A REVIEW ON THE USAGE OF BASALT FIBER REINFORCED POLYMER (BFRP) IN CONCRETE

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Keywords: BFRP, concrete, mechano-physico-chemical, polymer matrix

Abstract
Basalt-Fiber-Reinforced Polymer (BFRP) composites have been used in civil engineering for decades. A recent increase in the use of environmentally friendly, natural fibers as reinforcement for the fabrication of lightweight, low cost polymer composites can be seen globally. One such material of interest currently being extensively used is basalt fiber, which is cost-effective and offers exceptional properties over glass fibers and less inexpensive than carbon fiber. The prominent advantages of these composites include high specific mechano-physico-chemical properties, biodegradability. This article presents a review on BFRP used as a reinforcement material for concrete, and discusses the improvement in mechanical, thermal and chemical resistant properties achieved for the use of BFRP for applications in specific industries in recent 5 years. The paper also focuses on the basics of the modification of basalt fiber and its polymer matrix. Apart from this, an attempt to showcase the increasing trend in the usage of BFRP in concrete is also covered.

1. Introduction
As a sort of environment-friendly, natural fibers, basalt fiber has been currently being extensively used in variety of fields [1]. Previously, basalt was a preferred choice of material (as fibers) in the construction industry, and has been in extensive use since as an external or internal reinforcement within concrete materials [2-7]. Thanks to the utility-friendly and ductile, BFRP can be introduced as a reinforcement in concrete in various shapes such rods, bars, tubes, slabs, sheets, beams and textile fabrics.

Plenty of researches have been carried out based on the investigations of the properties of BF, glass fiber reinforced polymer (GFRP) reinforced concrete and carbon fiber reinforced polymer (CFRP) reinforced concrete [8]. Several mechanical properties of BFRP reinforced concrete have been studied Intensively: deflections of concrete beams reinforced with basalt rebar [9], flexural behavior of inorganic polymer concrete beams [10], bond-dependent coefficient [11], the compressive [12], splitting tensile and flexural strength[13], comparative study [14, 15, 16]. While some focused on the physical properties [17] and chemical properties [48] of BFRP reinforced concrete; some emphasis the design and simulation [2]. However, the polymer matrix of BFRP were few mentioned and researched in these above articles, which is proved to influence the ultimate performance(such as durability and freeze-thaw resistance) of FRP reinforced concrete [18, 19].

This paper focuses on the behavior of the surface of BF and polymer matrix and the surface of polymer matrix in concrete. In order to more convenient required in accordance with choice of resin, the discussion will be carried out according to the classification of resin style: thermoset, thermoplastic and biodegradable. Apart from these, herein the BFRP reinforced concrete will be regarded as a unity.

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2. Common polymer matrix

2.1. Thermoset polymer matrix

In recent years, basalt fibers were widely used as reinforcement of thermoset polymers in concrete. Particularly, thanks to their remarkable features as mechanical properties, moisture-resistance to corrosive environments, durability, versatility and accessibility, the vinyl ester resins and epoxy resin have been the polymer matrix most commonly investigated as matrix for basalt fiber reinforced composites.

2.1.1. Vinyl ester resins

Hassan et al. [20] investigated the bond durability of basalt-fiber-reinforced-polymer (BFRP) bars embedded in concrete in aggressive environments by testing deformed BFRP bars measuring with direct tensile loading after being exposed to an alkaline solution (pH 12.9) for 1.5, 3, and 6 months at temperatures of 40°C, 50°C, and 60°C. These bars are made of continuous longitudinal basalt fibers bound together with a vinyl-ester resin using a pultrusion process. The test results indicate an initial increase in the bond strength of the conditioned specimens as the temperature increased (a 26% increase in 60°C) compared to their unconditioned specimens after 1.5 months of exposure. Nevertheless, the bond strength of the conditioned specimens deteriorated during immersion in alkaline solution (a 16% loss in 40°C).

Wlodarczyk et al. [21] joining continuous basalt fiber with polymer vinyl-ester resin matrix by pultrusion process, and cut into separate uniform length pieces to reinforce concrete. Then concrete slabs were made of the concrete mixture with steel grid placed in the middle of element’s height. It was found that Destruction of S2BF series beams was similar to that observed in bending of concrete elements, while S3MB where similar to collapse mode observed in reinforced concrete beams.

Wang et al.[22] studied the creep behavior of pretension treated BFRP tendons under the sustained loads for up to 1000 h. These tendons were manufactured by using unidirectional basalt fiber roving of 2400 tex and a vinyl-ester resin through pultrusion. The BFRP tendons with pretension treatment displayed a 17% higher stress than the untreated BFRP tendons; The one million-hour creep rupture stress of the pretension-tread BFRP tendons is effectively increased. And the results demonstrated the effectiveness of the pretension on controlling the creep strain rate. In another research [23], a method of pretension to control the creep strain of BFRP tendons was proposed and the effectiveness was demonstrated via experimental study on pretention levels and durations. They also found the effects of tension stress and the tendon profile of the prestressing tendons on the flexural behavior of strengthened RC beams, including cracking load, yielding load, ultimate load, stiffness and ductility[24]. Apart from the above, they also presented an enhancement method for basalt fiber-reinforced polymer (BFRP) and the corresponding design optimization for application in long-span cable-stayed bridge. In the experiment, two kinds of hybridization, hybrid basalt/carbon fibers (B/CFRP) and basalt fibers/steel wire (B/SFRP), are adopted for impregnation with vinyl ester resin. The enhancement of basalt FRP on static and fatigue behavior is further studied by means of hybridization. It was found that not only superior mechanical properties can be realized but material potential strength can also be performed due to positive hybrid effect.

