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A refined prediction method for the long-term performance of BFRP bars serviced in field environments

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HIGHLIGHTS

- A refined prediction method for the long-term performance of BFRP bars.
- The effects of service year, concrete-wrap, environmental humidity and seasonal temperature fluctuations are considered.
- The environmental reduction factors for a BFRP bar are predicted.

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ABSTRACT

A new kind of advanced composite reinforcement, basalt fiber reinforced polymer (BFRP) bars, has not yet been widely adopted by design codes/guidelines worldwide, likely due to the lack of reliable long-term performance data. This paper proposed a refined prediction method for the long-term performance of BFRP bars that considers the effects of service year, concrete-wrap, environmental humidity and seasonal temperature fluctuations. According to the available accelerated aging tests data in the literature, the environmental reduction factors (ERFs) for a BFRP bar used as a concrete internal reinforcement in a field environment are predicted. The results showed that the ERF for BFRP bars can be recommended to be 0.84 or 0.72 for an RH < 90% and a moisture saturated environment (RH = 100%), respectively.

1. Introduction

Fiber reinforced polymer (FRP) composites are increasingly used in civil engineering due to their excellent corrosion resistance, high strength/stiffness to weight ratio, and ease of fabrication. Among them, FRP bars are used to replace steel bars in reinforced concrete (RC) structures to overcome the corrosion problems encountered in harsh environments. Traditional FRP bars mainly refer to glass, aramid and carbon FRP bars, with GFRP bars, which are cost efficient, most widely being used. Recently, basalt fiber reinforced polymer (BFRP) bars have been developed and are being widely investigated as a promising supplement. However, FRP bars, especially cost-effective GFRP and BFRP bars, are not completely immune to harsh environmental conditions. For FRP bars to be used as internal reinforcement, concrete could be unfavorable due to the inner pore alkaline solution that exists in moist environments. Therefore, long-term performance evaluation of FRP bars over a real-life cycle needs to be fully carried out.

Accelerated aging tests in the laboratory are often used to evaluate the durability of FRP bars subjected to different exposure conditions, e.g., freeze-thaw cycling, wet-dry cycling, distilled water, acidic solution, alkaline solution, saline solution, etc. [1–5]. Then, based on the degradation data from the aging tests, the long-term performance for a real-life cycle is estimated, and an environmental reduction factor (ERF) is provided for use in the design code. The most commonly used and easiest accelerated test method is to directly immerse bare FRP bars in corrosive solutions (acid, alkali, salt, or water) under elevated temperatures. The Arrhenius relation is then used to achieve a long-term performance prediction [6,7]. For FRP bars used as an inner reinforcement, an artificial alkaline solution is used to simulate the inner pore alkaline environment that is present in concrete [8]. However, numerous studies have shown that direct immersing in a liquid solution will seriously accelerate the degradation rate, making the laboratory test results

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quite different from what is observed in an actual service environment.

FRP bars are embedded in a concrete cover when used as internal reinforcement in a field environment. Even if the concrete structure is in a 100% relative humidity (RH) environment, the penetration rate of the ions to the FRP bar in a concrete solid medium is significantly slower than if the bar is immersed in liquid media. Robert [9] reported that, in the same condition, the degradation of bare GFRP bars directly exposed to an alkaline solution was three times greater than that of concrete-wrapped GFRP bars exposed to tap water. Furthermore, the concentration of H_2O/OH^- in concrete depends on the moisture content of the concrete, which is closely related to the environmental humidity in the actual service environment [10]. Therefore, it is also necessary to consider the influence of the environmental humidity when predicting the long-term performance of FRP bars in an actual service environment. Additionally, existing studies normally use the mean annual temperature (MAT) to represent the actual service environmental temperature for prediction models based on the Arrhenius relation. In fact, the temperature fluctuates throughout a year. The higher the latitude, the greater the temperature fluctuation will be. In the Arrhenius relation, the relationship between the material degradation rate (k) and the reciprocal of the temperature ($1/T$) is exponentially, rather than linearly. Hence, further analysis for the error caused from using the MAT as a representative value is required.

In this paper, based on the model first proposed by Huang [10] that considers the effects of service year and RH, we propose a more refined long-term prediction method that addresses the effects of concrete-wrap and seasonal temperature fluctuations. Using the proposed model and the current available aging data on bare BFRP bars conditioned in an alkaline solution, the long-term performance of BFRP bars in a field concrete environment are preliminarily predicted.

