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Effect of waterproofing coatings on steel reinforcement corrosion and physical properties of concrete

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Abstract

This paper reports the results of a study conducted to evaluate steel reinforcement corrosion and some physical properties of concrete specimens coated with two polymer-based, a cement-based polymer-modified, and a cement-based waterproofing coatings. The coated and uncoated concrete specimens were subjected to accelerated corrosion to determine the time-to- corrosion initiation. The physical properties were also evaluated by subjecting the concrete specimens to wetting/drying cycles and heating/cooling cycles for five months. The physical properties evaluated were water absorption, water permeability, chloride permeability, and adhesion. The accelerated corrosion test results clearly showed that the specimens coated with the polyurethane elastomer-based waterproofing material performed better than concrete specimens coated with other waterproofing materials. This was followed by the specimens coated with cement-based polymer modified, epoxy-based, and cement-based coatings in descending order. The two polymer-based coatings showed better performance than the cement-based polymer-modified and cement-based coatings in terms of the evaluated physical properties. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Absorption; Adhesion; Cement-based coating; Cement-based polymer-modified coating; Chloride permeability; Epoxy-based coating; Polyurethane coating; Steel reinforcement corrosion; Water permeability

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1. Introduction

Concrete structures in environments with adverse geomorphic and climatic conditions such as severe ground and ambient salinity and high temperature-humidity regimes are prone to early deterioration. Such aggressive environments induce several deterioration problems, and the most frequent and damaging one is the corrosion of reinforcing steel, which causes early deterioration of concrete structures. Several measures have been tried to combat this problem and extend the service life of concrete structures [1]. One such measure is the application of a waterproofing coating on the external surface of concrete structure. The main function of a waterproofing system is to prohibit water and any soluble salts from penetrating the concrete to cause corrosion, leaking, and other problems. In addition, waterproofing materials can be very effective in minimizing the rate of corrosion once it has initiated by preventing access of moisture and oxygen to the steel surface.

There are several generic types of waterproofing materials, which are commonly used for protecting concrete structures, such as cement-based, epoxy resin, polyurethane resin, acrylic resin, and silane/siloxane. These generic types have considerable variations in terms of the price, durability performance, and method of application.

Al-Dulaijan et al. [2] investigated the performance of five resin-based surface coatings. The results showed that the adhesion of all the epoxy-resin- based coatings, to the concrete substrate, was better than that of the acrylic- resin-based surface coatings. The adhesion values of the resin-based surface coatings ranged from 1.25 to 2.03 MPa. The chloride permeability in the concrete specimens coated with the selected resin-based surface coatings ranged between 12 and 233 C.

Al-Dulaijan et al. [3] investigated the performance of four cement-based surface coatings. The results showed that the adhesion of the tested coatings ranged between 1.10 and 1.60 MPa. The chloride permeability was also evaluated and the values ranged between 552 and 1113 C.

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Umoto et al. [4] evaluated the performance of small repaired reinforced concrete test beams under marine exposure. A range of coating systems were studied including epoxy, silicone, urethane, acrylic rubber, acrylic resin, polyester, and polymer-modified cement and mortar. After 18 months, uncoated specimens exhibited corrosion at the interface and in the concrete substrate adjacent to the interface. On the other hand no evidence of corrosion was observed in any of the coated beams.

In another study Cabrera and Hassan [5] conducted accelerated American Association of State Highway and Transportation Officials (AASHTO) diffusion tests on concrete specimens coated with several coatings, where epoxy coating demonstrated high chloride resistance, and the sodium silicate-based coating showed the least performance among the tested systems. After 12 months of exposure to environmental chamber, simulating the Arabian Gulf conditions, the reduction in chloride penetration for different surface treated concrete specimens was in the range 15–98% as compared to uncoated ones.

Vassie [6] tested five surface coatings on concrete with 0.5 w/c ratio to establish the effect of the coating on the corrosion rate of active steel in concrete. The results showed that four of the five coatings prevented further penetration of chloride over a four-month period. The successful coatings were solvent-free urethane, alkyl alkoxy silane, silane/acrylic, and liquid plastic dressing.

Swamy et al. [7] examined the performance of concrete slabs coated with acrylic-based coating against chloride and atmospheric carbon dioxide attacks. The slabs were exposed to repeated cyclic wetting by sodium chloride solution followed by drying. After long-term exposure the results showed no chloride penetration into the concrete beneath the coating. During the period of field exposure, the uncoated concrete specimens showed carbonation depth ranging from 7.6 to 8.9 mm, whereas the acrylic-based coating prevented the penetration of carbon dioxide into the concrete.

