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Study on the Elevated Temperature and Durability Performances of Basalt FRP Rebars

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ABSTRACT: In an effort to comprehensively understand the mechanical, thermal and durability performances of novel basalt fiber reinforced polymer (BFRP) rebars for application in civil engineering, a series of studies on the elevated temperature properties and durability in water have been undertaken. At elevated temperatures, the tensile strength of BFRP rebars almost keeps constant at the temperature up to 250^{o}C, while the modulus decreases steadily. Owing to the decomposition of resin matrix, further increase of the temperatures reduces both the tensile strength and modulus dramatically. Immersion in distilled water brings in a remarkable degradation in the tensile properties of the BFRP rebars, especially at elevated temperatures. As revealed by scanning electron microscopy (SEM), hydrolysis of the resin matrix as well as the debonding of the basalt fiber and resin is responsible for the remarkable degradation.

1 INSTRUCTION

Being considered as a novel reinforcement, basalt fibers are manufactured directly from basalt rock through a melting process with high mechanical properties and chemical resistance Sim et al. (2005). Compared to the commonly used carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), basalt fiber reinforced polymer (BFRP) composites are reported to possess numerous advantages, such as a relative low price, high mechanical and thermal properties, good chemical resistance, and environmental friendship, etc. Since BFRP has been applied in civil engineering only for several years, the comprehensive knowledge of the BFRP from the basic physicochemical properties to the long term durability is not completely understood yet.

In the past several years, some works have been conducted on the performances and application of BFRP composites used in rehabilitation etc. Sim et al. (2005), Cerny (2007), Deak & Czigany (2008), Wang et al. (2008) Yongsheng (2009). Some contradictory results, however, have been reported up to date, which may be due to the fact that the properties of the basalt fibers vary from each other seriously, dependent on the basalt rock mines and manufacturing technologies. Without consistent and reliable property data of BFRP, as believed, it is difficult to be applied in the civil engineering practices, especially for some key infrastructures.

Generally, long term durability of FRPs is a serious concern when being used in civil engineering under harsh environments, such as chemical solution immersion, hygrothermal exposure, freeze thaw, high temperatures and even fire, etc. Karbhari (2003). In view of this, the FRP group at the school of civil engineering, Harbin Institute of Technology (HIT) has been conducting a series research projects to illuminate the advantage and disadvantage of BFRP rebars used as internal strengthening systems for concrete structures.

It is generally accepted that FRP composites exhibit a sharp decrease of the stiffness and strength when the temperatures exceeds the glass transition temperature (T_g) of the polymer matrix, e.g., in the range of 60 ~ 200^{o}C. Besides, it is also very important to evaluate the safety of the FRP related elements / structures after a fire.

In view of this, the present work is focused on a thorough performance investigation of commercial BFRP rebars for civil engineering application. The effects of water immersion, and elevated temperatures on the performance degradation of BFRP rebars are investigated in the present paper. The study is aimed to evaluate the possible advantages and drawbacks of the BFRP applied in civil engineering.

2 EXPERIMENTAL

2.1 Materials

The studied BFRP rebar is spirally wound with glass fiber rovings and coated with sands to improve the bonding strength between the rebar and concrete. Figure 1 shows the photograph of the BFRP rebars, which has a nominal diameter of 8 mm. The tensile properties were tested according to ACI 440.3R-04. The tensile strength is 899 MPa, and the elastic modulus is 50.8 GPa, which is acquired based on 25 testing specimens. The gauge length of the specimen is 320 mm, and the anchor length is 140 mm. Griping anchor is selected as the anchorage system, which consists of binding material (mixture of epoxy resin and plugging compound) and steel tubes. This kind of anchorage system can make sure the rupture occurred in the middle of the rebar.

2.2 Tension Characterization at Elevated temperatures

The during-fire testing is loading BFRP rebar at elevated temperature ranging from 100℃ to 350℃ to measure the variation of the strength and stiffness with temperatures.

