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Tensile bonding strength of epoxy coatings to concrete substrate

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Abstract

In this study, four commercially available epoxy coatings were selected to investigate their tensile bonding characteristics to dry and wet concrete with and without 105-kPa backwater pressure. The CIGMAT CT-2 (modified ASTM D4541-95e1) and CIGMAT CT-3 (modified ASTM C321-00) tests were used to determine the tensile bonding strength of the coatings with curing time. The tests were conducted over a period of 2 years. Fifty-three CIGMAT CT-2 tests and 26 CT-3 tests were performed for the four epoxy coatings. Five failure types were identified for both the test methods based on the failure mechanisms observed during the tests. In situ bonding tests (CIGMAT CT-2, full-scale test with back pressure on) were also performed on coatings that were tested under a hydrostatic (back) pressure of 105 kPa (simulating 10 m of groundwater) for at least 6 months (full-scale test). All the coatings investigated were epoxy based, but their bonding strength and failure modes to dry and wet concrete surfaces were different. For all the coatings investigated, in situ bonding strength with dry concrete was higher than wet concrete. Epoxy-A and Epoxy-D (fiber-mat-reinforced epoxy) had good bonding strength (>1.3 MPa, 190 psi) to both dry and wet concrete surfaces during the 2 years of testing period. The bonding strength of Epoxy-B and Epoxy-C varied with time for both dry and wet concrete surfaces. Although for coatings with higher bonding strength, better correlations between the two test methods were observed, in general, the bonding strength from CIGMAT CT-3 test was higher than that from CIGMAT CT-2 test for the coatings tested.

Keywords: Coating; Concrete; Bonding; Epoxy

1. Introduction

Cement concrete has been widely used in the construction of civil infrastructure facilities to carry liquids in industrial facilities and sewage in wastewater systems. Many municipalities are discovering that cement concrete and other structures in the wastewater collection and treatment facilities are subjected to microbial-induced deterioration and the concrete is degrading rapidly [1,2]. Concrete surfaces are more difficult to prepare and protect than metal surfaces. There are several methods in practice to control the degradation of concrete in wastewater facilities [3]. The primary goal of in situ rehabilitation is to return these facilities to their original working conditions. Coating is one method currently being adopted, but the effectiveness of this method for rehabilitating concrete lift stations and sewer treatment facilities must be evaluated. Vipulanandan and Liu [4,5] studied the performance of polymer coatings in 3% sulfuric acid solution and proved the effectiveness of the coatings in protecting the concrete substrate.

Protective coatings must tightly bond to the concrete substrate to provide long-term protection against corrosive environments. Most of the field evaluations of coatings applied to concrete substrate are based on ASTM D4541-95e1 [6] bonding strength test. Soebbing et al. [1] suggested that the minimum recommended bonding strength for coatings was in the range of 1.4 to 1.75 MPa (200–250 psi).

The bonding properties of coatings to concrete substrates is affected by a several variables, including the characteristics of the coating or primer, the application method, the quality of concrete substrate, and the way in which the concrete substrate was prepared for coating. To protect

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concrete structures, the coating must have good bonding strength to the concrete substrate and good acid resistance. In this study, two different test methods were used to determine the bonding strength to concrete of selected epoxy-based coating materials. The bonding strengths of the coatings to dry (simulating new concrete structures) and wet (simulating old concrete structures) concrete substrates were investigated. Limited in situ tests were performed to evaluate the effect of backwater pressure on the bonding strengths of the coatings to concrete substrates.

At the present time, ASTM D4541 is widely used to measure the in situ bonding strength of coatings. In this method, the coating is cored and a piece of metal is glued to the coating for testing. Hence, the test is time consuming, and during the specimen preparation process for testing, there is a possibility of damaging the coating. In ASTM C321-00 [7], no specimen preparation is needed for testing. Hence, use of ASTM C321-00 for determining the bonding strength of coatings must be investigated.

2. Objectives

The overall objective of this study was to evaluate two test methods for determining the bonding strength of epoxy-based coatings to concrete substrate. The specific objectives are as follows:

1) to determine the bonding strength and failure modes of epoxy coatings to concrete substrate and
2) to determine the correlation between the two test methods.

