DESIGNING FRP FOR STRENGTH AND CORROSION RESISTANCE

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ABSTRACT

Fiber reinforced polymers (FRP) were first used to repair corrosion damage in a prestressed girder bridge located near Tokyo in the 1970's. Forensic analysis following replacement of the bridge showed that FRP had slowed down the ingress of active species such as chlorides, oxygen and water that are responsible for sustaining electro-chemical corrosion of steel in concrete. This finding was later confirmed by researchers in several countries and also through field demonstration projects. But in the absence of quantitative information on FRP barrier properties, repairs were conservative, e.g. nine layers were used for the repair and confinement of the Champlain Bridge, Montreal. Quantitative information on the oxygen permeability of epoxy, FRP, concrete and FRP-concrete systems was recently determined. Its availability makes it possible to design FRP corrosion repairs and also to identify the FRP-concrete combinations that will lead to effective repairs. This paper provides a brief outline on how corrosion repairs can be optimized by making use of oxygen permeation characteristics.

INTRODUCTION

Corrosion of reinforced or prestressed steel in concrete is a world-wide problem. Since chloride-induced corrosion is electro-chemical, traditional repair methods such as chip and patch are seldom long lasting. Durable repair requires removal of all chloride contaminated concrete and its replacement by appropriate repair material [1]. In practice this can rarely be achieved because the boundaries of the chloride contaminated concrete are ill-defined. Not surprisingly, a survey reported that 98% of 47 bridge pier repairs failed within three years despite the use of quality materials and good construction practice [2]. The need for repeated re-repair of corrosion damage has led to increased use of alternative repair materials and systems such as fiber reinforced polymers (FRP).

Fiber reinforced polymers (FRP) are lightweight, high strength, corrosión-resistant materials. In fabric form, they offer unprecedented flexibility; since fibers can be oriented as required they can provide strength in any desired direction. FRP is a barrier that cannot stop corrosion, but can reduce the corrosion rate. Because of the lack of quantitative information on FRP's barrier properties, repairs cannot be designed. Instead, design is carried out on an ad hoc basis that tends to be conservative, e.g. nine layers were used for the repair and confinement of the Champlain Bridge, Montreal [3]. Inevitably, such practices lead to unnecessary costs.

The performance of a FRP as a barrier can be determined by its diffusion properties. Of reactive species, oxygen molecules are smaller than both chloride or water molecules and can diffuse faster. As a result, it controls the rate of corrosion of steel in concrete. Quantitative information on the oxygen permeability of epoxy, FRP, concrete and FRP-concrete systems provides a basis for rational design. Their availability also makes it possible to identify FRP-concrete combinations that optimize FRP use [4-7].

The economics of FRP corrosion repair require the wrap to be properly engineered. The correct FRP material with the optimal fiber architecture should be selected to simplify field placement. Design must cover strength requirements but also optimize barrier properties.

BACKGROUND

Information on the oxygen diffusion characteristics of FRP is the first step towards the development of a theoretical model for predicting the performance of FRP used in corrosion repair.

Fick's law served as the basis of an experimental set up developed to characterize FRP. By this law, if the oxygen concentrations on two parallel faces separated by a thickness h are C_1 and C_2, the steady state flux F passing through the material (cc/s or in^3/min) is related to the diffusion coefficient D (units cm^2/sec. or in^2/ sec.) by Eq. 1 as:

$$F = -D\frac{dC}{dx} = D\frac{(C_1 - C_2)}{h} \qquad (1)$$

If the thickness, h, the concentrations C_1 and C_2 and F are known, the diffusion coefficient D can be directly determined from Eq. 1. However, experimentally it is easier to measure partial pressures p_1 and p_2 than concentrations. Eq. 2 gives the relationship between the partial pressures, flux and the permeability constant, P as:

$$F = P\frac{(p_1 - p_2)}{h} \qquad (2)$$

Unlike the diffusion constant D, there is some variation in the units and even the definition of P [8]. In this paper, P is defined in units of $mol.m^2/m^3.atm.sec.(mol.ft^2/ft^3.atm.sec.)$.

