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Acid penetration kinetics in externally bonded FRP-strengthened reinforced concrete structures: mechanism and prediction

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Abstract

The long-term performance of externally bonded fibre-reinforced polymer (FRP) in reinforced concrete (RC) structures within aggressive environment is of paramount interest for researchers, designers, and FRP manufacturers. Due to industrial activities and climate change, FRP-strengthened structures are more likely to be exposed to acid attack during their service life. However, research on the deterioration mechanism of such structures under acid attack is hardly reported. This paper evaluates the penetration kinetics of acid and predicts the long-term acid concentration profile in FRP-strengthened RC members. The predicted concentration profile suggests that the rate of acid diffusion within FRP-concrete connection is a function of penetration depth and time. In addition, an investigation on a reinforced concrete beam before and after FRP strengthening indicates that the FRP can provide a barrier against acid penetration into the concrete substrate and enhance the service life of the RC beam. The developed diffusion law accurately predicts the experimental results and can be used as a theoretical basis for the durability design and the service life prediction of FRP-strengthened RC structures when subjected to acid attack.

Keywords: externally bonded FRP; acid attack; diffusion; concentration profile; service life prediction

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Introduction

Externally bonded fibre reinforced polymer (FRP) plates have been used as reinforcement to strengthen and retrofit existing deteriorated reinforced concrete (RC) structures. The durability of FRP-strengthened RC structures is highly controlled by in-service environmental conditions such as temperature fluctuation, wetting-drying cycles, fire, ultraviolet (UV) radiation and chemical exposure [1]. Amongst these conditions, acid attack is an important factor that can undesirably impair the structural integrity. Acid rain, industrial water, and acidic soils are amongst primary sources of acid attack that concrete structures are exposed to [2].
In the process of acid ingress, solution can penetrate into adhesively bonded joints through: (i) a diffusion process through the FRP or substrate, and (ii) penetration of the attacking agent into the material via cracks [3]. The invading media chemically interacts with the constituent elements (i.e. fibre, resin, concrete), leading to various degrees of deterioration. Thus, the rate of acid permeation controls the overall performance of FRP-concrete connections.
Proper structural design and strengthening schemes in acidic environment are becoming more and more crucial due to the increasing acid rains and industrial activities. As a result, there is an urgent need to study the behaviour of FRP-strengthened RC structures in acidic environment. However, limited research is currently available to address the mechanisms of acid diffusion in the concrete members reinforced with FRP plates. This paper investigates acid penetration kinetics in FRP-concrete connections and provides a theoretical framework for service life design of strengthened RC beams.

Acid penetration kinetics

Governing diffusion law

The one-dimensional Fickian diffusion model can be used to state the rate of acid penetration through diffusive means. The depth of diffusion of acid in the concrete and the FRP follows Fick's second law, as characterized in Eq.1:

$$\frac{\partial c}{\partial t}=D\cdot\frac{\partial^2 c}{\partial x^2} \qquad (1)$$

where: c, x, t and D are concentration of acid (%), thickness through which acid is diffused (m), time (s) and diffusion coefficient in the direction of acid penetration (m^2/s), respectively. Assuming the FRP and the concrete are fully saturated before the acid penetration and neglecting the impact of other ion penetration mechanisms like capillary absorption, the proper initial and boundary conditions can be expressed as Eq. 2 and 3:

$$c(x,0)=0 \ (x>0) \qquad (2)$$
$$c(0,t)=c_s (t\geq 0) \qquad (3)$$

c_s is the constant surface acid concentration (%). The integral of Eq. 1 over thickness gives:

$$c(x,t)=c_s\cdot\left[1-\mathrm{erf}\left(\frac{x}{2\sqrt{D_{app}\cdot t}}\right)\right] \qquad (4)$$

where $c(x,t)$ and D_{app} are acid concentration (%) at the depth of x from exposed surface at exposure time t and apparent (or effective) diffusion coefficient (m^2/s), respectively. $\mathrm{erf}\,()$ is Gaussian error function given by Eq. 5:

$$\mathrm{erf}(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt \qquad (5)$$

