DURABILITY AND FATIGUE PERFORMANCES OF BASALT FIBER / EPOXY REINFORCING BARS

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Abstract
As a promising alternative to conventional glass- and carbon- fiber reinforced polymer (FRP) composites used in structural strengthening, basalt fibers based FRPs have been developed and studied recently. In the current paper, durability and fatigue performances of a basalt fiber / epoxy FRP reinforcing bar were studied. The durability study was focused on hygrothermal and alkaline environments. The bare basalt fiber immersed in the above environments, without protection from resin, exhibits a serious degradation in the tensile properties, due to serious corrosion of the fibers as revealed by scanning electron microscopy. On the contrary, basalt fiber reinforcing bars show a much improved durability performance subjected to the same conditions. The service lives of the reinforcing bars are predicted in various environments according to Arrhenius equations. Fatigue performance of the basalt fiber reinforcing bar was investigated before and after ageing in alkaline solution. The fatigue life of aged samples was remarkably reduced compared to the control samples.

Keywords: Basalt fiber, durability, hygrothermal ageing, alkaline, fatigue

1. Introduction
Fiber reinforced polymers (FRPs) have already been widely accepted in rehabilitation, strengthening and upgrading existing structures for more than twenty years. Generally, fiber reinforcement for FRPs is glass, carbon and aramid. In recent ten years, basalt fiber, a novel inorganic fiber from basalt rock, has been emerging, which is firstly developed in the Soviet Union, and now widely produced in China, Ukraine, and Russia 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 recent years, more and more attentions have been paid to basalt fibers as well as its FRPs on its mechanical properties, durability in various environments [1-7]. In 2005, Sim et al. [6] investigate basalt fiber’s durability and elevated temperature performance. Based on the investigation, Sim et al. [6] suggested that the basalt fiber can be a good alternative fiber reinforcement among glass and carbon fibers in structural strengthening and rehabilitation. Wang et al. [7] systematically studied the chemical durability and mechanical properties of basalt fiber and its epoxy resin composites. The experimental results show that after exposure to alkali solutions including saturated Na2CO3 solution, 10% NaOH and 10% NH3.H2O for 3 months, the modulus of BFRP is not affected while the strength is reduced by 40%.

It is worth noting, due to the variation in the producing processing and mineral components, basalt fibers may show a big fluctuation in its properties. Therefore, it should be careful to judge basalt fibers and BFRPs on limited experimental results. In the present study, basalt fiber reinforced epoxy BFRP rebars were studied on its hygrothermal ageing performance in distilled water and alkali solutions at elevated temperatures, and resulted fatigue performances. The study is aimed to understand the degradation of BFRP in such environments and evaluate the applicability in civil engineering, such as to replace the traditional steel rebars.

2. EXPERIMENTAL

2.1 Materials

Basalt fiber reinforced epoxy based rebars were produced by pultrusion technology, with sand coated and ribbed. The nominal diameter of the investigated BFRP rebar is 7 mm. Figure 1 shows the photograph of BFRP rebars. Fiber content of the BFRP rebar is around 72 vol.%.

2.2 Water uptake

The BFRP rebars were cut into 30 mm for water sorption tests. Samples without sustained load were soaked in distilled water baths and alkali solution bath (concrete pore solution) at 20 °C, 40 °C, 60 °C and 80 °C. Besides, samples of the same dimensions were exposed in ambient conditions [23oC and 30% relative humidity (RH)] for the same term.

The moisture uptake in the samples was detected by periodically recording the mass of the samples. Ageing in water or solutions, samples taken out of the baths were swiped off the surface water using tissue paper and weighted using an electronic balance with an accuracy of 0.01 mg. The presented data are an average of ten coupons.

2.3 Mechanical Properties

BFRP rebars were cut into 600-mm segments in length and soaked in distilled water or alkali solution, as shown in Figure 2. The samples were taken out periodically to be tested in tension performance according to ASTM D3039. BFRP bar was anchored with steel pipes at both of the ends. A high modulus epoxy adhesive developed at our lab was used to bond the rebar with the steel pipe. For each immersion condition, five repeats were tested.

For fatigue testing, one kind of unaged (control) rebar samples and aged rebar samples were tested to understand the effect of ageing on the fatigue life primarily. For aged samples, the rebar were immersed in alkaline solution at 80 °C for 30 days. The fatigue test was performed in tension with 4 Hz frequency and various stress levels. The fatigue testing machine is INSTRON8801 (INSTRON Co., USA).
3. RESULTS AND DISCUSSION

Table 1 presents the tensile properties of BFRP rebars. For comparison, properties of GFRP and CFRP bars from datasheet of Hughes Brothers, Inc. are also given. As shown, the current BFRP bars possess higher tensile strength and modulus by 10 ~ 20% than GFRP rebars, but are inferior to CFRP remarkably, consistent to literature reports [4, 7].

Table 1. Comparison of tensile properties of BFRP, GFRP and CFRP bars. Testing was performed according to ASTM D3039.

<table>
<thead>
<tr>
<th></th>
<th>STRENGTH, MPa</th>
<th>MODULUS, GPa</th>
<th>ELONGATION AT BREAK (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFRP</td>
<td>899</td>
<td>50.3</td>
<td>1.8</td>
</tr>
<tr>
<td>GFRP*</td>
<td>825</td>
<td>40.8</td>
<td>/</td>
</tr>
<tr>
<td>CFRP*</td>
<td>2100</td>
<td>124</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Note: GFRP Bar is ASLAN 100; CFRP bar is ASLAN 200 Both are from Hughes Brothers, Inc. USA.

