Durability of Glass Fibre Reinforced Polymer (FRP) Materials in Concrete – Effect of Carbonation on Bond Strength

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ABSTRACT

The research community agrees on that corrosion of reinforcing steel, due to the diffusion of carbon dioxide from the atmosphere and ingress of chloride ions (in combination with seismic loading) is the predominant factor responsible for premature concrete deterioration observed in a wide range of structures in the last decades. New technologies such as FRP increase the choice available to engineers for corrosion resistance solutions in aggressive environments. However, given the concerns expressed in some cases, on the effect of concrete alkalinity on certain types of FRP bars, the effects of environmental corrosion (through accelerated carbonation) on the bond properties of fibre reinforced polymer (FRP) bars with the surrounding concrete are presented in this paper, as part of an extensive project addressing the durability of FRP in concrete in environments of different initial alkalinity.

It was found out that, contrary to what is generally believed, concrete alkalinity does not have a major impact on the durability of FRP bar and its bond strength. Carbonation had a considerable effect on concrete strength, increasing the strength of carbonated concrete. Until the carbonation front reaches the FRP bar, no significant deterioration of bond took place. Soon after the carbonation front reaches the bar, a relative deterioration of bond was observed. However, the observed bond deterioration is more than compensated by the increase in strength due to time and carbonation, contrary to steel reinforcement, hence there is no need to take into account the carbonation effect on the stress reduction factors used for durability design.

KEYWORDS

FRP, carbonation, concrete, durability, bond strength

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1 INTRODUCTION

It is a widely accepted fact that corrosion of the steel reinforcement, impairs not only the appearance of a structure, but also its strength and safety due to the reduction in the cross-sectional area and on the mechanical properties of the reinforcement and also due to the the subsequent deterioration of bond with the surrounding concrete [Lundgren 2007; Fang et al. 2004]. Bond between reinforcement and concrete is of paramount importance to ensure the composite interaction of the two materials. A number of investigations have been undertaken to investigate the influence of corrosion on bond capacity [Lundgren 2007; Fang et al. 2004, 2006a, 2006b]. Conclusions on how a certain level of corrosion affects bond to a certain degree vary quite a lot, but the general trend observed is a small initial increase in bond strength with corrosion, due to an increased frictional component of bond caused by the radial stresses applied from the corroded bar to the surrounding concrete, , followed by a considerable decrease (caused in general by longitudinal cracking). Ways to overcome the above mentioned problem, by utilising traditional methods (of reducing the risk of reinforcement corrosion) do not always guarantee corrosion free steel for the service life of a structure [Demis 2007]. No system provides an ideal cost-effective solution to corrosion and the various techniques available might add further complications to the future maintenance requirements and expected service life of the structure. New technologies such as FRP increase the choice available to engineers for corrosion resistance solutions in aggressive environments.

FRP are composites comprising of at least two materials, fibres which act as reinforcement and polymer binders. The purpose of the polymer is to integrally bind the fibre reinforcement together so as to distribute external loads to the fibre via bond, whilst protecting it from adverse environmental effects [Demis 2007].



Figure 1. Schematic diagram of a Fibre Reinforced Polymer

There are currently a number of FRP reinforcing bars commercially available, composed of carbon, glass or aramid fibres within polyester or vinylpolyester-epoxy resins, manufactured using a number of techniques, with pultrusion being the most common [Demis 2007]. FRP rods have different properties and mechanical characteristics from conventional steel. The mechanical properties vary from one product to another, depending mainly on the nature and volume of fibres, the shape of the cross section and the resin. Great electromagnetic neutrality, corrosion resistance and tailored design are some of the advantages compared to steel reinforcement. FRP rods develop greater tensile strength than the steel bars, depending on the nature of the fibres and have strength to weight ratio of up to 10 times that of steel. Bond of FRP to concrete is different to that of steel. In the case of steel reinforcement, mechanical interlocking due to the bar lugs against concrete provide the necessary interaction [Achillides & Pilakoutas, 2004; fib, 2000]. However, in the case of FRP, once chemical adhesion is overcome, bond with concrete is usually achieved mostly through friction [Demis 2007].

