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Film model for coated cement concrete

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Abstract

The performance of a polymer concrete coated cement concrete under sulfuric acid environment was studied for 3 years. Both dry and wet concrete specimens were used in this study. The mass transfer coefficient ratio of cement concrete to polymer concrete was over 12. Coated cement concrete cylinders with pinholes were used to study the chemical resistance of the coated concrete under sulfuric acid environments to represent the worst sewer condition. Effects of pinhole sizes on the performance of coated concrete were studied, and changes in weight of the coated concrete specimens were measured regularly. The weight change in coated cement concrete was modeled using a film model and the effect of the pinhole sizes on the performance of the coated concrete was quantified.

Keywords: Diffusion; Coating; Concrete; Long-term performance; Modeling

1. Introduction

Cement concrete has been widely used in the construction of pipeline systems to transport liquids and sewage in industrial and wastewater facilities, respectively. Many municipalities are discovering that cement concrete structures in the wastewater collection and treatment facilities are subjected to microbial-induced deterioration and the concrete is degrading rapidly [1,2], The sulfuric acid-producing bacteria found on sewer crowns thrive at low pH, which are inhibitory to most competitors. Islander et al. [3] reported that the pH of sulfuric acid for the worst case in sewer environments was 0.5 (close to the pH of a 3% sulfuric acid solution). Fattuhi and Hughes [4] immersed cement concrete in a channel containing an approximately 2% solution of continuously flowing sulfuric acid, and reported an average weight change of 34.6% after 48 days of exposure. Ehrich et al. [5] studied biogenic and chemical sulfuric acid corrosion of mortars. For the ordinary Portland cement mortar, the weight loss of the samples in the biogenic sulfuric acid environment was about 20% after 100 days and the weight loss of the samples in the pH 2 chemical sulfuric acid environment was more than 15% after 25 renewals (every 1–3 days to renew the solution according to the pH of the solution).

To protect concrete facilities from sulfuric acid attack, coating the cement concrete is one method now being adopted. Redner et al. [6,7] evaluated more than 20 different coating systems in 10% sulfuric acid. Their test results showed that there were no failures in the coating films after 1 year of immersion for most of the coatings tested. Liu and Vipulanandan [8] investigated the performance of an epoxy-coated concrete specimen immersed in 3% sulfuric acid. The results showed that for specimens without pinholes on the coating film, the weight gain was only about 1% after 3 years and the probability of failure increased with the increase in weight for coated concrete in 3% sulfuric acid. Hence, the prediction of the weight change for coated concrete is very important for predicting the service life of coated concrete specimens and for evaluating the effectiveness of coating materials.

2. Objectives

The overall objective of this study was to evaluate and model the performance of the polymer concrete coated

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cement concrete with and without pinholes under sulfuric acid environments. The specific objectives are as follows:

1. to characterize the polymer concrete coating material;
2. to determine the performance of coated cement concrete with and without pinholes; and
3. to model the observed behavior of the coated concrete.

3. Materials and testing program

3.1. Materials

3.1.1. Coating

A polyester-based polymer concrete coating was selected to coat dry and wet (saturated) concrete specimens. Some of the properties of the pure coating are summarized in Table 1.

3.1.2. Concrete

Cylindrical concrete specimens (76 mm diameter × 152 mm height) were obtained from a pipe manufacturer, where concrete mix was made according to ASTM C 76. The unit weight of concrete specimens varied between 22.5 kN/m^3 (142 pcf) and 25.5 kN/m^3 (158 pcf). The pulse velocity results showed a normal distribution with a mean value of 4748 m/s (15,576 ft/s) and a coefficient of variation (COV) of 2%. The average compressive strength of 28-day water-cured concrete was 34 MPa (5000 psi), and the flexural strength was 8.3 MPa (1200 psi).

3.2. Testing program

3.2.1. Chemical test on coating

Cylindrical coating specimens, 38 mm (1.5 in.) diameter × 76 mm (3 in.) height, were collected from the coating manufacturer during the application of the coating to the cement concrete specimens. The coating specimens were immersed in a 3% sulfuric acid solution and deionized (DI) water to determine their performance in acidic and controlled conditions. At least two specimens were tested in each solution.

