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EFFECTS OF MOISTURE, CHLORIDES AND SULPHURIC ACID ATTACK ON CFRP TO CONCRETE BOND INTERFACES

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ABSTRACT

Externally bonding carbon fibre-reinforced polymers (CFRP) to reinforced concrete structures is now a widely accepted method for strengthening. Critical to the behaviour and durability of the strengthening system is the bond interface between the CFRP and concrete substrate. A series of bond tests were conducted to assess the effects of commonly occurring in-service environmental chemical conditions on the CFRP-concrete bond interface through accelerated laboratory testing with particular emphasis on the role of sulphuric acid attack. Results show that sulphuric acid attack by acid deposition is more detrimental than chloride ingress or water diffusion to peak debonding loads.

KEYWORDS

Reinforced concrete, strengthening, fibre-reinforced polymer, externally bonded, durability.

INTRODUCTION

Flexural strengthening of reinforced concrete (RC) beams with CFRP is a common means to combat structural deficiency by enhancing load carrying capacity. With wider applications, the long-term durability of the systems is becoming a growing concern. Current guidelines account for environmental effects through correcting the elongation at rupture of FRP by an environmental reduction factor in the order of 0.85-0.95 (ACI Committee 440 2008).

The presence of moisture has been shown to significantly deteriorate the critical interface between concrete (Au & Büyüköztürk 2006; Wan et al. 2006). Moisture can be defined as 100% relative humidity, generally simulated in the laboratory through complete immersion of samples in water baths for extended periods of time. FRP bonded to exterior faces has shown to impede chloride ion ingress into concrete has been gaining increased attention in bond and beam tests (Soudki et al. 2007; Silva & Biscaia 2008; Silva et al. 2013). Cycles of salt water in CFRP strengthened flexural beams correlate to a failure within the concrete substrate with a 20 per cent reduction in ultimate capacity of the beam in comparison to the an equal strengthened beam maintained under ambient conditions (Silva & Biscaia 2008). In other instances, no impairment of flexural strength has been reported (Almusallam 2006). The role of acid attack is not as well understood. Tests on hydrochloric acid attack on CFRP sheets bonded to concrete have shown less bond strength degradation than that of seawater solutions (Woods

2003), and very little to no degradation of CFRP coupons in highly acidic exposures (Teng 2001; Kajorncheappunngam et al. 2002). While, sulphate attack, in concrete is generally well understood (Kong & Orbison 1987; Attiogbe & Rizkalla 1988), to the authors' extended review of the literature, no tests have been conducted on the role of sulphuric acid attack on bond interfaces between concrete and CFRP plates, this shall be the emphasis of this paper.

EXPERIMENTAL PROGRAM

A modified single lap shear pull out test was performed with CFRP plates externally bonded to concrete substrates and exposed to environmental conditioning through continuous immersion for a period of 8 weeks. It is commonplace to simulate the IC debonding phenomena (Figure 1) in plated beams with pull-out tests (Standards Australia 2008). Key to the modification is the positioning of a linear variable displacement transducer (LVDT) at the simulated crack face on the fixed end of loading to directly measure interfacial slip between the plate and the concrete substrate (Gravina et al. 2014).

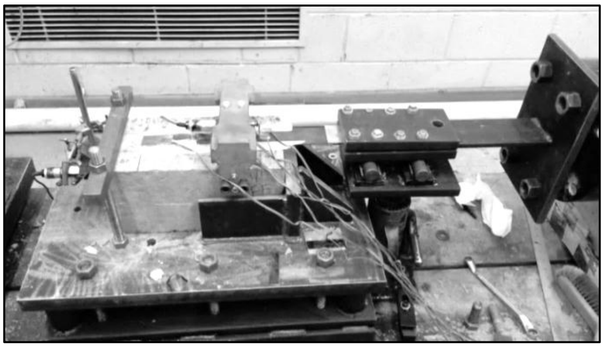


Figure 1. Modified single lap shear test

Test surfaces of 12 concrete prisms of 150x150x300 mm of 25 MPa characteristic compressive strength were mechanically grinded to a depth of 2 mm to remove surface mortar and expose aggregates. After a concrete curing time of 28 days, a two-part structural epoxy adhesive was used to bond a CFRP plate to a height of 4 mm above the concrete surface, controlled with metal rods acting as formwork for the adhesive. The specimens were left to cure for seven days prior to conditioning. The CFRP laminates were 1.4 mm thick, 40 mm wide, bonded 200 mm along the concrete substrate with a 40 mm unbonded length located at the loaded end to avoid concrete wedge failure. The test comprises of four series with three samples for each series. Post-conditioning, the first sample in each was series, denoted Mx.1, was instrumented with six strain gauges along the top surface length of the CFRP plate, spaced at graduating intervals to measure strain distribution in the full range of loading. Samples were loaded at a rate of 0.2 mm/min until failure.