3. Materials

3.1. Coatings

Four commercially available epoxy coatings were selected to coat both dry and wet (saturated) concrete substrates. Some of the properties of the coatings are summarized in Table 1. The thickness of the coatings was from 1.5 to 2.0 mm. The hardness of the coatings was similar (between 70 and 73, Shore hardness Type D). The density of the coatings varied from 1190 to 1635 kg/m^3. The pulse velocity of the bulk coatings varied from 2512 to 2863 m/s, which increased with the increase in density of the coating.

3.2. Concrete

Cylindrical (152 mm high×76 mm diameter) and prism (203 mm long×95 mm wide×57 mm thick) concrete specimens were obtained from a pipe manufacturer, where concrete mix was made according to ASTM C76-00 [8]. 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 (CV) of 2%. The average compressive strength of 28-day water-cured concrete (cylinder) was 34 MPa (5000 psi) and the flexural strength (prism) was 8.3 MPa (1200 psi).

4. Testing program

In this study, CIGMAT CT-2 [9] and CT-3 [10] tests were used to determine the bonding strength of coatings to concrete over a period of 2 years. Dry concrete specimens were stored at room condition (temperature 23±2 °C and humidity 50±5%) and wet concrete specimens were submerged in water at least for 7 days before coating. All the concrete specimens were sandblasted and coated by the respective coating manufacturers.

4.1. CIGMAT CT-2

In this test a 51-mm (2 in.)-diameter circular area was used for testing [Fig. 1(a)]. In this case, the coatings were cured with one free surface. Dry- and wet-coated concrete blocks were cored with a diamond core drill to a predetermined depth to isolate the coating. A metal fixture was then glued to the isolated coating section by using a rapid setting epoxy. Bonding strength was determined by pulling the metal fixture of the substrate. Two tests were

Table 1
Properties of coatings

Coating	Material	Density (kg/m^3)	Pulse Velocity (m/s)	Hardness (Shore[a])	Thickness (mm[b])	Application condition
Epoxy-A	Epoxy	1190	2512	70	2.0	Dry and wet surfaces
Epoxy-B	Epoxy	1530	2730	73	1.5	Dry and wet surfaces
Epoxy-C	Epoxy	1200	2532	71	2.0	Dry and wet surfaces
Epoxy-D	Glass-fiber-reinforced Epoxy	1635	2863	72	1.5	Dry and wet surfaces
Remarks	All are epoxy-based coatings	Varied from 1190 to 1635 kg/m^3	Increase with density	Similar hardness	Varied from 1.5 to 2.0 mm	Physical properties of coatings are similar

[a] Durometer Type D.
[b] Ultrasonic multilayer coating thickness gage (PosiTector 100).