The results of the study conducted by Pfeiffer and Scali [8] indicated that epoxies, methyl methacrylates, urethanes and silane provide an excellent barrier against the ingress of chloride ions into concrete cubes after 21 days of continuous immersion in 15% NaCl solution.

Ibrahim [9] investigated the effect of concrete surface treatments on several properties of concrete including water absorption, initiation of reinforcement corrosion, and cracking due to reinforcement corrosion. The results showed that the reduction in water absorption, for the concrete specimens treated with different surface coatings, were in the range 10–93% as compared to uncoated ones. The results indicated that silane/siloxane sealants with a topcoat and an acrylic coating were the most effective in reducing reinforcement corrosion. The time-to-initiation of reinforcement corrosion in concrete specimens coated with silane/siloxane sealants with topcoat was 320 days compared to 10 days for the uncoated concrete specimens.

Iob et al. [10] and Saricimen et al. [11,12] showed that some of the cementitious-based coatings improved concrete permeability as well as retarded reinforcement corrosion at the end of a two-year field exposure. Results of accelerated study of proprietary silicious and organic coatings did not indicate, however, any improvement in the durability and corrosion resisting properties of concrete.

The objective of this study is to evaluate the performance of four waterproofing types in terms of corrosion resistance and related physical properties including water absorption, water permeability, chloride permeability, and adhesion. The prepared specimens were subjected to wetting/drying cycles and heating/cooling cycles up to five months.

2. Experimental program

2.1. Materials

2.1.1. Concrete

The concrete specimens were prepared with 370 kg/m^3 of Type I cement and an effective water-cement ratio of 0.45. A coarse-to-total aggregate ratio of 1.63 was used. The coarse aggregate was 12.5 mm maximum-size crushed limestone. The fine aggregate was dune sand. Concrete specimens were cast in three layers and consolidated on a vibrating table. They were covered with wet burlap and cured under laboratory conditions for 24 h, and then demolded and water-cured for 27 days. After 28 days of casting the concrete specimens were allowed to dry for a week under laboratory conditions ($T = 25°C$, $Rh = 50\%$) before they were coated with the selected waterproofing material.

2.1.2. Waterproofing materials

The following proprietary waterproofing materials representative of different generic types were evaluated in this study:

1. Cement-based polymer-modified coating (WP1): This coating is designed for use on concrete surfaces exposed to atmosphere to stop ingress of salts and vapors into concrete pores.
2. Cement-based coating (WP2): It consists of gray Portland cement, specially treated quartz, and a compound of active chemicals. Active chemicals combine with the free lime in concrete to form insoluble complexes. This coating is designed for water retaining structures.
3. Polyurethane-based coating system (WP3): It consists of epoxy-based barrier, interlaminar primer, and polyurethane-based coating.

4. Epoxy-based coating system (WP4): It consists of an epoxy-based sealer, and solvent-free epoxy with high viscosity.

2.2. Specimens preparation and conditioning

2.2.1. Physical properties

Five groups of concrete specimens were prepared. One group consists of uncoated concrete specimens, and the other four groups represent concrete specimens coated with the selected four coating materials described above.

The concrete specimens were cast and wet-cured under fully immersed condition for 28 days and then allowed to dry for a week under laboratory conditions. The coating materials were applied on the concrete specimens according to the suppliers' recommendations.

All the prepared specimens were then subjected to the following laboratory conditions:

1. *Wetting/drying cycles*: Each cycle consists of 24 h wetting by submersion in water followed by 24 h drying at room temperature in the laboratory. The wetting/drying cycles continued for five months.
2. *Heating/cooling cycles*: Each cycle consists of 8 h of heating at 70°C followed by cooling at room temperature in the laboratory for 16 h. The durations required to heat specimens from room temperature to 70°C and to cool specimens from 70°C to room temperature were 15 and 90 min, respectively. The heating/cooling cycles continued for five months.

2.2.2. Accelerated reinforcement corrosion

Concrete specimens, measuring 75 mm in diameter and 150 mm high, and with a centrally placed reinforcing steel bar, were prepared and subjected to accelerated corrosion in a sodium chloride solution. The objective of this test was to determine the effectiveness of the selected coating materials in protecting the reinforcement against the ingress of aggressive ions. An effective cover of 25 mm was provided at the bottom of the specimen. The steel bars were coated with cement slurry overlaid with an epoxy resin at the bottom and at the concrete air interface to avoid crevice corrosion. After casting, the concrete specimens were covered with wet burlap for 24 h and were then demolded. After demolding, they were cured for 28 days and then allowed to dry for a week under laboratory conditions before reinforcement corrosion was accelerated by impressing an anodic potential. The number of specimens tested is given in Table 1.

