Available online at www.sciencedirect.com

SCIENCE DIRECT

Cement and Concrete Research 35 (2005) 1754–1763

Cement and Concrete Research

Performance of polyurethane-coated concrete in sewer environment

C. Vipulanandan*, J. Liu

Center for Innovative Grouting Material and Technology (CIGMAT), Department of Civil and Environmental Engineering, University of Houston, Houston, TX 77204-4003, USA

Received 20 May 2004; accepted 25 October 2004

Abstract

Polyurethane-based coatings are used to protect concrete facilities against corrosive environments. The performances of two commercially available polyurethane coatings were evaluated under sulfuric acid environment (representing sewer condition) for over 5 years. Both dry (representing new construction) and wet (representing rehabilitation) concretes were used in this study. A combination of the full-scale hydrostatic test, bonding test, and chemical resistance tests were performed to evaluate the coatings to protect concrete structures below ground water. The full-scale hydrostatic test was used to evaluate the application and performance of coatings under hydrostatic pressure to simulate underground concrete structures below ground water. Visual inspections and in situ bonding tests were performed on coated concrete under a hydrostatic pressure of 105 kPa. Test results showed that bonding strength of one coating was affected by the moisture condition and hydrostatic water pressure in the full-scale test. Coated cement concrete specimens with pinholes were used to study the chemical resistance of the coated concrete in sulfuric acid to represent the worst sewer condition. Change in weight of coated concrete specimens was measured at regular intervals. Types of failures in coated concrete under acidic environment have been identified. Test results showed that the performance of the two coatings were noticeably different and one coating with pinholes extended the service life of concrete by 14 times while the other coating extended the service life of concrete by 57 times. There was no direct correlation between bonding strength and chemical resistance of the polyurethane-coated concrete. Although both coatings were polyurethane-based, their performances were different under the testing conditions adopted in the study.

Keywords: Concrete; Bond strength; Long-term performance; Polyurethane; Transport properties

1. Introduction

Cement concrete is extensively used in the construction of buildings, transportation facilities and sewage systems. Cement concrete is highly alkaline and can easily deteriorate under acidic environments. Many municipalities are discovering that cement concrete structures in the wastewater collection and treatment facilities, such as wet wells, holding tanks, manholes, and sewer pipelines, are subjected to microbial-induced deterioration and the concrete is degraded with time [1,2], The sulfuric acid-producing bacteria found on sewer crowns thrive at low pH values which are inhibitory to most competitors. Islander [3] reported that the concentration of sulfuric acid for the worst case in sewer environments was pH 0.5 (close to the pH of 3% sulfuric acid solution). Fattuhi and Hughes [4] immersed concrete in a channel containing an approximately 2% solution of continuously flowing sulfuric acid and the results showed that after 48 days of exposure, the average weight change was 34.6%. Ehrich et al. [5] studied biogenic and chemical sulfuric acid corrosion of mortars. For the ordinary Portland cement mortar, the weight loss in the biogenic sulfuric acid environment was about 20% after 100 days and the weight loss in the pH 2 chemical sulfuric acid environment was more than 15% after 25 renewals (every 1–3 days based on the pH of the solution).

To protect concrete facilities from sulfuric acid attack, coating the concrete is one method now being adopted. Redner et al. [6,7] evaluated more than 20 different coating systems in 10% sulfuric acid and reported varying performance after 1 year of immersion. Liu and Vipulanandan [8]

* Corresponding author. Tel.: +1 713 743 4278; fax: +1 713 743 4260. *E-mail address:* cvipulanandan@uh.edu (C. Vipulanandan).

0008-8846/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2004.10.033

studied epoxy-coated concrete specimens immersed in 3% sulfuric acid. Their 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. Liu and Vipulanandan [9] also developed a film model to predict the weight change of a polymer-concrete-coated cement concrete in 3% sulfuric acid. Predicting the weight change in coated concrete specimens is very important for predicting the service life of coated concrete and in evaluating the effectiveness of coating materials [9].

2. Objectives

The overall objective of this study is to investigate the performance of concrete coated with polyurethane coatings under sewer environment. The specific objectives are as follows: (1) to evaluate the applicability of the selected coatings on concrete surface under hydrostatic back pressure; (2) to determine the performances of coated cement concrete with and without pinholes in sulfuric acid environment; and (3) to measure the changes in bonding strength of coating with time.

3. Materials and testing program

In this study, commercially available two polyurethane based coatings were used. It must be cautioned that the results from this study cannot be generalized to apply to all polyurethane coatings available in the markets.

3.1. Material characterization

3.1.1. Coatings

Two polyurethane coatings were selected to coat dry and wet (saturated) concrete surfaces. Cylindrical specimens (3.8 cm in diameter×7.6 cm in height) were used to measure density and pulse velocity of the coatings. Pulse velocity was measured using a commercially available portable V-meter. Lead–zirconate–titanate ceramic transducers with natural frequency of 150 kHz were used. The hardness of the coating films was measured by using two methods: Durometer Type D (ASTM D 2240 [10]) and Barcol Hardness Tester GYZJ 934-1 (ASTM D 2583 [11]). An ultrasonic coating thickness gauge (PosiTector 100 C) was used to measure the thickness of the coating films (ASTM D 6132) on the concrete. The properties of the coatings are summarized in Table 1.

