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Glass-fiber mat-reinforced epoxy coating for concrete in sulfuric acid environment

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Abstract

Deterioration of Portland cement concrete exposed to acidic environments is a major problem in wastewater and industrial facilities. Coating of new and in-service concrete facilities is one method currently adopted to protect concrete from acidic attack. In this study, cylindrical concrete specimens were coated with a glass-fiber mat-reinforced epoxy under dry (simulating new concrete surface) and wet (simulating in-service concrete surface) conditions and then tested in 3% sulfuric acid solution. The average coating thickness was 1.5 mm with a hardness of 38 (Barcol Hardness). Chemical resistance tests were performed on uncoated and coated concrete specimens with and without surface holidays. Test results showed that the epoxy-coated concrete with holidays in acidic environments showed no failure up to 20 months. There was no noticeable difference in the performance of coated concrete with different holiday sizes (3, 6 or 12.5 mm) in long-term immersion. Failures were first observed around the holiday resulting in cracking of the coating. The average increase in diameter of specimens at the holiday was 1.5% when the first cracks occurred. A time-to-failure factor (K) showed that the lifetime of the coated concrete in 3% sulfuric acid can be extended by more than 70 times without failure occurring. This coating also passed the application and hydrostatic tests.

Keywords: Coating; Concrete; Durability; pH; Sulfuric acid attack; Long-term performance

1. Introduction

Deterioration of sewer pipes made of concrete is a major problem in most areas in the United States. Many municipalities are noting that sewer pipes and in particular concrete structures in wastewater collection and treatment facilities are subjected to microbiologically induced concrete corrosion (MICC) and are degrading rapidly [1]. In most cases, the pH on the surface of concrete sewer pipes is less than 1 (in the worst case, the pH is 0.5) [2]. It is important to find how to control this corrosion to extend the life of the facilities. Coating is one method currently being adopted to control the degradation of wastewater facilities. However, the effectiveness of this method for rehabilitating sewer pipes and treatment facilities is still in question [3].

Sewage and industrial facilities are generally wet and experience hydrostatic pressure due to ground water under normal service conditions. The surface moisture will depend on the porosity of the concrete and hydrostatic pressure due to the water table. Coatings can debond and blister if the hydrostatic pressure exceeds the tensile adhesion of the coating material. For new concrete facilities, the surface is relatively dry and highly alkaline. The compatibility of coatings with such surfaces is also very important. Epoxy coatings can provide high bonding strength to substrates and high chemical resistance. However, they are brittle and inflexible [4]. In order to improve some of these properties, glass-fiber mats are added to the coating system by some manufacturers. When fibers are added to the coating system, certain coating properties can be improved, such as tensile strength and modulus. In this study, a comprehensive testing program was undertaken for testing a glass-fiber-reinforced epoxy coating material for concrete protection.

The objective of this study was to investigate the performance of the fiber-reinforced epoxy coating used for protecting dry and wet concrete. Specific objectives

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were as follows: (a) to evaluate the applicability of the coating on dry and wet concrete surfaces, and its performance under hydrostatic pressure and (b) to evaluate the performance of coated concrete (dry and wet) with and without holidays (pinholes) under immersion conditions, such as acidic solutions.

2. Material and testing program

2.1. Coating material

Glass-fiber mats were used with the epoxy coating during the application process on dry and wet concrete cylinders and concrete pipes. Overall thickness of the coating was measured as 1.5 mm using Ultrasonic Multi-Layer Coating Thickness Gage (ASTM D 6132) [5], and the average hardness was 38 (Barcol Hardness, ASTM D 2583) [6]. The flexibility (% elongation, ASTM D 638) was 2.0% according to the manufacturer's data sheet.