3.3. Pinhole test chemical resistance (ASTM G 20, CIGMAT CT-1)

In order to study the chemical resistance of coated cement concrete, the ASTM G 20 test [9] was modified to use with coated concrete. The specimens were immersed in a selected test reagent to half the specimen height in a closed bottle so that the specimens were exposed to the liquid phase and vapor phase [8]. This method was intended for use as a relatively rapid test to evaluate the acidic resistance of coated specimens under anticipated service conditions. Dry and wet (water saturated) cement concrete specimens were coated on all sides and tested. For the test, two radial holes were drilled into the coated specimen approximately 15 mm deep. In this test, the changes in (1) weight of the specimen and (2) appearance of the specimen were monitored at regular intervals. The two test reagents selected for this study were (1) DI water (pH = 5–6) and (2) a 3% sulfuric acid solution (pH = 0.45; representing the worst reported condition in the wastewater system). Control tests were performed without pinholes.

Table 1
Properties of the polymer concrete coating

Coating material	Density (kg/m^3)	Pulse velocity (m/s)	Hardness		Thickness (mm)	Application condition
			Barcol	Shore		
Polymer concrete	1750	3165	38–45	78	3.2	dry and wet surfaces

4. Results and discussion

4.1. Cement concrete

Weight changes in concrete cylinders in DI water and 3% sulfuric acid are shown in Fig. 1. For concrete cylinders immersed in DI water, the typical weight gain with time is shown in Fig. 1a. The weight increases for dry and wet concrete specimens were about 0.9% and 0.4%, respectively, after 80 days of immersion. Concrete specimens reached near saturation during this period. The cylindrical model developed by Mebarkia and Vipulanandan [10] can be used to predict the weight increase and determine the material parameters. The relationship for the cylindrical model is as follows:

$$M(t) = 2\pi h R^2 S_0 \frac{\lambda^b}{a}\left[1 - \frac{\lambda^b}{a} + \frac{\lambda^b}{a}\exp\left(\frac{-a}{\lambda^b}\right)\right] \qquad (1)$$

where $\lambda = Dt/R^2$; $M(t)$ = weight increase in the specimen at time t [kg]; S_0 = ultimate concentration of water in the specimen [kg/m^3]; D = effective diffusion coefficient [m^2/s]; h = height of the specimen [m]; t = immersion time [s]; R = radius [m]; a, b = constants (a = 0.04, b = 1.72).

The values of the material parameters in Eq. (1) for concrete in water are summarized in Table 2. For the dry concrete, the ultimate concentration was 23 kg/m^3 and the mass transfer coefficient of the concrete was 137×10^{-12} m^2/s.

When the wet concrete was immersed in 3% sulfuric acid, the weight gain was only observed for the first 2 days (Fig. 1b). After 20 days, the weight loss in the concrete cylinder was about 5% because sulfuric acid reacted with the binder (cement) in the concrete and debonded the aggregates from the surface of the concrete specimens.

