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Evaluation of the performance of surface treatments on concrete durability*

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Abstract: This paper reports on a laboratory-based study carried out to evaluate the effectiveness of surface treatments on the durability of concrete and suggests a number of different evaluation methodologies for assessing the performance of various surface treatments. Durability of untreated and treated concrete specimens was evaluated by measuring chloride diffusion, charge passing capacity, air permeability and water absorption. A total of six concrete surface treatments were selected to represent different generic types, including coating, penetrant and mixed-use treatments. Results show that the concrete specimens with a coating procedure have a better long-term performance and effectiveness than the specimens with the penetrant treatments. This work also indicates that the wetting and drying cycles test can be used to assess the weatherability of the surface treatments. The ASTM C 1202 and the Autoclam air permeability test can be used to evaluate the effectiveness of surface treatments quantitatively. Further work is needed, however, to assess the longevity of the various surface treatments.

Key words: Surface treatment, Concrete, Durability, Evaluation
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1 Introduction

Reinforced concrete has long been considered as an efficient and durable construction material. Its low-cost, excellent compressive strength and stiffness properties coupled with its ease of manufacture at the construction site are important factors that have established it as a major construction material. The reinforcing steel in the concrete carries load in regions of tensile cracking and provides confinement in areas of high compression while the intrinsically alkaline nature of concrete maintains the steel in an electrochemical stable state. In recent decades, enormous deterioration of concrete structures caused by reinforcement steel corrosion has emerged due to severe environmental conditions, changes in the composition of ordinary cements over the last 50 years, and improper design or bad workmanship. Long-term performance of concrete structures has been one of the most important problems in construction field.

Steel reinforcement in concrete remains protected against corrosion as long as it stays passive. The main agents associated with depassivation of the reinforcement steel corrosion are chloride ions, carbon dioxide and sulphur oxides. Water is also a critical agent responsible for the oxidation of reinforcement. Indeed, much of the deterioration of concrete can only occur in the presence of water, since aggressive agents penetrate concrete and react harmfully with the concrete only when dissolved in water (Wittmann *et al*., 2009). Water provides the transport path for chloride ions, is relevant to carbonation reaction and freeze-thaw durability, and also establishes electrolytic continuity inside concrete. Moreover, water is a key ingredient for the oxidation reaction of steel, as it is involved in the reduction of oxygen at catholic site.

One way of avoiding the action of the

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aforementioned harmful agents is to prevent their ingress into concrete. This has led to much greater attention to concrete cover over the reinforcement steel and the overall quality of concrete. High Performance Concrete (HPC) has thus been developed recently. HPC normally has high strength and low permeability due to mixture of additives such as pulverized fuel ash, silica fume, blast furnace slag and superplasticizer which reduce the water/binder ratio. However, it should be recognized, that concrete is intrinsically a porous material. Despite improvements in its formulation and quality control, it is not possible to completely prevent the ingress of potentially harmful agents into it. If the HPC permeability reduction and the thickness of the concrete cover are not sufficient to avoid deterioration, then surface treatments could be considered as an additional measure to improve the durability of concrete structures. Surface treatments can act as barriers between the environment and concrete, they can prevent or at least delay the penetration of harmful substances such as water and chlorides, etc. This method can also be used to rehabilitate corroding structures (Leung *et al.*, 2008; Medeiros and Helene, 2009).

Surface treatments are classified by Keer (1992) according to the manner by which the protection or benefit is achieved: (i) coatings, which form a pinhole-free film of finite thickness over the concrete surface to act as a barrier to the passage of harmful substances; (ii) pore-lining treatments, which involve hydrophobic materials that line concrete surface pores and repel moisture; and (iii) pore-blocking treatments, which make use of a family of products claimed to penetrate concrete and block pores. Whatever the type of surface treatment, it should fulfill some fundamental requirements, such as impermeability to harmful substances, good permeability towards water vapour and chemical/photochemical stability. In recent years, many experimental studies have been carried out to evaluate the effectiveness of surface treatments. The data in these studies have shown encouraging results in reducing the diffusion of oxygen, moisture and chloride ions (Medeiros and Helene, 2008), inhibiting carbonation (de Muynck *et al.*, 2008) and sulphate attack (Almusallam *et al.*, 2003), increasing frost resistance (Levi *et al.*, 2002; Moon *et al.*, 2007) and delaying reinforcement corrosion (Rodrigues *et al.*, 2000; McCarthy *et al.*, 2004). Basheer *et al.* (1997) provided a summary on the techniques utilized to evaluate the performance of surface treatments for concrete.