2. Backgrounds

2.1. Degradation mechanism

It is known that FRP bars are composed of three components: fibers, matrix and the fiber/matrix interface. For the resin matrix, the ester groups are prone to degradation by hydrolysis when free hydroxyl ions (OH^-) diffuse inside. The penetrating water molecules act as a plasticizer, resulting in swelling stresses, which causing matrix cracking and fiber/matrix debonding. For the fibers, the diffusion of the alkali ions out of the fiber structure, known as "leaching", and the breaking of the Si—O—Si structure as a result of alkali attack, known as "etching", may cause notching and embrittlement of the fibers [11,12]. In addition, for the fiber/matrix interface, which is an inhomogeneous region with a thickness of approximately 1 μm, the degradation is complicated and is treated as the weakest link in the system and can degrade easily. Numerous studies on the degradation mechanism all agree that debonding caused by the degradation of the fiber/matrix interface is critical to the durability performance of FRP bars [13–15]. Thus, improving the anti-permeability of the resin matrix and improving the hydrolytic stability of the interface layer are two important aspects that can improve the durability of FRP bars. For FRP bars embedded in concrete as inner reinforcement, the OH^- ions mainly come from the pore solution induced by moisture absorption.

2.2. Arrhenius relation

To forecast the long-term performance of FRP bars in a civil engineering environment based on accelerated short-term aging test data, the popular Arrhenius relation has been adopted by researchers. The degradation rate is expressed as:

$$k = A\exp\left(-\frac{E_a}{RT}\right) \tag{1}$$

$$\ln\left(\frac{1}{k}\right) = \frac{E_a}{R}\frac{1}{T} - \ln(A) \tag{2}$$

where k is the degradation rate (1/time), A is a material and degradation process constant, E_a is the activation energy, R is the universal gas constant, and T is temperature (in Kelvins). The basic assumption of the Arrhenius relation is that the single dominant degradation mechanism for the material does not change with time and temperature during the exposure, whereas the rate of degradation accelerates with the increase in temperature.

2.3. Degradation laws

Different mathematical equations describing the relationship between the strength retention and aging time have been proposed by researchers and are based on different theoretical foundations. Davalos [16] stated that there are generally four types of strength degradation models for FRP bars and the prediction procedures for those models are all based on the Arrhenius equations shown in Eqs. (1) and (2). Serbescu [17] claimed that there are mainly two approaches for the performance prediction of FRP bars: measuring either "strength retention" or "moisture absorption". The following is a brief description of the four widely used mathematical models present in the literature.

Tannous [18] proposed the "moisture absorption" model:

$$Y = 100\left(1 - \frac{\sqrt{2DCt}}{r_o}\right)^2 \tag{3}$$

where Y is the strength retention (%) in this and all other equations presented in this paper, t is the exposure time, D is the diffusion coefficient, C is the concentration of the solution, and r_o is the radius of the FRP bar. However, this model assumes that the affected area is completely degraded and unable to carry any load, which may not be entirely true. Additionally, the determination of the coefficients D and C from moisture absorption tests makes its use rather complicated. In addition, this equation cannot be used when the solution is distilled water, as the value of C would be zero.

The second model adopted an exponential relationship between the strength retention and aging time. Debonding at the fiber/matrix interface is assumed to be the major degradation mechanism in this model as is described via with the following equation:

$$Y = 100\exp\left(\frac{-t}{\tau}\right) \tag{4}$$

where τ is a fitted coefficient using the least squares method. It is worth noting that the tensile strength retention (%) at an infinite exposure time is assumed to be zero in this model. This model was originally used to predict the flexural strength retention of composite laminates and had been adopted by many scholars [15,16,19] to predict the long-term performance of FRP bars.

The third model adopted a linear relationship between the strength retention and the logarithm of the aging time via:

$$Y = a\log(t) + b \tag{5}$$

where a and b are regression constants. Litherland [20] first developed this model and successfully predicted the residual strength of glass fiber concrete (GRC) using this model. It is worth noting that Eq. (5) is a widely used degradation model [6,9,21], but does not hypothesize on the degradation mechanism.