The surface concentration of a gas, C, and its vapor pressure p are related through the solubility coefficient S by Henry's law as:

$$C = Sp \qquad (3)$$

From Eqs. 1-3, it is seen that the diffusion coefficient and the solubility coefficient are related by Eq. 4 as:

$$P = DS \qquad (4)$$

DEVELOPMENT OF DIFFUSION CELL

The goal of the present study was to develop a system that could be used to evaluate the oxygen diffusion characteristics of FRP-concrete systems used in infrastructure repair. A pair of blank, round, commercially available stainless steel plates was used. The plates were 11 mm thick and had a 144 mm outside diameter. They had eight bolt holes located symmetrically around the outside perimeter. The central part of the plates was machined to create 83 mm diameter and 4.5 mm deep recess that constituted the diffusion chamber. In case the time taken to complete a test was inordinate, the volume of this chamber could be reduced by placing appropriately sized aluminum inserts in the opening.

The diffusion cell is assembled by bolting the two stainless steel plates together using eight stainless steel bolts, nuts and washers. A special, calibrated digital torque wrench was used to ensure uniformity in the applied force. As the lengths of the bolts can be varied, it provided a simple yet effective means for testing samples of different thickness.

The diffusion cell was assembled in air and therefore one face of the specimen has the same oxygen concentration as air (20.7% of oxygen). The other face was flushed with 100% concentration oxygen to provide the needed concentration gradient. A similar gradient could also have been created by flushing pure nitrogen instead.

In any cell that is assembled manually, elaborate procedures are needed to ensure that there are no leaks. In this case, threaded inlet and outlet openings in the bottom plate were made leak proof by using liquid threaded seal Teflon in conjunction with a Swagelok male connector.

A Figaro electrochemical oxygen sensor was used and all data corrected to account for oxygen consumed by this sensor [4]. The sensor was connected to the Agilent 34970A data acquisition system to allow data to be recorded. Temperature data were also recorded at the same time since the diffusion coefficient depends on temperature.

Fig. 1 shows a photograph of a prototype diffusion cell with the oxygen sensor attached at the top. The bolted assembly and the rubber gasket can be clearly seen. Two cells are shown; the additional cell has an impermeable material such as steel. This set up served as an early warning system for detecting leaks.

Model Verification

The theoretical model developed allowed the permeation coefficient of the specimen to be obtained by numerical solution of the governing differential equation. Results obtained from testing polymers were in good agreement with those in the published literature [4].

Figure 1 Test set up showing diffusion cells and electrochemical oxygen sensors

PERMEABILITY COEFFICIENTS

Average values of oxygen permeability coefficients from tests on concrete, epoxy, FRP laminates and FRP-concrete specimens are presented in Fig. 1-2. Fig. 1 provides results for the concrete specimens while Fig. 2 summarizes results from tests on epoxy, FRP laminates and FRP-concrete specimens. The numbers in parentheses in these figures indicate the number of results used to obtain the average value. Complete results may be found elsewhere [4,5,7].

It may be seen from these figures that the order of magnitude for oxygen permeability (in mol. m2/m3.atm.sec.) ranges from 10^{-7} to 10^{-9} for concrete to 10^{-12} for epoxies. The results for FRP and FRP-concrete systems show more scatter.

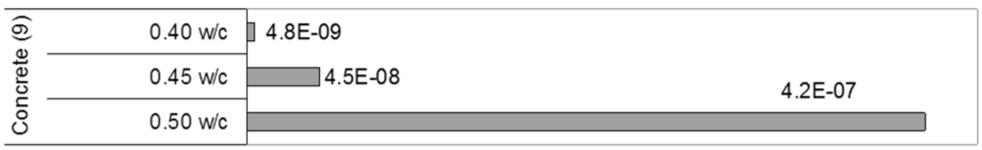

Figure 1. Average oxygen permeation constant for concrete specimens in mol. m2/m3.atm.sec. [6]