2.3. Physical properties

The following tests were performed on the coated and uncoated concrete specimens to evaluate the effect of the waterproofing materials on the physical properties of concrete. The specimens were tested at 0-, 2-, and 5-month intervals of conditioning:

2.3.1. Water absorption

The water absorption of the coated and uncoated concrete specimens was evaluated according to ASTM C 642 [13], see Fig. 1 for the typical specimens.

2.3.2. Water permeability

Water permeability of the coated and uncoated concrete specimens was determined according to DIN 1048 [14].

2.3.3. Chloride permeability

The chloride permeability test was conducted according to ASTM C 1202 [15].

2.3.4. Pull-off strength (Adhesion)

The adhesion of the selected waterproofing materials to the concrete substrate was evaluated according to ASTM D 4541 [16]. Concrete specimens, measuring 62 × 100 × 300 mm, were coated with the selected waterproofing materials and the adhesion of the coating was evaluated using an adhesion tester.

2.4. Accelerated reinforcement corrosion

The coated and uncoated concrete specimens were partially immersed in a 5% sodium chloride solution and the steel bar (working electrode) was connected to the positive terminal of a DC power source while the negative terminal was connected to stainless steel

Table 1
List of the tests and number of specimens

Test	Test method	No. of specimens	Specimen size
Adhesion	ASTM D 4541	45	62 × 100 × 300 mm (concrete)
Water permeability	DIN 1048	60	150 × 150 × 150 mm (concrete)
Absorption	ASTM C 642	60	75 mm diameter and 150 mm high (concrete)
Cl permeability	ASTM C 1202	60	75 mm diameter and 50 mm high (concrete)
Accelerated corrosion	–	15	75 mm diameter and 150 mm high (concrete)

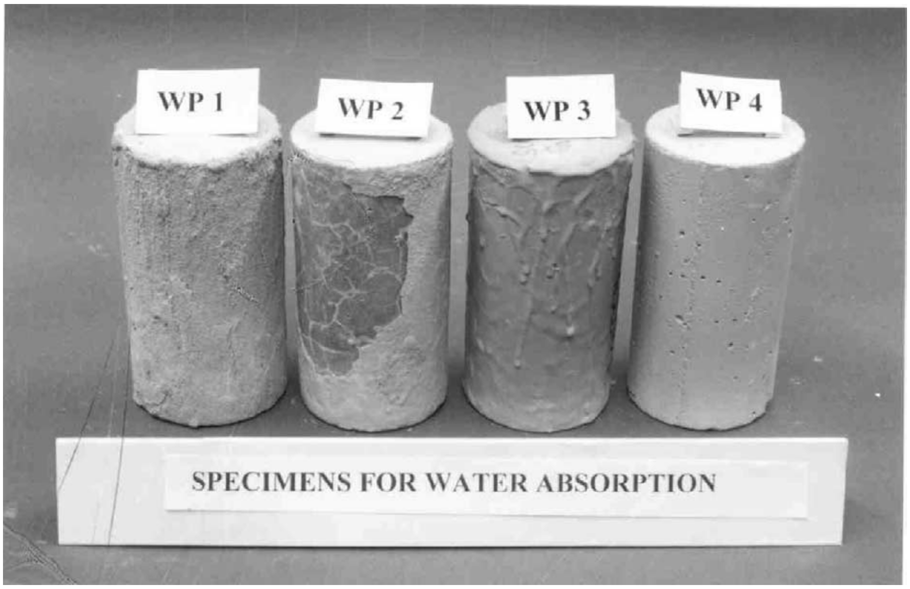

Fig. 1. Typical specimens utilized to determine the water absorption capacity (after five months of W/D cycles).

plates (counter electrode) placed near the specimen. The corrosion process was initiated by impressing an anodic potential of 4 V. The current required to maintain this potential was evaluated by measuring the potential drop over the two leads of a precision resistor. The current measurements were recorded every hour. Fig. 2 is a schematic representation of the experimental setup for the accelerated corrosion test. The time–current curves were utilized to evaluate the time-to-initiation of reinforcement corrosion, which was taken as the point where a significant increase in the current or a change in the slope of the time–current curve occurred.

