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Models for predicting elastic modulus and tensile strength of carbon, basalt and hybrid carbon-basalt FRP laminates at elevated temperatures

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HIGHLIGHTS

- Mechanical properties of basalt and carbon FRP laminates with temperature.
- Carbon, basalt and carbon-basalt sheets were used.
- The elastic modulus and tensile strength were significantly reduced.
- Analytical models were developed to predict the mechanical properties as a function of temperature.

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ABSTRACT

Basalt fiber-reinforced polymers (B) composite laminates have been extensively used over the last decade in externally strengthening of reinforced concrete (RC) slabs and beams in flexure and shear. Basalt fibers have higher thermal resistance, corrosion resistance, and ductility than the commonly used carbon (C) laminates. However, there is a lack of knowledge about the mechanical properties of such laminates and their hybrid combinations when exposed to elevated temperatures. This paper presents the results of an experimental program that studies the mechanical properties of carbon (C), basalt (B), and their hybrid combinations (BC, CBC, CCB, BBC, and BCB) of multiple layers at elevated temperatures. The experimental program consists of 140 coupon specimens were prepared and tested after being exposed to different temperatures ranging from 25 to 250 °C. The results showed that both the elastic modulus and the tensile strength of the C and B laminates degraded with the increase in temperature. However, the degradation was greater in the C composite sheets. Based on the experimental results, it was also observed that the mechanical degradation was the highest in C laminates, which reached to almost 90% at 250 °C. In addition, the elastic modulus and tensile strength values had shown that the BBC and B laminates had the highest mechanical performance when exposed to elevated temperatures. In addition, analytical models are proposed from the generated test data to predict the variation in the elastic modulus and tensile strength with temperature. The obtained results and proposed models can be used as input parameters in the analysis and design of externally strengthened members with such FRP laminates. This study strongly endorses the use of B and hybrid combination of B and C laminates in strengthening RC slabs and beams.

1. Introduction

Externally bonded fiber reinforced polymer (FRP) laminates are widely used in strengthening of reinforced concrete (RC) members. These laminates have been used to improve flexural and shear capacity of slabs and beams to adapt with the increase of the live load and to maintain a longer service life time for concrete structures [1–3]. Strengthening with FRP laminates have been recognized to be one of the most practical, effective, and efficient systems to increase the load-carrying capacities of concrete structural members. Recently, many studies showed a great improvement in the load-carrying capacity of concrete members when strengthened with carbon, basalt, or glass fiber sheets [4–13]. On the other hand, there are few studies that investigated the effect of using different combinations of carbon laminates with other types of composites on the load-carrying capacity and ductility of structural concrete members [14–16]. Although FRP have been

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successfully used in strengthening and repair of damaged RC slabs and beams there is a knowledge gap in the mechanical behavior of the different FRP laminates under elevated temperatures. Investigating the performance of these sheets under a range of elevated temperatures is a major issue that requires more attention by researchers and engineers in order to provide FRP-strengthening systems that perform well under high environmental temperatures.

In this paper, the authors investigated the effect of elevated temperatures on the mechanical properties of carbon laminates (C), basalt laminates (B) and their hybrid combinations (BC, BCB, CCB, CBC, and BBC) up to 3 layers. The coupon specimens were heated in an oven at the specified temperature for 45 min and then left to cure at room temperature for 24 h prior to testing. The obtained temperature-dependent material properties are the elastic modulus, the tensile strength, and the stress-strain response curves. The mechanical properties could be used by engineers and researchers as an input in the design and analysis of RC slabs and beams externally strengthened with such composite materials when exposed to elevated temperatures.

2. Literature review

Limited studies investigated the performance of structural members (slabs, beams, columns, etc.) externally strengthened with FRP composite sheets when exposed to elevated temperatures. An experimental program was conducted by Blontrock et al. [17] to test the effect of fire on concrete slabs strengthened with FRP sheets and protected with resistant plates with different arrangements. The slabs were placed in the oven and subjected to a sustained constant load applied at mid-span. The results showed that when the temperature of the adhesive ranged between 47 °C and 69 °C, an excessive increase in the deflection occurs prior to failure.

