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Effects of water immersion on the bond behavior between CFRP plates and concrete substrate

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HIGHLIGHTS

- The adhesive layer thickness and immersion affect the CFRP-concrete bond remarkably.
- The water diffusion in multi-material systems was modeled by FEM.
- The adhesive-concrete bond is susceptible to the moisture ingress.

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ABSTRACT

Effects of water immersion on the behavior of bond between CFRP plates and concrete substrate were experimentally investigated and analytically modeled. The finite element method was used to simulate the distribution of the moisture content in the interfacial zone. Single lap shear test results showed that water immersion decreases the maximum bond stress, bond capacity, and fracture energy as well as the maximum slip. Increasing the immersion time led to more moisture uptake in the adhesive layers, and more degradation of the bonding properties. The thickness of the adhesive layers (i.e., 0.2 mm and 1 mm) affects the bonding properties and the resistance to the water immersion. The thinner the adhesive layer, the higher moisture content is found at the adhesive/concrete interface. Water immersion altered the debonding mode from cohesive concrete fracture to adhesive separation from the concrete substrate, which was attributed to the weakening of the bonding strength between silica and epoxy adhesive due to moisture ingress.

1. Introduction

Externally bonded fiber reinforced polymer (FRP) for civil rehabilitation has become a popular technology in recent years. Strengthening depends highly on the integrity of the bond between FRP and concrete substrate [1]. Lots of research works have been conducted to investigate the bond properties numerically and experimentally [2–4], but by now, the long-term performance of the FRP–concrete bond is not completely understood yet [3]. Since long service lives are required for civil structures under various harsh environmental conditions (e.g., water immersion, high humidity exposure, freeze–thaw cycles or their combination), the lack of adequate long term bonding performance data became a major concern [5].

Long term durability of the FRP–concrete bond has been studied previously [3,4,6–9], and the bond performances were found to be susceptible to hygrothermal exposure [4,9]. The presence of water molecules in the bond zone decreases the bond fracture energy, significantly [10,11]. As reported, a concrete/CFRP bonded system showed a reduction in the fracture toughness by 62.8%, after water exposure at 23 °C and 50 °C for 8 weeks [7]. In addition, exposure to 100% humidity for 10,000 h was reported to reduce the bonding strength by 37% for a CFRP plate–concrete beam, and by 10% for a CFRP wet layup – concrete system [12].

Durability of the bond between FRP–concrete substrate subjected to water immersion is mainly related to the water ingress in the bonding zone. Water molecules were found at the interface between the adhesive and concrete after 338 h of immersion [13]. Moisture diffusion mainly migrates from the bond free area of the concrete substrate to the FRP–concrete interface [14]. The accumulation of the water molecules at the bond interface tends to

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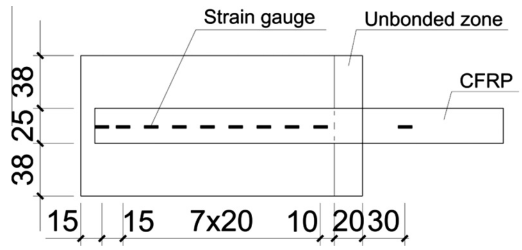

Fig. 1. Schematic sketch of the single-lap shear testing setup (all units in millimeters).

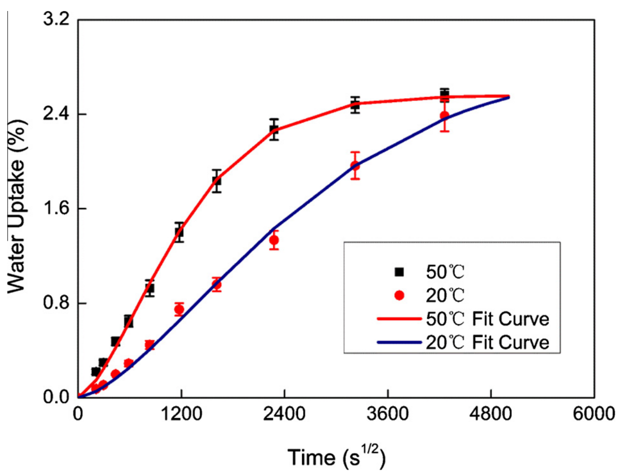

Fig. 2. Water uptake curves of the adhesive samples immersed in water at 20 °C or 50 °C.