3.1.2. Concrete

Cylindrical concrete specimens (76 mm in diameter×152 mm in height) were obtained from a pipe manufacturer, where concrete mix was proportioned according to ASTM C 76. The unit weight of concrete specimens varied between 22.5 (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 28th day compressive strength of water-cured concrete was 34 MPa (5000 psi) and the flexural strength was 8.3 MPa (1200 psi). The direct tensile strength of the concrete was 2.1 MPa (303 psi) based on the average value of concrete failure in the CIGMAT CT-2 tests.

3.2. Testing program

3.2.1. Hydrostatic test

In order to stimulate hydrostatic pressure on concrete structures due to the ground water table, it was decided to use concentrically placed concrete pipes to develop the necessary full-scale testing conditions (Fig. 1). This was achieved by using 900-mm (36 in.) inner pipes and 1600-mm (64 in.) outer pipes with two concrete end plates. Based on the input from contractors, 900-mm (36 in.)-diameter pipe was the smallest man-entry pipe in which a coating applicator could operate with reasonable ease. Steel elements were used to support the entire setup. Inner concrete pipe surface was representing a concrete surface under hydrostatic pressure and coating a pipe (laid horizontally) surface represented most of the difficult conditions encountered in coating structures such as lift stations. The total area available for coating was 14 m^2 (150 ft^2). Pressure chamber used for the full-scale test was designed and built by Hanson (formerly Gifford-Hill and Company), Houston Division, which was representing the American Concrete Pipe Association.

3.2.1.1. Dry test. Coating was applied to new 900 mm (36 in.) diameter concrete pipe at the Hanson concrete pipe yard in Houston. The coated pipes were then placed in the pressure chamber for hydrostatic pressure testing.

Table 1
Properties of the polymer concrete coating

Coating material	Density[a] (kg/m^3)	Pulse velocity[a] (m/s)	Hardness[b]		Thickness[b] (mm)	Application condition
			Barcol	Shore		
Polyurethane-1	1130	2283	28–35	67	1.1	dry and wet surfaces
Polyurethane-2	1355	3165	38–45	78	4.7	dry and wet surfaces

[a] Property of bulk material.
[b] Property of coating film.

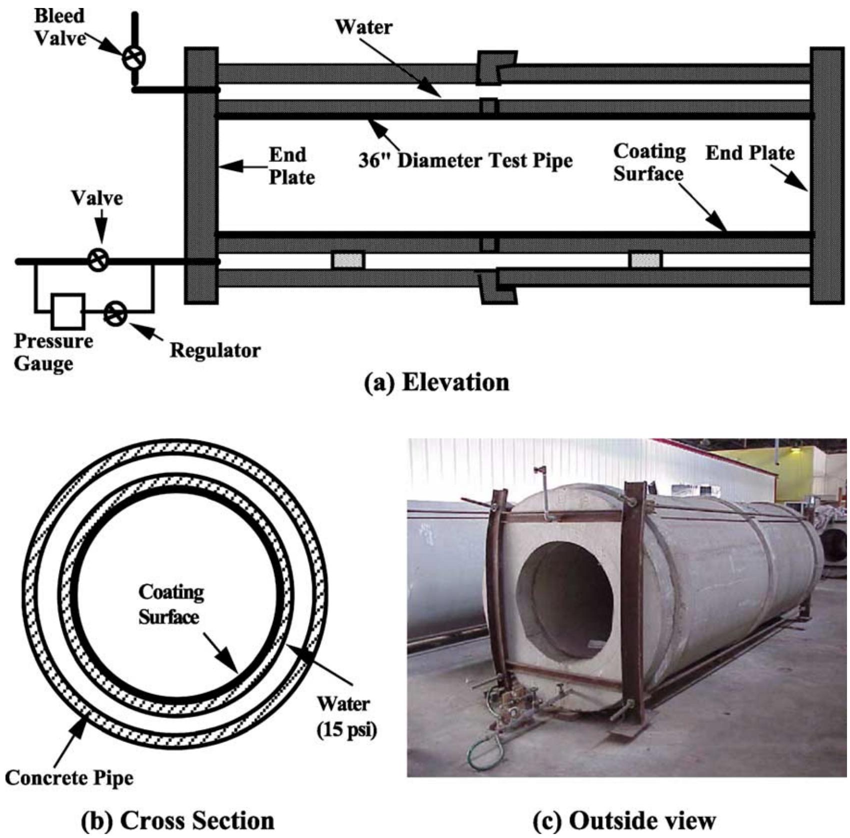

Fig. 1. Hydrostatic test configuration.

3.2.1.2. Wet test. The 900 mm (36 in.) concrete pipe was installed in the test chamber and pressurized at 105 kPa (32 ft of water head) for at least 2 weeks before applying the coating. The coatings were applied after water jet blasting or sand blasting the surface. The average application temperature was 65 °F. The moisture emission rate was 536 μg/(s m^2) (9.49 lb/1000 ft^2 24 h, ASTM E 1907) on the concrete surface.

3.2.1.3. Measurements. Visual inspection and in situ bonding test (CIGMAT CT-2 [12], Modified ASTM D 4541 [13]) were performed during the tests.