Conditioning

Samples in series M2.x, M3.x and M4.x were conditioned after 7 days of adhesive curing to ensure full strength as per manufacturers recommendations and immersed, above the height of the bond line, in respective solutions. To simulate the conditions of 100% relative humidity samples M2.x were immersed in tap water. To simulate seawater and chloride effects, samples M3.x were immersed in 5% NaCl solutions.

Acid Deposition

Sulphuric acid attack by deposition was simulated by immersing samples M4.x in pH 4.0 sulphuric acid solutions. Sulphur dioxide emissions, responsible for sulphuric acid depositions and precipitation are ordinary in highly industrialised cities. New York City, for example, has an average pH of rainfall ranging from 4.0 to 4.5 (NYSDEC 2014). Tests simulate wet depositions at this pH level of 4.0 and subsequent pooling on strengthened concrete surfaces. Acid solutions were replenished fortnightly and changes were recorded using a portable electronic pH meter. The average change in pH over the 8 week period is presented in Figure 2.

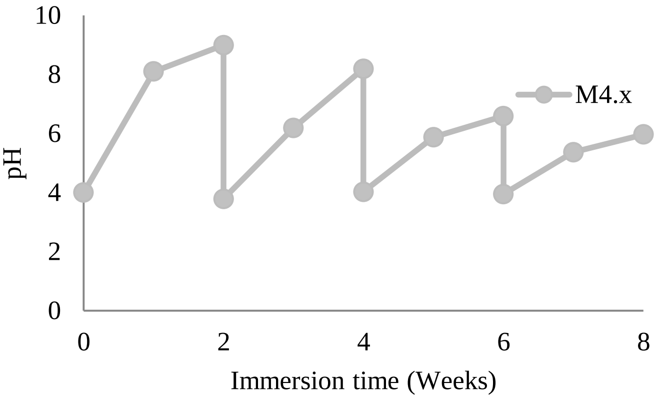
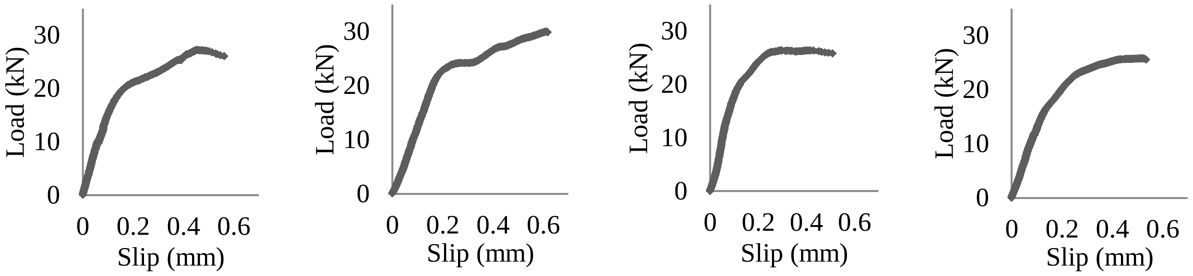


Figure 2. Average change in pH

RESULTS AND DISCUSSIONS

Changes in pH from initial acid conditions of pH 4.0 over time are attributable to the high alkalinity of cement which raises the pH of the solution to 9.0 by the end of the initial 2 week replenishment cycle. Yellow discolouration of concrete prisms is due to the formation of gypsum on the concrete surface. In acidic water, gypsum is formed from the reaction between calcium hydroxide in the concrete, $Ca(OH)_2$ and sulphuric acid H_2SO_4 (Fattuhi & Hughes 1988) to form calcium sulphate precipitate $CaSO_4$ also known as gypsum. The formation coincides with the needle shaped crystals on the concrete surface. As the thickness of the gypsum layer grows, the rate of uptake of sulphate ions diminishes.

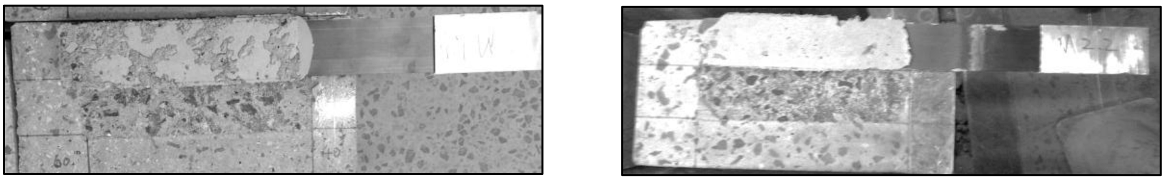
Load deformations curves (Figure 3) show no discernible decline in bond strength or stiffness of specimens immersed in water (b) and chloride exposure (c) in comparison to that of the ambient control specimens (a). Load increase, after debonding is initiated, in sample M2.1 is due to segregation of aggregates which are concentrated at the free end of the sample. Bond strength is most heavily degraded by acid attack (d). Of all tests, only useful results are presented. Samples M1.3 and M2.3 were removed, due to excessive deformation caused by bondline thickness irregularities in the FRP attachment process, a common disadvantage of pultruded systems in contrast to emerging vacuum consolidation processing techniques (Gravina et al. 2014). All conditioned samples exhibited some degree of adhesive layer failure in contrast to control specimens.