The testing apparatus include following parts: WDW-10E computer controlled electronic universal tensile machine (UTM), lab-made electrically heating kiln, thermocouples and temperature controlling device. The maximum loading capacity of the UTM is 100 KN and its relative error reading can be less than 1%. The electrically heating kiln, which is purpose-built, contains 10 heating rods, which are arranged in a curved line. The kiln can heat rebar to the temperature up to 500℃. The thermocouple has two probes, which can record the temperature of air in the kiln (T_1) and the temperature of rebar (T_2), which will be transferred into computer directly.

To do the elevated temperature testing, the below procedure will be followed. Firstly, two thermocouple probes and extensometer are fastened on the rebar. Then, fix the rebar to the UTM and install the heating kiln. During this procedure, be sure that the extensometer doesn't touch the kiln. Thirdly, raise the temperature to the targeted values, and hold this temperature for 10 minutes (±5℃). In succession, load the rebar to failure with a grip speed of 5mm/min. The UMT will record the stress vs. strain curve. Using high-temperature extensometer, the stress-strain relationships at the temperatures ranging from 100℃ to 250℃ can be obtained. However, at the temperature ranging from 300℃ to 350℃, a serious slippage between extensometer and the rebar happens due to softening of the superficial resin and then loosening the fastening spring of the extensometer. As a result, the modulus can not be obtained in those cases.

Figure 1. Photograph of BFRP rebars with a nominal diameter of 8 mm.

2.3 *Durability study*

Distilled water immersion of BFRP bar was performed with water bath at 23, 40, 60 and 80^{o}C. For water uptake testing, BFRP rebar samples of 30 mm in length and 8 mm in diameter were taken out of the baths, swiped off the surface water using tissue papers and weighed using an electronic balance with an accuracy of 0.01 mg. The weight testing was performed periodically. The presented data are an averaged for 10 coupons for each condition.

Tensile properties of aged samples were tested according to ASTM D 3039.

3 RESUTLS AND DISCUSSION

3.1 *Elevated temperature performances of BFRP rebar*

Tensile strength and modulus of BFRP rebars are presented in Figures 2 & 3 as a function of testing temperatures. As found, the tensile strength keeps unchanged as the temperature increases by 200^{o}C. After that, with further increase of the testing temperatures, the tensile strength shows a dramatic reduction. At the highest testing temperature of 350°C, the residual strength of the BFRP rebar is only about 28.3% of the room temperature value.

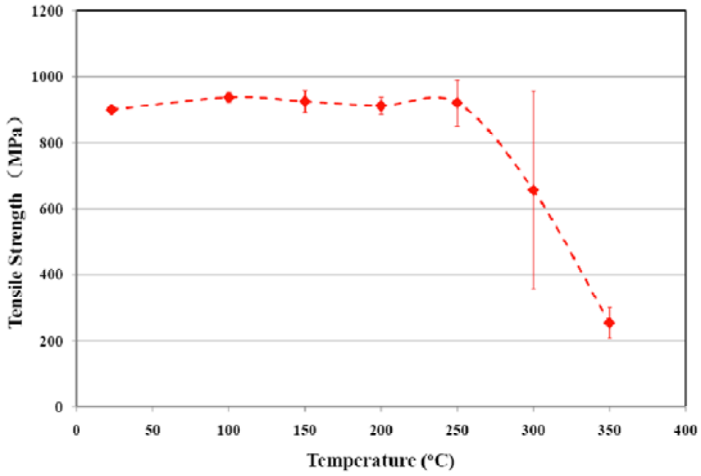

Figure 2. Tensile strength of BFRP rebar at various temperatures.

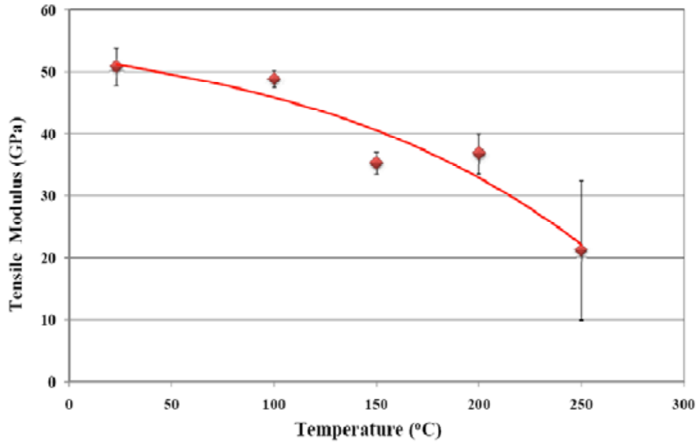

Figure 3. Tensile modulus of BFRP rebar at various temperatures.