3.2.2. Bonding strength (CIGMAT CT-2 [12], modified ASTM D 4541 [13])

In this test, 51-mm (2-in.)-diameter circular area was used for testing (Fig. 2). Coated concrete blocks were cored

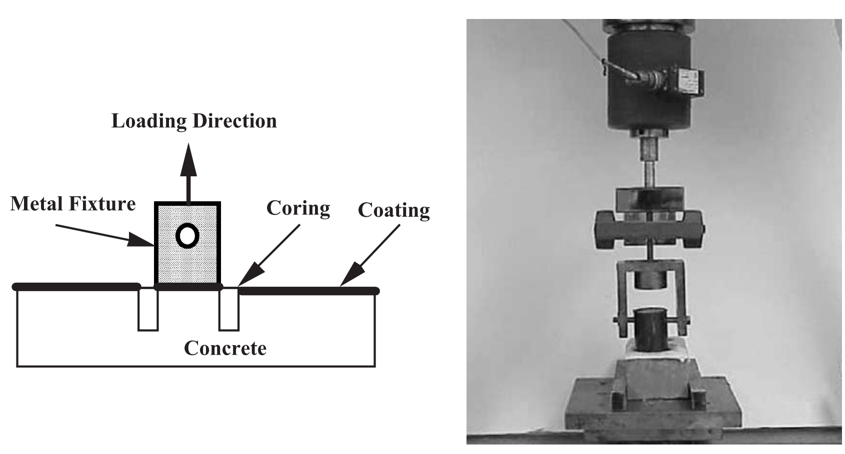

Fig. 2. CIGMAT CT-2 bonding test setup.

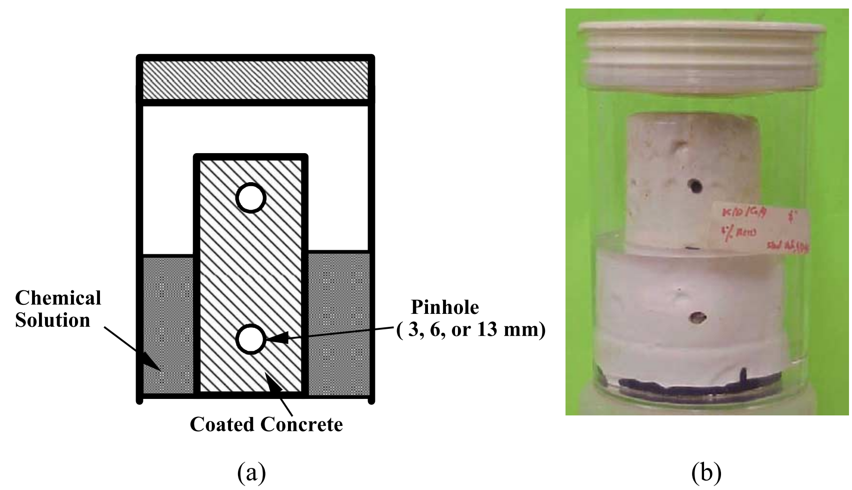

Fig. 3. Chemical tests on coating materials for concrete (CIGMAT CT-1, Modified ASTM G-20).

using a diamond core drill to predetermined depth to isolate the coating. A metal fixture was then glued to the isolated coating section using a rapid setting epoxy. Bonding strength (pull-off strength) between the concrete and the coating material was determined over a period of 2 years.

3.2.3. Pinhole test—chemical resistance (CIGMAT CT-1 [14], modified ASTM G 20 [15])

In order to study the chemical resistance of coated cement concrete, the ASTM G 20 test was modified to use with coated concrete. As shown in Fig. 3, 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. 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 (considering the sizes of aggregates used in the concrete specimens). Pinhole sizes 3 and 6 mm were selected. 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 are (1) deionized (DI) water (pH=5 to 6) and (2) 3% sulfuric acid solution (pH=0.45; representing the worst reported condition in the wastewater system). Control tests were performed without pinhole.

4. Results and discussions

4.1. Physical properties

Based on measured properties (Table 1), polyurethane-2 was harder and denser than polyurethane-1. The density of polyurethane-2 was 20% higher than polyurethane-1. The thickness of polyurethane-2 coating was four times the thickness of polyurethane-1 (thickness was selected by the coating manufacturer).

4.2. Hydrostatic pressure test

The performance rating criteria are as follows: (i) Overall condition (appearance): good, satisfactory, bad; (ii) Surface texture: smooth, rough; (iii) Blistering: yes, no; (iv) Cracking: yes, no; (v) Change in color: yes, no; (vi) Overall finish (quality of the job): good, satisfactory, bad; (vii) Overall Rating: Pass, Satisfactory, Fail.

In the hydrostatic test, all of the coatings had smooth surfaces on both dry and wet coating conditions. No color change and/or no cracking were observed in the test. polyurethane-1 had good in-situ bonding strength (2.0 MPa) on the dry concrete surface and poor in-situ bonding strength (0.4 MPa) on the wet concrete surface. The overall rating of the coating was a “pass” on the dry application condition and a “satisfactory” on the wet application condition. The in situ bonding strengths of polyurethane-2 on dry and wet concrete surfaces were 0.5 (73 psi) and 0.8 MPa (111 psi), respectively. Delamination and hard blisters were observed on polyurethane-2-coated dry concrete. The overall rating on the dry application condition was “satisfactory with small pockets of blisters and delamination” and, on the wet application condition, it was a “pass”.

