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Durability of glass fiber-reinforced polymer bars conditioned in moist seawater-contaminated concrete under sustained load

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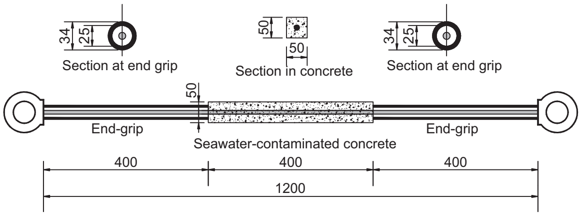
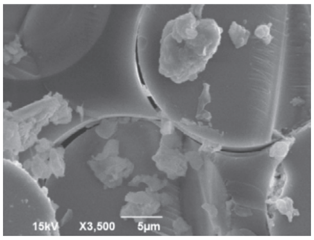
HIGHLIGHTS

- Durability of GFRP conditions in concrete environment under load was investigated.
- GFRP bars experienced creep rupture were analyzed for microstructure changes.
- New durability design models for GFRP bars in severe environments were developed.

GRAPHICAL ABSTRACT





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ABSTRACT

The combined effect of sustained loading and moist seawater-contaminated concrete environment on the durability performance of two types of glass fiber-reinforced polymer (GFRP) bars was investigated. A sustained load of 25% of the ultimate tensile strength was applied to concrete-encased GFRP bars immersed in tap water for up to 15 months at temperatures of 20, 40, and 60 °C. None of the loaded specimens conditioned at 20 °C were creep-ruptured during conditioning. In contrast, many bars were creep-ruptured during conditioning at the higher temperatures of 40 and 60 °C. At a conditioning temperature of 20 °C, Type I and II GFRP bars retained 84 and 70% of their original tensile strength after 15 months of conditioning under a sustained load. At the higher temperature of 60 °C, trivial tensile strength retentions of 15 and 12% were recorded for Type I and Type II GFRP bars, respectively, after 15 months of conditioning under a sustained load. A comparative analysis between results of loaded and unloaded specimens demonstrated the detrimental effect of the presence of a sustained load during conditioning on the tensile strength retention of GFRP bars. The detrimental effect of the sustained load was intensified at the higher temperatures. The accelerated aging test data along with Arrhenius concept were employed to develop a durability design model that can predict the tensile strength retention of both types of GFRP bars in moist seawater-contaminated concrete.

1. Introduction

The use of glass fiber-reinforced polymer (GFRP) bars as a replacement to the traditional steel reinforcement would eliminate corrosion problems and prolong service life of reinforced concrete structures [1–3]. Even with their superior performance and relatively competitive cost, the use of GFRP has been hindered in regions of high temperature and high relative humidity due to concerns about their durability performance under sustained loading in such harsh environmental conditions.

GFRP bars conditioned in simulated pore solution (pH 13.5) under a sustained load of 10% of the ultimate tensile stress (UTS) lost 70% of their initial tensile strength after 9 months of conditioning [4]. Increasing the sustained load to 15 and 25% of UTS resulted in a creep-rupture of GFRP specimens within 100 and 20 days,

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respectively [4]. Nkurunziza et al. [5] assessed the creep behavior of GFRP reinforcing bars enclosed by either an alkaline solution (pH 12.8) or de-ionized water (pH 7.0) at two percentages of sustained tensile stresses of 25 and 38% UTS for 417 days. While the tensile strength of the GFRP bars after conditioning in de-ionized water was unaffected, conditioning in alkaline solution under sustained loading of 25 and 38% of UTS caused tensile strength reductions of 12 and 32%, respectively. In either loading case, conditioned specimens did not experience any creep rupture [5]. Debaiky et al. [6] studied the combined effect of sustained loading and harsh environment on the performance of GFRP bars immersed in water and alkaline solution. The reduction in tensile properties of sand-coated GFRP bars conditioned at elevated temperatures in alkaline and water environments under sustained load were in the range of 7–13%.

The presence of sustained load during conditioning in concrete or mortar-wrapped GFRP bars could intensify degradation of GFRP bars [7,8]. Increasing the stress levels caused a shift in the degradation mechanism of GFRP from being influenced by the diffusion rate of alkaline solutions to being controlled by solution transport through resin cracks at higher stress levels [9]. Davalos et al. [10] investigated the performance of GFRP bars exposed to concrete environment with and without displacement-controlled load for up 210 days at temperatures between 20 and 60 °C. None of the GFRP bars experienced creep-rupture. Loaded and unloaded specimens exhibited similar tensile strength retentions with conditioning at 60 °C being most critical [10].