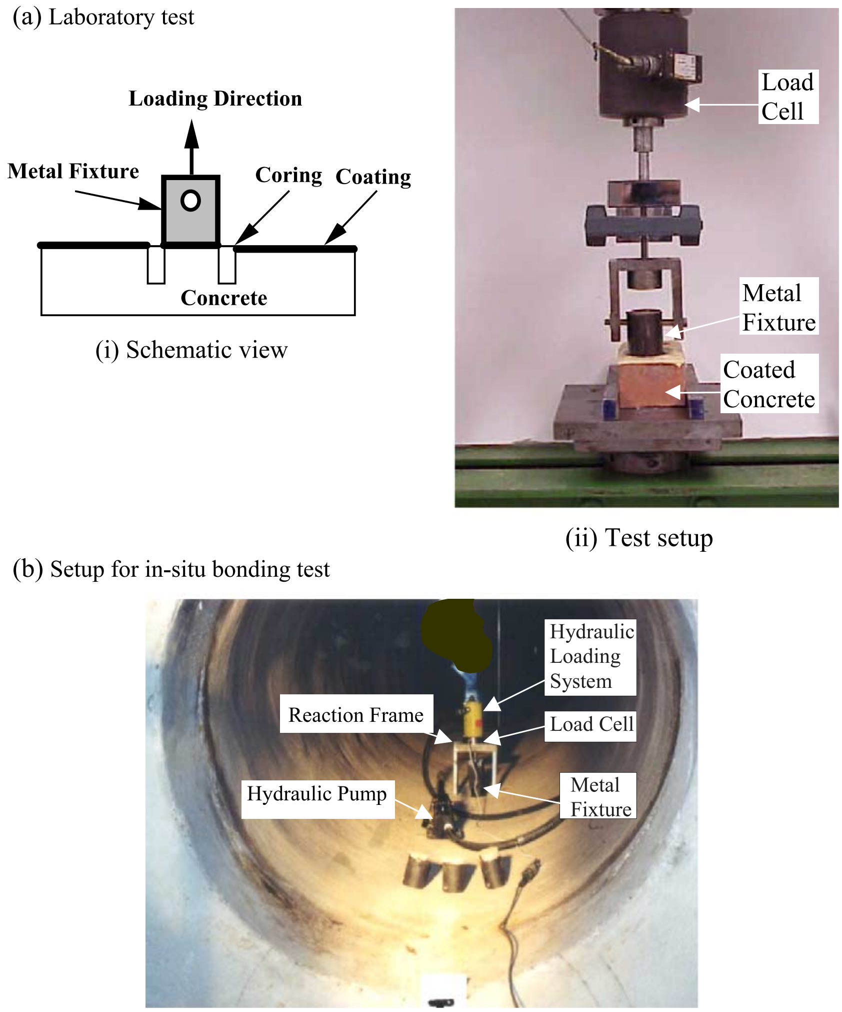


Fig. 1. CIGMAT CT-2 test setup. (a) Laboratory test, (b) field test.

performed for dry- or wet-coated concrete per curing time. Limited in situ tests on concrete pipes were also performed for each coating by using a portable bond-strength tester [Fig. 1(b)].

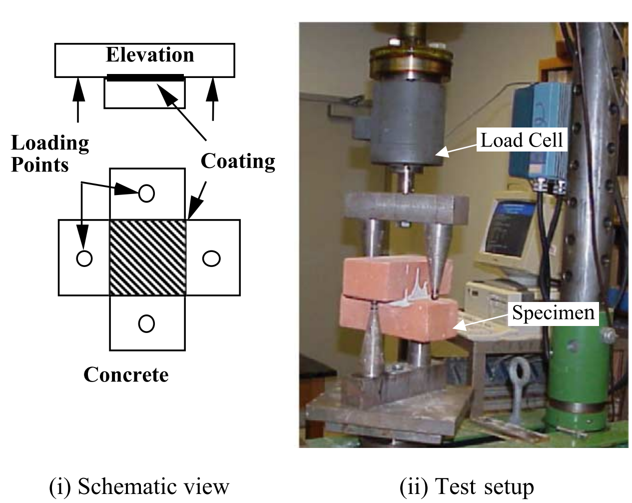


Fig. 2. CIGMAT CT-3 test setup.

4.2. CIGMAT CT-3

In this test, coating was sandwiched between a pair of rectangular concrete block specimens and then tested for bonding strength (Fig. 2). In this case, the coatings were cured without free surfaces. Both dry and wet specimens were used to simulate the dry and wet coating conditions. The bonded specimens were cured under water up to the time of testing. One test was performed for dry- or wet-coated concrete per curing time. Compared with the CIGMAT CT-2 test, this is an easier test to perform and there are no possibilities of damaging the coating in the test because no coring or gluing of metal fixture is required.

5. Test results and discussion

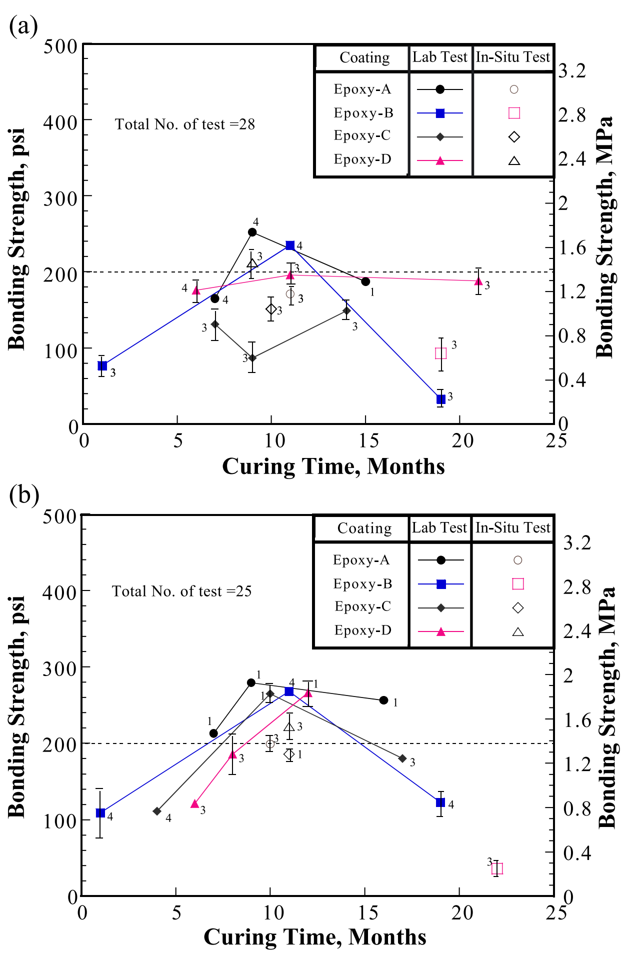
Seventy-nine bonding tests were performed using CIGMAT CT-2 (53 tests) and CT-3 (26 tests) tests for the selected coatings in the laboratory. Sixteen in situ bonding tests were performed with 105-kPa backwater pressure. The purpose of using the two bonding tests was to verify the test results and to compare the sensitivity of these two tests. The bonding strengths versus the curing times for the four epoxy-based coatings determined by CIGMAT CT-2 and CT-3 tests are shown in Figs. 3 and 4, respectively.