4.3. Bonding test

The bonding test results of the two polyurethane coatings are shown in Fig. 4. As shown in Fig. 4, polyurethane-1 had very good bonding strength on dry concrete surface (Fig. 4(a)). The failures were concrete failure, which indicated that the bonding strength of polyurethane-1 was higher than the tensile strength of the concrete in the testing period. On the other hand, polyurethane-2 had very low bonding strength on the dry concrete surface. All failures were bonding failure with an average bonding strength of 0.12 MPa (17 psi). In situ

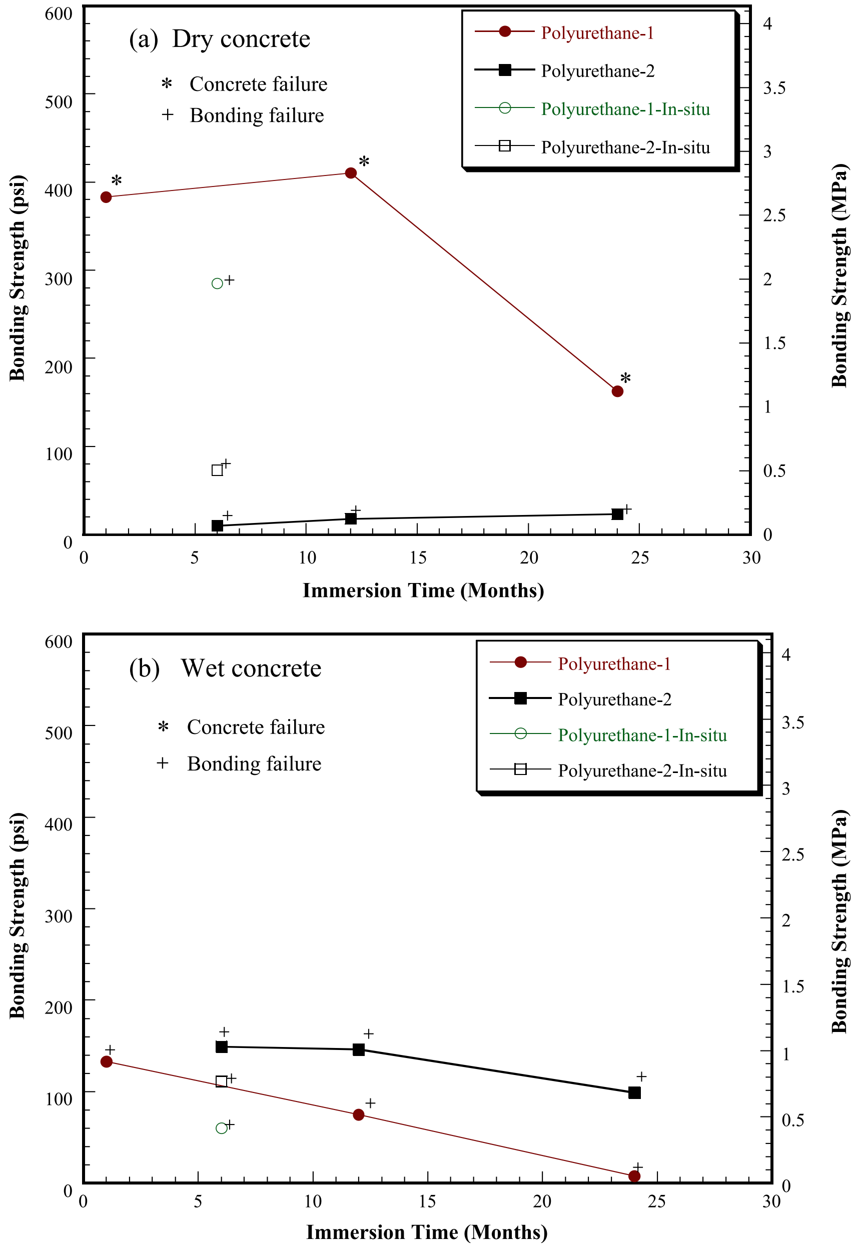

Fig. 4. Bonding strength of coated concrete in (a) dry concrete and (b) wet concrete.

bonding tests were also performed on the coated concrete pipes in hydrostatic tests. Although the failure on the in-situ test was bonding failure, polyurethane-1 still had very high bonding strength (2.0 MPa, 285 psi; Fig. 4(a)) on the dry surface of the coated concrete pipe. Polyurethane-2 had bonding failure with a bonding strength of 0.51 MPa (73 psi) on the dry surface of the coated concrete pipe.

Polyurethane-1 had low bonding strength on the wet concrete surface (Fig. 4(b)). All failures were bonding failure with an average bonding strength of 0.50 MPa (72 psi). The results indicated that the moisture on the concrete surface before applying the coating affected the bonding strength of polyurethane-1. On the other hand, polyurethane-2 had better bonding strength on the wet concrete surface than on the dry concrete surface, but the failure types of polyurethane-2 were the same (All bonding failure). The average bonding strength was 0.92 MPa (131 psi). In situ bonding test results also indicated low bonding strength of the coatings on wet concrete surface (Fig. 4(a)). The average bonding strengths of polyurethane-1 and polyurethane-2 in the in situ tests were 0.42 (60 psi) and 0.78 MPa (111 psi), respectively.