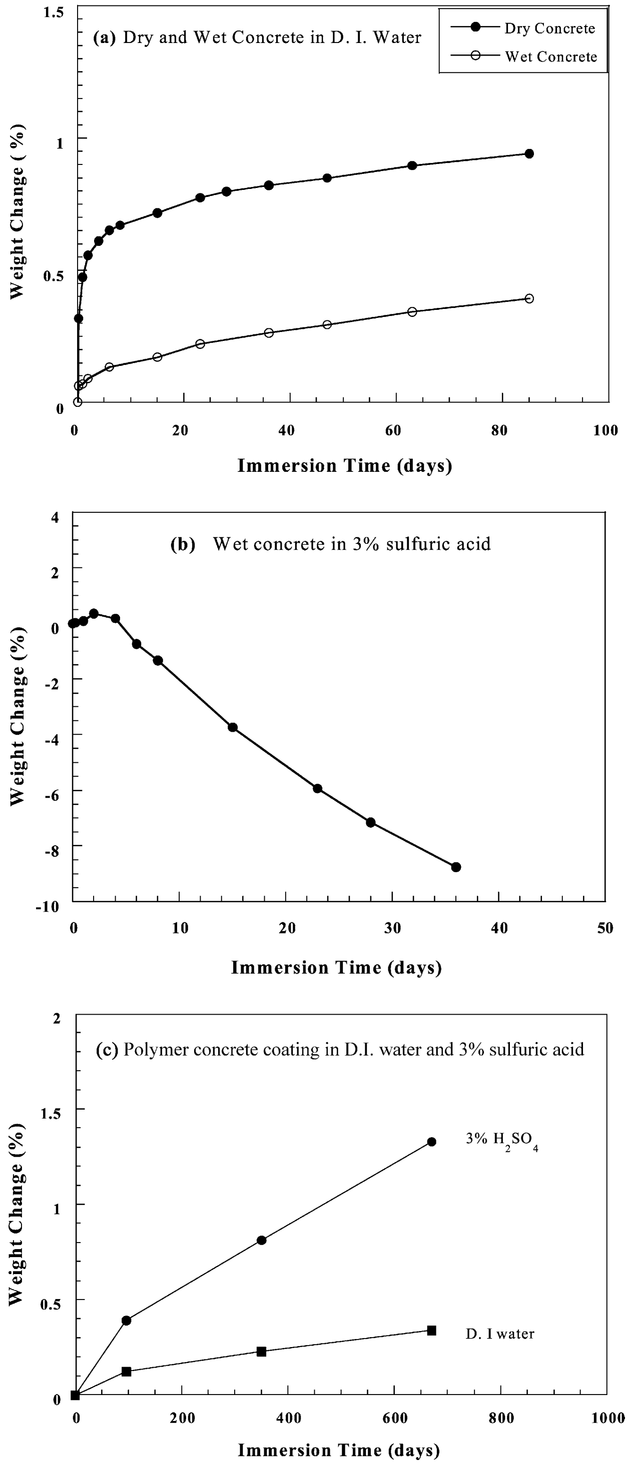

Fig. 1. Weight change in tested materials: (a) concrete in DI water; (b) concrete in 3% sulfuric acid; and (c) coating in DI water and 3% sulfuric acid.

4.2. Bulk coating material

Since the coating is applied on high alkaline concrete surface and then required to perform in acidic environments, the behavior of the coating in acidic and alkaline environments must be evaluated. The weight change with immersion time for bulk coating specimens in different solutions is shown in Fig. 1c. The weight increase in the bulk coating specimens in DI water after 22 months of immersion was 0.4%, and the weight increase in a 3% sulfuric acid solution was 1.3% during the same period of immersion.

The mass transfer coefficients of the coating in DI water and 3% sulfuric acid are summarized in Table 2. From Table 2, the mass transfer coefficient for the polymer concrete coating (10.6×10^{-12} m^2/s) in DI water was of the same order of the mass transfer coefficient for a polyester polymer concrete (22×10^{-12} m^2/s) in water reported by Mebarkia and Vipulanandan [10]. The mass transfer coefficient of the polymer concrete coating with the 3% sulfuric acid solution was lower than DI water by about 50%. The ultimate saturation concentration (S_0) in the 3% sulfuric acid solution was more than four times higher than in DI water, indicating that the polymer concrete had higher affinity to acid solutions. Concrete-to-polymer concrete ratio of mass transfer coefficients was over 12.

4.3. Coated concrete

4.3.1. DI water

The relationships between weight change and immersion time for coated specimens in DI water are shown in Fig. 2. No failure was observed with the polymer concrete coated dry and wet concrete specimens in DI water (Fig. 2a and b). Weight increase in dry and wet coated concrete specimens without pinholes was about 0.3% after 400 days of immersion, while the weight increase for specimens with 3- and 6-mm pinholes were about 0.5%.

4.3.2. Acid

Testing coated wet concrete specimens in 3% sulfuric acid represents the worst service conditions that the coating will be subjected to in wastewater systems. The weight increase of the coated wet concrete specimens with time in 3% sulfuric acid is shown in Fig. 2c. The weight increase was about 0.5% for the wet coated concrete specimens without pinholes after 400 days of immersion, while the weight increases for the wet coated specimens with pinholes varied from 1.1% to 1.4% (Fig. 2c). There were no failures (cracks and blisters) observed on the coated wet concrete

Table 2
Material parameters in DI water and 3% sulfuric acid

Material	Ultimate concentration, S_0 (kg/m^3)		Mass transfer coefficient, D ($\times 10^{-12}$ m^2/s)	
	DI water	3% Sulfuric acid	DI water	3% Sulfuric acid
Cement concrete	23.0	–	137.0	–
Polymer concrete	6.0	26.0	10.6	5.74