5.1. Failure types

During the tests, several failure types were observed. To understand the failure mechanism, the failure types in CIGMAT CT-2 and CT-3 tests were defined and summarized in Table 2.

From Table 2, Type 1 failure is concrete failure. The failure occurred in concrete due to tension in the CIGMAT CT-2 test or bending in the CT-3 test. This type of failure is the most desired failure type because the bonding strength between coating and concrete is higher than the tensile strength or flexure strength of concrete.

Type 2 failure is coating failure, which is cohesive failure of coating. This type of failure indicates that the tensile strength of the coating is lower than the bonding strength and the tensile strength of concrete.



* Number next to the data point indicates the mode of failure.

Fig. 3. Test results from CIGMAT CT-2 test. (a) Dry-coated concrete, (b) wet-coated concrete.

Type 3 failure is bonding failure in which the failure occurs between coating and substrate. This type of failure indicates that the coating has poor bonding strength to concrete substrate.

The three failure types above were the most common observed failure types in the bonding tests. In addition to the three failure types, some other failure types were also observed in the tests.

Type 4 failure is a combined bonding and concrete failure, in which the bonding strength of coating to concrete is close to the tensile/flexure strength of concrete.

Type 5 failure is a combined bonding and coating failure, in which the bonding strength of coating to concrete is close to the tensile/flexure strength of coating.

5.2. CIGMAT CT-2 test

5.2.1. Epoxy-A

Based on the CIGMAT CT-2 test [Fig. 3(a) and (b)], Epoxy-A had good bonding strength on both dry and wet concrete surfaces. The average bonding strength of Epoxy-A on the dry and wet concrete surfaces was above 1.40 MPa (200 psi) during the testing period. Type 1 failure (concrete failure) was observed on the wet-coated concrete specimens. Type 1 (concrete failure) and Type 4 (combined bonding and concrete bonding failure) were observed on the dry-coated concrete specimens.

5.2.2. Epoxy-B

This coating had large variation in the bonding strength on both dry and wet concrete surfaces. The bonding strength was more than 1.4 MPa after 1 year of immersion. Thereafter, the bonding strength of the coating decreased to less than 0.3 (43 psi) and 0.9 MPa (130 psi) on dry and wet concrete surface, respectively. Type 3 failure (bonding interface failure) and Type 4 failure (combined bonding and concrete bonding failure) were observed on dry-coated concrete and Type 4 failure was observed on wet-coated concrete.

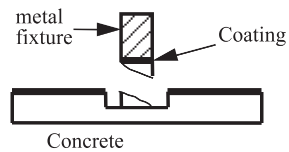
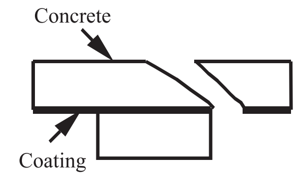
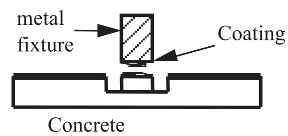
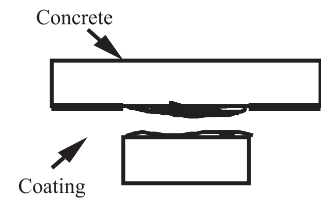
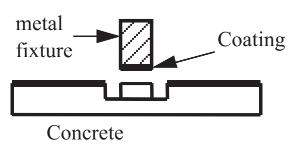
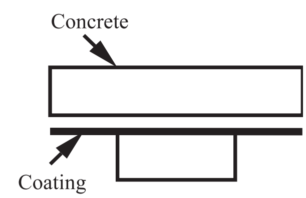
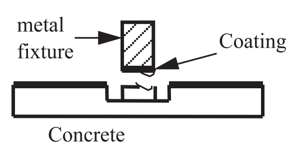
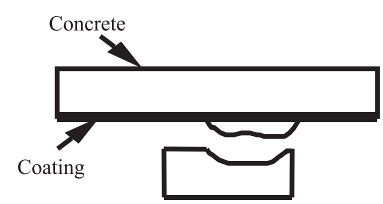
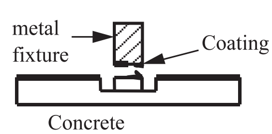
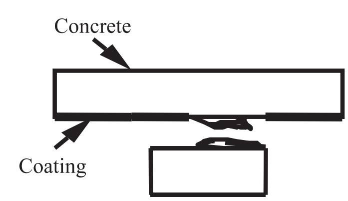
5.2.3. Epoxy-C

