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Experiments and probabilistic models of bond strength between GFRP bar and different types of concrete under aggressive environments

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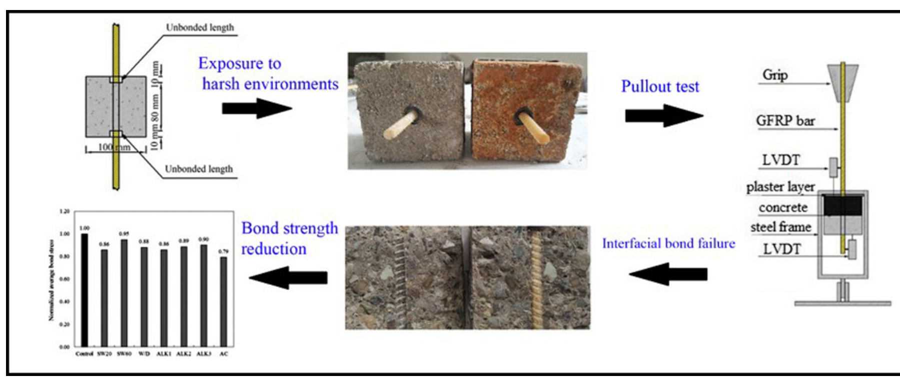
HIGHLIGHTS

- Bond strength degradation of GFRP bars under aggressive environments is investigated.
- High strength and self-compacting concrete showed appropriate bond durability.
- Bond strengths of light-weight concrete showed considerable reductions.
- Maximum development lengths were obtained for acid conditioned specimens.

GRAPHICAL ABSTRACT



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ABSTRACT

Bond durability of FRP bars and concrete is an important issue to the overall integrity and long-term performance of a strengthening structure. This paper examines the bond durability of GFRP bars embedded in different types of concrete (Normal, self-compacting, light weight, and high strength) exposed to aggressive environments, namely, sea water, alkaline, and acid. A total of 132 specimens were tested in direct pull-out. The development lengths of both control and conditioned specimens were obtained and compared to the current standards. The results revealed bond strength reductions of 0–21% for the light weight, 1–16% for the normal, 5–9% for the high strength, and 4–12% for the self-compacting concrete in different environmental conditions. Furthermore, the specimens immersed in acid solution had the maximum development length. According to the results, using concrete with higher strength and density may lead to a higher bond durability of GFRP bars and concrete in aggressive environments. Finally, the contribution of variable parameters in bond strength reduction was investigated by Bayesian regression method.

1. Introduction

For the last 20 years, using non-corrodible fiber-reinforced polymer (FRP) reinforcement has become one of the most effective alternative solutions for overcoming the corrosion of reinforcing steel, which is an important problem in concrete structures built in aggressive environments [1–3]. High strength-to-weight ratio, high stiffness-to-weight ratio, low cost-to-performance ratio, good fatigue properties, ease of handling, and primarily resistance to corrosion have made the FRP bars an appropriate alternative material to steel reinforcement in concrete structures [4–6].

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Glass-fiber-reinforced polymer (GFRP) bars are being remarkably noticed by construction industry because of their lower cost compared to other types of FRP materials [7,8]. There are many available research on structural application and parameters affecting durability of FRP materials [9,10]. Durability of the GFRP bars remains unresolved under different harsh environmental conditions, such as alkaline solutions, acidic solutions, sea water, and elevated temperatures [11,12].

According to ACI 440.2R-08, keeping records of the current ambient conditions on the site, including temperatures, general weather observation, and relative humidity for a minimum of 10 years, during fabrication of a FRP system is recommended [13]. Since the FRPs are known as novel construction materials, their durability is simulated by accelerated aging methods, such as immersion in alkaline solutions, acidic solutions, sea water, and elevated temperatures in order to investigate the long-term behavior of FRP materials under different environmental conditions [14–19]. Several studies were carried out to investigate the long-term effects of different environmental conditions on the GFRP bare bars [14,20,21]. Sawpan et al. [20] studied the elastic modulus of a GFRP bar exposed to alkaline environment (pH = 13) at 60 °C during 14 months and predicted the quasi-static tensile, quasi-static flexural and dynamic mechanical moduli to be reduced by about 7%, 5% and 15%, respectively, after 100 years in alkaline environment at 60 °C.

Bond strength has been commonly accepted as a primary factor that should be considered for developing design recommendations for steel or FRP bonded concrete [22,23]. Variety of materials geometry and properties are known to be the reasons of significant difference in bond mechanisms between concrete and FRP bars from that of steel [24,25]. Bond durability is an important issue to the overall integrity of the strengthening structure and consequently, to its long-term performance [26,27]. Therefore, preventive measures shall be carried out to assure a sufficient bonding strength [28]. The bond performance of the FRP bars with concrete is obviously different from that of the steel bars. The bond strength of steel bars with concrete is mainly controlled by the shear strength of the concrete while for FRP bars, it is controlled by both the surface of the bar and the shear strength of the concrete [24,29].