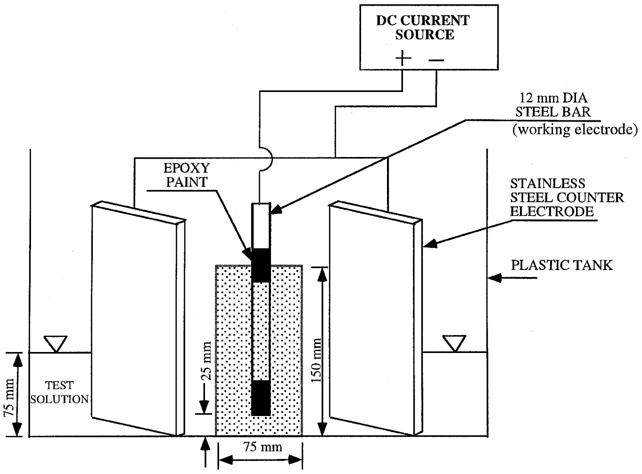

Fig. 2. Schematic representation of the setup for the accelerated corrosion test.

3. Experimental results

3.1. *Effect of waterproofing materials on physical properties of concrete*

3.1.1. *Water absorption*

Results of the water absorption capacity of the coated and uncoated concrete specimens subjected to wetting/drying cycles and heating/cooling cycles are summarized in Tables 2 and 3, respectively.

For the unconditioned specimens, a comparison of the water absorption capacity of the coated specimens indicated that WP2 had high absorption capacity and is only 14% less than the uncoated specimen. This is followed by WP1, which had an absorption capacity of 1.98%. The best performance was obtained by the WP3 followed by WP4.

The two and five months of wetting/drying cycles did not significantly affect water absorption, except for WP1 coating, which showed a better performance and became better than WP4 coating. On the other hand WP3 coating was not affected by the wetting/drying cycles, it continued to be superior to the other coatings. The poor performance of the WP2 coating after wetting/drying cycles is due to the delamination and cracking of the coating observed during the exposure.

After two months of exposure to the heating/cooling cycles, the water absorption capacity of the specimens increased. The WP4 coating showed an increase of more than fourfolds, which can be attributed to the formation of blisters in the coating due to heating/cooling cycles. The best performance by far was shown by the WP3 coating, followed by the WP1

Table 2
Water absorption results of specimens subjected to wetting/drying cycles

Coating type	Water absorption (%)					
	Unconditioned		Wetting/drying cycles			
	Average	S.D.	Two months		Five months	
			Average	S.D.	Average	S.D.
Uncoated	7.43	0.16	6.74	0.49	6.60	0.24
WP1	1.98	0.10	0.44	0.07	0.33	0.01
WP2	6.41	0.18	6.98	0.09	6.80	0.27
WP3	0.17	0.02	0.20	0.02	0.09	0.02
WP4	0.70	0.04	1.39	0.17	1.20	0.34

Table 3
Water absorption results of specimens subjected to heating/cooling cycles

Coating type	Water absorption (%)					
	Unconditioned		Heating/cooling cycles			
	Average	S.D.	Two months		Five months	
			Average	S.D.	Average	S.D.
Uncoated	7.43	0.16	7.57	0.11	7.40	0.13
WP1	1.98	0.10	2.57	0.04	2.88	0.14
WP2	6.41	0.18	7.85	0.13	8.07	0.15
WP3	0.17	0.02	0.22	0.07	0.15	0.03
WP4	0.70	0.04	2.8	0.31	3.05	0.48

coating, the WP4 coating, and the WP2 coating, in that order.

After five months of exposure, the water absorption capacity of all coated specimens increased except for WP3 coating. The WP4 coating showed an increase of more than fourfolds. The best performance by far was shown by the WP3 coating, followed by the WP1, and the WP4 coating in that order. On the other hand the water absorption capacity of the WP2-coated specimens was even higher than that of the uncoated concrete specimens. This phenomenon can be attributed to the high absorption capacity of this coating.

3.1.2. Water permeability

Results of the average depth of water permeability of the specimens subjected to both wetting/drying cycles and heating/cooling cycles are given in Tables 4 and 5, respectively. The reported values are the average maximum depth of penetration from three specimens.

Results of the water permeability of the unconditioned specimens indicated that the WP2 coating had a poor performance, showing about 84% of the depth of water penetration of the uncoated specimens. For the other three coatings, no water penetration was noticed.