2.2. Testing program

2.2.1. Hydrostatic test

In order to stimulate hydrostatic back pressure on concrete structures due to the ground water table, a pressure chamber with concentrically placed concrete pipes was used to develop the necessary full-scale testing conditions [3] (Fig. 1). This was achieved by using 900-mm (36 in.) inner pipes and 1600-mm (63 in.) outer pipes with two concrete end plates. The inner concrete pipe surface represented a concrete surface under hydrostatic pressure. Hence, coating this surface represented conditions similar to the concrete surface encountered in wastewater systems. The total area available for coating was 14 m^2 (150 ft^2). Based on discussions with coating applicators, a 900-mm-diameter pipe was considered the smallest pipe in which a person could comfortably apply the coating. The pressure chambers used for the full-scale test were designed and built by Hanson Concrete Products, (formerly Gifford-Hill), Houston Division, representing the American Concrete Pipe Association.

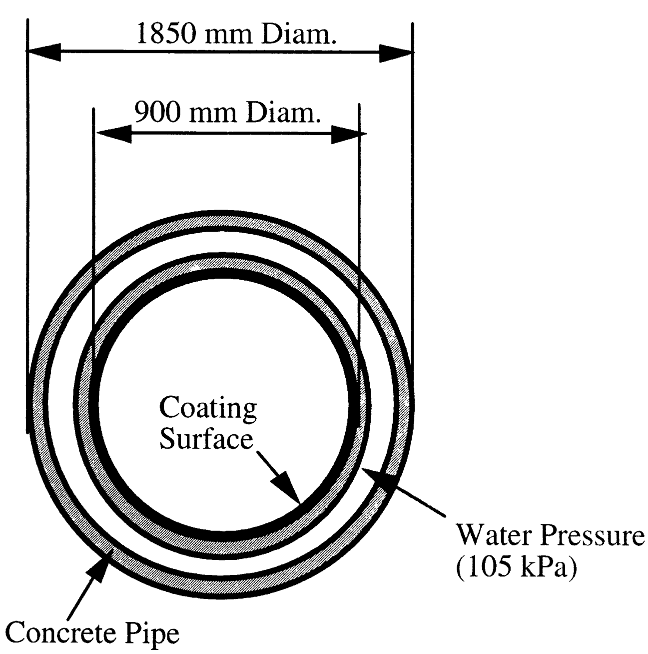

Fig. 1. Vertical cross-section of the hydrostatic test setup.

2.2.1.1. Dry test. Coating was applied to new 900-mm-diameter concrete pipe at the Hanson Concrete Products, concrete pipe yard in Houston [the water vapor emission rate of the concrete pipe was 144 $\mu g/(s\ m^2)$ (2.45 lb/1000 ft^2 24 h) before coating]. The coated pipe was then placed in the pressure chamber for hydrostatic pressure testing.

2.2.1.2. Wet test. The 900-mm concrete pipe was installed in the test chamber and pressurized at 105 kPa (15 psi) for at least 2 weeks before applying the coating. The water vapor emission rate of the concrete pipe was 536 $\mu g/(s\ m^2)$ (9.00 lb/1000 ft^2 24 h). The coating was applied after water jet blasting the surface. Application temperature was 24 °C (75 °F).

The coated surfaces were inspected once a week and occurrence of blistering, spalling, discoloring and cracking were noted and photographed.

2.2.2. Holiday test—chemical resistance

In order to study the chemical resistance, the ASTM G 20-88 [7] test was modified to use with coated concrete materials. 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 used as a relatively rapid test to evaluate the acid resistance of coated specimens under anticipated service conditions. In this test, cylindrical concrete specimens with 76-mm (3 in.) diameter and 152-mm (6 in.) height were used. Dry specimens (at the room temperature condition for at least 2 months) and wet specimens (water saturated) were coated on all sides except the base (leaving the base of the plastic mould in place). Two radial holidays were drilled into the specimen approximately 15 mm deep. Holiday sizes of 3, 6 and 12.5 mm were selected in this test. Control tests were performed on specimens with no holidays. In this test, the changes in weight of the specimen and appearance of the specimen were monitored at regular intervals. The two test reagents selected for this study were (1) deionized (DI) water (pH = 5–6) and (2) 3% sulfuric acid solution (pH = 0.45; representing the worst reported condition in the wastewater system). Twenty specimens were used in this test. Fig. 2 shows the setup of the chemical resistance test. The sulfuric acid solution was changed once a month during the first 6 months of test, and was changed once in 3 months thereafter or as needed based on the change in pH (pH change of 0.3).