The encouraging results obtained from the aforementioned experimental investigations have led to the development of a variety of commercially available concrete surface treatments. Given so many options, selection of the most suitable surface treatment remains difficult. This study was carried out to evaluate the effectiveness of surface treatments on durability of concrete and suggest a number of different evaluation methodologies for assessing the performance of various surface treatments based on a series of experimental works concerning chloride diffusion, charge passing capacity, air permeability and water absorption.

2 Experimental procedures

2.1 Materials

Three concrete mixes were manufactured to produce different water/concrete (w/c) ratio concrete. The mixture proportions of the concrete are given in Table 1. Six concrete surface treatments were selected to represent different generic types and are shown in Table 2.

Table 1 Concrete mix composition

Parameter	Concrete		
	X	Y	Z
Cement (kg/m^3)	366	436	476
Water (kg/m^3)	248	276	222
Sand (kg/m^3)	676	633	618
Aggregate (kg/m^3)	1102	1125	1099
w/c ratio	0.68	0.63	0.47
Superplasticizer (%)			1
28-d compressive strength (MPa)	33.6	34.0	35.8

Note: X, Y and Z represent different concrete types

2.2 Test specimens

Concrete specimens of 200 mm×200 mm×150 mm were used to carry out the chloride diffusion test. A block of 1200 mm×110 mm×200 mm was cast and cut by a circular diamond blade saw to individual specimens of size 100 mm in diameter and 110 mm in height. These cylindrical specimens were further cut to obtain 84 standard samples ($\Phi(100\pm1)$ mm, $h=(50\pm2)$ mm) and subsequently used in the rapid chloride permeability test in accordance to ASTM C 1202.

Table 2 Different types of surface treatments

Surface treatment		Generic type	Classification	Application procedure	
				Dosage	Brushing
A	Primer coat	Silane/siloxane	Pore-lining	0.4 L/m^2	Once
	Top coat	Acrylate	Coating	0.175 L/m^2	Twice
B	—	Mixture of silicate and acrylic	Coating/pore-blocking	0.1 L/m^2	Once
C	Primer coat	Epoxy resin	Pore-lining	100 g/m^2	Once
	Base coat	Epoxy resin	Coating	333 g/m^2	Once
	Top coat	Polyurethane	Coating	208 g/m^2	Once
D	—	Silane	Pore-lining	450 g/m^2	Three times
E	—	Silane	Pore-lining	240 g/m^2	Twice
F	—	Silane	Pore-lining	200 g/m^2	Once

Note: A–F represent different surface treatments

Concrete specimens of 300 mm×150 mm×150 mm were cast to evaluate the air permeability and water absorption of the surface-treated concrete.

All the concrete constituents were filled into the molds and vibrated for consolidation. After casting, the specimens were covered with wet burlap. They were demolded after 24 h of casting and then curing was continued for two weeks, the burlaps were wetted from time to time. Following the curing period, specimens were kept in the lab and dried at room temperature for several weeks. After preparation of the test surfaces, the selected treatments were applied with a brush as per manufacturer’s instruction.

2.3 Test methods

2.3.1 Chloride diffusion depth

The selected surface treatments were applied on one 200 mm×200 mm face of each specimen. A rapid set epoxy coating was used on the other uncoated surfaces to enable unidirectional diffusion of chloride ions. Two weeks after applying the surface treatments the specimens were subjected to alternate wetting, with chloride solution, and drying cycles. In this study, a 5-d cyclic exposure regime was used to accelerate the chloride ingress. The cycle consisted of immersing specimens in a 6.15% (w/w) sodium chloride solution for 24 h, drying them in the oven for the following 2 d at 50 °C, and then keeping them at room temperature for another 2 d.

After 6, 12, 18 and 24 cycles, holes were drilled through the test surfaces to obtain powder samples in different depths at 5-mm intervals. The water-soluble chloride ion content of the samples was determined by chemical analysis using the Rapid Chloride Test (RCT).

2.3.2 Charge passing capacity

The selected surface treatments were applied on one face of 100 mm diameter and 50 mm thickness concrete discs. To ensure the surface treatments were fully dry, the specimens were kept in room temperature for two weeks before saturated with water under vacuum as per procedure outlined in ASTM C 1202. The charge passed through the specimens was recorded and used to evaluate the effectiveness of surface treatments.

