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Time dependence and service life prediction of chloride resistance of concrete coatings

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HIGHLIGHTS

- Concrete chloride resistance can be remarkably improved using coatings.
- Organic film coatings usually deteriorate faster than infiltrating coatings.
- Service lives of concrete coatings are closely related with solar irradiance.

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ABSTRACT

This study aims to determine the effects of coating category and degradation on chloride resistance and service life of concrete coatings. Four typical coatings were applied on concrete specimens, and aged under outdoor natural climate conditions and indoor artificial accelerated experiments using ultraviolet light radiation and wetting/drying cycle. Coulomb electric fluxes of the specimens were periodically tested to determine their chloride resistance before and during aging. The chloride resistance of concrete is remarkably improved with the use of coatings, and organic film coatings provide superior improvement to infiltrating coatings. The chloride resistance of coatings is time-dependent, and organic film coatings exhibit faster aging than infiltrating coatings. The experimental time needed for coating degradation can be shortened through artificial accelerated aging experiments. The service lives of concrete coatings against chloride resistance are closely related and can be predicted through sunlight irradiance of the service environment.

Steel bar corrosion, a major problem that deteriorates the durability of concrete structures, is primarily caused by penetration of chloride ions [1,2]. Adding protective surface coatings to concrete structures is an important method to improve their durability; this method is convenient, simple, and feasible, as well as suitable for new and deteriorated concrete structures. However, different coatings correspond to different protective mechanisms, protective efficacies, and applicable conditions [3–7]. Organic film-forming coatings can form a protective barrier with 0.1–1-mm depth on the concrete surfaces to isolate aggressive substances from the outside [3,4]. Cementitious coatings, particularly polymer-modified ones, can form a physical barrier of up to 10-mm depth on the concrete surface to reduce the permeability of the concrete, thereby decreasing the penetration of moisture and corrosive medium. Cementitious coatings also exhibit breathing and good weathering resistance [5–7]. Organic silane-based water repellents can change the hydrophilicity of concrete, thereby significantly improving water absorption and permeability, which are beneficial to frost resistance, carbonation, and chloride resistance of concrete [8–10].

Applying surface coatings can generally improve concrete durability to a certain degree, but the protective efficacy cannot be maintained and gradually degrades over service time; thus, the protective effect of coatings on concrete is time-dependent [11–13]. Six concrete coatings were implemented and tested for 5 years in the Persian Gulf tidal zone, in which epoxy polyurethane and aliphatic acrylic are the most efficient coatings and the performances of surface coatings are time-dependent [11]. Accelerated wet–dry cycle experiments using a salt solution were conducted on concrete specimens with four commercial coatings (a polymer-modified cementitious mortar and three elastomeric coatings) for 7 years; the cement-based coatings exhibited an optimal effect on delayed chloride penetration in concrete by acting as a physical barrier in addition to the concrete cover [12]. Carbonation experiments using concrete with four types of surface coatings were tested after natural exposure and indoor accelerated aging; the

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carbonation resistance of concrete with epoxy resin or polyurethane paint decreases with the increasing aging time and minimally changes for concrete with cement-based permeable crystallization or organic silicon coating [13].

Extensive research has been conducted on the protective performance of coatings for metals and their weathering ability [14–17]; however, coatings for metal significantly differ from those for concrete. Studies should be performed on the application and aging laws of coatings for concrete structures compared with traditional metal coatings [18,19]. Correct assessment and evaluation of the time-varying performance of concrete coatings is important to calculate their service life. In this study, four commonly used coatings for concrete were selected. The chloride resistance of the coated specimens was periodically tested under outdoor natural and indoor accelerated aging using ultraviolet radiation and wetting/drying cycle. Thus, the relationship between anti-chloride capabilities of coatings with aging time can be obtained.

1. Experimental

1.1. Raw materials

Raw materials, such as P·O 42.5 ordinary Portland cement which is similar to type I cement meeting ASTM C 150 requirement, natural river sand with fineness modulus of $M_x = 2.6$, crushed limestone with a size of 5–20 mm, and tap water were utilized to prepare concrete specimens. The designed compressive strength of the concrete was 25 MPa with water/cement ratio of 0.6. The specific concrete mixture proportion was 1:2.47:4.03:0.6 for cement:fine aggregates:coarse aggregates:water. The specimens were fabricated in cylinders with 100-mm diameter and 250-mm height.

Four commonly used commercial coatings were selected and implemented on the concrete surface. These coatings included two types of film-forming organic coatings, namely, PLH52-3 epoxy glass-flake paint (EP coating) and PLS52-2 polyurethane paint (PO coating), as well as two types of infiltrating coatings, namely, BH-502 cement-based permeable crystallization waterproof coating (CE coating) and silane-based water repellent coating (SI coating).