It is worth noting that the glass transition temperature (Tg) of the rebar is 132°C, tested with a differential scanning calorimeter (DSC) at a heating rate of 10°C/min. When the temperature excesses Tg, the resin matrix will become soft and cannot transfer the external force to each filament effectively. In view of this, the inflexion of the tensile strength should be occurred around Tg of the resin. However, as shown in Figure 2, the strength shows the abrupt decrease at 250°C, far higher than Tg. It is to be noted that the rebar is produced by pultrusion process, with very aligned fibers and a high fiber content (>72 vol.%). Besides, the ends of the rebar where the steel anchors are installed, are kept at a lower temperatures (around room temperature). Therefore, albeit the resin is soft at the temperature higher than Tg, the well aligned filament still can sustain the external force simultaneously, because of the cooled anchorages.

As the temperature increases further and excesses 250°C, the resin starts to decompose and carbonize. An intensive smoke was found and spread out from the kiln. The dramatic decrease of the tensile strength occurred, which may be due to the degraded resin, and / or the degradation of fibers in the strength.

The evolution of the tensile modulus is shown in Figure 3. The reported modulus is only by the temperature of 250°C, due to the problem of strain measurement. The modulus decreases with the testing temperatures gradually (Figure 3). The dramatic decrease is found when the temperature exceeds the Tg of the resin matrix. For example, the tensile modulus is reduced only by 3.8% at 100°C, but by 30% at 150°C and 58% at 250°C. This conflicts with some reported results on GFRP and CFRP bars Wang (2007), that the modulus almost shows no change by 400°C. This contrast results can be attributed to the configuration of the rebar/bars. The current tested rebars possess ribs with spiral fiber roving, while the sample tested by Wang (2007) is only sand-coated without ribs. Consequently, for the current test, due to the softening of the resin matrix, the constraint effect of the spiral fiber roving (in the ribs) to the BFRP rebar may be able to relax under low forces. Therefore, the basalt fiber roving under the rib is stretched under a low force, leading to a low modulus.

3.2 Water and alkaline solution immersion

Figure 4 presents the water uptake curves of BFRP samples, immersed in distilled water for 6 months. As shown, the water uptake curves did not reach saturation for all four temperature cases. With the temperature increasing from 23, 40, 60 and 80°C, the water uptake is increased from 0.1%, 0.26%, 0.32% and 0.56% after 6 months water immersion, respectively. It should be noted that the water uptake curve is not consistent with the Ficken's mode. As indicated, after saturation, the water uptake will level off for Ficken's mode Karbhari & Xian （2009). On the contrary, the water diffusion mechanisms at high temperatures, e.g., 80°C and 60°C, seems to follow the two-stage model Wrosch (2008), Karbhari & Xian (2009). A longer immersion time is needed to determine the diffusion model of the system reliably.

It is worth noting that the water uptake of the BFRP rebars includes hydrolysis of resin matrix, which is indicated by SEM analysis in the current work. Therefore, the water uptake curves may not easily explained by the water diffusion models.

The fiber content of the BFRP rebar is about 85% in weight, measured with the ignition method. Suppose that the water is only absorbed by the resin system. The water uptake content in the resin is about 0.67%, 1.73%, 2.1% and 3.73% at the above temperature conditions in an increasing sequence. Generally, the saturation water content for a pure epoxy resin is about 4%, which indicate the BFRP in 30mm length may be closed to the saturation state at 80°C after 6 months.

