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Experimental study on bond durability of glass fiber reinforced polymer bars in concrete exposed to harsh environmental agents: Freeze-thaw cycles and alkaline-saline solution

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ABSTRACT

This study presents an experimental investigation on the bond durability of GFRP bars in concrete when subjected to harsh environments. The pullout specimens having different concrete covers were designed based on a created database to demonstrate the generality of the current experimental program. The freeze-thaw (FT) cycles, alkaline-saline (AS) solution, and both coupled effects were used to simulate environmental conditions in cold regions. The durability performance in terms of the failure mode, weight loss, relative dynamic modulus of elasticity, durability factor, as well as the bond strength, were measured and investigated accordingly. The test results revealed that the concrete cover with three times of the bar diameter was not sufficient to resist the environmental agents when exposed to weathering, including FT cycles, in which all the pullout specimens failed by concrete splitting. The coupled scenario of FT cycles and AS solution was observed to be the worst case among all the environmental conditions. Moreover, the analytical models: modified Bertero-Eligehausen-Popov (mBPE) model and Cosenza-Manfredi-Realfonzo (CMR) model, were calibrated by considering the environmental influences based on the experimental data to better demonstrate the degradation of GFRP-concrete bond.

1. Introduction

Conventional reinforced concrete (RC) structures subjected to aggressive environments are prone to corrosion-induced damages. Following the reduction of cross sectional area of reinforcing steel bar [1], the build-up of corrosion product, such as the ever-growing and expanding rust, results in cracking or even spalling of concrete. As a result, the damages degrade the bar-concrete interfacial bond, and thus have adverse impacts on the load-carrying capacity and long-term durability of RC structures. The reinforcement corrosion is the leading causes of malfunction or even failures of RC structures in the United States, Canada and most European countries [2–4]. To overcome this drawback, glass fiber-reinforced polymer (GFRP) composites have been recognized due to their superior corrosion resistance as alternative reinforcing bars to be implemented in the RC structures [5–8].

Wide acceptance and application of GFRP bars in construction industry requires comprehensive investigation of their structural behavior [9]. Bond development is of great importance to ultimately achieve the force transfer mechanism at the bar-concrete interface, thereby dominating the integrity and ductility of the structural member. Due to different material and mechanical behaviors, the bond mechanism of FRP bar-concrete is more complicated and quite different from that of steel reinforcement. Critical factors and their impacts on failure mode and bond strength of GFRP bars to concrete, have been extensively investigated in Refs. [10–15] and summarized in Ref. [1]. Besides, bond durability under harsh environmental agents, such as alkaline or saline solutions, elevated temperatures, and freeze-thaw (FT) cycles, also plays a crucial role in the long-term performance of the concrete structures reinforced with GFRP bars.

Bond degradation mechanism is a complex process that normally initiates from the bar surface. The two constituents of GFRP bars, glass fibers and resin matrix, tend to deteriorate in strength when exposed to wet alkaline environments. Considering that concrete presents highly alkaline with a pH of about 12.5–13.5, this may not only deteriorate the resin matrix due to hydrolysis of the ester group and hydroxide ions, but also damage the glass fibers

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due to leaching and etching [16,17]. Thus, it requires that the resin should be fully cured to provide appropriate protection to fibers. On the other hand, moisture could diffuse through the resin up to the fiber-matrix interphase or even to the fibers, resulting in hydrolysis and plasticization of the resin, as well as a bond loss of the fiber-matrix interphase. As the major load-carrying component of GFRP composites, glass fibers may even deteriorate in properties due to the moisture extracting ions from the fibers [18,19]. Moreover, bond degradation of GFRP bars to the surrounding concrete become more serious in the presence of moisture containing chloride ions [20,21]. Such phenomenon is inevitably encountered for structures in cold regions, where the concrete pore solution may be contaminated with chloride ions as normally found in de-icing salts [22]. In addition, FT cycles, another environmental agent, also need to be considered for those structures [23–26]. Damage in concrete due to FT cycles depends on the saturation of concrete. The water can permeate through the voids (or new developed micro-cracks) in concrete matrix, while the growth of ice crystals during repeated freezing process generates high pressure to concrete, thus leading to microcracks in concrete. As a result, this will break down the bar-concrete interface. Also, presence of concrete cracks also yields a low confinement to GFRP bar and thus causes less bond strength.

