Basalt Fiber-reinforced Polymer Properties

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Reducing the fingerprint of infrastructure has become and is likely to continue to be at the forefront of stakeholders' interests, including engineers and researchers. It necessary that future buildings produce minimal environmental impact during construction and remain durable for as long as practicably possible

Keywords: basalt fiber-reinforced polymers ; concrete ; reinforcing bars ; sustainable construction ; durability ; bond to concrete

1. Introduction

Sustainability and durability of building structures are amongst the leading design criteria for new infrastructure. The contribution of the production of cement to the emission of CO_2 and environmental pollution prompted the pursuit of alternative cementitious materials, including, but not limited to, fly ash and slag. Partial replacement of cement with fly ash, slag, and/or silica fume has become a common practice and the mechanical properties of such concrete types have been studied extensively. On the other hand, exclusive use of materials such as fly ash and slag as sole cementitious materials activated using carefully selected alkalis has attracted the attention of researchers. Similarly, traditional reinforcing steel bars, despite their favorable mechanical properties, are associated with significant emission of CO_2 during the manufacturing process, not to mention corrosion that may lead to a loss of cross-section. In the past two decades, interest has been renewed in reinforcing bars made of fiber-reinforced polymers (FRPs). The unidirectional fibers that constitute typically more than 75% by volume are made of glass, carbon, aramid, and, more recently, basalt. Basalt FRP (BFRP) reinforcing steel bars offer numerous favorable properties over traditional reinforcing steel bars, including, but not limited to, high tensile strength, corrosion resistance, and nonmagnetic nature. Studies by [1] concluded that BFRP-reinforced beams have similar global warming potential (GWP) compared to cast-in-place concrete reinforced with 100% recycled carbon steel and, as a result, BFRP-reinforced beams have a limited environmental advantage compared to steel-reinforced concrete beams. On the other hand, concrete beams reinforced with BFRP prestressing bars have much lower GWP compared to beams prestressed with steel bars.

In aggressive environments, traditional reinforcing steel bars are susceptible to corrosion that could influence the structure′s life span. Marine environments and parts of the world where deicing salts must come in contact with concrete are examples of situations where traditional reinforcing steel bars may be subjected to corrosion. It is often less expensive and environmentally friendly to use sea sand for concrete structures that will be in contact with seawater, in which case the noncorroding FRP reinforcing bars would be a durable alternative to traditional steel. The magnetic properties of FRP bars make them suitable for consideration in structural elements surrounding magnetic resonance imaging (MRI) units and any other equipment sensitive to magnetic fields. Sea sand typically contains chloride irons that may cause corrosion of reinforcing steel bars. Design guides for concrete reinforced with FRP bars, such as ACI440.1R-15 [2], were developed and are continuously updated. Most design guides explicitly refer to FRP bars made of glass (GFRP), carbon (CFRP), or aramid (AFRP) fibers, which were studied extensively. However, ACI440.1R makes no explicit reference to concrete-reinforcing FRP bars made of basalt fibers. BFRP bars offer many favorable properties such as high temperature resistance and favorable behavior in an acidic environment, in addition to ease of manufacturing. BFRP reinforcing bars typically fall between CFRP and GFRP bars in terms of strength and stiffness. Studies have shown that GFRP reinforcing bars can be used effectively as corrosion-resistant reinforcement for hollow concrete columns (HCCs) that have many applications, such as bridge piers [3]. Glass fibers were also used successfully in nonbuilding structures such as composite sleepers for railway tracks [4]. GFRP reinforcing bars are susceptible to simulated alkaline environments, resulting in degrading of the fiber–matrix interface [5].