Epoxy-C had poor bonding strength to dry concrete surface. All failures were Type 3, which was bonding failure of the coating to concrete surface. The bonding strength varied from 0.6 (86 psi) to 1 MPa (143 psi). Epoxy-C had good bonding strength on wet concrete surface. The bonding strength varied from 0.9 (130 psi) to 1.7 MPa (243 psi) and Type 1 (concrete failure), Type 3 (bonding interface failure) and Type 4 failure (combined bonding and concrete bonding failure) modes were observed during the tests.

5.2.4. Epoxy-D

Although the predominate failure type of Epoxy-D (the fiber-mat-reinforced epoxy) was Type 3 (bonding interface failure), the average bonding strength of the coating was

Table 2
Failure types in CIGMAT CT-2 and CT-3 bonding tests

Failure type	CIGMAT CT-2	CIGMAT CT-3
Type 1, concrete failure		
Type 2, coating failure		
Type 3, bonding interface failure		
Type 4, bonding+concrete failure		
Type 5, bonding+coating failure		

about 1.3 MPa (190 psi) on both dry and wet concrete surfaces during the test period.

5.3. Comparison of CIGMAT CT-2 laboratory test with in situ test

Limited in situ tests were performed for each coating under simulated underground service conditions. The test results of the bonding strength and the comparison of the bonding strength from laboratory and in situ tests are shown in Fig. 3(a) and (b) and Fig. 4. The predominate failure type from in situ test was Type 3 (bonding interface failure), whereas there were different failure types observed in the laboratory tests for the same curing period (Fig. 3). The results indicated that the backwater pressure in the hydrostatic test affected the bonding of the coatings to the concrete surface. Fig. 4(a) showed that the bonding strength from in situ tests was higher than the bonding strength from laboratory tests on the dry-coating condition for most of the coatings, whereas the results were reversed on the wet-coating condition. The results indicate that the initial coating conditions affected the bonding strength of the epoxy coatings for underground applications. The failure modes for epoxy on dry-coated concrete were comparable in laboratory and in situ tests, but there were variations on the failure modes for