Concerns have been raised for the effect of concrete alkalinity on certain types of FRP bars. It is believed that particular types of FRP composites can be damaged by chemical attack of the alkaline environment of cement and by the growth of hydration products between fibre filaments [Karbhari et al. 2005; Yilmaz et al. 1992]. The implication of this is that whilst these materials may perform well structurally in the short term, they may well still degrade in alkaline concrete environments.

Considering that although significant steps have been taken on uderstanding and modeling the physiochemical processes and mechanisms which lead to the reduction of the service life of a reinforced (with conventional reinforcement) concrete structure, inluding the development, verification and utilisation of proven predictive tools for the estimation of service life under harsh environments [Papadakis et al. 1991, 2007], in the case of FRP reinforcement, the effect of the above mentioned mechanisms have not been examined to such an extend. The key question that has not been answered until now is what is the rate at which this deterioration takes place and how this is affected by the pH level of the concrete.

On that note, an extensive project addressing the durability of FRP in concrete, under different conditions of initial alkalinity, aiming to develop test methods and predictive models was undertaken [Demis 2007]. A part of this work, the effect of low alkalinity (an important factor for the initiation of corrosion) through the use of cement replacement materials and accelerated environmental carbonation, on the bond strength of FRP bars, is briefly presented in this study.

2 EXPERIMENTAL METHODOLOGY

Pull-out concrete cubes (150 mm), made from Portland Cement (CEM I) and pozzolanic cement replacement materials (30% fly ash and 70 % blastfurnace slag), with a centrally embedded glass FRP bar, were immersed in an accelerated environmental carbonation facility for a period of 2 years. A large-scale computerised controlled carbonation tank was designed, manufactured and calibrated by the author, for the purpose of this study [Demis 2007] (CO₂ 15%, RH 55%). The bond strength of the specimens was determined at different time intervals. The compressive strength of the tested concrete and its carbonation development were also monitored at each testing age. In addition to the use of phenolphthalein indicators on concrete prisms carbonation growth was also evaluated relative to the position of the embedded FRP bar using pull-out samples [Demis 2007].

3 RESULTS

An initial observation is that bond increased with exposure time for every environment (Figure 2a). The observed gain in bond, since the quality of the embedded FRP bar does not improve, can only be attributed to the effect of the environment surrounding the bar, hence to the obvious factor improving with time, the concrete compressive strength. Relationships that correlate bond strength to concrete tensile strength can be found in most European Codes [Demis 2007; Demis et al. 2007]. Tensile concrete strength is also related to the concrete compressive strength, through empirical equations. As a result, the relationship between the concrete compressive strength and bond strength, can be easily determined. Using the Eurocode 2 [2004] previously briefle mentioned relationships, the measured bond strength results were normalised to a common compressive strength, according to Equation 1:

$$f_{b,n} = f_b \cdot \left(\frac{f_{c,m28d}}{f_{c,m(t)}}\right)^{2/3}$$
 (Equation 1)

where, $f_{b,n}$ is the normalised bond strength (MPa), f_b the measured bond strength (MPa), $f_{c,m28d}$ the mean 28 day concrete compressive strength (MPa) and $f_{c,m(t)}$ the mean concrete compressive strength on the day of testing.

It was seen (Fig. 2b) that although bond strength increased for all concrete environments used (carbonated or not), the non-carbonated (control) samples exhibited the biggest increase.



Figure 2. Bond Strength Development

Investigating the effect of carbonation on the concrete compressive strength, it was found that carbonation increased the compressive strength of concrete by around 15 % (Fig. 3).



Figure 3. Cube compressive strength of carbonated cements vs carbonation growth

However, this increase in strength is confined in the part of the concrete that is carbonated. Since the bond of the bar is influenced by concrete strength, then the effect of carbonation away from the bar should be taken out of the equation. A new concrete strength of the carbonated samples around the bar (f_{cu} ') was calculated by subtracting the carbonation effect (until the carbonation front reaches the bar) as:

$$f_{cu} = f_{cu(t)} - \left(0.15 \cdot f_{cu(t)} \cdot \frac{d_{pr}}{100}\right)$$
(Equation 2)

Where, d_{pr} is the carbonation depth measured on a concrete prism, and $f_{cu(t)}$ is the compressive concrete strength at age (t).