2.3.3 Air permeability

The selected surface treatments were applied on one 300 mm×150 mm face of the specimens. Two weeks after applying the surface treatments, the air permeability test was carried out on the test surfaces by use of Autoclam. The pressure inside the apparatus was increased to 5×10^4 Pa and the decay in pressure was monitored every minute from 5×10^4 Pa for 15 min. A plot of natural logarithm of pressure against time is linear, hence, the slope of the linear regression curve between the 5th and 15th minutes for tests is defined as an air permeability index K_a, with unit of ln(pressure)/min. This was used to evaluate the effectiveness of surface treatments in this test.

2.3.4 Water absorption

Water absorption test was carried out on the same surfaces by use of Autoclam but more than one hour after the air permeability test. The test chamber of Autoclam was completely filled with water and 2×10^4 Pa pressure was increased in the test area. The volume of water delivered was measured and recorded every minute for a duration of 15 min. The quantity of water absorbed and the square root of time elapsed is linear, so the slope of the graph is reported as an absorption index K_{wa} with unit of $m^3/min^{1/2}$, this being used to evaluate the effectiveness of surface treatments.

3 Results and discussion

3.1 Chloride diffusion depth

Figs. 1a–1c show the chloride ingress depth in treated and untreated concrete specimens exposed to 6, 12, 18 and 24 cycles wetting and drying. In those figures, the specimens are designated according to the material type and surface treatment. For example, the specimen designated as “X-A” represents the specimens made from Concrete X with surface treatment A, and “Y-N” represents the specimens made from Concrete Y without surface treatment. The chloride concentration in untreated concrete specimens is more than those in the concrete specimens with treated surfaces at all depths. All the selected surface treatments are effective in reducing chloride ingress. This effect is more pronounced in specimens where the surface treatments include the application of a coating procedure (surface treatments A, B and C) compared with those consisting only of penetrant (pore-lining) treatments (surface treatments D, E and F). The best performing protective measure is surface treatment C where three distinct coatings comprising of an epoxy primer coat, epoxy base coat and polyurethane top coat are applied. Clearly the application of multiple brushing gives more effective protection from chloride ingress compared with single brushing.

The chloride concentration in the specimens treated by the surface treatments A, B and C is steady during 24 cycles of wetting and drying, whereas in general the chloride concentration in specimens treated by penetrant type increased with time, especially after the 18th cycle. This suggests that the longevity of these surface treatments (A, B and C) with coating on the top of the concrete surface is better than that of the penetrant treatments (D, E and F). This work also indicates that the alternate wetting and drying cycles can be used to assess the weatherability of the surface treatments. However, further work is needed to assess the long-term performance of various surface treatments. It is hoped that ongoing work will suggest an evaluation methodology for the long-term performance of surface-treated concrete.

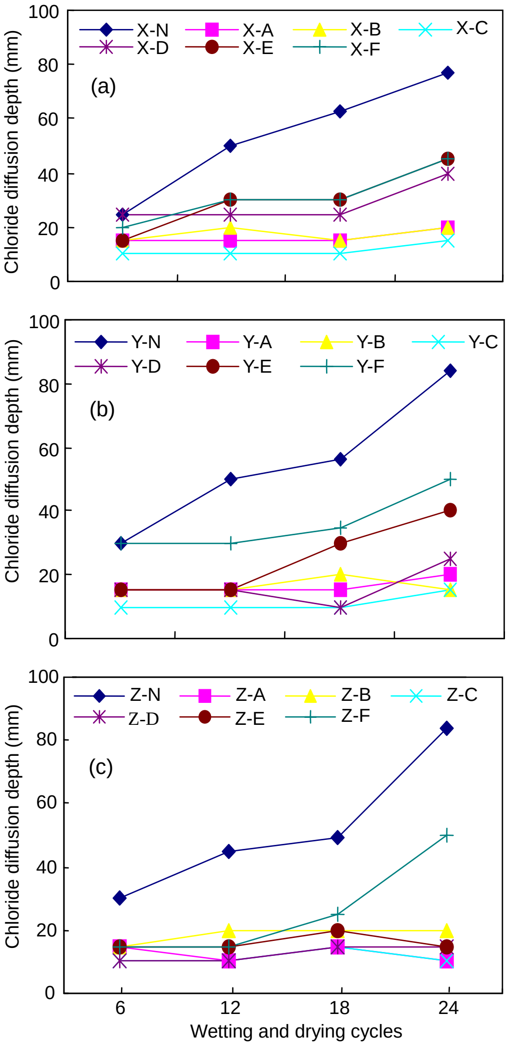

Fig. 1 Chloride diffusion depths for series (a) X, (b) Y and (c) Z of concrete specimens

The performance of surface treatments studied in this experimental work can be express in the following order: C>A & B>D & E>F.