2. Composition and Properties of Basalt Fiber-Reinforced Polymers (BFRPs)

A basalt FRP bar is a composite material consisting of rigid polymer resin bounding unidirectional basalt fibers. Basalt fibers are produced by melting queried and crushed natural volcanic basalt rocks at a temperature of nearly 1400 °C [6]. The molten rock is extruded through small nozzles to produce continuous filaments of basalt fibers ranging in diameter from 13 to 20 µm. A critical process in the manufacturing of fibers, in general, is known as fiber sizing. Sizing involves the application of a thin layer of mainly organic material known as the size to the surface of the fiber. Most importantly, the short-term and long-term performance of FRP bars is critically influenced by the optimization of the fiber sizing as well as the fiber–matrix interface [7]. The fiber sizing film consists of a film former and a coupling agent. The film former protects, lubricates, and holds the fibers together while ensuring their separation when the fibers come in contact with the resin. The coupling agent, typically an alkoxysilane compound, serves to bond the fibers to the matrix resin [8]. However, the composition and process of applying the fiber size layer vary significantly amongst manufacturers, resulting in variations in properties of FRP bars made of the same type of fiber and sometimes the same resin type.

The resulting composite material, consisting of polymeric resin and fibers, offers numerous favorable properties, including, but not limited to, high tensile strength, with applications in building new structures, such as FRP reinforcing bars, or retrofitting/strengthening deficient existing structures using FRP sheets and/or strips [9].

BFRP bars are commonly manufactured through the pultrusion process, which involves pulling the continuous fibers through a die that is circular in cross-section and contains resin. The FRP bars are formed once the resin cures (thermosets) in the die. The amount of basalt fiber in BFRP bars is not standardized, but the fiber content most frequently reported in the literature falls in the range 75% to 90% [10][11]. Automated wet-layup is another method to manufacture BFRP bars that reportedly offers the same degree of variation in mechanical properties as the pultrusion process [12]. As the resin has much lower strength compared to the fibers, the tensile strength and stiffness of BFRP bars varies depending on the overall volume of fibers to volume of FRP. Vinyl ester and isophthalic polyester are common types of resin matrix used to manufacture BFRP.

FRP bars are more sensitive to fire than steel bars. However, because the FRP bars are embedded in concrete, they do not contribute to fire severity nor toxicity. Nonetheless, FRP-reinforced concrete elements have lower resistance to fire compared to steel-reinforced concrete elements [13]. More importantly, at temperatures close to the glass transition temperature of the polymer, T_g, mechanical properties of the polymer deteriorate, and its ability to transfer stresses between the fiber and the surrounding concrete decreases [14]. The structural implication is the degrading of the bond strength between FRP bars and concrete. Glass transition temperatures for most resins used to manufacture FRP reinforced bars range from 93 °C to 120 °C.

BFRP bars may be 2.3 times stronger or more , in terms of ultimate strength (f_u), than traditional steel reinforcing. However, the modulus of elasticity of traditional steel may be 3.5 times or greater than BFRP. BFRP elastic moduli varying from 44.5 to 71 MPa were reported in the literature [11][15][16], depending on resin type, manufacturer, and sometimes bar diameter. Unlike traditional carbon steel, FRP bars do not exhibit yielding, as shown in Figure 1. Tensile strength reported in the literature varied from 1100 to 1565 [11][15][16]. These wide ranges of values for the tensile strength and modulus of elasticity were reported for BFRP produced by different manufacturers, which not only reflect variation in the properties of resin but also manufacturing. Nonetheless, variability in moduli and strength were reported in BFRP bars produced by the same manufacturer, although with less dispersion. In comparison, due the homogeneity of steel, the modulus of elasticity of and tensile strength can largely be assumed to be constant for all practical purposes.

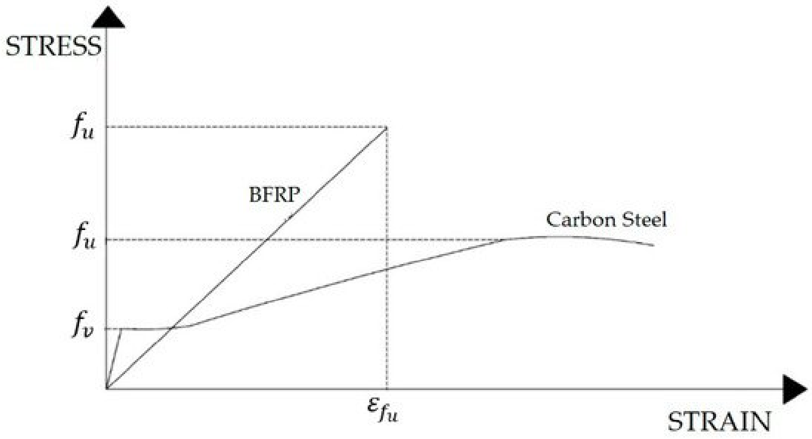

Figure 1. Typical stress–strain relationship of carbon steel and basalt fiber-reinforced polymer (BFRP) bars.