Elgabbas et al. [25] investigated durability and long-term performance were assessed by conditioning the BFRP bars (made of continuous basalt fibers impregnated in vinyl ester resin according to the pultrusion process) in an alkaline solution simulating the concrete environment (up to 3000 h at 60°C) to determine their suitability as internal reinforcement for concrete elements. The test results revealed that the BFRP bars had good mechanical behavior and could be placed in the same category as grade II and grade III GFRP (glass fiber reinforced polymer) bars; The basalt fibers and resins used in this study were not affected by the conditioning, and the strength degradation observed in the BFRP bars was attributed to poor bonding between the resin and basalt fibers.
2.1.2. Epoxy resins

In the latest years, many researchers payed more and more attention to the effect of temperature, loading style, and manufacture method on the ultimate performance of BFRP reinforced concrete under variety of chemical environments.

Li et al. [26] used BFRP bars as a reinforcing material in concrete to study the effect of high temperature embedding length, diameter and type of FRP bars, concrete strength, thickness of the concrete cover and a fireproof coating material on the bond performance between BFRP and the matrix, in the meantime, GFRP were used as control group. Based on the results presented in the paper, they drew conclusions: The bond strength of the FRP bar pullout specimens declined gradually with the increase of the temperature, and the heat-resistance of BFRP bar specimens was better than that of GFRP bar specimens. When the bond failure occurred at the interface of the FRP bars and concrete, the surface treatment and resin type had a more significant influence on the bond strength than the type of FRP bar used and the concrete strength. The bond strength between the BFRP bar and concrete reduced with the increase of the bonded length and BFRP bar diameter. The effect of a fireproof coating material on the surface of the concrete increased when the temperature increased. Yao et al. [27] also studied the bonding properties of basalt FRP/steel single-lap joints under different loading rates and temperatures. The results showed the bond strength and shear stiffness increase with increasing loading rates. The elevated temperature has pronounced effect on the mechanical performances, and higher strain is achieved on the joint edge where the load is applied as compared to the center of the overlapping area.

Yeboah et al. [28] studied pull-out behavior of axially loaded BFRP rods bonded perpendicular to the grain of glulam elements with BF-epoxy laminates then glued by melamine adhesives. It was found that increased bonded lengths resulted in corresponding decrease in interfacial bond stress, and the bond stress of the theoretical model (at the ascending and descending branches) of the stress-slip curve was approximately 5-10% of that of the experiment. Hawilieh et al. [29] presented the results of an experimental program that studies the mechanical properties of carbon (C), basalt (B), and their hybrid combinations. 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.

Wang et al. [30, 31, 32] focused on the fatigue behavior and failure mechanism of BFRP composites under long-term cyclic loads, studied the degradation of the tensile properties of prestressed BFRP and hybrid FRP tendons in a marine environment. The results revealed that under high level of stress, the critical fiber breaking failure is the dominant damage, while the matrix cracking and interfacial debonding are main damage patterns at the low and middle fatigue stress level for BFRP. Hybridization can lower the degradation rate of basalt and carbon FRP (B/CFRP) without prestressing, whereas basalt and steel-wire FRP (B/SFRP) exhibit much faster degradation due to the internal corrosive steel wires. They also studied shear behavior of basalt fiber reinforced polymer (FRP) and hybrid FRP rods as shear resistance members by comparing the shear properties of basalt fiber reinforced polymer (BFRP) and the hybrid FRP rods (the matrix are epoxy and vinyl ester resins) as shear resistance members. The conclusion was drawn that the shear strength of the FRP rods was contributed mainly by their internal fibers, whereas the resin contributed only approximate 8% of the total strength.

Shen et al. [33] investigated the effect of strain rate on dynamic effective bond length, strain distribution along bond length dynamic maximum local bond stress, and failure mechanisms of BFRP and concrete double-lap specimens. It was found that strain rate has no effect on the failure modes of the BFRP concrete interface, and the dynamic elastic modulus increases with the increase in strain rate. Their investigations [34] on reinforced concrete shear walls strengthened with basalt fiber-reinforced polymers under cyclic load. The results revealed that the strengthening of RC shear walls by using
BFRP strips was an effective technique, and the strip configurations were a key issue in the seismic performance of strengthened walls, especially in ductility. Li et al. [35] manufactured the basalt-glass fiber reinforced polymer (B-GFRP) bars with different thicknesses of basalt FRP protecting layers. The results showed that, with the increase of loading rate, the tensile strength and elongation ratio of GFRP bar increased, while the elastic modulus remained roughly constant.