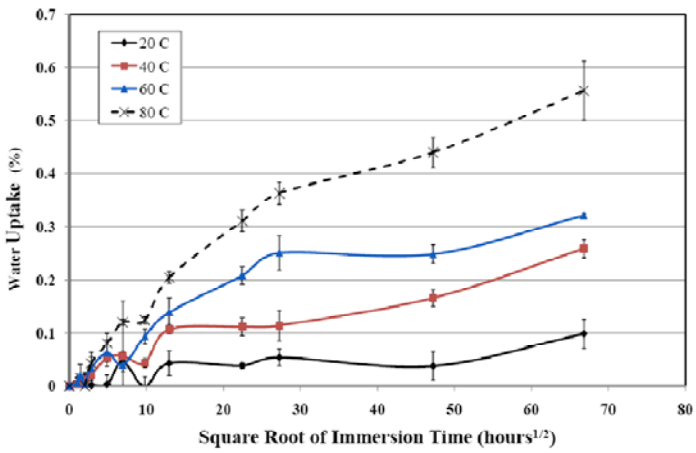

Figure 4. Water uptake of BFRP rebars of 30 mm in length and 8 mm in diameter immersed in distilled water.

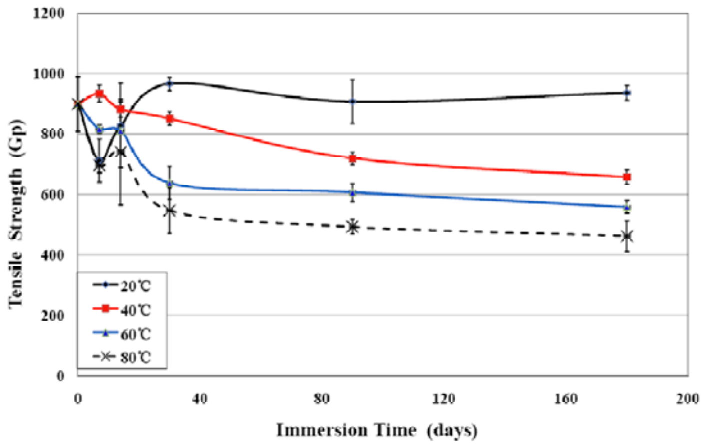

Figure 5. Variation of the tensile strength of BFRP rebars as a function of immersion time in distilled water at different temperatures.

Figure 5 shows the variation of tensile strength of BFRP rebars exposed to water bath at various temperatures for up to 6 months. As shown, the tensile strength shows a remarkable degradation with the immersion time, especially at elevated temperatures. At room temperature, the strength shows a rise, despite less than 10%. This is attributed to the postcuring effect of the resin as well as the relaxation of residual stress formed during pultrusion process. However, at high temperatures, the tensile strength shows a remarkable decrease in the tensile strength. The decreases mainly occurred in the first 1 month, and after that, the degradation rate shows much reduced. After 6 months, BFRP rebars immersed in 40, 60 and 80^{o}C water show significant degradation in the tensile strength by about 27%, 38% and 49%, respectively.

The dramatic deterioration of the tensile strength is assigned to degradation of the bonding strength of the fiber and resin matrix. This can be elucidated by the scanning electron microscopy (SEM) pictures (Figures 6~7) of the fracture surface of BFRP rebars after tension. It is clear, at room temperature, the fibers are still bonded resins well, indicating a good bonding performance. However, there are no much resins attached on the smooth basalt fibers after 80°C water immersion (Figure 7), indicating a remarkable deterioration of the interface between the fiber and the resin matrix.

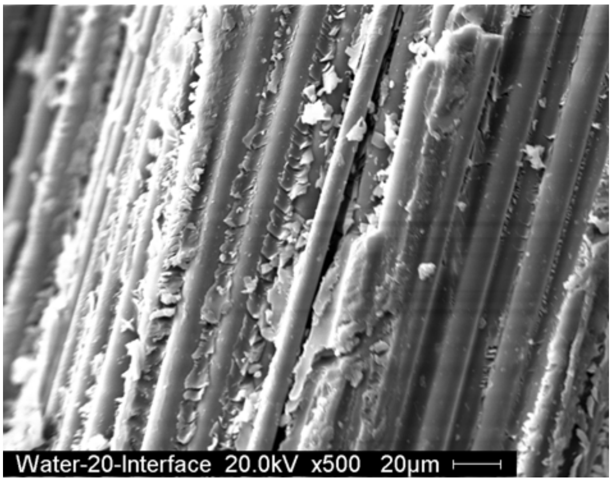

Figure 6. Fractography picture of BFRP rebars (23°C water immersion for 6-month) after tension test.