4.4. Chemical resistance

4.4.1. Uncoated concrete

The weight changes of uncoated dry and wet concretes (immersed in water for 7 days) in 3% sulfuric acid were tested. The dry and wet concrete specimens in 3% sulfuric acid had a weight loss over 2% in 7 days.

4.4.2. Coated concrete

4.4.2.1. In DI water. No failure was observed in the coated dry and wet concrete specimens in DI water over 5 years of immersion. The weight changes in the coated concrete specimens without pinholes in DI water are shown in Fig. 5(a). The weight increases in polyurethane-1-coated dry and wet concrete specimens coated without pinholes were 0.58% and 0.44%, respectively after 5 years of immersion. Polyurethane-2-coated dry and wet concrete specimens without pinholes had 1.2% and 0.9% weight increases respectively, which were higher than the saturation limit of uncoated dry concrete specimens (Fig. 5(a)) in 5 years of immersion. The reason may be that polyurethane-2 absorbed some of the water and/or water filled the interface between coating and concrete.

4.4.2.2. In acid. Polyurethane-1-coated dry concrete specimens had a weight increase of 0.88% in 500 days of

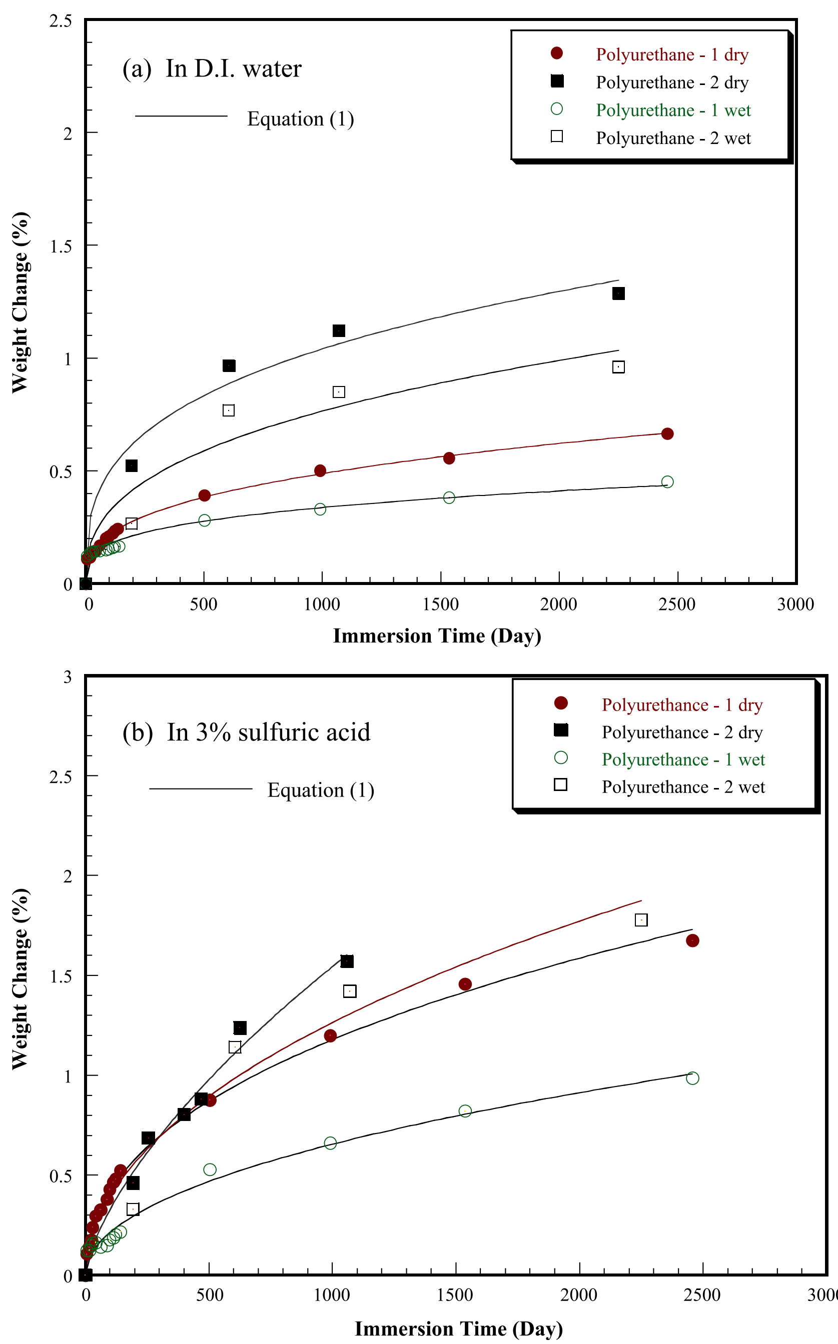

Fig. 5. Weight change of coated concrete in (a) DI water and (b) 3% sulfuric acid.

