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Fire structural resistance of basalt fibre composite

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ABSTRACT

Basalt fibres are emerging as a replacement to E-glass fibres in polymer matrix composites for selected applications. In this study, the fire structural resistance of a basalt fibre composite is determined experimentally and analytically, and it is compared against an equivalent laminate reinforced with E-glass fibres. When exposed to the same radiant heat flux, the basalt fibre composite heated up more rapidly and reached higher temperatures than the glass fibre laminate due to its higher thermal emissivity. The tensile structural survivability of the basalt fibre composite was inferior to the glass fibre laminate when exposed to the same radiant heat flux. Tensile softening of both materials occurred by thermal softening and decomposition of the polymer matrix and weakening of the fibre reinforcement, which occur at similar rates. The inferior fire resistance of the basalt fibre composite is due mainly to higher emissivity, which causes it to become hotter in fire.

1. Introduction

There is growing interest in reinforcing polymer matrix composites with mineral basalt fibres because of their moderate cost, high stiffness and strength, excellent corrosion and oxidation resistance, and heat resistance and thermal stability [1]. Basalt is the generic term for solidified volcanic lava, and it can be melt extruded into continuous filaments using a process similar to glass fibre production. Several types of basalt fibre are commercially available, with slightly different properties depending on the chemical composition of the basalt rock and the process conditions used to extrude the molten basalt into fibres. The stiffness and strength properties of basalt fibre is higher than E-glass fibre, which is the most common reinforcement for polymer matrix composites [1,2]. The Young's modulus of basalt fibre (100–110 GPa depending on the chemical composition and source of the basalt rock) is much higher than E-glass (76 GPa). The tensile failure stress of basalt fibre (4.15–4.8 GPa) is also greater than E-glass (3.45 GPa). Basalt fibre is resistant to most chemicals, and is less prone to damage from alkali solutions and water than E-glass [3]. Because of these properties, basalt fibre is being used or considered as a replacement to E-glass for several applications, including wind turbine blades, automotive components, and reinforcement in civil structures and concrete [1].

There is growing interest in using basalt fibre for high temperature applications. Basalt fibre is slightly inferior, similar or superior to E-glass fibre depending upon the specific thermal, physical or high temperature property [1,3–6]. Both basalt and glass fibres have similar thermal conductivity values (typically in the range of 0.031–0.038 W/(m K)) and specific heat capacity values (~840–860 J g^{-1} K^{-1}), which indicates they provide a similar level of heat insulation. Basalt fibre is superior to E-glass for high temperature properties such as elastic modulus at elevated temperature [4], operating temperature limit (~650 °C for basalt compared to ~460 °C for E-glass), and higher softening temperature (1050 °C for basalt and 600 °C for E-glass). For these reasons basalt is being used or considered for use in high temperature applications, such as in hot gas filtration systems and fire resistant electrical cable systems [1]. However, other properties of basalt are inferior to E-glass, including lower creep onset temperature and tensile strength at elevated temperature [6].

Despite the high temperature applications of basalt fibre, the fire resistance of basalt reinforced polymer composites is not known. It is not known whether the higher stiffness, operating temperature and softening temperature of basalt fibre translates into superior fire resistance when used as the reinforcement to polymer composite materials. A large body of research has been published on the fire structural resistance of E-glass reinforced composites under compressive and tensile loading [7–19]. Similarly, the fire resistance of carbon fibre laminates have also been studied [20,21]. However, the structural response and failure of

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basalt fibre composites under combined loading and one-sided heating by fire has not been investigated.

This study investigates the fire structural resistance of a basalt fibre reinforced polymer composite. The fire resistant properties of a woven basalt fibre composite are experimentally determined using fire structural tests involving combined tensile loading and one-sided unsteady-state heating representative of one possible fire. These tests provide new insights into the mechanical integrity and survivability of basalt fibre composite structures in fire. The effects of the applied tensile stress and the radiant heat flux on the structural survivability of basalt fibre composite are assessed. In addition, the mechanisms controlling the tensile softening and failure of basalt fibre composite in fire are investigated by residual property testing of basalt fibre tows following exposure to high temperature. The fire structural survivability of the basalt fibre composite is compared against an equivalent E-glass fibre composite to assess their relative performance. This comparison is performed because of the growing interest in replacing glass fibre composites with basalt fibre composites in certain applications [1].