Long-term performance of concrete specimens reinforced with GFRP bars exposed to different environmental conditions has also been investigated [11–14]. Experimental results indicated that the strain in GFRP bars was highest in RC beams subjected to seawater at 40 °C for 300 days with cyclic wetting and drying [11]. Fergani et al. [12] reported that the tensile properties of GFRP bars embedded in concrete was critically affected by exposure to elevated temperature of 60 °C rather than sustained stress levels (up to 5000 $\mu\varepsilon$). Microstructure investigations of these GFRP bars showed a degradation of the resin matrix, formation of microcracks due to a hydrolysis reaction [13]. Additionally, a stress level corresponding to in-service conditions complied with limits set by current guidelines, while higher loads and wet conditioning resulted in excessive deflections and crack widths that could not be predicted by codified models [14]. In other work, Laoubi et al. [15] investigated the behavior of GFRP bars imbedded in concrete beams and subjected to sustained load and 100, 200, and 360 freeze-thaw cycles. The authors concluded that the coupled action of sustained loading and harsh conditioning had no significant effect on the performance of the GFRP reinforcement or the concrete beams. On the contrary, it was found that the limits set by ACI 440.1R [16] were conservative. Robert and Benmokrane [17] reported data on GFRP specimens that were preloaded up to 80% of the UTS prior to conditioning at temperatures between 23 and 50 °C for 240 days. Results highlighted a progressive hydrolysis reaction and up to 11% tensile strength reduction [17]. Robert et al. [1], Almusallam and Al-Salloum [18], and Trejo et al. [19], concluded that GFRP bars imbedded in concrete exposed to harsh environments or alkaline solutions did not properly simulate those left in natural conditions.

Despite the significant amount of research conducted in this area, the tensile strength reduction of GFRP bars caused by different environmental exposures and levels of sustained loading has witnessed wide variations. While several studies have been conducted on durability of GFRP bars in concrete environment, the long-term performance of GFRP bars in seawater-contaminated concrete under sustained load has received little attention. Seawalls, marine docks and waterfront/offshore concrete structures are continuously exposed to seawater and/or seawater splash. Although seawater is not used in steel-reinforced concrete structures because of the corrosion problem, there might be a potential to use seawater in concrete structures reinforced with non-metallic corrosion-resistant composite reinforcement such as GFRP bars. The use of seawater in steel-free concrete structures would preserve natural resources and promote sustainability, particularly in desert areas where water is scarce and expensive. More research is, therefore, needed to examine the behavior of GFRP in such environments and facilitate the development of a durability design model of GFRP reinforcing bars in seawater-contaminated concrete structures.

This paper aims to provide an improved understanding into the durability performance of two different types of commercially-produced GFRP bars conditioned in in moist seawater-contaminated concrete under a sustained load. The ACI 440.1R [16] limits the tensile stress in GFRP under service conditions to 14% of UTS, considering the strength reduction factor for environmental exposure. Specimens of the present study were conditioned at a stress level of 25% of UTS to investigate the possibility of increasing the allowable limit set by the ACI 440.1R [16]. Tensile strength retentions of GFRP bars conditioned under a sustained load were measured. Bars experienced creep rupture were analyzed for microstructure changes while highlighting the influence of hydrolysis reaction on mechanical and durability properties. New durability design models were developed based on Arrhenius concept to predict the long-term tensile strength retention of GFRP bars in moist seawater-contaminated concrete.

2. Material details

2.1. GFRP bar specimens

In this study, two types of ribbed GFRP bars made of high strength continuous glass fibers impregnated in epoxy resin were used as shown in Fig. 1. Physical and mechanical properties of Type I and II GFRP bars and corresponding ASTM standard procedures are summarized in Table 1. Both types of GFRP bars had similar mass fraction of glass fibers. Such fiber content included fibers and fillers, as reported in ASTM D3171 [20]. As shown in Table 1, the voids content in Type II GFRP was higher than that of Type I. Also, the as-received ultimate tensile strength was higher in Type II than in Type I GFRP.

2.2. Surrounding concrete

GFRP test specimens were cut into 1200 mm lengths. The test region had a length of 400 mm, given the minimum length set by the ACI 440.3R [21] as 40 times the bar diameter. The middle third (test region) was encased by 50 × 50 mm seawater-contaminated concrete to simulate concrete exposed to seawater in field conditions. The ACI 318 building code [22] requires a minimum concrete cover of 40 mm for steel-reinforced concrete structures, with a steel bar diameter ≤ 16 mm, exposed to earth or weather. The use of GFRP bars would eliminate corrosion problems; hence, a thinner concrete cover maybe adequate for GFRP-reinforced concrete structures. Further research is certainly needed to investigate the effect of varying the thickness of the concrete cover on the durability of GFRP bars in severe environments. The 400 mm-long end regions of the bars were used as grips for applying the sustained load. Table 2 presents the mixture proportions of the surrounding concrete. The main binding agent of concrete was ASTM Type I ordinary

Fig. 1. GFRP bars used in the current study.