Table 1
Diffusion coefficients of the adhesive and CFRP samples.

Material	Temperature (°C)	Diffusivity (10^{-9} mm^2/s)	Water uptake (wt.%)
Adhesive	20	78	2.52
	50	343	2.82
CFRP plate	20	9	0.73
	50	33	0.73

decrease the free surface energy and induce additional vapor and osmotic pressures [7,15,16].

Recent studies indicated that water immersion caused significant degradation in the bond strength between the adhesive and concrete, and changed the debonding failure modes [3,4,7,17]. Premature debonding between concrete and adhesive interfaces occurred when the system was soaked in water, and the failure mode may shift from concrete fracture to interfacial debonding due to moisture ingress [4,7,8,17,18]. The interfacial debonding was attributed to the plasticization effects induced by the absorbed moisture on the adhesive since the water molecules weaken the bond between the adhesive and silica components of the concrete substrate [7,15,16]. The interlocking resistance, including friction force and mechanical connection besides chemical bond, also contributes to the bonding strength [14]. The effects of the water immersion on the interlocking were not reported yet. The molecular dynamics simulation results based on the effect of van der Waal and Coulomb type forces show that the binding energy between concrete (silica) and adhesive in the wet scenario (of 10.2 kcal/mol) is only about one third of that in the dry scenario (of 31.8 kcal/mol) [15,16]. The molecular dynamics simulation also showed that the

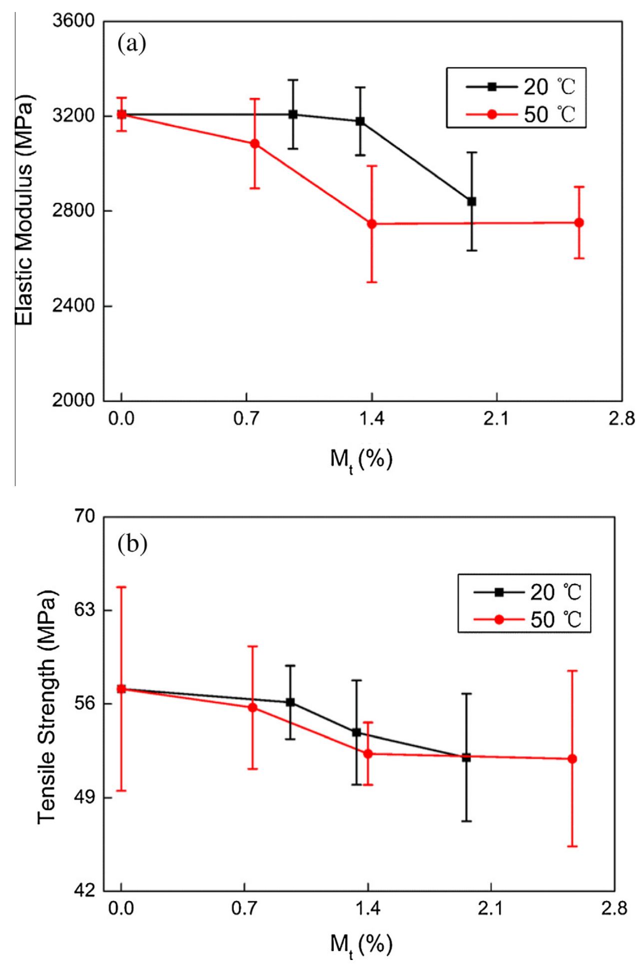

Fig. 3. Variation of the tensile strength (a) and modulus (b) of adhesive samples as function of water uptake M_t for 20 °C and 50 °C water immersion.

moisture molecules can seep into the gap between adhesive and concrete (silica) under water immersion.

Bond between FRP and concrete substrates is more susceptible to harsh environments [4,16] than the mechanical properties of other components (such as FRP and concrete). For example, exposure to water at 20 °C for 2 years was reported to bring in a reduction in the tensile modulus of an epoxy (e.g., T_g is about 70 °C) by less than 11%, while the reduction in the bond fracture energy of a FRP–concrete system was 57% [19].

As expected, the thickness plays an important role on the long term durability of the bond between a FRP and concrete, since the thickness will affect the water ingress in the bond zone obviously. However, study on the effects of the adhesive thickness on the durability of the FRP–concrete bond has been scarce up to date,