DSC testing shows the as-received BFRP bars have a glass transition temperature (Tg) about 132°C. After post-cured by heating to 200°C and cooling down slowly in DSC machine, Tg is increased to 142°C. The increase of Tg indicates that the BFRP bar was not fully cured during pultrusion process.

![Figure 2 - Water uptake of 30 mm BFRP rebar immersed in distilled water as a function of square root of time.](image)

Figures 2 and 3 show the water uptake of BFRP (30mm in length and 7 mm in diameter) samples immersed in distilled water and alkali solutions, respectively. In both immersion cases, BFRPs did not reach the saturation state, even at 80°C. After 6 month immersion in distilled water, the reached maximum water uptake at 20°C, 40°C, 60°C and 80°C is 0.1, 0.26, 0.32 and 0.56%, respectively. As immersed in alkaline solutions at the same temperature conditions, the reached maximum water uptake is 0.14, 0.20, 0.47 and 0.63%, respectively. Except for the temperature of 40°C, BFRPs immersed in alkaline solutions absorbed more water with the same immersion periods. The more water uptake may brings in severer degradation of BFRP rebars, since water uptake will plasticize the resin and may cause debonding between fiber and matrix, etc. [8].
Figure 3 – Water uptake of 30 mm BFRP rebar immersed in alkali solutions as a function of square root of time.

Figure 4 – SEM photographs of the surface of BFRP rebars immersed in alkali solution at 60°C (140°F) for 6 months.

Figure 4 shows SEM (scanning electron microscopy) photographs of 600°C alkaline solution aged BFRP rebars. A remarkable hydrolysis of resin was found and resulted in the exposure of basalt fibers. For water immersion, the resin on the rebar surface does not show such degradation. In view of this, the weight increase shown in Figure 3 for alkaline solution immersion can be ascribed to the combined effect of water uptake and resin hydrolysis.

Since BFRP did not reach its saturation during immersion, it is impossible to calculate the water diffusion parameters. However, according to the approximate linearity of the water uptake ~ square root of immersion time, the rough water absorption rate can be estimated. Immersed in alkali solution, BFRP bars show a higher absorption rate than those immersed in distilled water.

Variation of tensile properties of BFRP rebars due to distilled water immersion and alkali solutions at various temperatures is shown in Figure 5 – 8. For distilled water immersion for 6 months (Figure 5), despite of remarkable fluctuation in the original 2 weeks, the tensile strength of BFRP rebars show a little bit increase (~4%) at 20°C, but decrease by 26% at 40°C, 38% at 60°C and 49% at 80°C, respectively. As believed, the increase of the strength at
20 °C is due to postcuring effect. A slight amount of water uptake shows an acceleration effect on the postcuring process. The tensile modulus shows a distinct trend with immersion time as shown in Figure 6. The first three weeks of immersion causes the modulus reduced by about 5%, and then slightly comes back except for 80°C. The competition between postcuring and plasticization as well as permanent degradation is responsible for the variation of the modulus.

![Figure 5](image-url)  
**Figure 5 –** Variation of tensile strength of BFRP rebars immersed in distilled water vs. time at various temperatures.

![Figure 6](image-url)  
**Figure 6 –** Variation of tensile modulus of BFRP rebars immersed in distilled water vs. time at various temperatures.

Immersed in alkali, BFRP rebars show much pronounced degradation in both strength and modulus. At relatively low temperatures (e.g., 20 °C and 40 °C), the tensile strength firstly increase by about 4% and then decreases (Figure 7). The increase can be assigned to the postcuring effect. At relatively higher temperatures, the tensile strength dramatically reduces in the first month and then slows down. After 6 months immersion, the reduction of the tensile strength is 13%, 37%, 56% and 56% at four testing temperatures, respectively. It is worth noting that the reduction of the tensile strength is much higher than that immersed in distilled water (Figure 5).
Similarly, the tensile modulus of the BFRP rebars also show a remarkable reduction after immersion in alkaline solution for 6 month, especially at 60 and 80°C (see in Figure 8). After initial decrease (about 10%) in first two weeks of immersion at 20 and 40°C may due to water plasticization, the modulus recovers back by about 5%. At higher temperatures, the modulus decreased by 20% at 60°C and 36% at 80°C.

![Figure 7](image1.png)

Figure 7 – Variation of tensile strength of BFRP rebars immersed in Alkali vs. time at various temperatures.

![Figure 8](image2.png)

Figure 8 – Variation of tensile modulus of BFRP rebars immersed in alkali vs. time at various temperatures.

The fatigue resistance of the two sets can be clearly seen from the S-N curves described in Figure 9. Both of the two S-N curves were created within the semi-logarithm coordinates. From unaged to aged S-N curve, the fatigue resistance moved backward to the original point a lot, take the stress level of 0.5 for example, the fatigue life fell down from 102000 circles to only 7000 circles, the fatigue life was 93% cut off from the initial.
Figure 9. Logarithmic S-N curves for aged specimens and un-aged specimens

4. Conclusions
This study investigated the durability and fatigue performances of BFRP rebars exposed to distilled water and alkaline solutions at various temperatures. Water uptake and tensile properties of the BFRP rebars have been tested as a function of immersion time. As found, immersed in alkaline solution, BFRP rebars absorb more water with a higher absorption rate. The studied BFRP rebars show poor alkali resistance, and exhibit a remarkable reduction in both tensile strength and modulus. Compared to alkali resistance, BFRP rebars possess a better distilled water resistance. SEM photograph indicates the hydrolysis of resin, debonding of resin and fibers are responsible the remarkable degradation in alkaline solutions. The fatigue test indicates aged BFRP exhibit a much reduced fatigue life.

5. Acknowledgement
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6. References