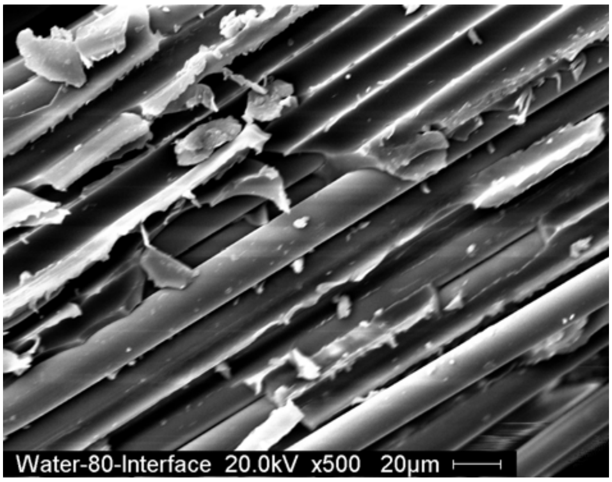

Figure 7. Fractography picture of BFRP rebars (80°C water immersion for 6-month) after tension test.

In contrast, the tensile modulus was affected by water immersion insignificantly (Figure 8). The tensile modulus decreases in the initial 30 days immersion, and then recovers a little bit with extended immersion time. Compared to the un-aged rebar, after 6 months water immersion, the tensile modulus shows the decrease ranging from 3 to 11% with various temperatures. The higher the immersion temperatures, the more degradation is found.

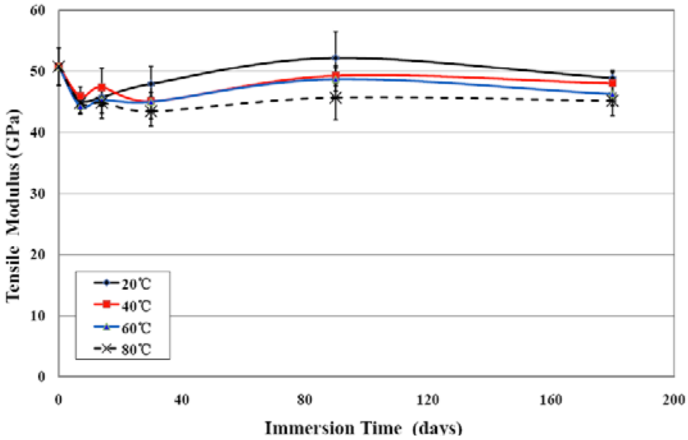

Figure 8. Variation of the tensile modulus of BFRP rebars as a function of immersion time in distilled water at different temperatures.

4 CONCLUSIONS

The high temperature performance and durability of BFRP rebars were investigated in the present paper. Based on the experimental results, the following conclusions can be drawn.

The tensile strength of BFRP rebars keep almost constant with the testing temperature by 250^{o}C, followed by a remarkable decrease with further increases of the temperatures. When the testing temperature exceeds Tg of the resin matrix (132^{o}C), the tensile modulus of the BFRP rebars shows a remarkable decrease. The maximum reduction at 250^{o}C is about 58% of the room temperature values. The rib configuration of the tested rebar is responsible for the poor high temperature resistance of the tensile modulus.

Durability study of BFRP rebars subjected to water immersion at the temperature ranging from 20 to 80^{o}C indicates a remarkable deterioration of tensile strength at high temperatures. The degradation of the interface between fiber and resin system is assigned to the strength decrease. Tensile modulus of the BFRP rebar is affected by the water immersion insignificantly.

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