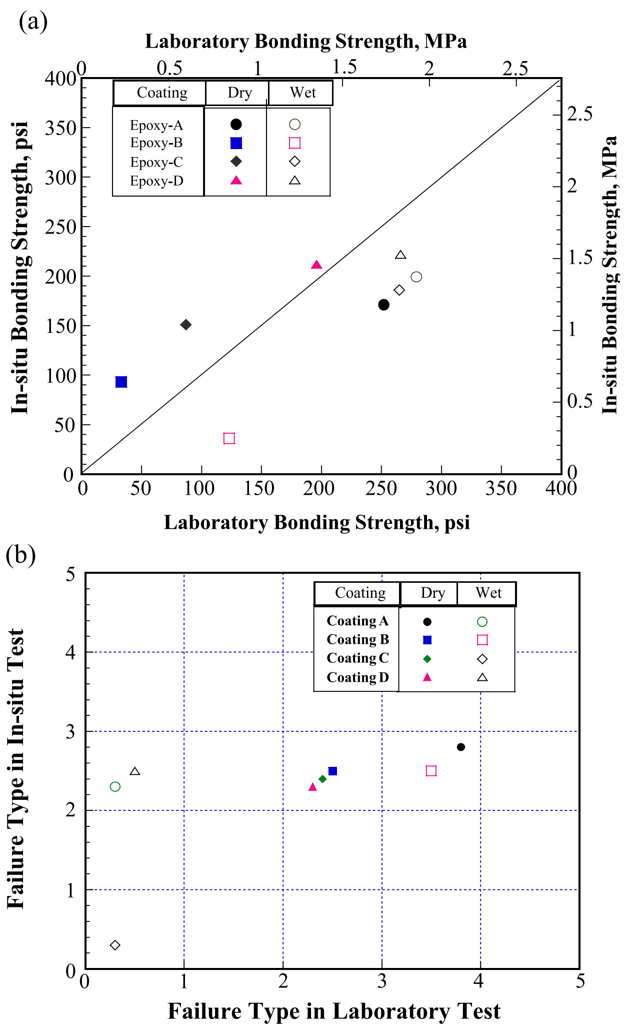


Fig. 4. Comparison of laboratory and in situ bonding strength and failure types in CIGMAT CT-2 test. (a) Bonding strength, (b) failure type.

epoxy on wet concrete in laboratory and in situ tests (Fig. 4).

5.4. CIGMAT CT-3 test

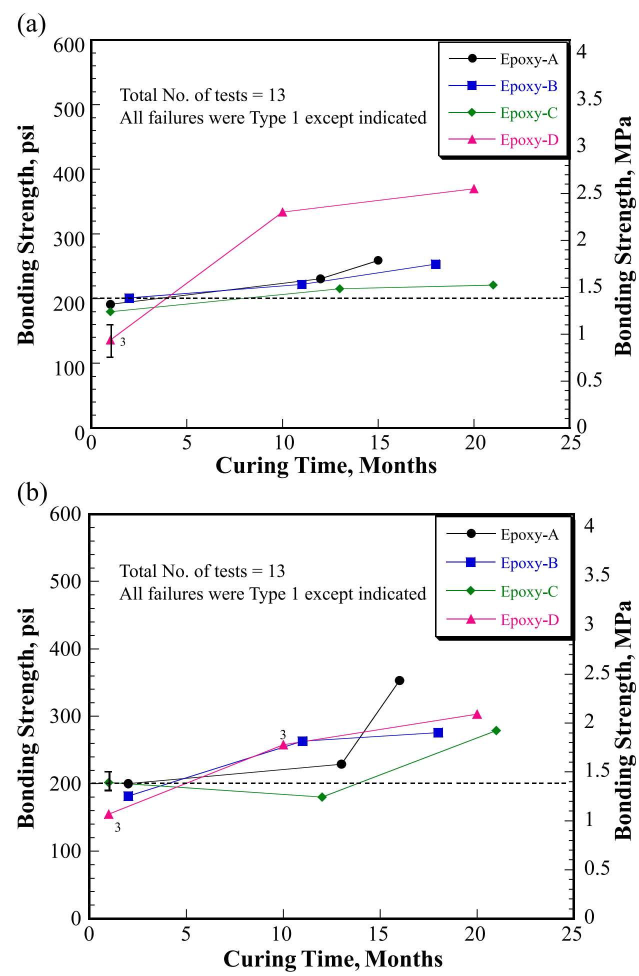
The variations of the bonding strength with time using the CIGMAT CT-3 tests are shown in Fig. 5(a) and (b). Type 3 failure mode was observed on both dry- and wet-coated concrete for Epoxy-D. All failures in other coatings were Type 1, in which the specimens failed in concrete. All of the coatings had good bonding strength in the CIGMAT CT-3 tests. The average bonding strength of the coatings was higher than 1.4 MPa (200 psi) on both dry and wet concrete surfaces. The bonding strength of the coatings did not change much during the testing period.

5.5. Comparison of CIGMAT CT-2 and CT-3 tests

The comparison of bonding strength and failure types from the CIGMAT CT-2 and the CT-3 tests under dry and wet conditions are shown in Figs. 6 and 7.

In Fig. 6, the bonding strength from CIGMAT CT-2 and CT-3 tests are compared for the tested coatings. From Fig. 6, 75% of the bonding strength in CIGMAT CT-3 tests was higher than the bonding strength from CIGMAT CT-2 tests for the coatings in the same curing period. Because the flexure strength was higher than the tensile strength for concrete, most failures in the CIGMAT CT-3 test were Type 1, in which the failure was in concrete due to the bending of the concrete; hence the results showed that the bond strength of the coatings was higher in the CIGMAT CT-3 test than in the CT-2 test for most of the coatings on both dry and wet concrete surfaces (Fig. 6).