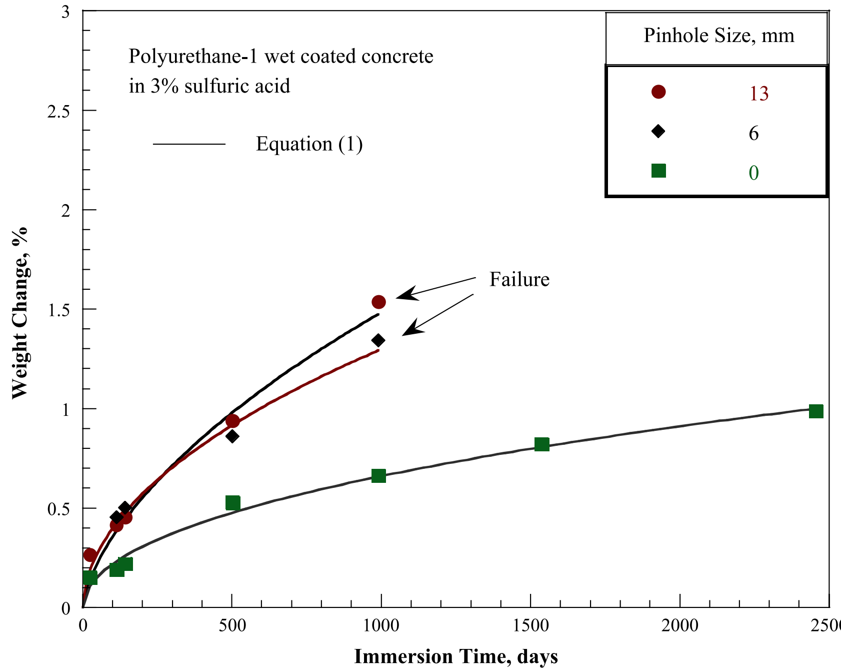

Fig. 6. Pinhole effect on weight change of polyurethane-2-coated dry concrete in 3% sulfuric acid.

immersion, but only 0.5% for the wet coated specimen (Fig. 5(b)). Polyurethane-1-coated dry specimens failed in 5 years of immersion and 50% of the wet coated specimens passed the test. The weight increase in polyurethane-1-coated dry and wet specimens were 1.55% and 0.88%, respectively, in 5 years of immersion. Polyurethane-2-coated dry and wet specimens had weight increase of 0.64% and 0.98%, respectively after 500 days of immersion. Although the weight increase in the coated dry and wet specimens were 1.67% and 1.13%, respectively, after 5 years of immersion, there was no failure observed on the coated specimens. Although the bonding strength of polyurethane-2 was low, this coating performed well under the immersion test conditions. Typical pinhole effect on the weight change of the coated concrete is shown in Fig. 6. The results showed that the size of the pinholes influenced the weight change in coated concrete.

4.4.3. Failure analysis

4.4.3.1. Failure criteria. When coated concrete specimens were immersed in sulfuric acid solutions, acid will penetrate through the pinhole, coating film, and interface (exposed at the pinholes) and reacted with the $Ca(OH)_2$ and other complexes in the cement. Based on the pH and sulfate concentration in the specimen, gypsum, and/or ettringite were formed. Ettringite expands and causes coating cracking and blistering. Failure types observed when sulfuric acid attacked the coated concrete specimens included blistering at the pinhole, cracking of coating starting from the pinhole, or on the surface of the specimens. The failure patterns are illustrated in Fig. 7.

In order to evaluate the performance of various coatings, the failure criteria for coated concrete in 3% sulfuric acid were defined as follows: Criteria-1 is when the crack

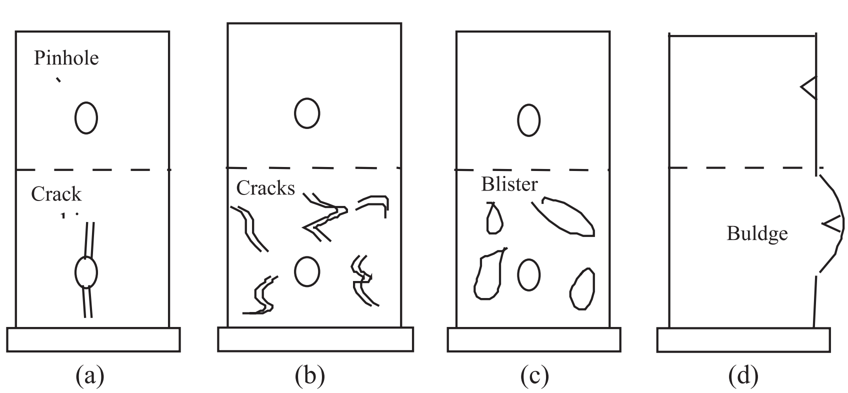

Fig. 7. General failure types in coated concrete specimens with pinholes in sulfuric acid solution.