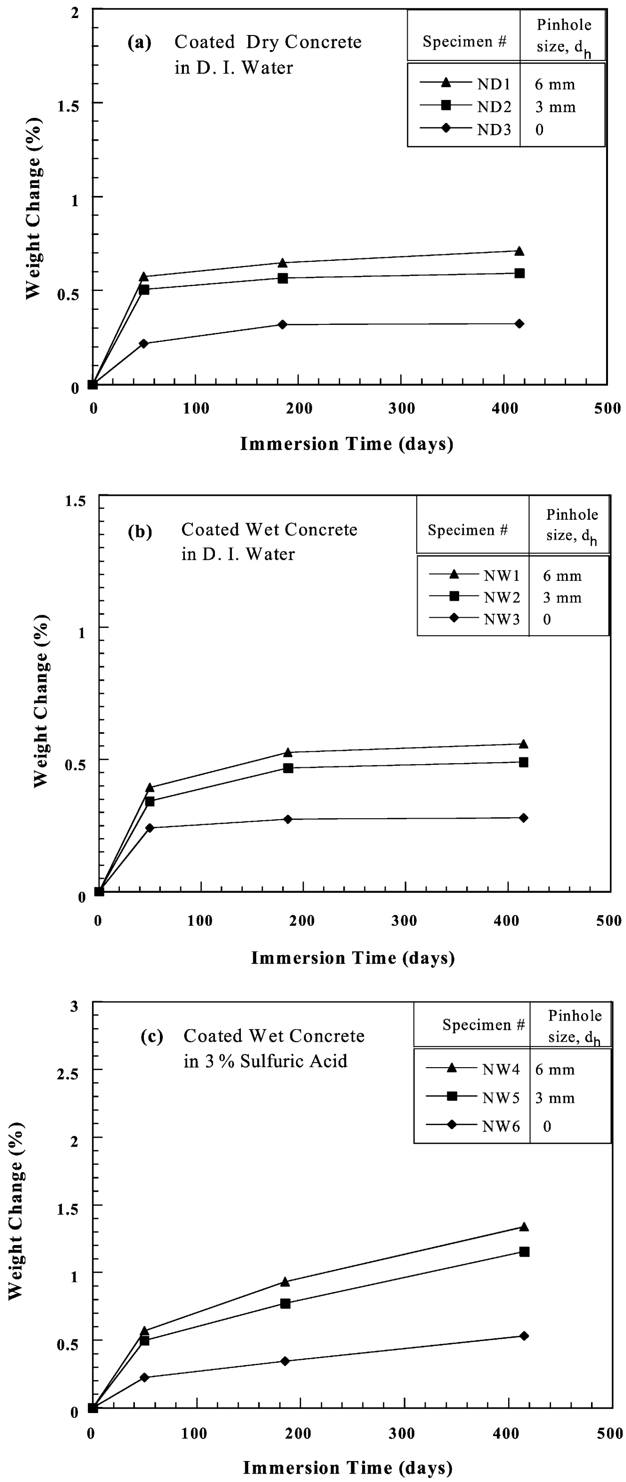

Fig. 2. Percentage weight change with immersion time for coated (a) dry concrete in DI water; (b) wet concrete in DI water; and (c) wet concrete in 3% sulfuric acid.

specimens with and without pinholes after 400 days of immersion (Fig. 2c). The wet coated concrete specimens without pinholes exhibited good ability to resist acid solution penetration.

5. Modeling

A weight increase in coated concrete indicates the degree of deterioration of the concrete when immersed in sulfuric acid. Modeling the weight increase of coated concrete can lead to the prediction of the service life of the coated concrete structure when it is in immersion service. The physical model of liquid penetrating through a coating film is shown in Fig. 3.

In modeling, the coating film was treated as a plane sheet. The distribution of the degree of saturation within the coating film can be obtained using the boundary conditions $x=0$, $S=S_0^{CT}$ and $x=\ell$, $S=S_i^{CT}$:

$$\frac{S-S_0^{CT}}{S_i^{CT}-S_0^{CT}}=\frac{x}{\ell} \quad (2)$$

where S_0^{CT} = degree of saturation of the coating film on the outer surface [kg (solution)/m^3 (solid)]; S_i^{CT} = degree of saturation of the coating film on the interface [kg (solution)/m^3 (solid)]; λ = coating film thickness [m].

The rate of mass transfer, F (g liquid/s), through a plane sheet under steady state is given by Crank [11]:

$$F=-D_{CT}\left(\frac{dS}{dx}\right) \quad (3)$$

where D_{CT} = mass transfer coefficient of the coating film [m^2/s].