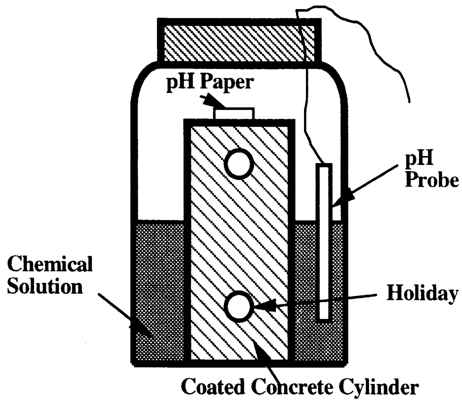

Fig. 2. Chemical test on coated concrete with holidays.

The coated concrete specimens were considered to have failed when the crack length in the coating was longer than 25 mm (1 in.) and/or the diameter of the blister on the coating surface was more than 25 mm (1 in.).

3. Results and discussion

3.1. Hydrostatic pressure test

3.1.1. Application rating

(i) The coating (dry) passed[1] the application test. Coverage[2] of the concrete surface was good.
(ii) The coating (wet) passed[1] the application test. Coverage[2] of the concrete surface was good.

The coating was applied to dry and wet concrete without any difficulty. However, there were small hard blisters on the coating surface, which may have been caused by fiber projection. Uneven surface areas were also seen in some areas of the coating surface (Fig. 3), which were caused by fiber mats.

3.1.2. Performance rating

The performance of the coating was evaluated based on the following factors: (i) overall condition (mainly appearance, rated as: good, satisfactory or bad), (ii) blistering, (iii) cracking and (iv) change in color. Based on all these factors, overall rating (pass, satisfactory or fail) was assigned to the coating.

After 5 months of hydrostatic pressure test, the coating was in good overall condition under both dry [moisture emission rate 144 μg/(s m^2)] and wet [moisture emission rate 536 μg/(s m^2)] application conditions. There were no soft blisters, no cracks and no discoloration on the coating.

3.2. Chemical resistance

3.2.1. Weight change

The weight changes in the uncoated concrete and coated concrete specimens with and without holidays in 3% sulfuric acid are shown in Fig. 4(a)–(c). For uncoated concrete specimens in 3% sulfuric acid (Fig. 4(a)), weight gains were observed during the initial 5 days. After 10 days, the weight loss for all the specimens exceeded 2%. From Fig. 4(b), all dry coated concrete specimens with and without holidays failed after 3 years of immersion. For specimens with holidays, small cracks occurred across the holiday after 500 days. There were no visible cracks on the coating surface for specimens without holidays, but still a weight gain of 1% was observed. For wet coated specimens, the specimens with 6- and 12.5-mm holidays failed after 3 years of immersion and these specimens also had small cracks after 500 days. For both dry coated specimens and wet coated specimens, when cracking occurred, the rate of weight change increased due to additional exposure of the concrete. Expansion was observed in the holiday region subjecting the coating to tensile stresses. Addition of glass-fiber mat increased the tensile strength and modulus of the epoxy coating. Hence, this coating tends to confine the expansion of concrete resulting in tensile stresses in the coating. Holidays in the coating further magnified the stresses causing the cracking to occur at the holidays.