After two and five months of wetting/drying cycles, the depth of water penetration of the uncoated

Table 4
Water permeability results of specimens subjected to wetting/drying cycles

Coating type	Depth of water penetration (mm)					
	Unconditioned		Wetting/drying cycles			
	Average	S.D.	Two months		Five months	
			Average	S.D.	Average	S.D.
Uncoated	77.9	4.7	48.9	4.3	54.5	5.2
WP1	0	0	0	0	0	0
WP2	65.7	6.3	50.2	2.7	94.4	9.1
WP3	0	0	0	0	0	0
WP4	0	0	0	0	0	0

Table 5
Water permeability results of specimens subjected to wetting/drying cycles

Coating type	Depth of water penetration (mm)					
	Unconditioned		Heating/cooling cycles			
	Average	S.D.	Two months		Five months	
			Average	S.D.	Average	S.D.
Uncoated	77.9	4.7	103.7	5.4	114.2	5.7
WP1	0	0	0	0	0	0
WP2	65.7	6.3	Completely wet	0	Completely wet	0
WP3	0	0	0	0	0	0
WP4	0	0	0	0	0	0

specimens was reduced by about 30% due most probably to additional curing. Similarly, the specimens coated with the WP2 experienced about 31% reduction due to the same reason. The other three coatings did not show any water penetration.

After two and five months of heating/cooling cycles, the depth of water penetration of the uncoated specimens increased by about 33% and 47%, respectively. The specimens coated with WP2 were completely wet even before the conclusion of the permeability test. The water was leaking between the coating and the sealing ring, indicating that this coating is a very absorptive material. The other three coatings did not show any water penetration even after five months of heating/cooling cycles.

3.1.3. Cl permeability

Results of the chloride permeability test are reported as the total charge in Coulomb (C) passed through the testing specimens. The results of the chloride permeability of the specimens subjected to wetting/drying cycles and heating/cooling cycles are given in Tables 6 and 7, respectively. These tables also provide chloride permeability classification according to ASTM C 1202 [15].

According to the classification of the ASTM C 1202, the chloride ion permeability of unconditioned specimens is low (1000–2000°C) for the uncoated concrete specimens and negligible (<10°C) for the coated specimens.

After two and five months of wetting/drying cycles, the chloride ion permeability of concrete specimens

Table 6
Chloride permeability results of specimens subjected to wetting/drying cycles

Coating type	Chloride permeability (C)		
	Unconditioned	Wetting/drying cycles	
		Two months	Five months
Uncoated	1759.9 (low)	2916.3 (moderate)	3169.7 (moderate)
WP1	9.1 (negligible)	268.0 (V. low)	396.2 (V. low)
WP2	25.1 (negligible)	1072.4 (low)	790.6 (V. low)
WP3	2.7 (negligible)	6.8 (negligible)	3.6 (negligible)
WP4	5.4 (negligible)	24.3 (negligible)	90.2 (negligible)

Table 7
Chloride permeability results of specimens subjected to heating/cooling cycles

Coating type	Chloride permeability (C)		
	Unconditioned	Heating/cooling cycles	
		Two months	Five months
Uncoated	1759.9 (low)	1775.8 (low)	1614.1 (low)
WP1	9.1 (negligible)	794.0 (V. low)	858.8 (V. low)
WP2	25.1 (negligible)	1457.0 (low)	1363.3 (low)
WP3	2.7 (negligible)	4.7 (negligible)	4.0 (negligible)
WP4	5.4 (negligible)	21.3 (negligible)	22.5 (negligible)

coated with WP2 and WP1 increased to low (1000–2000°C) and very low (100–1000°C), respectively. The concrete specimens coated with the WP3 and WP4 coatings continued to show negligible chloride permeability.

For the specimens subjected to heating/cooling cycles for two and five months, the chloride ion permeability of concrete specimens coated with WP2 and WP1 increased from negligible to low and very low, respectively. On the other hand, the concrete specimens coated with WP3 and WP4 coatings did not change, but showed negligible chloride permeability throughout the exposure period.

3.1.4. Pull-off strength (Adhesion)

Results of the pull-off strength (adhesion) of the four coatings with concrete specimens subjected to wetting/drying cycles and heating/cooling cycles are given in Tables 8 and 9, respectively. The values for the unconditioned specimens are in the range 1.00–1.70 MPa. The usual performance criterion requires the adhesion of surface coatings to be greater than or equal to 1.0 MPa. All the considered coatings satisfied this criterion. As expected, the adhesion of the polymer-based coatings was stronger than that of the cement-based surface coatings. The WP3 coating showed the highest adhesion for the unconditioned specimens.

