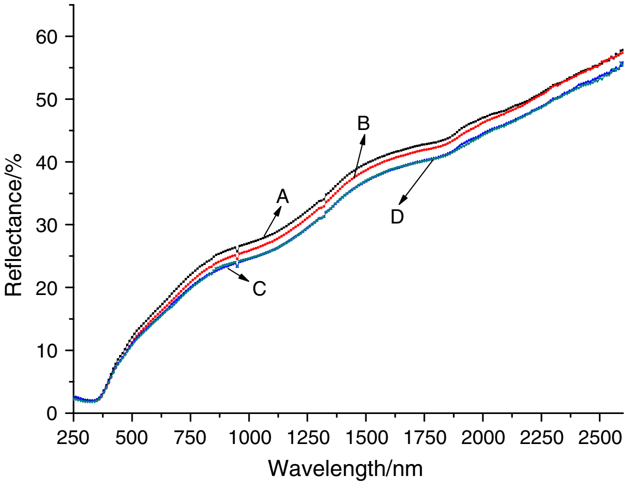

Fig. 3 Spectral reflectance for nonwoven fabrics

Table 4 Average properties of fabrics in different wavebands

Sample	UV reflectance/%	Vis reflectance/%	NIR reflectance/%	NIR transmittance/%
A	2.3	14.9	41.0	10.1
B	2.2	14.0	40.2	4.7
C	2.3	13.6	38.6	3.7
D	2.1	13.4	38.2	1.7

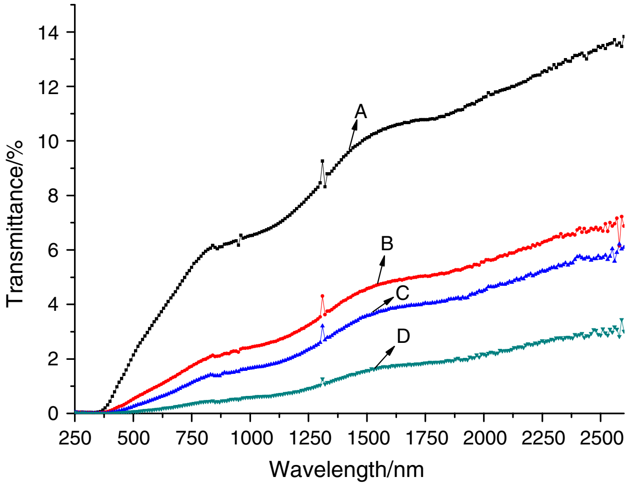

Fig. 4 Spectral transmittance for nonwoven fabrics

As is known, one important function of thermal protective fabric is the thermal protection and comfort of fire fighters during exposure to flash fires. Measurements have indicated that the heat flux from flash fire is primarily due to radiation, being less than 30% convective heat even for a body immersed in it [11]. The peak heat flux level lies in the range 16.7 to 22.6 J cm^{-2} sec^{-1} and is concentrated over the wavelength range 1–6 μ with a peak at about 2 μ [12]. So the main thermal protection for firefighters is radiant heat. From the UV–Vis–NIR spectrophotometer results, it can be concluded that the nonwoven fabrics have good thermal radiation protective performance, and the nonwoven fabric with a thickness of 4 mm presents the optimum thermal radiation protective performance.

Conclusions

The jointly analysis of projection microscopy and SEM showed that the cross-section of basalt fiber is circular and the surface is smooth. This can be attributed to the spinning process of the fiber.

Thermal analysis, by thermogravimetry, indicated that the basalt fiber and glass fiber resemble in the thermal behavior with a one-step decomposition mode and very small mass loss. Besides, continuous basalt fiber presents a higher thermal stability than glass fiber. The onset temperature for the decomposition process of basalt fiber is about 40 °C higher than for glass fiber. This behaviour could be related to the crystallinity degree as well as the orientation of the fibers.

UV–Vis–NIR spectrophotometer results indicated that nonwoven fabrics made of basalt fiber has good thermal protective performance, and the nonwoven fabric with a thickness of 4 mm presents the optimum thermal radiation protective performance. Since the spectral reflectance of fabrics in NIR waveband is high, up to 40%, while the spectral transmittance of fabrics in NIR waveband is low, less than 11%. It can be predicted that the basalt nonwoven fabrics have prospective potential use in the fields of fire protection and thermal insulation.

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