It is to be expected that the external surface configuration of BFRP bars affects the effectiveness of bonds to the surrounding concrete. The external surface may be helically wrapped with fibers, as shown in Figure 2, with or without additional sand coating. BFRP bars may also have deformations (ribs or indents) without helical fiber wrapping, with or without sand coating. The most common are ribbed BFRP bars with helical fiber wrapping and sand coating. Kevlar fibers (0.4 mm in diameter) are often used for helical wrapping [17]. Figure 2 shows schematics of various FRP bar configurations. Ribbed and helically wrapped BFRP bars that are sand coated provide the highest bond strength, as will be discussed later in this article. Nonetheless, the method of sand coating appears to also affect the bond strength although no standardized method of sand coating is available. Sand coating of FRP reinforcing bars was used before the advent of BFRP bars to enhance bond strength and was proven to enhance bond strength [18]. It is typical to apply the helically wound fibers and sand coating after the pultrusion process, but before the thermosetting of the polymeric resin [19].

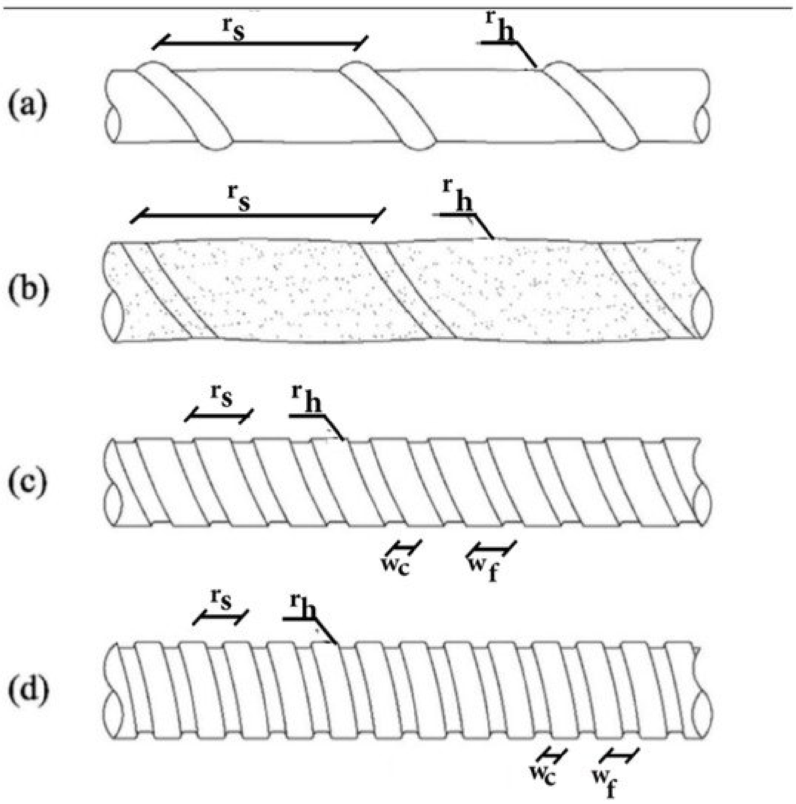

Figure 2. Fiber-reinforced polymers (FRP) bar surface configurations: (**a**) Ribbed and helically wrapped, (**b**) ribbed, helically wrapped, and sand coated, (**c**) indented, (**d**) ribbed.

As a result of a lack of standardization, the increase in BFRP bar area due to sand coating is inconsistent and may vary with bar diameter, even when produced by the same manufacturer [20]. Similarly, tensile strength and modulus of elasticity also varied from one bar size to another in BFRP obtained from the same source. For wrapped BFRP bars without sand coating, variations in bond strength were also reported based on rib size and rib spacing [21], but further studies are needed to quantify the observation. BFRP bars with woven surfaces (no ribs) are manufacturing for use as prestressing bars, with lower bond strength compared to ribbed bars [22].

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