a) Ambient condition b) Water immersion c) Saltwater immersion d) Sulphuric acid attack

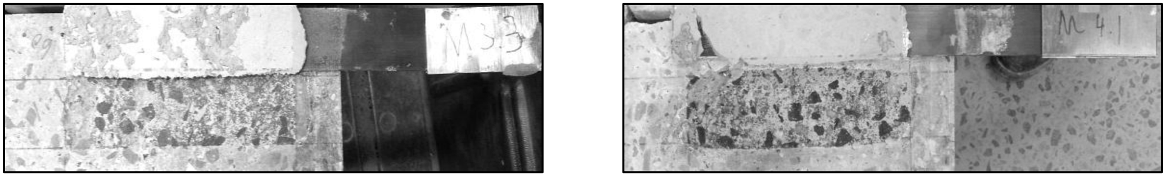
Figure 3. Average load deformation

Figure 4 shows the various failure modes shifting from concrete layer (a) to the adhesive layer in water (b) and saltwater samples (c), and in the case of the acid exposed sample M4.1, failure at the adhesive FRP layer (d). This change from concrete delamination to adhesive epoxy-to-concrete interface failure has been reported in other research (Au & Büyüköztürk 2006; Wan et al. 2006). A summary of experimental results and failure modes may be found in Table 1.



a) M1.1 Concrete debonding

b) M2.2 Adhesive delamination



c) M3.3 Concrete debonding and adhesive delamination

d) M4.1 Minor concrete debonding, adhesive layer delamination and separation

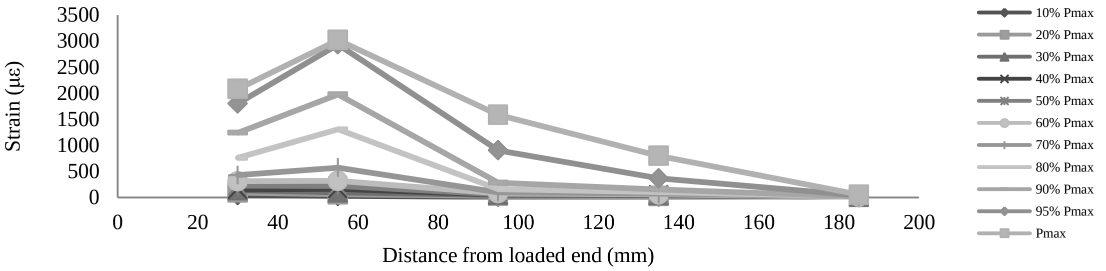
Figure 4. Typical failure modes by exposure

Table 1. Summary of test results

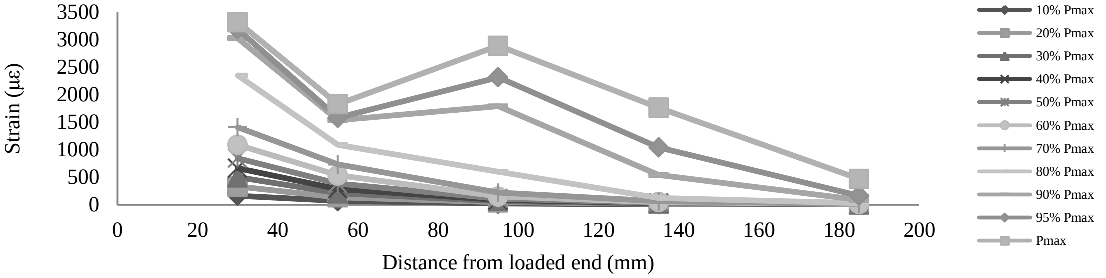
Conditioning		Peak		Ultimate				
	Specimen ID	Load (kN)	Slip (mm)	Load (kN)	Slip (mm)	Failure plane (mm)	Interface Failure mode*	% Weight gain
Ambient	M1.1	26.632	0.448	26.163	0.556	0.416	a	-
	M1.2	27.698	0.577	25.884	0.577	0.431	a	-
	Mean	27.161	0.513	26.024	0.567	0.424		
Moisture	M2.1	34.990	0.726	34.684	0.749	0.214	a, b, c	1.48
	M2.2	24.935	0.509	24.826	0.516	0.449	b	1.46
	Mean	29.963	0.616	29.755	0.633	0.332		
Saltwater	M3.1	20.330	0.177	19.623	0.318	0.141	a, b	1.79
	M3.2	26.187	0.402	24.950	0.569	0.345	a, b	1.45
	M3.3	33.564	0.377	32.699	0.655	0.928	a, b	1.50
	Mean	26.693	0.319	25.757	0.514	0.471		1.58
Acid attack	M4.1	28.723	0.521	28.455	0.551	0.691	a, b, c	2.11
	M4.2	24.178	0.426	24.061	0.477	0.985	a, b	1.78
	M4.3	24.342	0.569	24.059	0.581	0.117	a,b	1.76
	Mean	25.748	0.506	25.525	0.536	0.598		1.89

