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Flexural behavior and microstructure of hybrid basalt textile and steel fiber reinforced alkali-activated slag panels exposed to elevated temperatures

Tao Li[a], Yamei Zhang[a,*], Jian-Guo Dai[b,*]

[a] School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing 211189, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong

HIGHLIGHTS

- Basalt textile and steel fiber were used as hybrid reinforcement to produce thin AAS panels.
- The flexural behavior of panels was observed under both normal and elevated temperatures.
- The panels experienced linear-elastic, nonliner and failure stages.
- SEM, EDS and XRD tests revealed that AASM decomposition and bond deterioration of textiles occurred at high temperatures.
- Changes of Ca/Si and Al/Si ratios in AASM matrix were found indicating the phase transformation at elevated temperatures.

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ABSTRACT

This study investigates the effects of high temperatures and exposure duration on the flexural behavior and microstructure of hybrid basalt textile and steel fiber reinforced alkali-activated slag panels. Three-point bending tests were conducted after heating specimens to 400 °C, 600 °C, and 800 °C for durations of 1 and 2 h. The effects of thermal exposure on the matrix and the basalt fibers from the panels were investigated with scanning electron microscopy. Element and phase analyses of the matrix were performed after exposure to high temperatures via energy dispersive spectroscopy and X-ray diffraction, respectively. The first crack and peak flexural strength of the specimens not exposed to heat reached 8.9 and 20.5 MPa, respectively. Obvious decreases in flexural performance occurred as temperature and duration increased as a result of the decomposition of the alkali-activated slag mortar (AASM) matrix and the deterioration of the bonding performance between the basalt textile and the matrix. Changing of the Ca/Si ratio, the Al/Si ratio, and the crystalline phase of the AASM matrix indicated that phase transformation occurred after heat exposure at 800 °C.

1. Introduction

Textile reinforcement is an efficient strengthening method that can significantly enhance the tensile strength and ductility of composites. Due to their good strengthening effects, different types of textile reinforcements are used in a wide range of applications in the construction field, such as the strengthening and repair of structural elements, thin-walled elements, façade elements, bridges, and lightweight structures [1]. Textiles such as AR-glass (ARG), carbon fiber (CF), aramid, basalt, and polyethylene demonstrate more effective strengthening than short-fiber reinforcements when placed in the main stress direction of the composite [1–5].

Due to its low cost and good mechanical and durable properties, Portland cement is an ideal binding material to use as the matrix of textile reinforcements, such as textile-reinforced concrete (TRC). However, the cement industry is known for high greenhouse gas emissions and energy consumption, and the per-ton production of Portland cement generates approximately 0.85 tons of CO_2 [6]. Thus, the pursuit of new eco-friendly alternatives to replace cement has great significance for the sustainable development of construction materials. Compared to Portland cement, alkali-activated slag is a material that demonstrates high early strength, good frost resistance, and chemical resistance [6–13]. Similar to

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* Corresponding authors.
E-mail addresses: ymzhang@seu.edu.cn (Y. Zhang), cejgdai@polyu.edu.hk (J.-G. Dai).

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hardened Portland cement paste, alkali-activated slag paste (AASP) is a quasi-brittle material with limited strain capacity and low tensile strength. One way to overcome this deficiency is to incorporate fibers or textiles into the matrix to increase the pre-crack tensile strength, strain, post-peak ductility, and durability [14–16].

Basalt fiber is a kind of inorganic fiber fabricated by melting basalt rocks. It has better tensile strength, a higher resistance to impact load, and a higher working temperature than glass fiber, which make it useful in the construction industry [17]. Larrinaga et al. studied the tensile behavior of several basalt TRC-based mortars with four different reinforcing ratios (i.e., from one to four basalt textile layers). For the matrix, redispersible resins were used with approximately 1–3 wt% of cement-based mortar to enhance the fireproof ability. The water/cement ratio of the mortar mix was 0.2. The tensile strength of the cementitious composites was strongly affected by the reinforcing ratio, and the four basalt textile layers led to a superior tensile load of 16,679 N [18]. Basili et al. studied the numerical simulation of tuff stone masonry panels strengthened with a surface bonded basalt textile reinforced composite mortar [19]. They presented a relatively simple model for the analysis and the prediction of the in-plane shear behavior of reinforced masonry panels. Rambo et al. investigated the thermal-mechanical properties of basalt textile reinforced composites under tensile loading [20]. The reinforcement ratio was a critical factor in the tensile behavior of the TRC. The bonding performance between the filaments and the matrix was enhanced when the preheating temperature reached 150 °C. A clear drop in tensile performance was observed due to the thermal decomposition of polymer coating and the dehydration process of the matrix when the temperature exceeded 150 °C.

Although textile reinforcement can greatly enhance the tensile performance and ductility of composite panels, the matrix itself remains brittle and is prone to cracking. Load transfer from the matrix to the textile in the composite occurs after the relatively short linear elastic stage. The bonding performance between the textile and the matrix plays an important role in dominating the nonlinear and post-crack behavior [21,22]. If the bond is weak, the textile debonds quickly and the load-carrying capacity of the composite panels decreases rapidly. The addition of randomly distributed fibers to a brittle matrix is a very effective way of enhancing its toughness, deformation capacity, and energy absorption [23,24]. Therefore, short steel fibers were added to the alkali-activated slag mortar (AASM) matrix to limit the crack width and improve the matrix toughness, facilitating a smoother transfer of the load from the matrix to the textile after cracking. Many researchers have studied the effects of short fibers on the performance of TRC [25–28]. Barhum extensively studied how different types of short fibers (i.e., dispersed ARG, integral ARG, and dispersed CFs) affect the mechanical performance of ARG TRC [27]. Barhum and Mechtcherine studied the effects of short ARG and CFs on the fracture behavior of an ARG textile reinforced cementitious composite [28]. The volume fractions of dispersed ARG and CFs were 0.5% and 1.0%, respectively. The tensile strength was enhanced, and more and finer cracks were found on the specimens to which short fibers had been added. When the short fibers were added to the matrix, the bond between multifilament yarns and the surrounding matrix was improved by means of new cross-links.