3.2 Charge passing capacity

Table 3 shows the total charge passed through the untreated and treated specimens. For the untreated specimens the effect of the w/c ratio is readily observed: the bigger the w/c ratio is, the more charge passes, whilst the variation of the w/c ratio has little effect on the treated specimens. That is, because the density of concrete specimens increases with a decreasing w/c ratio, charge passes through specimens less easily. For treated specimens, however, the chloride permeability depends primarily on the porosity of the surface film rather than that of concrete substrate. The polyurethane and acrylate coating (surface treatments A, B and C) provide better resistance to the chloride ingress because they leave a tough film with low porosity.

Table 3 Charge passed through the treated and untreated specimens

Specimens*	Charge passed (C)	ASTM C 1202 classification	Charge ratio (%)
X-N	1906	Low	—
X-A	231	Very low	12.1
X-B	177	Very low	9.3
X-C	37	Negligible	1.9
X-D	532	Very low	27.9
X-E	568	Very low	29.8
X-F	662	Very low	34.7
Y-N	1569	Low	—
Y-A	175	Very low	11.2
Y-B	260	Very low	16.6
Y-C	28	Negligible	1.8
Y-D	466	Very low	29.7
Y-E	563	Very low	35.9
Y-F	705	Very low	44.9
Z-N	908	Very low	—
Z-A	184	Very low	20.3
Z-B	145	Very low	16
Z-C	30	Negligible	3.3
Z-D	438	Very low	48.2
Z-E	522	Very low	57.5
Z-F	659	Very low	72.6

* X, Y and Z represent different concrete types, A–F represent different surface treatments, and N denotes the untreated specimens

The ASTM C 1202 classification based on the total charge passed is also listed in Table 3. The chloride permeability of the uncoated concrete specimens is “low”. The surface treatment C, classified as “negligible”, is the most effective surface treatment, which agrees with the result from the previous chloride diffusion test. However, the classification of chloride permeability for all the other five treatments are “very low”; therefore, it is not possible to differentiate the effectiveness of these treatments by this classification method. This problem can be solved by defining a “charge ratio” which, for each scenario, is the ratio of charge passing through the treated and untreated specimens for the same concrete mix. The charge ratios of the specimens are provided in Table 3 and Fig. 2. Fig. 2 also illustrates that the relative benefit is greater for poorer quality concrete (An observation was also previously reported by Basheer *et al.* (1998)).

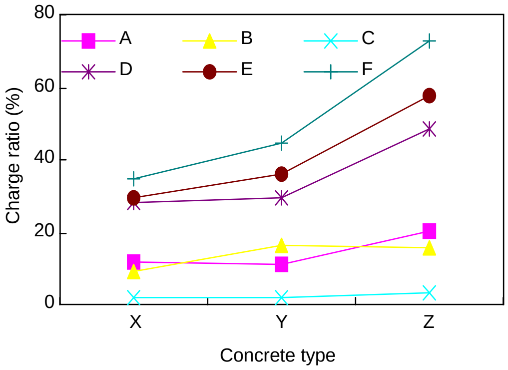

Fig. 2 Charge ratio of the treated and untreated specimens

The performance of the selected surface treatments as per chloride permeability test (ASTM C 1202) is in the following order: C>B & A>D>E>F.

3.3 Air permeability

Table 4 gives the air permeability indexes K_a and the pressure reduction between 5th and 15th minutes ΔP for the untreated and treated specimens. Compared with the untreated specimens the air permeability of the treated specimens with polyurethane or acrylate coating (surface treatments A, B and C) reduces significantly because of the dense film on the surface of the specimens. Meanwhile, the air permeability of specimens prepared with penetrant treatments (surface treatments D, E and F) is in the same order of magnitude as the untreated specimens because these types of treatments only line the capillary walls and bond to the substrates without fully blocking the capillaries. Therefore, the concrete specimens where the surface treatments include the application of a coating procedure perform better in reducing air permeability compared with the specimens with the penetrant treatments.