Assuming that the degree of saturation on the interface varies with time t and can be represented by the exponential function:

$$S_i^{CT}=S_0^{CT}(1-e^{-\beta^{CT}t}) \quad (4)$$

where β^{CT} = a coating material-related parameter.

The amount of solution, W_t, passing through the coating film from time 0 to t can be obtained as follows:

$$W_t=\frac{2\pi RhgS_0^{CT}}{\beta^{CT}}\frac{D_{CT}}{\ell}(1-e^{-\beta^{CT}t}) \quad (5)$$

where R = radius of the specimen [m]; h = height of the specimen [m].

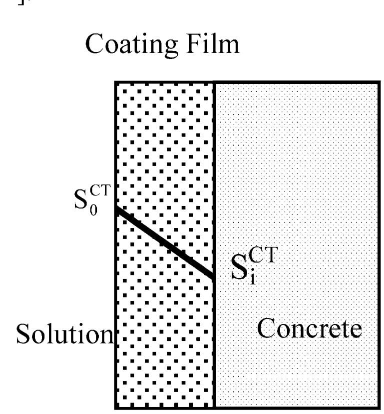

Fig. 3. The distribution of the degree of saturation in the coating film.

Table 3
Values of k_1 and k_2 for different conditions

Coating condition	DI water		3% Sulfuric acid	
	k_1	k_2	k_1	k_2
Dry	1.50	0.89	–	–
Wet	2.30	0.77	2.70	0.30

Eq. (5) is the film model to predict the weight change in coated concrete after different periods of immersion. If the initial weight of the specimen is W_0, the percentage weight change (ΔW) of the tested specimen can be represented as:

$$\Delta W\% = \frac{W_t}{W_0} \times 100 \tag{6}$$

where $W_0 = \pi R^2 h\gamma$; γ = unit weight of concrete [kN/m^3].

Eq. (6) can be rewritten as:

$$\Delta W\% = \frac{2gS_0^{\mathrm{CT}}}{R\gamma\beta^{\mathrm{CT}}}\frac{D_{\mathrm{CT}}}{\ell}\left(1 - \mathrm{e}^{-\beta^{\mathrm{CT}}t}\right) \times 100. \tag{7}$$

The effect of pinhole sizes on the liquid uptake of a coated substrate can be taken into account by incorporating a parameter, ξ (which is a function of pinhole sizes), to Eq. (7). The parameter ξ is defined as:

$$\xi = 1 + \frac{d_{\mathrm{h}}}{k_1 + k_2 d_{\mathrm{h}}} \tag{8}$$

where d_{h} = pinhole diameter [mm]; k_1, k_2 = constants.

Substituting Eq. (8) to Eq. (7):

$$\Delta W\% = \xi\frac{2gS_0^{\mathrm{CT}}}{R\gamma\beta^{\mathrm{CT}}}\frac{D_{\mathrm{CT}}}{\ell}\left(1 - \mathrm{e}^{-\beta^{\mathrm{CT}}t}\right) \times 100. \tag{9}$$

The ultimate degree of saturation, S_0^{CT}, was obtained from experiments on the coating material. By using Eq. (9) to predict weight change of coated concrete, the mass transfer coefficient D_{CT}, parameter β^{CT} of coatings and the pinhole effect parameters k_1 and k_2 were obtained. The percentage weight change of coated concrete at different immersion times can be predicted by Eq. (9). The lower the parameters k_1 and k_2, the greater the influence of pinhole size on the weight change of coated specimens. The

Table 4
Parameters for the model

Surface condition	Ultimate degree of saturation, S_0^{CT} (kg/m^3)		Material parameter, β^{CT}		Mass transfer coefficient, D_{CT} ($\times 10^{-12}$ m^2/s)	
	DI water	3% Sulfuric acid	DI water	3% Sulfuric acid	DI water	3% Sulfuric acid
Dry	6.0	26.0	0.023	–	20.9	–
Wet	6.0	26.0	0.041	0.0075	32.0	2.59