Exposure to wetting/drying cycles decreased the adhesion of the cement-based coatings by 43% for coating WP2 and by 45% for coating WP1 after five months of exposure. The WP4 coating was not adversely affected by the wetting/drying exposure and, by far, it showed better adhesion than the two cement-based coatings.

Exposure to heating/cooling cycles also decreased the adhesion of the cement-based coatings by 57% for coating WP2 and by 15% for coating WP1 after five months of exposure. The WP4 coating was not adversely affected by the heating/cooling exposure, and showed better adhesion compared to the two cement-based coatings.

The data in Tables 8 and 9 show also that the failure of the WP1 coating occurred in the substrate concrete in all the specimens except the specimens subjected to five months of wetting/drying cycles where the failure occurred at the concrete–coating interface. For the specimens coated with WP2 the failure always occurred at the concrete–coating interface. In the case of the WP3 coating debonding occurred at the topcoat–basecoat interface in all the specimens with continuous stretching in the topcoat during the pull-off test. On the other hand, the WP4

Table 8
Adhesion results of coated specimens subjected to wetting/drying cycles

Coating type	Adhesion (MPa)					
	Unconditioned		Wetting/drying cycles			
	Average	S.D.	Two months		Five months	
			Average	S.D.	Average	S.D.
WP1	1.53 (SC)	0.06	1.27 (SC)	0.21	0.85 (CC)	0.15
WP2	1.00 (CC)	0.10	0.88 (CC)	0.19	0.57 (CC)	0.21
WP3	2.10 (TB)	0.11	1.0[a]	0.14	0.80[a]	0.11
WP4	1.47 (SC)	0.06	1.73 (SC)	0.40	1.70 (SC)	0.34

CC: Failure in concrete–coat interface; SC: Failure in substrate concrete; TB: Debonding at the topcoat–basecoat interface.
[a] Debonding at the dolly–topcoat interface.

Table 9
Adhesion results of coated specimens subjected to heating/cooling cycles

Coating type	Adhesion (MPa)					
	Unconditioned		Heating/cooling cycles			
	Average	S.D	Two months		Five months	
			Average	S.D.	Average	S.D.
WP1	1.53 (SC)	0.06	1.33 (SC)	0.15	1.30 (SC)	0.26
WP2	1.00 (CC)	0.10	0.73 (CC)	0.06	0.43 (CC)	0.11
WP3	2.10 (TB)	0.11	0.9[a]	0.13	1.80 (TB)	0.21
WP4	1.47 (SC)	0.06	1.27 (SC)	0.21	2.33 (SC)	0.32

CC: Failure in concrete–coat interface; SC: Failure in substrate concrete; TB: Debonding at the topcoat–basecoat interface.
[a] Debonding at the dolly–topcoat interface.

coating showed good adhesion to concrete as the failure always occurred in the substrate concrete even after exposure to wetting/drying cycles and heating/cooling cycles.

3.2. *Effect of waterproofing materials on reinforcement corrosion*

The accelerated corrosion behavior of steel bars embedded in concrete specimens representing the five groups was obtained by impressing an anodic potential of 4 V. The current required to maintain the fixed potential was plotted against time, and a typical plot is shown in Fig. 3 for WP1 coating. Typical corrosion specimens after the conclusion of the test are shown in Fig. 4.

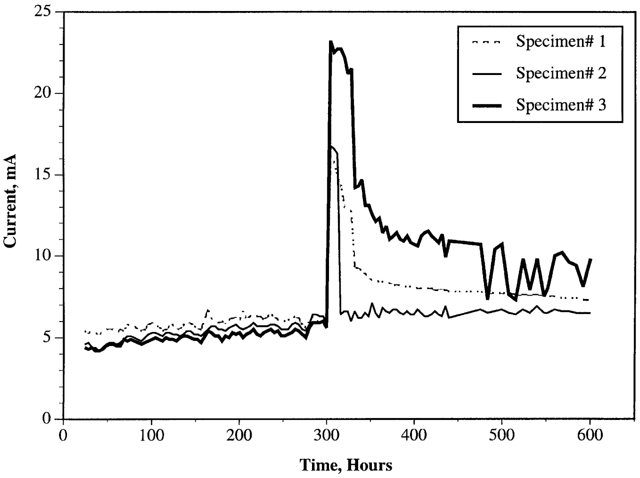

Fig. 3. Time–current curves for WP1 coated concrete specimens.