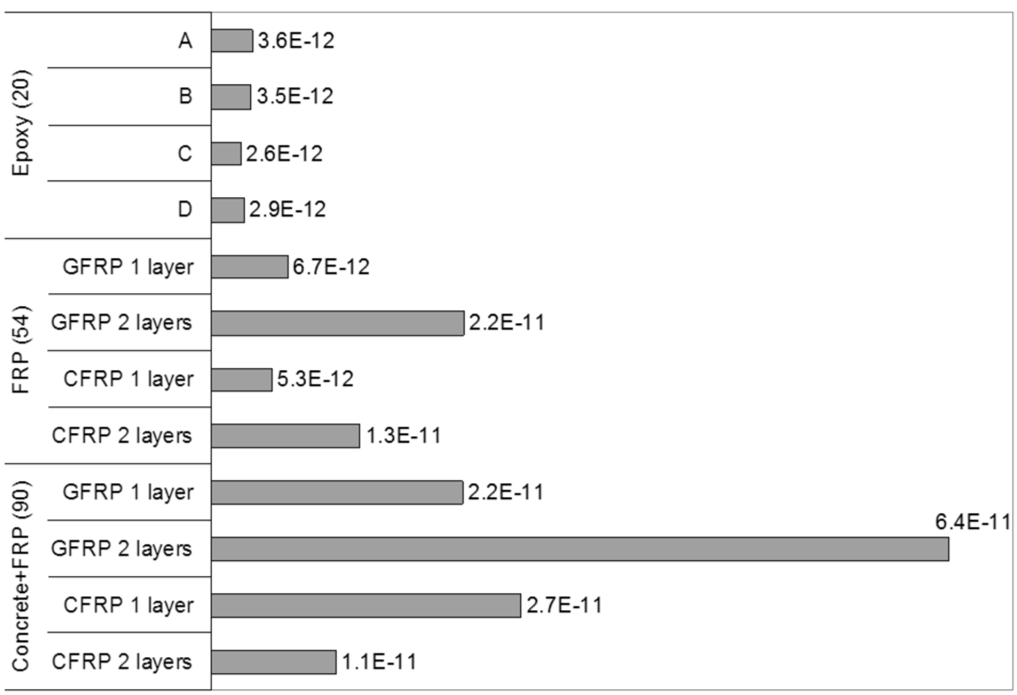

Figure 2. Average oxygen permeation constant for epoxy, FRP, and FRP-concrete specimens in mol. m2/m3.atm.sec. [6]

Fig. 2 shows that the results for two FRP layers are inferior compared to those for single layer systems. SEM studies [5] indicated that this was because of voids present at the interface between the layers. This helps explain seemingly anomalous results reported in the literature in which the performance of multiple FRP layers was found to be inferior to those with fewer layers.

In general, the permeability constants for FRP-concrete systems are higher than those for FRP. This may be due to fabrication issues though no SEM studies were conducted. Nonetheless, the oxygen permeability for FRP-concrete systems is notably better compared to concrete.

DESIGNING FOR STRENGTH

If capacity loss due to steel corrosion is known, the FRP required to make up this shortfall can be determined using strain compatibility-based analysis. In case of vertical elements that are subjected to both axial loads and moments, interaction diagrams are the most convenient. This can provide information on the fiber architecture required to withstand design loads [9]. If bi-directional FRP is used it provides an increase in strength while providing resistance to transverse expansion due to corrosion. The barrier properties of the FRP can then be determined following the procedure that is described.

APPLICATION

The permeability coefficients in Figs. 1-2 may be used to *estimate* the reduction in corrosion rate in FRP-concrete repairs. The proposed predictive model assumes idealized conditions, e.g. uniform corrosion, complete destruction of the protective passive layer on steel. It disregards environmental factors such as temperature and humidity that are known to affect the corrosion rate. Nonetheless, this model provides the first steps for selecting FRP/concrete combinations that provide the most effective solution for infrastructure corrosion repair.

Equivalent FRP Thickness

The oxygen permeability of concrete is a function of its water-cement ratio. Where concrete has a high water-cement ratio or if it is cracked, it is porous and its oxygen permeability may be disregarded. In contrast, the oxygen permeability of uncracked concrete made using a low water cement ratio mix is small and should not be ignored in design. In this case, it is convenient to define an equivalent FRP thickness of the FRP-concrete system.

Experimental results for the oxygen permeability for FRP laminates and FRP-concrete systems showed that the interfacial resistance was negligible. This meant that the FRP-concrete system could be idealized as a two-layer system. For this case, it is possible to determine an equivalent thickness, ΔX_{eqv}, given by Eq. 7 [7].

$$\frac{\Delta X_{eqv}}{P} = \frac{\Delta X_A}{P_A} + \frac{\Delta X_B}{P_B} \tag{1}$$

In Eq. 1, the thickness and oxygen permeability of concrete is denoted by ΔX_A, P_A while those for FRP are given by the terms ΔX_B and P_B. The oxygen permeability of the equivalent FRP-concrete system, ΔX_{eqv} is denoted as P.

Eq. 1 allows the oxygen permeation characteristics of FRP-concrete systems to be idealized as a homogeneous system. If the permeability of the two materials were identical, the equivalent thickness is the sum of the thicknesses of the two materials. This applies to repairs where multiple FRP layers are used. On the other hand, if the permeability differs significantly (typical for concrete), the thickness of the significantly more permeable material can be disregarded. For values that are in-between, Eq. 7 allows the determination of an equivalent thickness.