Therefore, this study aims to investigate the bond durability of GFRP bars to concrete, especially in cold regions. In order to simulate and approximate field conditions that the structures normally experience in service-life stage, GFRP bars embedded in concrete were designed and exposed to different weathering: a) FT cycles, b) alkaline solution contaminated with chloride ions were considered; and (c) elevated temperature to accelerate the degradation rate. Some critical indices associated with the environmental conditioning, such as the weight loss, the relative dynamic modulus of elasticity and durability factor, and the bond strength reduction, were measured to evaluate the durability performance of the GFRP-concrete elements. Moreover, the analytical models were integrated with experimental data to better demonstrate the degradation of GFRP-concrete bond.

2. Background and research to date

2.1. Bond durability

It is well established that aqueous solutions with high pH can reduce the tensile strength of bare GFRP bars despite test results showed great differences in Refs. [27–31]. Also, considerable studies have gone into various environmental attacks on the bond strength of GFRP bars. However, the combined effect of the environmental agents including alkaline solution, saline solution, and freeze thaw cycles, remains unsolved or even holds contrary opinions.

Chen et al. [16] used several types of solutions, the tap water, alkaline solutions with respective pH of 12.7 and 13.6, saline solution, and alkaline solution contaminated with chloride ions, to investigate the durability of bare GFRP bars and GFRP-concrete elements. Those specimens also experienced FT cycles and wet-dry cycles before testing. Significant reductions in tensile strength and bond strength were observed for the respective bare and embedded GFRP bars. Alkali attack was stated to be more serious than the FT cycles and wet-dry cycles. Davalos et al. [9] reported bond performance of GFRP bars in concrete subjected to different environmental conditions: tap water at normal temperature and 60 °C, thermal cycles ranging from 20 to 60 °C. They reported that there were 0–20% reductions in bond strength being observed for the GFRP bars. Similar results of the bond strength reduction can also be found in Ref. [32]. Fursa et al. [33] conducted experiments on sixteen GFRP-concrete samples subjected to FT cycles. They used the electric response to evaluate the bond strength, and found that the bond strength reduced nearly 50% after 18 FT cycles ranging from −40 to 20 °C.

On the contrary, Mufti et al. [34,35] conducted studies on five field GFRP reinforced concrete bridge structures exposed to natural environments for durations of five to eight years. The environmental conditions encompassed FT cycles, wet-dry cycles, de-icing salts, thermal range from −35 to 35 °C. The GFRP bars in those selected demonstration structures were all composed of E-glass and vinyl ester resin. The analysis results stated that the structures maintained a good bond at the GFRP bar-concrete interface and no degradation was observed by either optical microscope or Fourier transformed infrared spectroscopy. Robert and Benmokrane [36] performed experimental investigation on the bond durability of GFRP bars embedded in concrete. The specimens were exposed to tap water at different temperatures (23, 40, 50 °C) for three immersion durations (60, 120, 180 days). It was concluded that the bond strength decreased as the exposure durations increased whereas minor reductions of the bond strength were observed with increasing the exposure temperature. They also conducted experiments of mortar-wrapped GFRP bar specimens immersed in saline solutions with 50 °C for 365 days and 70 °C for 120 days [7]. The micrographs showed that no significant damage was captured at the bar-concrete interface. Moreover, the bar-concrete interface and fiber-matrix interface appeared uninfluenced by the moisture absorption and high temperatures. Zhou et al. [37] studied the bond durability of GFRP bars in concrete under different environments, including the tap water, alkaline solution (pH = 13.5), acid solution (pH = 2), and ocean water for different exposure durations (30, 60, and 90 days) at 20 °C. It was reported that there was no bond degradation under the simulated environments except for the acid solution. Even more, Alves et al. [38] conducted experiments on GFRP-concrete elements under sustained and fatigue loading conditions, and stated that the FT cycles enhanced the bond strength between the sand-coated GFRP bar and concrete by approximately 40%.

2.2. Statement of the problem

Clearly, although extensive studies have been carried out on the bond durability of the GFRP bars to concrete, the literature review generally demonstrates large discrepancies. This can be attributed to the different test methods and diversities in the characteristics of those test bars. Also, some laboratory tests considering the extreme environmental conditions may not correspond to field conditions that the structures actually experienced in reality. On the other hand, limited resources dedicated to GFRP reinforced structures exposed to aggressive cold environments including the combined effect of FT cycles, alkaline solution and saline solution. As such, the concrete pore solution that displays highly alkaline would be contaminated with chloride ions from de-icing salts, resulting in bond degradation of structures. Engineers need to comprehensively consider these environmental attacks on the long-term structural performance. Based on this, the objective of this study is to present an experimental study on the durability performance of the GFRP-concrete element, providing a reference and supplement to the current and future database for engineers and researchers.

3. Experimental program

3.1. Sample design

3.1.1. Material selection and sample size determination

The sample design was on the basis of a database generated in early work [1]. The database consisted of over 680 pullout

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