Accelerated corrosion of steel reinforced concrete specimens was monitored by measuring the current of reinforcing steel. The current–time curves were utilized to determine the time-to-initiation of reinforcement corrosion by observing the instantaneous rise in the current requirement or the change in the slope of the current–time curve.

At the beginning of experiment and due to the constant potential impressed, the steel bar in concrete is anodic. However, the anodic reaction or the corrosion reaction rate on the steel bar surface is very slow because of the limited access of chloride ions and oxygen to the surface of the steel bar in the case of coated concrete specimens, which explains the initial low current at the beginning of the test. As the experiment is continued, however, corrosion of the steel bar keeps more or less steady until the time when crack is developed through surrounding concrete and as a consequence the electrical resistivity between the anode and the cathode is sharply reduced with a simultaneous increase in current. Cracking of the surrounding concrete allows easy access of the chloride ions and oxygen to the surface of the steel and hence increases the corrosion rate.

The time at which an increase in the current requirement was noted is summarized in Table 10. As expected initiation of reinforcement corrosion was noted much earlier in the uncoated concrete specimens than in the coated concrete specimens. While time-to-initiation of reinforcement corrosion was noted after 28 h in the uncoated concrete specimens, it was noted after 96, 164, and 304 h in the concrete specimens coated with coat-

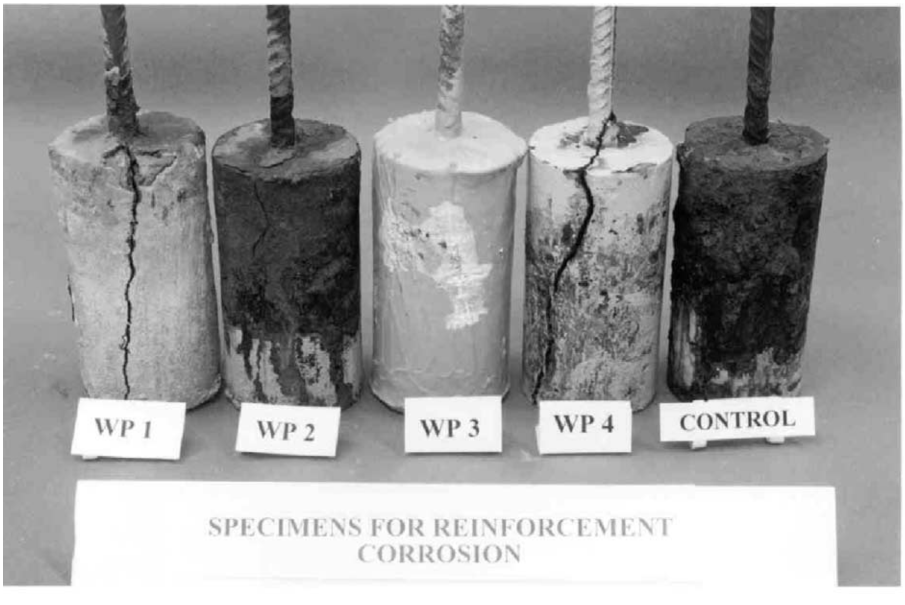

Fig. 4. Typical corrosion specimens after the accelerated corrosion test.

Table 10
Time-to-initiation of reinforcement corrosion

Coating type	Time-to-initiation of reinforcement corrosion (h)
Uncoated	28
WP1	304
WP2	96
WP3	No corrosion initiation noticed
WP4	164

ings WP2, WP4, and WP1, respectively. The current required to maintain an anodic potential of 4 V was very low, throughout 1100 h of the experiment, in the concrete specimens coated with WP3, and no corrosion initiation was noted.

Based on the results of the accelerated corrosion test, the best performance was shown by the specimens coated with polyurethane-based coating system (WP3). This was followed by the specimens coated with WP1, WP4, and WP2, in that order.

4. Discussion

Coatings are used to improve the durability of the whole structure other than for cosmetic reasons. They are beneficial to seal the surface against penetration of harmful species such as oxygen, CO_2, chloride ions, sulfate ions, and water into concrete for many years. At the same time, it is very essential that, the coating should enable the concrete to "breathe" and allow water vapor to escape for preventing formation of blisters [8,18].