This study focuses on the effects of elevated temperatures and exposure duration on the flexural properties of AASM panels with hybrid reinforcement composed of basalt textile and short steel fibers. Elevated temperatures of 400 °C, 600 °C, and 800 °C were used. The specimens were exposed to each target temperature for durations of 1 h and 2 h. Particular attention was paid to the microstructural changes of the matrix via scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD). The morphological changes in the basalt fibers were observed via SEM to evaluate the bonding performance between the textiles and the matrix. The results of this study allow for the evaluation of thermal resistance of hybrid reinforced alkali-activated slag panels in specific applications.

2. Experimental procedures

2.1. Materials

The granulated blast furnace slag (simply referred to as “slag” hereafter) used was the same as that in previous research [29]. Its specific surface area, density, and average particle size were 436 m^2/kg, 2.90 g/cm^3, and 11.86 μm, respectively. Its main chemical composition was 33.30 wt% CaO, 33.44 wt% SiO_2, 16.94 wt% Al_2O_3, and 7.0 wt% MgO. The alkali activator was prepared by mixing water glass (sodium silicate solution) with sodium hydroxide flakes. The industrial grade water glass with a modulus of 3.18 was composed of 9.0 wt% Na_2O, 27.7 wt% SiO_2, and 48.0 wt% water. The purity of the sodium hydroxide flakes was 99%. Sodium hydroxide was used to adjust the SiO_2 to Na_2O molar ratio of the water glass to a specific value. The alkali activator was allowed to cool to room temperature before use. Quartz sand with a particle size distribution of 0.075–1.18 mm and a fineness of 1.7 was used to prepare the mortar.

The hybrid reinforcement used in this investigation consisted of continuous basalt textile and short hooked steel fibers. The main physical properties of the basalt textile are shown in Table 1. The mesh size of the continuous basalt textile was 25 mm × 25 mm. The as-received basalt textile was coated with saline by the producer during the weaving process. Both the linear density of the warp yarn (0°) and the weft yarn (90°) were 800 tex. The average diameter of a single basalt fiber was approximately 13 μm. The physical and mechanical properties of the steel fibers are presented in Table 2. Basalt fibers are easily corroded and decomposed in alkaline environments [30]. Therefore, the continuous basalt textile was cut into 1000 mm (length) × 1000 mm (width) pieces and then coated with epoxy resin to prevent possible alkaline corrosion in the AASM matrix. After the above surface treatment, three layers of basalt textile (i.e., 1000 mm × 1000 mm) were bonded again with epoxy resin to produce a reinforcement with sufficient stiffness.

2.2. Panel preparation

Hybrid reinforcement was used to produce thin AASM panels characterized as sandwich structures consisting of two layers of basalt textile reinforcements to sustain the biaxial load. However, the panels were subjected to uniaxial loading only for simplicity. The depths of the top and bottom steel fiber reinforced mortars of the corresponding basalt textile reinforcements were fixed at 10 mm, and the distance between the two textile reinforcements was set at 18 mm to control the total depth of the panel at approximately 40 mm (Fig. 1).

The manufacturing process of the panels is shown in Fig. 2. The first step was the preparation of the mold fixed with two layers of basalt textile reinforcements. A reusable self-made mold with dimensions of 1000 mm (length) × 1000 mm (width) × 40 mm (depth) was used (Fig. 3(a)). The positions of the upper and bottom layers of the basalt textile reinforcements were fixed at the edges of the mold. The second step was the preparation of the steel fiber reinforced AASM. The mix proportion of the steel fiber reinforced AASM is given in Table 3. For the AASM, the optimized alkali concentration and modulus of the alkali activator were 5.0% and 1.5, respectively, and the water to binder ratio was kept at 0.4. To achieve high flexural strength over 20 MPa, the volume fraction of the steel fiber was set at 2.5%. Slag and quartz sand were first dry-mixed for 2 min. The cooled alkali activator was poured into the mixer and mixed for another 1 min, and the steel fibers were added in and mixed for another 2 min to ensure uniformity. The fluidity of the fresh mixture with 2.5% steel fiber was tested following ASTM C1437 and reached a value of 170 mm. Finally, the fresh steel fiber reinforced AASM was poured into the mold and compacted on a vibration table (Fig. 3(b)). After surface finishing, the mold was covered with plastic film and cured in a room at a temperature of 20 °C ± 2 °C and a relative humidity (RH) of 70% ± 5% for the first 24 h. After it was demolded, the panel was cut into 350 mm (length) × 100 mm (width) × 40 mm (depth) specimens (Fig. 1) and then cured in an environmental chamber at 20 °C ± 2 °C and an RH of 90% ± 5% for 25 days. After this period, they were allowed to air dry for another 2 days before undergoing high-temperature treatment.

2.3. Heat treatment

The specimens were heated to 400 °C, 600 °C, and 800 °C in an electric furnace at a heating rate of 10 °C/min. They were exposed to these temperatures for durations of 1 h and 2 h and subsequently cooled in the furnace. The heating regime applied to the hybrid reinforced AASM panels is presented in Fig. 4.