In Fig. 7, the failure types from CIGMAT CT-2 and CT-3 tests for each coating are compared. From Fig. 7, the failure type for the pure epoxy coatings (Epoxy-A, -B and -C) was Type 1 from CIGMAT CT-3 tests on both dry and wet concrete surfaces, whereas failure Types 1, 3 and 4 were observed in CIGMAT CT-2 test. One reason that caused the difference in failure types is the method in which the specimens were prepared. In the CIGMAT CT-2 test, the coating was restrained on the concrete surface,



* Number next to the data point indicates the mode of failure.

Fig. 5. Test results from CIGMAT CT-3 (Modified ASTM C 321) Test. (a) Dry-coated concrete, (b) wet-coated concrete.

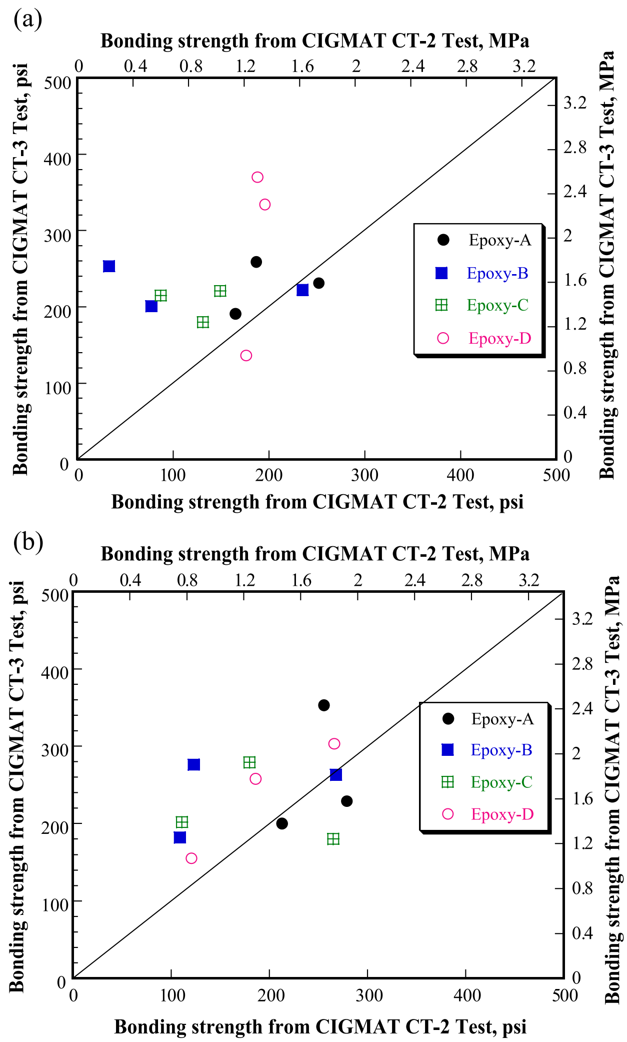


Fig. 6. Comparison of bonding strength from CIGMAT CT-2 and CIGMAT CT-3 tests. (a) Dry-coated concrete, (b) wet-coated concrete.

whereas the other surface was free, resulting in internal stresses. The unbalanced stress development would cause defects, such as debonding and cracks [11], on the coating film. In the CIGMAT CT-3 test, the coating was sandwiched in between two concrete surfaces. The stress development in the coating is balanced on both sides of the coating film.

For the glass-fiber-reinforced epoxy coating (Epoxy-D), the failure types were comparable for the two bonding tests. In this coating, the fibers could reduce the shrinkage of the coating film on the specimens for the CIGMAT CT-2 tests, resulting in the observed behaviors. Addition of fibers also affected the type of failure during the tests.

6. Conclusions

Two bonding tests (CIGMAT CT-2 and CT-3) were used to determine the tensile bonding strength of four commercially available epoxy-based coatings to concrete substrate. The epoxy-based coatings had similar physical properties. Based on the test results, the following conclusions are advanced:

1) Failure modes for epoxy-based coatings in CIGMAT CT-2 and CT-3 tests were identified. In general, the tensile bond strength for epoxy-based coatings determined using the CIGMAT CT-2 test was lower than the bonding strength determined from the CT-3 test. More failure types were observed in the CIGAMT CT-2 test than in the CT-3 test.
2) Wet and dry surface conditions at the time of coating affected the bonding strength of some of the epoxy coatings. In situ bonding strength (with backwater pressure of 105 kPa) was lower than the bonding strength in the laboratory tests for all of the wet-coated epoxy coatings. About 75% of the dry-coated epoxy coatings had higher bonding strength in the in situ tests than in the laboratory tests.