3.2.2. Failure types

The failures observed in the coated concrete cylinders after 3 years of immersion in 3% sulfuric acid are shown in Fig. 5. No changes in the appearance were observed in coated specimens in DI water. Coated specimens in 3% sulfuric acid failed when vertical cracks formed in the coating starting from the holiday as shown in Fig. 5(a)

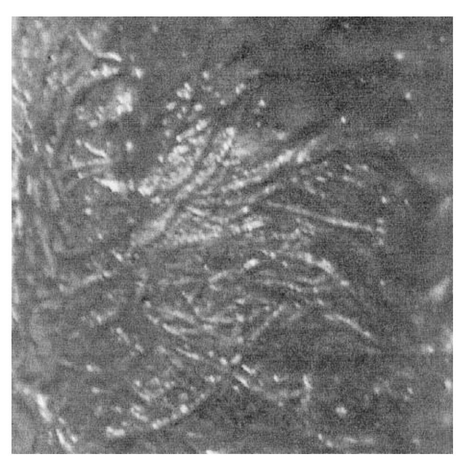

Fig. 3. Hard blisters and fiber feature seen on the coated concrete surface.

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[1] *Passing* means (1) no blistering, (2) no cracking, (3) no discoloration, (4) no spalling, (5) does not stick to the finger after 48 h of application and (6) cannot scratch-off.

[2] *Coverage* rating was selected from *good*, *satisfactory* or *bad*. *Good* rating means no visible spot of concrete surface; *satisfactory* rating means a few small spots of visible concrete surface; *bad* rating means several spots of visible concrete surface.

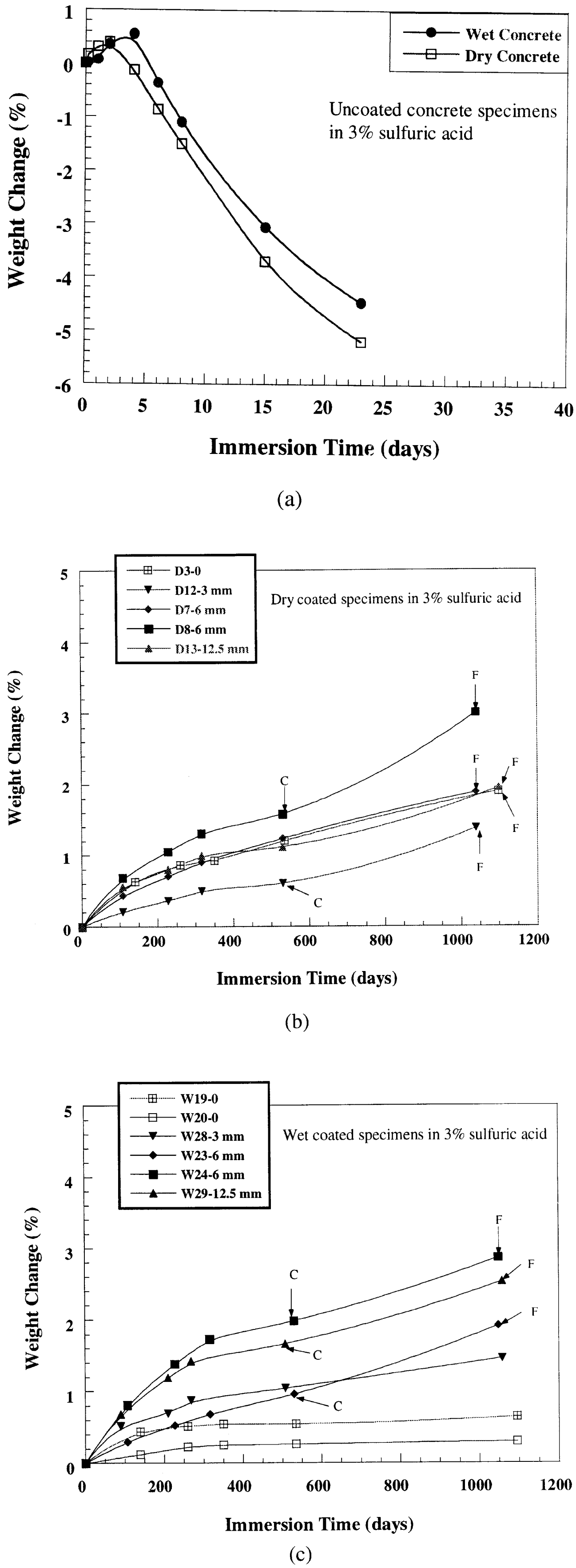

Fig. 4. Changes in weight versus immersion time for uncoated and coated concrete specimens with different holiday sizes (C—first visible crack, F—failed): (a) concrete only, (b) coated dry concrete and (c) coated wet concrete.