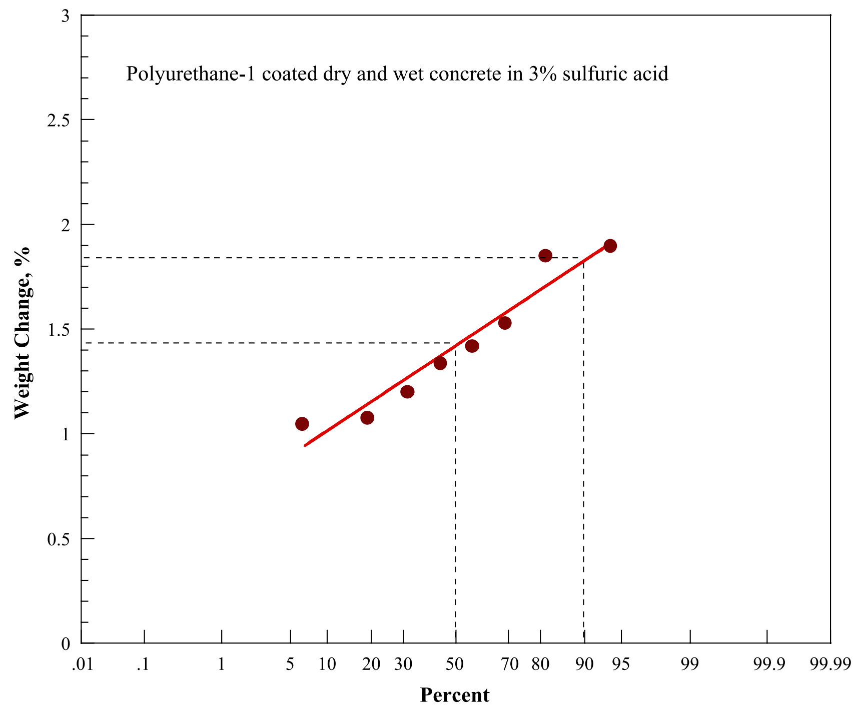

Fig. 8. Percent failure vs. weight change in polyurethane-1-coated dry and wet concrete in 3% sulfuric acid solution.

initiates from the pinhole and the length of the crack was longer than 25 mm (1 in.; Fig. 7(a)); Criteria-2 is when multiple blistering or multiple cracking on the coating surface was observed away from the pinholes (Fig. 7(b) or (c)); Criteria-3 is when the diameter of the blister at the pinhole becomes larger than 25 mm (1 in.) (Fig. 7(d)); and Criteria-4 is when the weight gain was more than 2%.

The percent failure with weight change of polyurethane-1-coated dry and wet concretes in 3% sulfuric acid is shown in Fig. 8. For 50% failure, polyurethane-1-coated dry and wet concretes had 1.43% weight gain. For the weight gain of 1.84% of polyurethane-1-coated concrete, the probability of failure was 90% because of cracks and blisters on the coating surface (failure criteria-1 or criteria-2)). All of the polyurethane-2-coated dry concrete failed because of big blister (failure criteria-3) or weight gain over 2% (failure criteria-4). All of polyurethane-2-coated wet concrete passed the test without failure in the testing period.

4.4.3.2. Time-to-failure factor. For uncoated specimens in 3% sulfuric acid, failure was defined by 2% weight loss, and all specimens failed in 7 days. In order to quantify the performance of coated concrete, the time-to-failure factor (K) is defined as the ratio of the failure–time of the coated specimens to the failure–time of the uncoated specimens in 3% sulfuric acid. For 100% passing, the K value was 14 for both dry and wet coated concrete using polyurethane-1 coating. The K value for polyurethane-2-coated dry concrete was 57. No failure was observed on polyurethane-2-coated wet concrete specimens after more than 5 years of immersion.

5. Mass transfer through coated substrate

The weight increased in coated concrete indicating 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 services. Liu and Vipulanandan [9] developed a film model to characterize the properties of coatings and the performance

Table 2
Values of β^{CT} and D_{CT} for different coatings

Coating material	Material parameter $\beta^{CT} \times 10^{-8}$ s^{-1}				Mass transfer coefficient D_{CT} from the Model, 10^{-13} m^2/s			
	DI water		3% sulfuric acid		DI water		3% sulfuric acid	
	dry	wet	dry	wet	dry	wet	dry	wet
Polyurethane-1	2.12	6.13	2.05	2.16	84.9	9.79	119	90.3
Polyurethane-2	1.94	2.15	1.94	1.17	259	319	637	606

Table 3
Values of k_1 and k_2 for different coatings

Coating code	Coating condition	DI water		3% sulfuric acid	
		k_1	k_2	k_1	k_2
Polyurethane-1	dry	1.05	2.42	1.24	1.27
	wet	0.14	0.60	0.19	0.71
Polyurethane-2	dry	1.97	0.49	1.28	1.47
	wet	0.44	1.75	0.98	2.81

of coated concrete submerged in solutions. Eq. (1) is the film model from Liu and Vipulanandan [9]

$$W_t = \xi \frac{2\pi R h S_0^{\mathrm{CT}}}{\beta^{\mathrm{CT}}} \frac{D_{\mathrm{CT}}}{\ell}\left(1 - e^{-\beta^{\mathrm{CT}} t}\right) \quad (1)$$

where

S_0^{CT}	= degree of saturation of coating film on the outer surface in g (solution)/cm^3 (solid),
D_{CT}	= mass transfer coefficient of the coating film in cm^2/s,
R	= radius of specimen in cm,
h	= height of specimen in cm,
t	= immersion time in s,
ℓ	= coating film thickness in cm,
β^{CT}	= coating material-related parameter.

$$\xi = 1 + \frac{d_{\mathrm{h}}}{k_1 + k_2 d_{\mathrm{h}}} \quad (2)$$

where

d_{h}	= pinhole diameter in cm;
k_1, k_2	= parameters related to the coating.