1.2. Fabrication of coated concrete specimens

The specimens were cut into 50-mm thick and 100-mm diameter concrete slices after 28 d standard curing (with curing temperature of 20 ± 2 °C and relative humidity more than 95%) to satisfy the size requirement for Coulomb electric flux test. The concrete slices were initially oven dried at 60 °C for 48 h. Each end surface of the concrete slice was polished using sandpaper initially to remove grease and cleaned with a moist cloth to remove dust. Thereafter, the slices were artificially painted using a pig hairbrush according to manufacturer requirements described in Table 1. Each level of brushing interval was 24 h. The slices for infiltrating coating were maintained in a climate chamber with a relative humidity of 70% for 24 h before brushing.

1.3. Plan of aging experiments

Three coating aging methods, namely, outdoor natural exposure, indoor accelerated ultraviolet radiation, and wetting/drying cycle, were used to determine the aging resistance of the coatings.

(1) Natural exposure aging experiment: Four generic coated concrete specimens were placed on the roof of a three-story building in the China University of Mining & Technology campus; this setup was used to expose the specimens to natural environmental factors, such as sunlight, rain, wind, temperature, and relative humidity, with an annual average temperature of 13.9 °C and a relative humidity of 72% in the Xuzhou region [20]. After 6, 9, 12, and 15 months of exposure, the specimens were obtained and periodically subjected to the Coulomb electric flux test. The average value of three pieces of each generic coated specimen was obtained as the representative value.

(2) Accelerated ultraviolet radiation aging experiment: Four generic coated concrete specimens were placed in an ultraviolet radiation climate chamber with a constant temperature of 60 °C and relative humidity of 10%. Two 400-W ultraviolet lamps were installed in the climate chamber, and the distance of the specimen surface from the ultraviolet lamp was 20 cm. After 120, 240, 360, and 480 h of exposure, the specimens were obtained and periodically subjected to the Coulomb electric flux test. The average value of three pieces of each generic coated specimen was obtained as the representative value.

(3) Accelerated wetting/drying cycle aging experiment: a wet/dry cycle device was designed to accomplish the aging experiment; the device comprised six 275-W infrared lamps to simulate the drying process and a self-suction pump that sprays tap water to simulate the wetting process. In the wet/dry cycle regime, one cycle constituted water spraying for 3 min and infrared light drying for 57 min. The distance of the specimen surface from the infrared light was 30 cm, and the temperature of the specimen surface during drying was 40 ± 10 °C. After 240, 480, 720, and 960 h of exposure, the specimens were obtained and periodically subjected to the Coulomb electric flux test. The average value of three pieces of each generic coated specimen was obtained as the representative value.

Table 1
Description of coatings used in this study.

Coating category	Coating system		Dosage (kg/m^2)
EP coating	Primer	Seal primer twice	0.13
	Top coat	Epoxy glass flake paint twice	0.40
PO coating	Primer	Seal primer twice	0.13
	Top coat	Polyurethane paint twice	0.40
CE coating	–	Twice	1.2
SI coating	–	Twice	0.16

1.4. Measurement of Coulomb electric flux

The Coulomb electric flux of each coated specimen was tested and calculated in accordance with the PRC national standard to determine the chloride resistance of the coated concrete specimens before and during aging [21]. The procedure is described as follows: the specimens were initially saturated under vacuum conditions with water and then fixed on the sink. After the installation, 3.0% NaCl solution and 0.3 mol/L NaOH solution were separately injected into the sealed water tanks at both ends. The current value I_t was recorded at 30-min intervals after a 60-V direct current electric potential was implemented. Finally, Coulomb electric flux can be calculated according to formula (1)):

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_t + \cdots + 2I_{300} + I_{330} + I_{360}), \quad (1)$$

where Q indicates the total Coulomb electric flux at 6 h/C, I_0 represents the initial current value/A, and I_t denotes the current value corresponding to time/A.

The risks of anti-chloride penetration of concrete with different Coulomb electric fluxes are shown in Table 2 based on the evaluation standard of ASTM C1202 [22].

2. Experimental results

2.1. Chloride resistance of coated concrete specimens before aging

The Coulomb electric flux of each generic coated specimen was tested before the start of the aging experiments. The results are presented in Fig. 1.

Application of coatings can improve the durability performance of concrete to a certain extent. Fig. 1 shows that the Coulomb electric fluxes of the specimens with coatings are significantly lower than those of the uncoated specimens (blank). According to the ASTM C1202 judgment, the penetration probabilities of chloride ions in the blank specimen and in the specimens with coating are in the middle and low grades, respectively. The specimen with EP coating obtains the lowest probability, followed by the specimens with PO, SI, and CE coatings with approximately 1/12, 1/10, 1/5, and 1/4 of the blank specimen, respectively. In the literature [23], the chloride resistance of concrete is highly related to its Coulomb electric flux; thus, high Coulomb electric flux results in a high chloride ion diffusion coefficient, indicating poor chloride resistance. By contrast, a low Coulomb electric flux corresponds

Table 2
Probability evaluation standards of ASTM C1202.

Coulomb electric flux of 6 h/C	<100	100–1000	1000–2000	2,000–4000	>4000
Probability of chloride penetration	Negligible	Very low	Low	Moderate	High