and (b). Failure types were similar for the dry and wet coated concrete. When coated specimens were immersed in sulfuric acid solution, acid penetrated through the coating and holidays and reacted with the concrete. As observed by other researchers, when concrete is exposed to sulfate under different pH levels, gypsum and/or ettringite is formed [8]. Formation of ettringite caused concrete specimens to expand. Cracking occurred predominantly across the holiday and in a few instances in the coating (remote from the holiday). Since sulfuric acid is in direct contact with concrete at the holidays, blisters were first formed around the holidays before cracks occurred. The average increase in diameter of specimens was 1.5% when cracks began to form. With further cracking, crack branching was observed in the coating (Fig. 5(c)). Cracking patterns were similar in both dry and wet coated specimens.

Performance of dry and wet coated concrete with 6- and 12.5-mm holidays was very similar. No failure was observed in wet coated concrete with no holidays or 3 mm holidays during this period of study.

3.2.3. Failure analysis

The percentage of failure (i.e., percentage of failed coated specimens) versus weight change for coated concrete specimens in 3% sulfuric acid is shown in Fig. 6. The results indicate that for a probability of failure of 50%, the weight gain in the coated specimens was about 2.3%. For most of the specimens, when weight gain exceeded 1%, small cracks were observed on the coating surface.

The percentage of coated and uncoated specimens passing in 3% sulfuric acid after a certain period of time is shown in Fig. 7. For uncoated concrete specimens in 3% sulfuric acid, failure was defined by 2% weight loss; all specimens failed in 10 days. For coated concrete specimens in 3% sulfuric acid, coating failures started after 500 days. 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 the same solution. As shown in Fig. 7, the ratios are as follows:

For 100% pass:

$$K_{100} = \frac{t_2}{t_1} = \frac{500}{7} = 71,$$

For 50% pass:

$$K_{50} = \frac{t_4}{t_3} = \frac{600}{7} = 86.$$

Hence, by coating the concrete, the lifetime of the concrete in 3% sulfuric acid without any failure can be extended by more than 70 times. Test results indicate that

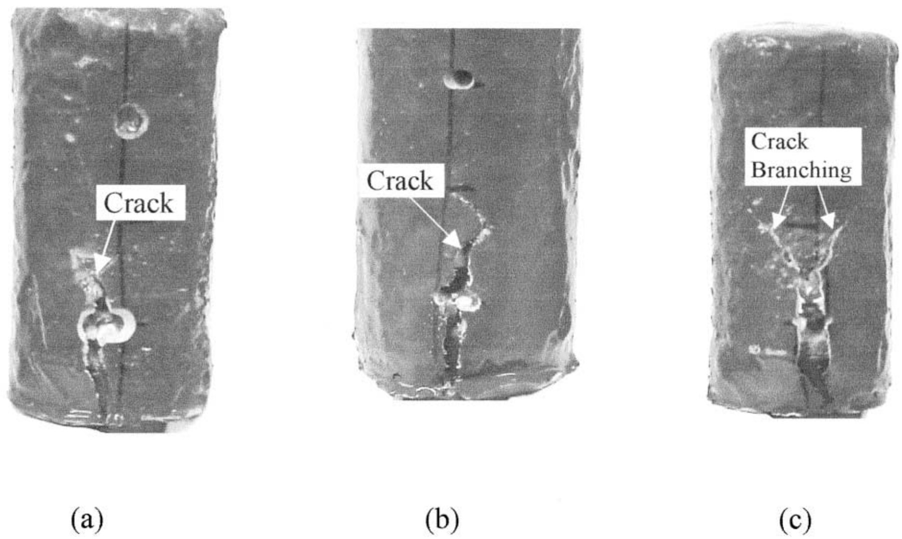

Fig. 5. Coated concrete cylinders after 3 years in 3% sulfuric acid: (a) cracking in a 12.5-mm holiday, (b) cracking in a 6-mm holiday and (c) crack branching.

after 500 days the coated concrete exposed to 3% sulfuric acid must be inspected for possible failure and maintenance.