Lu et al.[36] compared the effects of elevated temperatures on the mechanical properties of BFRP plates and E-glass fiber roving and pultruded glass fiber-reinforced (GFRP) plates, which use bisphenol-A epoxy as polymer matrix. It was found that the basalt fiber roving and BFRP plates showed much better mechanical tensile properties and temperature resistance.

Li et al.[37] studied the effect of γ irradiation on the properties of basalt fiber reinforced epoxy resin matrix composite, as an alternative of traditional materials used on nuclear facilities. The results indicated that the physical and chemical changes of resin matrix do not have significant effects on the mechanical property of BF composite after being dosed 60Co g irradiation at the dose ranging from 0 to 2000 kGy.

2.2. Thermoplastic polymer matrix

The scientific literature also reported basalt fiber reinforced thermoplastic in concrete. In particular, styrene acrylic, polypropylene and polymethyl methacrylate (PMMA) have been newly used as thermoplastic matrices for basalt fibers.

Du et al. [38] made a particular type of biaxial textile of basalt fiber bundles and coated with styrene-acrylic latex to study focuses on the influences of the number of textile layers, prestress levels and volume fractions of short steel fibers on the uniaxial tensile behavior of basalt textile reinforced concrete(TRC). The result showed that the tensile behavior of basalt TRC is considerably influenced by the number of textile layers.

Pehlivanlı et al. [39] obtained novel autoclaved aerated concrete (AAC) with autoclaved polypropylene, carbon, basalt and glass fiber and investigated the effect of fiber type and size in the production of AAC on compressive, flexural strength and thermal conductivity values. Fiber supplement increased flexural strength instead of main material quartzite. The reason of the increase of flexural strength and compressive strength were due to the increase in binding formation after adding fiber reinforcement.

Quagliarini et al. [40] studied the durability tests for usage of Basalt fiber ropes and rods in building engineering. The results indicated that the tested BFRP rods have a good resistance in water and to chloride attack and thus that the vinyl ester resin used in the composites adequately protects the basalt fibers in these environments. In particular, BFRP rods are sensitive to alkaline attack when vinyl ester resin is used because it does not provide adequate protection to fibers. BFRP rods with vinyl ester resin performed better in chloride environment as, i.e., in marine or in presence of deicing salts, underlining the importance of the selection of polymer matrix according to the particular case.

2.3. Biodegradable polymer and other research of BFRP in concrete

Smits et al. [41] made an investigation of Fiber-Reinforced Polymer Bridge Design in the Netherlands. The author of this paper is currently involved in research on the use of bio-composites in a load-bearing footbridge application which was built out of flax fibers, bio-based resins, poly lactic acid (PLA) foam, and natural cork.

Lipatov et al. [42] obtained basalt glasses and fibers with zirconia content in the range from 0 to 7 wt% using ZrSiO4 as a zirconium source, then determined weight loss and tensile strength loss of fibers after refluxing in alkali solution that basalt fiber with 5.7wt % ZrO2 had the optimum alkali resistance properties. Which worth to mention that alkali resistance of zirconia doped basalt fibers is
caused by insoluble compounds of Zr$^{4+}$, Fe$^{3+}$ and Mg$^{2+}$ in corrosion layer.

Cieślak et al. [43] carried out two kinds of synthesis methods, with and without the surfactant, to obtain a structural variety of TiO$_2$ coatings. For fibers, the formation of smaller, irregular, channel pores was observed. The greatest diversity of the TiO$_2$ coating structure was found for the 5% addition of CTAB.

Timber has been widely used as a structural material. Fernando et al. [44] presented an experimental, numerical and analytical study on the behavior of BFRP strengthened glued timber panels under tensile loading. The experimental study showed that BFRP increases both the strength and stiffness of the timber specimens. And it was also found that BFRP could yield significant benefits in terms of increasing the strength and stiffness for the timber sections with defects. Raftery et al. [45] studied basalt FRP rods for reinforcement and repair of timber. For repair applications, the basalt FRP rods can effectively bridge over damaged zones in the timber and comprehensively restore the mechanical strength and stiffness of the original undamaged section, exhibited considerable ductility with visible compression wrinkling in the top laminations.

3. Conclusions

In summary, the various factors affect the performance application of BFRP in the concrete are different according to the specific circumstance:

- The choice of the resin matrix smaller influence on shear properties and resistance to radiation performance;
- The performance of the resin matrix considerably influences freeze-thaw resistance and durability of BFRP reinforced concrete;
- Interface of resin matrix and BF and interface of BFRP and concrete matrix are sensitive to the chemical and temperature of the environment, affecting the durability of the BFRP reinforced concrete.

Therefore, all future research should be launched the following direction:

- Novel methods of BF surface modification, focus on increasing the alkali resistance of the BF;
- To enlarge the application range of BFRP, researchers should develop new resin matrix materials, especially green material;
- BFRP materials applied in special field application, such as materials have the properties of low-temperature resistance, radiation resistance, high ductility, electromagnetic shielding performance.

Acknowledgments

The authors extend their gratitude to all the publishers mentioned in this paper.

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