Considering that the aggressive environments mainly attack the bar's surface, the bond performance between the FRP bar and concrete may be particularly affected. However, few experimental data is available on the bond effects related to different environmental conditions [16,26,28,30,31]. Robert and Benmokrane [31] did not observe any decrease in the ultimate bond strength of GFRP bars embedded in concrete after 28 days of immersion in a saturated Calcium hydroxide ($Ca(OH)_2$) solution at a temperature of 80 °C followed by 5 days of drying. Al-Dulaijian et al. [32] conducted direct pull-out test for two types of GFRP rods. Deionized tap water, 10% ammonia (NH_3) solution as an alkaline environment, and 0.6% acidic acid ($C_2H_4O_2$) as an acid environment were used. The results showed that the alkaline solution at elevated temperature had the most aggressive effect on bond strength of GFRP rods and concrete.

Chen et al. [14] presented durability evaluations of different FRP bars under five simulated exposure conditions, tap water, alkaline solution with pH = 13.6, alkaline solution with pH = 12.7, ocean water, alkaline solution with chloride ion (pH = 13). They also conducted bond tests on FRP bars embedded in both normal concrete (NC) and high performance concrete (HPC) to investigate the effect of concrete type on durability issues of FRP bars. The results revealed that NC environment (pH = 13.6) was more aggressive to GFRP bars than HPC environment (pH = 12.7).

Based on the literature review, it can be found that there are significant variations between the reported strength reduction of GFRP bars after environmental exposure, which shows that in these studies, the simulated environments, the period of exposure, the type of GFRP bars, and test programs in each phase can alter widely. Hence to provide complete information of GFRP composites' durability more experimental data is needed.

Since very little experimental test data is available on the bond characteristics of GFRP bars embedded in different types of concrete under different environmental conditions, this research presents an experimental study for investigating the effect of various simulated aggressive environmental conditions on the bond strength of GFRP bars embedded in four different types of concrete. Moreover, it should be mentioned that, so far, specific environmental conditions such as the conditions used in the present study, have not been included in design standards and specifications. Therefore, the findings of this study will contribute to better understand the bond durability of GFRP bars embedded in different concrete types subjected to different harsh conditions and thus to modify the FRP standards and guides for their reduction factors.

2. Experimental program

Series of specimens were tested to investigate durability of bond performance of GFRP bars embedded in four types of concrete; normal concrete (NC), high strength concrete (HSC), light weight concrete (LWC), and self-compacting concrete (SCC). To obtain the bond strength durability of the specimens exposed to nine different environmental conditions, direct pull-out test was conducted.

2.1. Material

The commercial GFRP bars used in this study were composed of 75% E-glass and 25% vinylester resin by volume, produced by the pultrusion process with the nominal diameter of 8 mm (Fig. 1). The cross-sectional area of the bars obtained from immersion test was 50.89 mm^2. In this study the nominal diameter of the bars was used. The material properties of the GFRP ribbed bars, as provided by the manufacturer, are presented in Table 1.

Four types of concrete were casted using ordinary Type I Portland cement (CEM I 42.5 N). Three 150 × 300 mm cylinder specimens for each type of concrete were prepared and tested after the exposure process over 150 days. The average compressive strength was reported. Table 2 shows the concretes mix design and properties. It should be noted that to produce light weight concrete, lightweight expanded clay aggregate (LECA) made by rotary kiln process produced by LECA factory (Tehran, Iran), was used as coarse aggregate [33]. Dry density (kg/m^3) and absorption percentage (%) of LECA were 1150 and 25, respectively. The average density and permeable porosity of light weight concrete were 1585 kg/m^3 and 30%, respectively, which according to [34], can be classified as a structural lightweight concrete. It is also worth mentioning that, the high strength concrete naming was used for

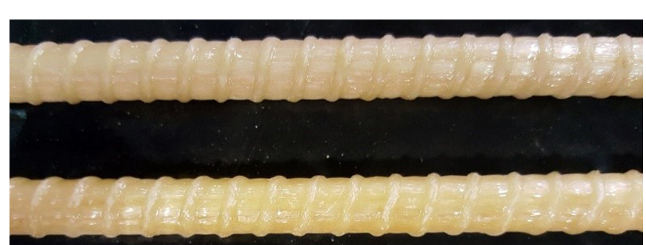

Fig. 1. GFRP bars.