* a. Concrete cover delamination, b. Adhesive delamination, c. CFRP/Epoxy interface separation

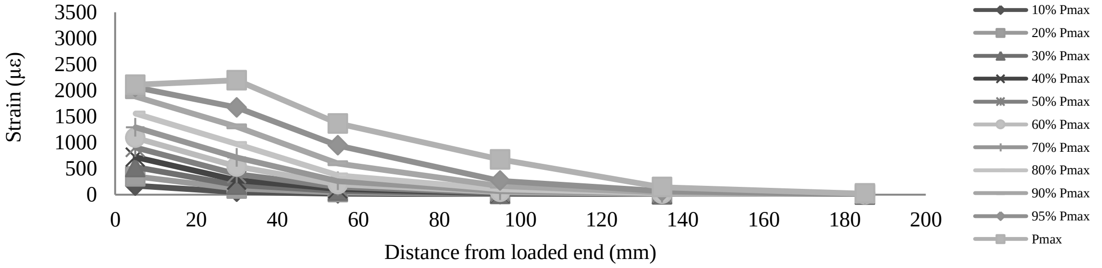
Strain distribution along the CFRP plate is show in Figure 5. Strain gauges located directly at the fixed end in samples M1.1 and M2.1 failed to record useful data due to strain gauge attachment failure and have been omitted. Strains measured at the loaded end, despite additional exposed perimeter, showed no discernible decline in debonding strains at this position nor did debonding initiate more rapidly. Similarly, there is no apparent decline in peak strains of degraded samples. Moisture and acid degraded samples have improved stress distribution along the plate characterised by high strains measured centrally in bonded regions of (b) and (d), indicating that there is full utilisation of the adhesive layer and explains the adhesive delamination and separation failure modes respectively. Subsequently, effective bond lengths are marginally increased, in line with existing studies of dry/wet cycle exposure (Silva et al. 2013). Rapid debonding in the saltwater exposed sample (c) indicates incomplete utilisation of the adhesive layer, limiting the effective bond length.



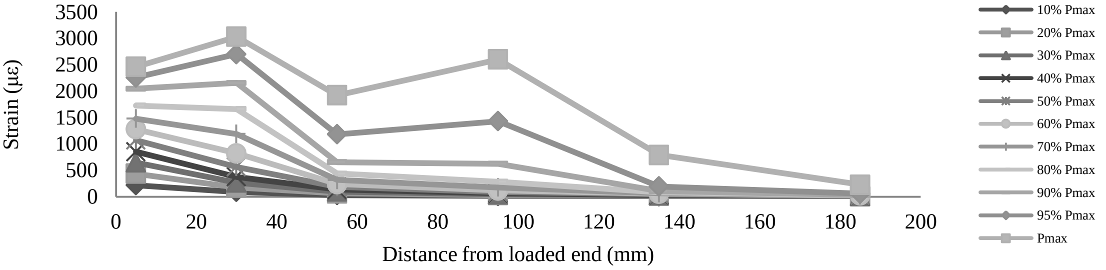
a) Ambient condition



b) Water immersion



c) Saltwater immersion



d) Sulphuric acid attack

Figure 5. Axial strain distribution with load range

CONCLUSIONS

A number of significant conclusions may be drawn:

- All exposures shift the dominant failure mode from concrete cover delamination to some degree of failure at the adhesive-concrete layer which is most prominent with acid degraded samples;
- Increase in stiffness of saltwater samples does not correspond to shorter effective bond lengths as expected, due to varying crack propagations and distribution of bond stress along bonded length. Full utilisation of the adhesive layer in the acid exposed samples increases effective bond length;
- Increased exposed perimeter at the loaded end has no apparent effect on debonding;
- Sulphuric acid deposition of pH 4.0 is more detrimental than chloride ingress or water diffusion to peak debonding loads.

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