To help decouple the effect of compressive strength, the mean values of bond strength versus the cube compressive strength are shown in Figs. 2d-f. It can be seen that the initial gain in compressive strength does not influence the bond strength, but the gain in strength after 12 months has a significant impact (Fig. 2d). By adopting the classical normalization of bond strength with respect to concrete strength (see Fig. 2e), a decrease in bond strength is noted following the initial gain in compressive strength. This is surprising since it goes against what is expected and may indicate a chemical deterioration mechanism. When bond strength is normalized with respect to the revised concrete compressive strength this reduction is almost eliminated (Fig. 2f). Bond increases marginally after 6 months, with respect to the concrete compressive strength. It can be concluded that the increase in bond strength obtained in the experiments can be attributed entirely to gain in compressive strength in the region of the bar. However, in comparison with the OPC (control) samples (Fig. 2c) there is a relative loss of bond strength. The reasons for this behavior and the relative differences in bond strength between the carbonated and the uncarbonated samples suggest a chemical mechanism of deterioration. Using ANOVA analysis (Table 1) to examine the statistical validity and significance of the key parameters in this investigation, crucial conclusions were made.

Source of Variation	Sum of Squares (SS)	df	Mean quare (MS)	P-value	F _A	F _{critical}	F _A / F _{critical}
Mean values of normalised bond strength							
Time of Exposure	1.49	3	0.49	0.011	6.69	3.86	1.73
Cement Type	0.66	3	0.22	0.089	2.98	3.86	0.77
Analysis of the mean values of the normalised bond strength							
Time of Exposure	4.58	3	1.53	0.004	5.19	2.90	1.79
Cement Type	2.03	3	0.68	0.096	2.30	2.90	0.79
Values up to 6 months of the control and normalised carbonation bond strength							
(carbonation has not yet reached the FRP bar)							
	0.07	3	0.02	0.665	0.57	6.59	0.09
Values after 6 months of the control and normalised carbonation bond strength (carbonation reached the FRP bar)							
	1.19	3	0.40	0.243	2.09	6.59	0.32
Values between and after carbonation of bond strength (comparison of bond strength values before CO_2 reached the FRP bar with the bond strength values after CO_2 reached the bar)							
	1.99	1	1.98	0.021	5.67	4.05	1.4
S is a measurement of the variability of the dependent variable (bond strength in this study), dF is the degrees of							

 Table 1. ANOVA Statistical analysis of key parameters

SS is a measurement of the variability of the dependent variable (bond strength in this study), dF is the degrees of freedom of the analysis, representing the number of observations of the variables in the analysis, MS is a measurement of the variance of the population of the analysis (of the total number of samples), F_A is a measurement of the contribution of the independent variables (time of exposure, cement type) in predicting the dependent variable (bond strength), P is the probability of being wrong in concluding that there is an association between the dependent variables (the smaller the P value, the greater the probability that there is an association).

As expected the time of exposure was found to have significant effect on bond (since the concrete strength increases with time), contrary to the effect of the cement type/initial alkalinity that was found to be marginally insignificant. Comparing the bond strength values between the control and the carbonated specimens, before and after carbonation, a significant statistical difference was found, indicating chemical deterioration once the carbonation front reaches the FRP bar. This is a key finding and two models are required to predict this behavior. One model for the prediction of the penetration of the carbonation front and another model for the estimation of the effect of carbonation on the bond strength.