The failure criteria were selected as the failure observed in coated concrete. Results showed that coating extended the lifetime (time-to-failure) as compared to uncoated concrete specimens. The number of time-to-failure factors (K) are more appropriate for comparing the performance of different coatings.

4. Conclusions

Based on 5 months of hydrostatic tests and 3 years of chemical tests, the following observations are advanced on the performance of a glass-fiber mat-reinforced epoxy coating.

(1) The glass-fiber mat-reinforced epoxy coating passed the application and performance tests under a hydrostatic water pressure of 105 kPa. There was no visible defect on the coating surface after 5 months of testing and the performance was similar under dry and wet application conditions.

(2) The coating extended the lifetime of concrete by over 70 times when immersed in 3% sulfuric acid.

(3) The coating failure usually occurred around the holiday first by cracking of the coating. There was no noticeable difference in the time-to-failure of the coated dry and wet concrete with 6- and 12.5-mm holidays. Coated wet concrete without holidays did not fail during 3 years of exposure to 3% sulfuric acid.

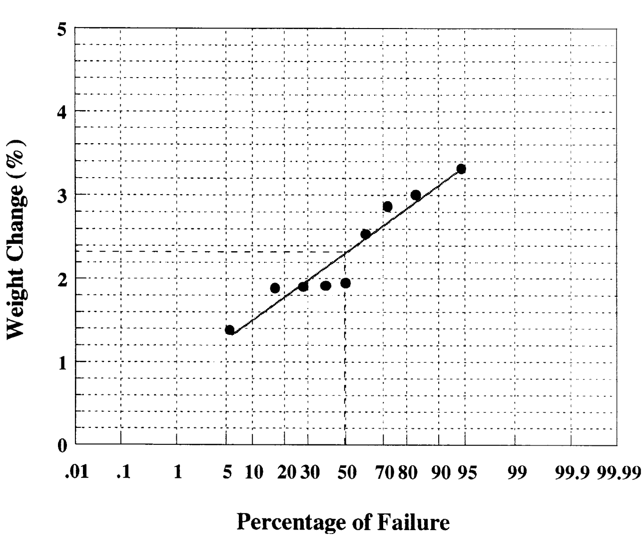

Fig. 6. Percentage of failure versus weight change for coated specimens in 3% sulfuric acid.

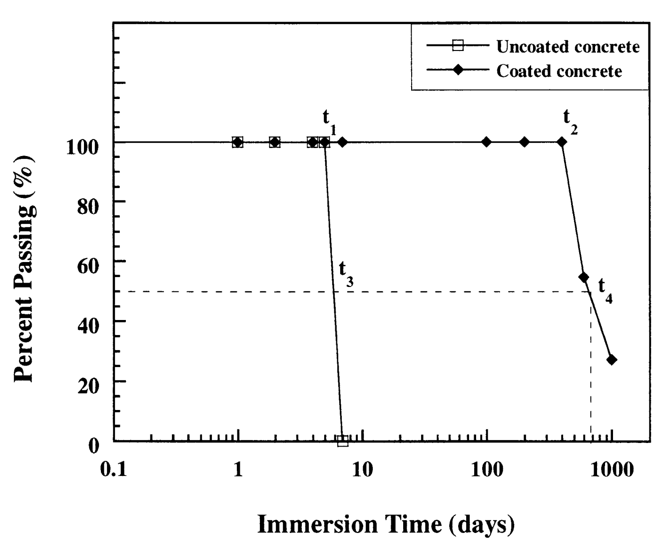

Fig. 7. Percentage passing versus immersion time for coated and uncoated concrete specimens in 3% sulfuric acid solution.

Acknowledgments

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