The material parameter β^{CT} and mass transfer coefficient D_{CT} for the tested coatings are summarized in Tables 2 and 3, respectively. The higher the β^{CT} and the lower the D_{CT}, the better the coating for intended application is. From Table 2, polyurethane-1 had higher β^{CT} and lower D_{CT} than polyurethane-2. polyurethane-1 had better liquid resistant than polyurethane-2. The pinhole effect parameters k_1 and k_2 are summarized in Table 3. The higher the parameters k_1 and k_2, the less the effect of pinholes on the weight gain in the coated concrete.

6. Conclusions

Two commercially available polyurethane based coatings were used in the investigation. The results cannot be generalized to all polyurethane coatings in the market. Based on the experimental results, the following observations are advanced:

(1) The hydrostatic test can be used to effectively evaluate the applicability of coatings onto concrete under hydrostatic back pressure with a moisture emission of 536 μg/(s m^2) (9.49 lb/(1000 ft^2 24 h)). Both of the coatings tested in this study were successfully applied on to the concrete surface. One coating developed blisters during the testing period.

(2) Polyurethane coatings had different bonding strengths with dry and wet concrete surfaces. Polyurethane-1 had very high bonding strength on the dry concrete surface and very low bonding strength on the wet concrete surface. Polyurethane-2 had low bonding strength on both dry and wet concrete surfaces and the moisture did have much influence on the bonding strength of polyurethane-2.

(3) Coated concrete specimens with pinholes failed sooner than without pinholes and the time to failure depended on the type of coating and pinhole size. Based on time-to-failure analysis, the selected coatings can prolong the service life of concrete by 14 and 57 times without failure. Testing coated concrete specimens with pinholes is considered to represent the critical condition in the field.

(4) There was no direct correlation between in-situ bonding strength and chemical resistance of polyurethane-coated concrete.

(5) Although both coatings were polyurethane-based, their properties and performance were different.

Acknowledgement

This project was supported by the Center for Innovative Grouting Materials and Technology (CIGMAT) under grants from the City of Houston, National Science Foundation (CMS-9526094, CMS-9634685), and various industries.

References

[1] J.B. Soebbing, R.R. Skabo, H.E. Michel, Rehabilitating water and wastewater treatment plants, J. Prot. Coat. Linings 13 (5) (1996) 54–64.

[2] W. Sand, T. Dumas, S. Marcdargent, A. Pugliese, J. Cabiron, Tests for biogenic sulfuric acid corrosion in a simulation chamber confirms the on site performance of calcium aluminate based concrete in sewage application, ASCE Material Engineering Conference, November 14–16, ASCE, San Diego, 1994.

[3] R.L. Islander, J.S. Devinny, F. Mansfeld, A. Postyn, H. Shih, Microbial ecology of crown corrosion in sewers, J. Environ. Eng. 117 (6) (1991) 751–770.

[4] N.I. Fattuhi, B.P. Hughes, The performance of cement paste and concrete subjected to sulfuric acid attack, Cem. Concr. Res. 18 (4) (1988) 545–553.

[5] S. Ehrich, L. Helard, R. Letourneux, J. Willocq, E. Bock, Biogenic and chemical sulfuric acid corrosion of mortars, J. Mater. Civ. Eng. 11 (4) (1999) 340–344.

[6] J.A. Redner, E.J. Esfandi, R.P. Hsi, Evaluating protective coatings for concrete exposed to sulfide generation in wastewater facilities, J. Prot. Coat. Linings 8 (11) (1991) 48–56.

[7] J.A. Redner, R.P. Hsi, E.J. Esfandi, Evaluating coatings for concrete in wastewater facilities: update, J. Prot. Coat. Linings 11 (12) (1994) 50–61.

[8] J. Liu, C. Vipulanandan, Testing epoxy coatings for dry and wet concrete wastewater facilities, J. Prot. Coat. Linings 16 (12) (2000) 26–37.
[9] J. Liu, C. Vipulanandan, Modeling water and sulfuric acid transport through coated cement concrete, J. Eng. Mech. 129 (4) (2003) 426–437.
[10] ASTM Designation D2240-03 Standard Test Method for Rubber Property-Durometer Hardness, 2001.
[11] ASTM Designation D2583-95(2001)e1 Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor, 2002.
[12] CIGMAT CT-2, CIGMAT Standards, Standard Test Method for Pull-off Strength of Coatings and Linings, Center For Innovative Grouting Materials and Technology, University of Houston, Houston, TX.
[13] ASTM Designation D4541-95e1, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers, 1996.
[14] CIGMAT CT-1 CIGMAT Standard, Standard Test Method for Chemical Resistance of Coated or Lined Concrete and Clay Bricks, Center For Innovative Grouting Materials and Technology, University of Houston, Houston, TX.
[15] ASTM G20 G20-88 Standard Test Method for Chemical Resistance of Pipeline Coatings, 2002.