Using equations that describe the growth of the carbonation front in the carbonation tank in the form of $d=K \cdot t^{1/2}$ (where "d" is the carbonation depth and "t" is the time of exposure), the time (months) of accelerated exposure that carbonation reached the FRP bar was estimated [Demis 2007]. Combining these equations with an effective time scale [Demis 2007], the time needed for carbonation to reach the position of the embedded FRP bar was calculated in real exposure time (years of natural exposure). Using the experimental data of bond strength, the relative bond strength retention (t_R) in time of exposure (years) after carbonation reaches the bar was estimated. The expected bond strength (t_{exp}) as increased with time due to the increase of concrete compressive strength was calculated according to Eurocode 2 [Demis 2007], by taking into account the gain in compressive strength due to both time and carbonation (15 % increase). In this way the expected bond strength due to the effect of carbonation was calculated as ($t_{exp} \cdot t_R$). Finally the total bond strength retention in time ($t_{R total}$) was estimated as the ratio of ($t_{exp} \cdot t_R$) after carbonation reached the bar to the ($t_{exp} \cdot t_R$) before carbonation reached the bar, and it is shown in Fig. 4, for different concrete cover depths.



Figure 4. Total bond strength retention

It is evident from the above figure that the negative effect of carbonation is counteracted by the gain in strength with time.

4 DISCUSSION

This work has shown that until the carbonation front reaches the FRP bar, despite differences in concrete alkalinity, no significant deterioration of bond takes place. Once the FRP is covered with concrete, the free moisture reduces and its adverse effects are mitigated. For concrete kept at moisture, of around 55 %, the adverse effects of moisture on FRP bond to concrete outstripped the beneficial effects of increasing concrete strength only marginally during the first 6 months. This was true for all concretes used. Since the three concretes started with different pH values, but behaved

similarly up to the point of carbonation means that the alkalinity did not play a major influence on the bar strength. In fact, the OPC which has the highest alkalinity exhibited less normalised bond reduction than the blended cements. Additional evidence that concrete alkalinity does not deteriorate the FRP by itself is given by the samples after carbonation reached the FRP bar. At this stage alkalinity drops from a pH value of 12.5 - 13.6 down to a pH of around 9. Despite the significance drop in alkalinity, the carbonated samples for all concretes showed a relative normalised bond deterioration. The carbonation process, is also responsible for reducing the permeability of concrete and that again should have reduced any alkali attack.

Since it has been established above that alkalinity does not have a major impact on FRP bond, the impact of carbonation has to be viewed with respect to the other processes that are taking place. The first major impact is on concrete strength. The gain in strength can be associated with the formation of $CaCO_3$ and to some extend to the release of moisture which can lead to further hydration. The strength gain has been attributed only to carbonated regions and has been eliminated from the bond strength through normalization with compressive strength, in the same way as the effect of time has been taken into account.

It was found out that soon after the carbonation front reaches the bar, a relative deterioration of bond takes place. This deterioration can be attributed to the detrimental effect of CaCO₃ crystals that penetrate into the FRP surface and can damage both the resin and the glass fibres. The incorporation of blended cements, that facilitate the formation of C-S-H gel, assists in the deterioration of the fibres. That is despite the fact that their carbonation proceeds at a slower rate than the carbonation of calcium hydroxide in OPC. It has been suggested that C-S-H is responsible for dissolution and thus degradation of the glass fibre [Demis 2007]. Their refined pore structure does not contribute as much as expected in lessening the carbonation attack. A relative decrease of 11.4 % in normalised bond was noticed on carbonated OPC/PFA samples, compared to 13.7 % and 14.8 % on OPC/GGBS and OPC carbonated samples, respectively. Hence the conclusion that carbonation operates as a switch on the deterioration of FRP can be made.

3 CONCLUSIONS

No significant difference in the relative bond behaviour of FRP bars was observed between the different concretes, neither in the pre- nor post-carbonated state. Hence, contrary to what is generally believed, it is concluded that alkalinity does not have a major impact on the FRP bar and its bond. Carbonation had a major impact on concrete strength, increasing the strength of carbonated concrete. Until the carbonation front reaches the FRP bar, no significant deterioration of bond takes place. Soon after the carbonation front reaches the bar, a relative deterioration of bond takes place. It was out found that the expected bond deterioration due to carbonation is more than compensated by the increase in strength due to time and carbonation, contrary to steel reinforcement. Hence there is no need to take into account the carbonation effect on the stress reduction factors used for durability design.

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