2. Materials and experimental methods

2.1. Composite materials

Basalt fibre composite was produced for high temperature and fire structural testing using woven basalt fabric and vinyl ester resin. The basalt fabric was plain woven by the supplier (Zhejiang GBF Fiber Co. Ltd.) using 300 tex tows to an areal density of 350 g/m^2. The basalt fibres had an average diameter of 12.7 μm (standard deviation of 1.4 μm). The basalt fabric was stacked so the warp tows were aligned to create a cross-ply fibre pattern. Vinyl ester resin (SPV 1349 Nuplex Composites) was infused into the fabric at room temperature using the vacuum bag resin infusion (VBRI) process. Following infusion, the vinyl ester matrix was gelled and partially cured under ambient conditions (23 °C, 50% RH) and then post-cured at 80 °C for two hours. The fibre volume content of the basalt composite was determined to be 53% using the ASTM D-3171 burn-off technique.

The fire resistant properties of the basalt composite were compared against an equivalent glass fibre composite. The composite was reinforced with plain woven E-glass fabric (800 g/m^2) with an average fibre diameter of 12.2 μm (standard deviation of 1.5 μm). The diameter of the basalt and E-glass fibres was similar (within 0.5 μm). The glass fibre composite was made with the same vinyl ester resin and using the same VBRI process and cured under the same conditions as the basalt fibre composite. The fibre stacking sequence of the glass fibre laminate was also cross-ply and the fibre volume content was 55%. The only significant difference between the basalt and glass fibre composites was the type of reinforcement.

2.2. High temperature property testing of basalt fibre tows and composites

2.2.1. Mechanical testing of fibre tows

The tensile properties of basalt fibre tows were measured following exposure to high temperature to determine the fibre softening rate and strength loss. This information is used to understand the fire structural resistance of the basalt composite under tensile loading. The tows (300 tex) used for testing were the same as those in the woven basalt fabric used to reinforce the polymer composite. The basalt tows were heated to temperatures between 150 and 650 °C for different times up to two hours. The tows were then cooled to room temperature and their residual tensile strength was measured at 20 °C. The tensile failure load was measured by loading a basalt tow with a gauge section of 150 mm at an extension rate of 2 mm/min to failure using a 10 kN load capacity Instron machine (Model: 4501). The tensile strength value of the basalt tows measured at high temperature was similar to that measured at room temperature after thermal treatment. Table 1 shows the residual failure stress of basalt tows measured at 20 °C following heating at several temperatures. Also given in the table is the failure stress of the basalt tows measured in-situ at elevated temperature. The bundle strength at high temperature was measured using the procedure described by Feih et al. [15]. Table 1 shows that the basalt tow strengths measured at high temperature and at 20 °C following high temperature exposure are very similar (within about 5%). It appears that any weakening of the basalt tow that occurs at high temperature is 'locked-in' and does not change when cooled slowly to room temperature. For convenience, therefore, the tensile strength of the tows was measured at 20 °C after thermal treatment rather than in-situ at high temperature.

For comparison, the tensile failure load of E-glass tows (280 tex) were measured for the same heat treatment and test conditions as the basalt tows. Feih et al. [18] have shown that any weakening of E-glass fibre at high temperature is also 'locked-in' when cooled to room temperature. Therefore, similar to the basalt tows, the residual tensile properties of the E-glass tow were measured at 20 °C following heat-treatment at different temperature and heating times.

Five tows of basalt and E-glass were tested at 20 °C following exposure to identical temperature and heating time conditions to determine the scatter in the failure load.

2.2.2. Mechanical testing of composites

The tensile properties of the basalt and glass fibre composites were measured at temperatures between 20 and 300 °C. The tensile tests were performed according to ASTM D3039 using composite coupons with a gauge length of 150 mm, width of 25 mm, and thickness of 4 mm. To achieve the same thickness, the basalt and glass fibre composites contained 18 and 7 plies of woven fabric, respectively. A larger number of basalt plies was needed because they were thinner than the glass plies. Despite this difference, the fibre volume contents of the two composites were virtually the same. The tensile tests were performed at a loading rate of 2 mm/min using a 100 kN MTS machine. The basalt and glass fibre composites were loaded in the 0° (warp) tow direction at different temperatures to failure. Three samples were tested at different temperatures to assess the variability in the measured tensile properties. The ends of the tensile specimens were tabbed, and this region was clamped via pressure grips to the MTS machine. Failure always occurred within the gauge region of the samples, and never within the tabbed region.

2.3. Fire structural testing of composites

Small-scale fire structural tests were performed on the basalt and glass fibre composites to assess their fire resistance. This test is designed to replicate the condition of a tensile-loaded plate

Table 1
Comparison of the tensile failure load of the basalt tows measured at 20 °C following elevated temperature exposure and measured in-situ at elevated temperature. The percent values give the residual failure load relative to the original (room temperature) failure load.

Temperature	Following heat exposure	During heat exposure
150 °C	85 N (100%)	82.5 N (97%)
350 °C	78.2 N (92%)	79.1 N (93%)
450 °C	57.8 N (68%)	62.1 N (73%)