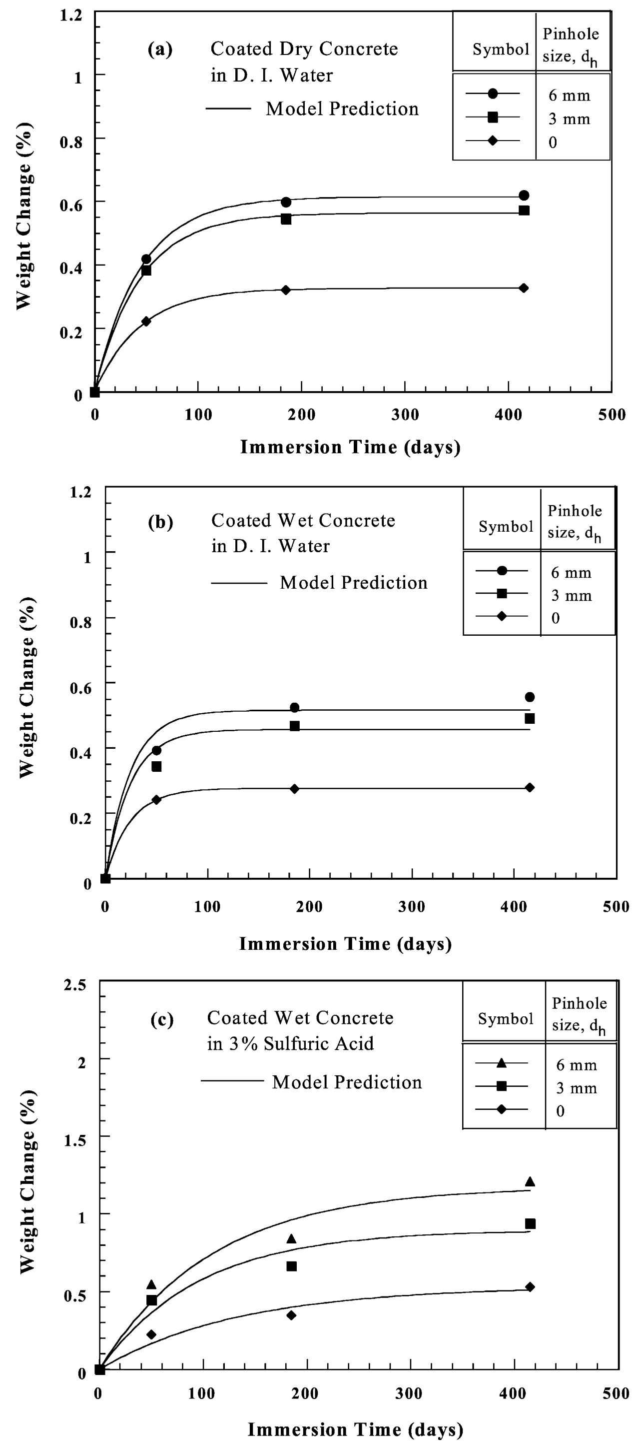

Fig. 4. Comparison of model predictions and experiment data: (a) dry concrete in DI water; (b) wet concrete in DI water; and (c) wet concrete in 3% sulfuric acid.

parameters in Eq. (8) for the coated concrete specimens are summarized in Table 3.

The mass transfer coefficients, D_{CT}, of the coating film (Eq. (9)) are summarized in Table 4. The results showed that the mass transfer coefficient in the coating film was higher than the mass transfer coefficient in the bulk coating in DI water, while the mass transfer coefficient in the coating film was lower than the mass transfer coefficient of the bulk material in 3% sulfuric acid. The results indicate that the concrete substrate may affect the performance of the coating when submerged in nonreactive and reactive solutions.

The prediction of the weight increase in coated concrete is compared to experimental results in Fig. 4. The model predictions are in agreement with the experimental data in Fig. 4.

6. Conclusions

A laboratory test was developed based on ASTM G 20 [12] and was used to evaluate the performance of a polyester-based polymer concrete coating material for protecting concrete substrates exposed to sulfuric acid environments. The mass transfer coefficient ratio of concrete to the coating was over 12. A model was developed to predict the weight change in the coated concrete in acidic solutions. Based on the experimental results and model prediction, the following observations are advanced:

1. The bulk coating material had four times more weight increase in 3% sulfuric acid as compared to water. The mass transfer coefficient of the polymer concrete in 3% sulfuric acid was half the value in water.
2. All coated wet concrete specimens in 3% sulfuric acid passed the test after 400 days. Testing coated concrete specimens with pinholes is considered to represent the critical condition in the field.
3. The prediction of weight change in coated concrete using the film model was in agreement with the experimental data.

Acknowledgements

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