Eq. 4 represents the acid concentration in the FRP or the concrete at any position and time. The value of $c(x,t)$ can be measured experimentally from bulk diffusion tests [4]. Apparent acid diffusion coefficient is thereby obtained by fitting Eq. 4 to the measured acid content with a non-linear regression analysis. Furthermore, the probabilistic service life of an RC structure strengthened with FRP plates can be estimated in terms of the time taken for the initiation of reinforcement corrosion. The acid content increases gradually at the interface between FRP and concrete and will reach a threshold, known as critical concentration, c_{crit}. Then, the exposure time (t) can be directly calculated if the values of other parameters in Eq. 4 are known (i.e. c_s, D_{app}, x and c_{crit}). The time at this point is the estimated in-service life of the FRP-strengthened RC structures under acid-induced corrosion.

Diffusion coefficient (diffusivity)
Diffusion coefficient ranges for concrete and epoxy resins are found through the limited reported experimental data [5-7], depicted as a box and whisker plot (Figure 1). Diffusion coefficients of sulphate ions in concrete are collated here because of the scarce experiments on investigating acid diffusion in concrete. The database is comprised of 46 experimental results. Inspecting Figure 1 suggests that the median value is an appropriate measure of the central tendency since both boxplots are extremely right-skewed. It is observed that the median diffusivity of sulphate ions in concrete is 7×10^{-13} m^2/s, which is three magnitudes higher than that of acid in epoxy (0.95×10^{-16} m^2/s). This difference in ability to resist acid permeation is consistent with the feasibility of strengthening of concrete structures with FRP plates under acid attack. Figure 1 also reveals that epoxy has a smaller dispersion of acid diffusion coefficients compared to the more distributed sets of experimental data on diffusion coefficient of acid in concrete.

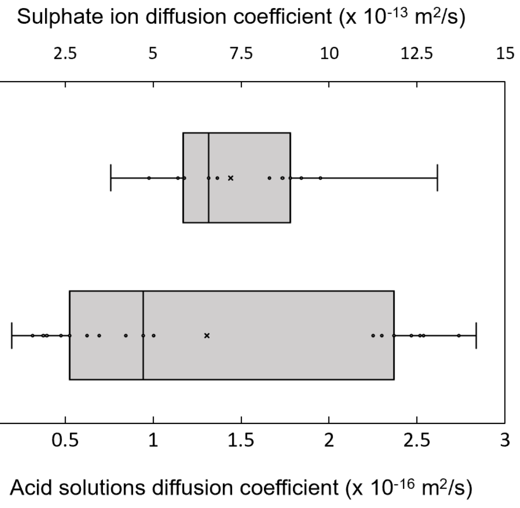

Figure 1: Diffusion coefficients of sulphate in concrete and acid in epoxy resin

Proposed concentration profile
This section presents a prediction model for acid penetration and estimation of service life in an externally carbon FRP (CFRP) plate-bonded RC beam. CFRP plates are attached to the tensile side of the beam. A one-dimensional idealized acid concentration profile is developed to visualize the proposed diffusion model (Eq. 4) based on Fick's second law. The cross section of the singly-reinforced rectangular beam is 350 mm x 550 mm and the diameter of the three

rebars is 20 mm (N20). Elastic modulus of concrete and steel is 30 GPa and 200 GPa, respectively. The characteristic compressive strength of concrete is 32 MPa and the concrete cover is 40 mm. The corrosion of steel reinforcement bar due to acid attack is deemed as the sign of the structural failure [4]. Hence, the concrete cover has a great impact on forecasting the durability of CFRP-strengthened RC members. The tensile strength and modulus of elasticity of carbon fibre are 4,300 MPa and 238 GPa, respectively [8]. The total thickness of CFRP reinforcement is 0.52 mm which consists of 4 layers of the CFRP using wet lay-up processing technique.

The diffusion coefficient of the CFRP plate is greatly dependent on the epoxy resin used to bond it onto the concrete substrate, hence the diffusion coefficient of epoxy can be approximately adopted for the overall CFRP plate. Therefore, the diffusion coefficients of the concrete and the CFRP are considered 7×10^{-13} m^2/s and 0.95×10^{-16} m^2/s, respectively.