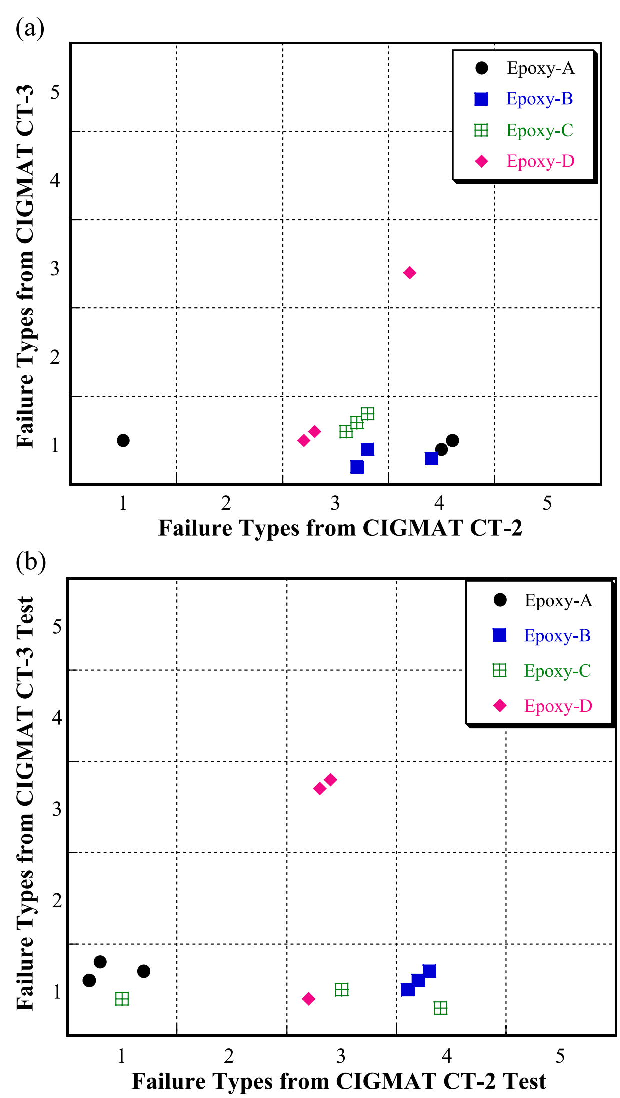


Fig. 7. Comparison of failure types from CIGMAT CT-2 and CIGMAT CT-3 tests. (a) Dry-coated concrete, (b) wet-coated concrete

3) Coatings with higher bonding strength (>1.3 MPa) had similar types of failure in both tests.

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References

[1] J.B. Soebbing, R.R. Skabo, H.E. Michel, G. Guthikonda, A.H. Sharaf, 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, San Diego, ASCE, 1994.

[3] K. Kienow, H.C. Allen, Concrete pipe for sanitary sewers corrosion protection update, Pipeline Infrastructure II, Proceedings of the International Conference held in San Antonio, Texas, August 16–17, ASCE, Reston, Virginia, 1993, pp. 229–250.

[4] C. Vipulanandan, J. Liu, Glass-fiber mat reinforced epoxy coating for concrete structures in sulfuric acid environment, Cem. Concr. Res. 32 (2) (2002) 205–210.

[5] C. Vipulanandan, J. Liu, Film model for coated cement concrete, Cem. Concr. Res. 32 (12) (2002) 1931–1936.

[6] ASTM Designation D4541-95e1, Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesion Testers, West Conshohocken, PA, 1996.

[7] ASTM Designation C321-00, Standard Test Method for Bond Strength of Chemical-Resistant Mortars, West Conshohocken, PA, 2000.

[8] ASTM Designation C76-00, Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe, West Conshohocken, PA, 2000.

[9] 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.

[10] CIGMAT CT-3, CIGMAT Standards, Standard Test Method for Bonding Strength of Coatings and Mortars: Sandwich Method, Center for Innovative Grouting Materials and Technology, University of Houston, Houston, TX.

[11] L.F. Francis, A.V. McCormick, D.M. Vaessen, Development and measurement of stress in polymer coatings, J. Mater. Sci. 37 (22) (2002) 4717–4731.