Similarly, Al-Salloum et al. [18] reported the effect of high temperatures on 42 concrete cylinders wrapped with two types of FRP sheets. Fourteen cylinders were left unwrapped and the remaining 28 specimens were wrapped with one layer of carbon and glass sheets, respectively. The specimens were then cured for 7 days at room temperature. Before performing the compression testing, the specimens were placed in an oven at a temperature of 100 °C and 200 °C for time periods of 1–3 h. Then, a uniaxial compression test was conducted on every specimen till failure. The results indicated that the unwrapped samples presented significant strength degradation at high temperatures with long exposure time which caused a rapid loss of concrete compressive strength. However, the remaining specimens, wrapped with carbon and glass sheets, showed lower reduction in their strength since the heat required a longer time to be transferred to the concrete through the epoxy and the sheets. The results showed considerable loss in the compressive strength of the unwrapped cylinder when exposed to elevated temperatures, compared to that of the wrapped ones. In addition, the test results indicated that FRP composite materials are sensitive to fire and experience changes in strength and bond performance when the ambient temperature exceeds the glass transition temperature (T_g) of the polymer matrix used as an adhesive/bonding agent.

Few experimental studies investigated the behavior of composite laminates under high temperatures. Zhishen [19] investigated the FRP composite behavior under elevated temperatures and concluded that the properties of FRP laminates are significantly influenced when exposed to high temperatures. The results of the experimental tests showed that the residual strength of the hybrid basalt-carbon sheets which was 200 mm in length can maintain 59% of the tensile strength at 200 °C after two hours of heating, which is considered to be acceptable compared to the tensile strength of dry fibers which is only 45%. Whereas, basalt bars showed a higher tensile strength at elevated temperatures due to their high glass transition temperature.

Foster and Bisby [20] investigated the effect of temperature on the mechanical properties of carbon (C) and glass (G) sheets. The specimens were tested at temperatures of 20, 100, 200, 300, and 400 °C, respectively. The sheets were covered with epoxy on both sides and then placed in the oven for 3 h. Then, tensile tests were conducted on the cured samples. The test results showed that the reduction in the tensile strength of the C sample was not significant up to 300 °C. Whereas, G laminates showed a major loss in the tensile strength at 200 °C.

Sim et al. [21] conducted an experimental study to shed light on the behavior of basalt fibers as a strengthening material for RC structures, compared to carbon and laminates. The three types of FRP sheets were heated at different temperatures that ranged from 100 to 1200 °C for two hours and then tested after one day of cooling at room temperature. The results showed that the change in strength was not significant for the three material types when the applied temperature was less than 200 °C. However, as the temperature exceeded 200 °C, the reduction in strength for carbon and glass was significant. On the other hand, the basalt fibers retained 90% of its strength at 600 °C. Moreover, the volumetric stability of carbon fibers was lost and the fibers were completely molten, while the glass fibers were partially lost during heating.

In addition to Sim et al. [21], other researchers investigated the use of basalt fiber polymer (B) sheets in strengthening of RC members as an alternative to carbon and glass fibers [11–13]. Campione et al. [12] studied the compressive strength of concrete cylinders externally wrapped with basalt fiber sheets. A total of 26 monotonic and cyclic compressive tests were performed. It was concluded that the specimens confined with the basalt sheets exhibited a strain-softening behavior with a negligible increase in resistance but a significant increase in ultimate strain (up to 5 times the peak strain of unconfined concrete) corresponding to basalt failure and concrete crushing.

Among the limited studies [22], Cao et al. [23] carried out an experimental study to examine the mechanical properties of CFRP and hybrid CFRP-GFRP sheets at elevated temperatures up to 200 °C. It was observed that the elastic modulus and tensile strength experienced a significant reduction at elevated temperatures. In addition, the authors [24,25] investigated the variation of the mechanical properties of carbon (C) laminates, glass (G) laminates, and their hybrid combination (CG) under temperatures ranging from 25 to 300 °C. The results showed that the mechanical degradation of the composite C and G sheets were more noticeable than that of the hybrid CG laminates. In particular, the modulus of elasticity of the C, G, and CG was dropped by about 28%, 26% and 9%, respectively, at an elevated temperature of 250 °C. They recommended that the measured values of the mechanical properties of C, G, and CG at elevated temperatures can be used as a valuable input in computer modeling of concrete members externally strengthened with such composites.

3. Experimental program

3.1. Material properties

MAPEWRAP-C-300-UNI-AX [26] carbon fiber fabric and FIDBASALT-UNIDIR-400-C95 [27] basalt sheets were used in this study. It is noteworthy that these fabric sheets are commonly used in FRP-strengthening applications of RC members. The adhesive used was a MapeWrap-31SP two-part epoxy adhesive provided by MAPEI [28]. The average measured glass transition temperature (T_g) of the epoxy adhesive was 85 °C, as reported by the manufacturer. It was obtained through dynamic mechanical analysis (DMA). The material properties of these materials including the elastic modulus, tensile strength, elongation at rupture, and design thickness of the FRP sheets as reported by the manufacture are provided in Table 1.