A comparison is made between the proposed prediction model (see Figure 2 (a)) and the experimental results obtained from Khanzadeh Moradllo et al. [9]. The predicted profile shows a good agreement with the experimental data which demonstrates the capability of the proposed model in precise prediction of the concentration profile in the long-term.

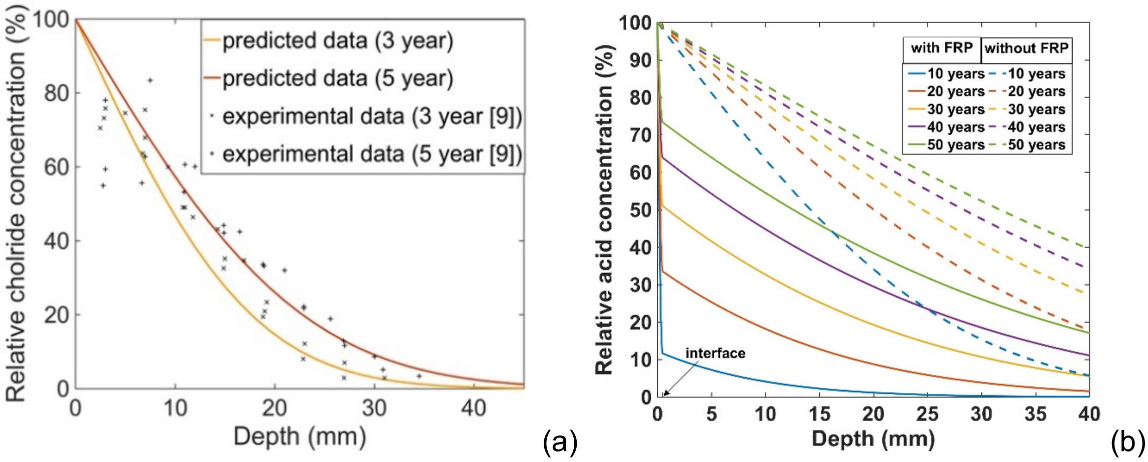

Figure 2: Proposed model (a) comparison between experimental and predicted results, and (b) idealized acid concentration profile of a CFRP-strengthened beam

Figure 2 (b) illustrates an idealized acid concentration profile for the CFRP-strengthened RC beam during 50 years of its service life. Relative concentration indicates the amount of acid that has diffused into the material, by dividing the concentration at the position of interest by the initial surface concentration. Figure 2 (b) shows a sudden slope change at the CFRP-concrete interface. The acid concentration drops dramatically in the CFRP plates, while decreases gradually through the concrete. This agrees with the much lower diffusivity of acid in CFRP. In addition, the lower slope in Figure 2 (b) suggests that the rate of acid concentration decreases with the increasing depth. It can also be seen that the rate of acid content lessens with time as the gap between each curve is narrowing slightly.

Furthermore, a comparison of the performance of the section before and after strengthening is made to determine the effect of CFRP strengthening (Figure 2). This figure shows that the acid content of unstrengthened beam is far greater than that of the corresponding beam reinforced with the CFRP plates. Investigating both beams reveals that at 50 years, the acid content at the level of concrete-steel bar in the unstrengthened beam is more than twice as that of the CFRP-strengthened beam. These demonstrate that the CFRP as externally bonded reinforcement is able to delay the penetration of acid into RC members and enhance the service life of reinforced concrete structures.

Conclusion

In this study, the transport mechanism of acid from externally bonded CFRP plates to concrete substrate was predicted on the basis of Fick's second law. A one-dimensional idealized acid concentration profile was generated for a concrete section externally bonded with CFRP plates. Results showed that the acid diffusion decreases with the increasing depth and exposure time. It was demonstrated that the proposed model can predict the experimental results with high precision. Based on the proposed model, it was shown that CFRP plates can decelerate the acid penetration and improve the service life of RC structures.

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