This short-term study showed that cement-based coatings demonstrated inferior durability performance compared to polymer- and epoxy-based coatings. The performance of polymer-modified (WP1), polyurethane (WP3) and epoxy-based (WP4) coatings in reducing water absorption was superior to that of cement-based coating (WP2). The water absorption in the concrete specimens coated with polymer-modified and epoxy-based coatings increased appreciably with the increasing exposure to heat/cool cycles, possibly because of formation of blisters in the latter case. According to water permeability results, the concrete specimens coated with cement-based coating (WP2) allowed water to penetrate its whole depth, whereas, the others, polymer modified, polyurethane and epoxy-based coatings, were impermeable to water penetration under all test conditions evaluated. In Cl-permeability tests, all of the coatings performed well. However, the polyurethane- and epoxy-based coatings performed better than the others.

The accelerated corrosion tests showed that the polymer modified and polyurethane-based coatings performed better than the cement-based and epoxy-based coatings, in terms of reducing the ingress of chloride ions into the steel–concrete interface. Adhesion strength to concrete surface of all the coatings passed the criteria in unconditioned state. The polymer-modified and cement-based coatings showed lower adhesion than the polyurethane- and epoxy-based coatings. However, the wet/dry and heat/cool cycling reduced the adhesion strength of WP2 and WP3 coatings drastically but did not affect the adhesion strength of the other two coatings WP1 and WP4 significantly.

Iob et al. [10] and Saricimen et al. [11,12] reported that cementitious coatings did not improve durability and corrosion protection property of concrete during short duration studies. Results published by Uomoto et al. [4] showed that specimens coated with polymer-modified cementitious material improved the corrosion resistance of concrete significantly. Several researchers [5–8] found significant reduction in Cl-permeability and reinforcement corrosion in concrete coated with epoxy, urethane, alkyl-alkoxy-silane, silane/acrylic, acrylic, methylmethacrylate-based coatings and liquid plastics.

Some of the coatings such as acrylic resin solutions, water-repellent silicon resins, certain types of silane resins, epoxies, and polyurethanes form a barrier on the concrete surface and effectively prevent the ingress of Cl^- ions into the substrate. Provided that these coatings fill the pores within the surface of concrete as intended, they are expected to give a good long-term durability [17].

McCurrich et al. [18] reported results of 17 silane-, acrylic- and polyurethane-based coating systems. They tested the systems for carbon dioxide and water vapor permeability, chloride and sulfate ion diffusion, and water absorption. Their results showed that systems such as epoxies, polyurethanes, and chlorinated rubber coatings form a film on the surface of the concrete. With little penetration they can provide excellent protection for concrete. However, in the long term, there is always the risk of adhesion failure, particularly if these coatings are subjected to water vapor from behind as also reported by Saricimen et al. [19] on failure of epoxy coatings.

Therefore, although short-term evaluation of surface coatings may reveal very valuable information about their effectiveness in improving concrete durability, long-term studies should be included in the study program to understand their performance for extended durations. Provisions should also be made to determine the depth of penetration of the coatings into the concrete surface.

The accelerated corrosion performance of the four coating systems studied correlates well with the performance results obtained from the physical properties, in particular, water absorption, water permeability and chloride permeability.

The obtained results clearly showed that the water absorption capacity is the most simple physical property that can be considered to predict the protection performance of coating systems against corrosion.

5. Conclusions

Based on the results obtained from the accelerated laboratory testing program, the following conclusions can be made:

1. The water absorption results of the unconditioned and conditioned coated specimens indicate that the polyurethane-based coating system (WP3) showed the best performance among the four coating systems.
2. The polyurethane-based coating system (WP3), epoxy-based coating system (WP4), and cement-based polymer-modified coating system (WP1) were equally superior with regard to water permeability and did not show any water penetration.
3. The resistance to chloride permeability of both the polyurethane-based coating system (WP3) and epoxy-based coating system (WP4) was superior to the two cement-based waterproofing materials.
4. The cement-based polymer-modified coating system (WP1) and epoxy-based coating system (WP4) showed adhesion strength values higher than 1 MPa for both exposure conditions.
5. The accelerated corrosion test results clearly showed that the specimens coated with the polyurethane-based coating system (WP3) had superior performance compared to the other three waterproofing materials.
6. The results clearly showed that the water absorption capacity is the simplest property that can be considered to predict the protection performance of coating systems against corrosion.
7. The polyurethane-based coating system (WP3) is by far superior to the other three coating systems.
8. The accelerated corrosion performance of the four coating systems studied correlates well with the performance results obtained from the physical properties, in particular, water absorption, water permeability, and chloride permeability.

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