This work also indicates that the air permeability which is related with the breathability and the carbonation resistance of surface-treated concrete, can be assessed by carrying out the Autoclam air permeability test.

Table 4 Air permeability of the treated and untreated specimens

Specimens	K_a (ln(pressure)/min)	ΔP ($\times 10^2$ Pa)
X-N	0.0380	120
X-A	0.0082	36
X-B	0.0056	26
X-C	0.0021	10
X-D	0.0486	138
X-E	0.0230	85
X-F	0.0736	158
Y-N	0.0319	109
Y-A	0.0037	17
Y-B	0.0045	46
Y-C	0.0010	4
Y-D	0.0590	151
Y-E	0.0313	106
Y-F	0.0668	158
Z-N	0.0538	147
Z-A	0.0096	42
Z-B	0.0112	49
Z-C	0.0002	1
Z-D	0.0390	124
Z-E	0.0321	108
Z-F	0.0595	151

[*] X, Y and Z represent different concrete types, A–F represent different surface treatments

The air permeability of surface-treated specimens in this test has the following order: C>A & B>D & E & F.

3.4 Water absorption

Table 5 shows the water absorption indexes K_{wa} and the volume of water absorbed between 5th and 15th minutes ΔV for the untreated or treated specimens. For the untreated specimens, the water absorption indexes K_{wa} increases with the growth of the w/c ratio as expected, which proves that Autoclam can be utilized to assess the water absorption of untreated concrete specimens. However, in this test, the water absorption indexes K_{wa} of the surface-treated specimens cannot be obtained except for surface treatment D. Even in this case the water absorption indexes K_{wa} and the volume of water absorbed ΔV are very small and therefore of little significance. The reason for this can be attributed to the short duration of the test period (15 min) which is not of sufficient length for the water to penetrate through the treated surface into the concrete substrate. Additionally, the test area is not large enough to make the volume change of water in chamber noticeable. Therefore, the Autoclam water permeability test cannot be used directly for classifying surface-treated concrete. This limitation has been acknowledged by the producer of the Autoclam. Accordingly, improvements have been made to the Autoclam to enable it to examine surface-treated concrete with a longer test period and a larger test area. The relevant experimental work is yet to be undertaken and will be carried out in the near future by the authors.

Table 5 Water absorption of the treated and untreated specimens

Specimens	K_{wa} ($\times 10^{-7}$ m^3/min$^{1/2}$)	ΔV (μl)
X-N	1.423	234
X-A	0	0
X-B	0	0
X-C	0	0
X-D	0.044	8
X-E	0	0
X-F	0	0
Y-N	1.167	194
Y-A	0	0
Y-B	0	0
Y-C	0	0
Y-D	0.02	4
Y-E	0	0
Y-F	0	0
Z-N	0.687	124
Z-A	0	0
Z-B	0	0
Z-C	0	0
Z-D	0.006	2
Z-E	0	0
Z-F	0	0

[*] X, Y and Z represent different concrete types, A–F represent different surface treatments

4 Conclusion

1. The concrete specimens where the surface treatments include the application of a coating procedure perform better in reducing the chloride ingress and air permeability compared with the specimens with the penetrant treatments.

2. The long-term performance of these surface treatments with coating on the top of the concrete surface is also better than that of the penetrant treatments.

3. The procedure specified for applying the surface treatments does have an influence on the effectiveness of each of the treatments. The treatment C with three distinct coatings performs best in all the surface treatments. And clearly the application of multiple brushing gives more effective protection from chloride ingress compared with single brushing.

4. The wetting and drying cycles test can be utilized to assess the weatherability of the surface treatments. Further work is needed, however, to assess the long-term performance of the various surface treatments.

5. The charge ratio which is defined as the ratio of charge passing through the treated and untreated specimens, enables the use of the ASTM C 1202 test for a quantitative evaluation of the effectiveness of surface treatments.

6. The Autoclam air permeability test can be utilized to assess the air permeability of surface-treated concrete.

7. The current Autoclam water absorption test cannot be used directly for classifying surface-treated concrete. Improvements have been made to the Autoclam to enable it to examine surface treated concrete with a longer test period and a larger test area. The relevant experimental work is yet to be undertaken.

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