Eq. 1 was used to determine the equivalent FRP thickness for alternative FRP-concrete repairs in which the water / cement ratio of the concrete varied from 0.4 to 0.5. Three different concrete covers ranging from 25 to 75 mm were used in conjunction with a 2 mm thick laminate. The results summarized in Table 1 confirm that the thickness of the equivalent FRP layer is a function of the w/c ratio: the larger this ratio, the more porous the concrete, the more modest its influence. The equivalent thickness is highest for the lowest water cement ratio as summarized in Table 1.

TABLE 1. Equivalent FRP Thickness

w/c ratio	**P_A**	**P_B**	**ΔX_A mm**	**ΔX_B Mm**	**ΔX_{eqv} mm**	**Remarks**
0.4	1E-11	1E-9	2	25	2.250	Equivalent thickness is
			2	50	2.500	useful for this range of
			2	75	2.750	permeability
0.45	1E-11	1E-8	2	25	2.025	Concrete cover makes
			2	50	2.050	little difference for
			2	75	2.075	porous concrete
0.50	1E-11	1E-7	2	25	2.003	
			2	50	2.005	
			2	75	2.008	

(P_A, P_B in mol.m^2/m^3.atm.sec)

CORROSION REPAIR DESIGN

In the simplified analysis presented, the corrosion process is assumed to be diffusion step limited. And both concrete and iron oxide are assumed to be dry so that it offers no resistance to oxygen diffusion. The analysis permits the determination of the corrosion rate of steel in chloride contaminated concrete whose exposed surface is protected by FRP. In essence, results from the study allow calculation of the number of moles of oxygen that reach the steel surface. The metal loss corresponds to the number of moles of iron that react with this oxygen as explained later.

Permeability is a property of the polymer that is *independent* of thickness. The *permeation rate,* N, (mol/m^2.sec), however, depends on the thickness of the FRP-concrete system, ΔX_{eqv}. By definition, N is given by:

$$N = P \times (p_0 - p_i) / \Delta X_{eqv} \tag{2}$$

In Eq. 2, P is the permeability coefficient of the system and p_o and p_i the partial pressures on its outer and inner surfaces. If the FRP surface is exposed outdoors, p_o is 1 atm. The partial pressure on the inner surface, p_i, is taken as zero since it is assumed that whatever oxygen permeates through the barrier is immediately consumed. This implies that there is perfect bond between the epoxy and the concrete surface. The total amount of oxygen (M in moles) that can reach the steel surface through the FRP bonded surface (area A in m^2) over time t (in seconds) is obtained from the permeation rate, N by multiplication.

Substituting $p_i = 0$, in Eq. 2, M is given by Eq. 3 as:

$$M = N \times A \times t = \frac{P \times p_o \times A \times t}{\Delta X_{eqv}} \quad (3)$$

Eq. 3 may be used to calculate the number of moles of oxygen that reach the steel surface.

From basic electro-chemical corrosion theory, one mole of oxygen reacts with two moles of iron to form rust. Therefore, if the number of moles of oxygen, M, reaching the steel surface is known (from Eq. 3), the number of moles of iron converted to rust is twice this quantity. Using the relationship between molecular weight and moles, the metal loss can be determined. Knowledge of the metal loss allows calculation of the corrosion rate. Illustrative numerical examples may be found in the references [4,6,7].

The analysis describes makes several simplifying assumptions. Most notably, the protective passive layer that forms on steel is completely destroyed and all oxygen reaching the steel surface is immediately consumed. Corrosion is also assumed to take place at a constant rate throughout. This is an idealized condition and disregards the effect of factors such as temperature and humidity that significantly modify the corrosion rate. Nonetheless, it provides an approach for selecting suitable FRP/concrete combinations that can result in its optimal use.

CONCLUSIONS

This paper provides an overview of an experimental study to evaluate the oxygen barrier characteristics of materials used for infrastructure repair. A new diffusion cell was developed along with a quasi-steady state model that enabled oxygen permeation constants to be determined. The results help to explain why FRP can slow down but cannot stop corrosion. It also explains anomalous test results in which the performance of repairs using multiple FRP layers was found to be poorer compared to those with fewer layers. An approach is presented that can be used in design to optimize concrete/FRP combinations.

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