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Time dependence of carbonation resistance of concrete with organic film coatings

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HIGHLIGHTS

- Organic film coatings can remarkably improve concrete carbonation resistance.
- Organic film coatings' carbonation resistance will decrease with aging.
- Coating's carbonation resistance exhibits an S-shaped curve with aging time.
- S-shaped curve models can be used to predict organic coatings' service lives.

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ABSTRACT

Concrete specimens with three types of organic film coatings, namely, polyurethane (PO), epoxy resin (EP), and chlorinated rubber (CR), were fabricated to study the time-dependent relationship between the aging of organic film coating and the corresponding degradation of concrete carbonation resistance. Then, three coating aging methods were adopted: artificial ultraviolet radiation, coupled ultraviolet radiation and moisture, and natural outdoor climate exposure. After different aging stages, the specimens were subjected to accelerated carbonation experiments, and partial specimens were examined by scanning electron microscopy. Results indicated that organic film coatings can significantly improve concrete carbonation resistance, and a thicker film coating can obtain better improvement. According to the parameter α for the improvement of concrete carbonation resistance per unit thickness, the ranking order of the three types of coatings is as follows: PO > CR > EP. Defects in organic coatings caused by aging, such as granulation, porosity, and cracking, are the causes of degradation of coating carbonation resistance. As an organic film coating ages, its carbonation resistance gradually decreases and exhibits an S-shaped curve. On this basis, regression models for the carbonation depth with aging time of the coated specimens were established. These models were used to predict the service lives of the coatings. The ranking order of the service lives of the coatings is PO > EP > CR. Increasing the thickness of a coating can enhance its service life.

1. Introduction

Surface coatings on concrete are among the important measures for the durability protection of concrete structures [1–2]. Organic film coatings, owing to their good adornment, convenient construction, and high protective efficiency, among other desirable characteristics, have become an important option to improve the carbonation resistance of structures, avoid the corrosion of steel bars in concrete, and prolong the service lives of concrete structures [3–10].

Ahmed et al. [5] conducted accelerated carbonation experiments on concrete coated with acrylic and epoxy resins (EPs) and found that the application of coatings can improve concrete carbonation resistance, with the improvement of EP coating better than that of acrylic coating. Li et al. [6] conducted an accelerated carbonation experiment on concrete specimens with acrylic resin, cementitious waterproof coating, and organic silicone emulsion, and found that the improvements of acrylic resin on concrete carbonation resistance are significantly higher than those of the other

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two coatings. Sun et al. [7] indicated that, aside from organic silicone emulsion, other organic coatings, such as acrylic emulsion, styrene–acrylic emulsion, tertiary carbonate emulsion, all improve concrete carbonation resistance. Park [8] investigated the CO_2 diffusion coefficients of four types of organic coatings and concluded that significant differences in CO_2 diffusion coefficients exist across different coatings; the order of carbonation resistance from high to low is as follows: polyvinyl chloride, polyurethane (PO), epoxy, and acrylic. Ho and Harrison [9] suggested that coating effectiveness depends not only on the coating material, but also on its mode of application and the conditions of its concrete substrate.

Generally, the aforementioned studies show that organic coatings can effectively improve concrete carbonation resistance. However, organic materials are prone to aging because of weathering as a consequence of the environmental climate, which will gradually deteriorate the concrete protection [3,4,10-12]. Khanzadeh et al. [10] performed long-term natural exposure experiments on concrete specimens with six types of organic coatings in the Persian gulf tidal zone for five years and found that the protection by coating on concrete is decreasing and time dependent. Li et al. [11] conducted artificial accelerated aging and carbonation experiments on concrete specimens with four types of coatings. They found that carbonation resistance decreases with aging time for the specimens with PO and EP coatings, whereas the carbonation resistance only slightly changes for specimens with cementitious waterproof coating or organic silicone emulsion. Kozak [12] indicated that the barrier properties of an acrylic coating against CO_2 permeability decreases quite rapidly in the aging process of UV radiation. However, other researchers presented different findings. Beushausen and Burmeister [13] conducted accelerated ultraviolet aging and carbonation experiments for concrete specimens coated with acrylic emulsion, acrylic resin, polymer modified cementitious mortar, and cementitious fiber reinforced mortar and observed that UV radiation on coatings do not decrease the specimens' carbonation resistance but instead further enhances their carbonation resistance.

The aging of organic coatings and degradation of protection effects on concrete are considerably complex problems because they involve many factors, and only very few studies on them have been published [14–18]. The study on the time-dependent relationship between coating aging and carbonation resistance degradation is of importance to the evaluation of the time-varying effectiveness of organic coatings. The purpose of the current study is to obtain the quantitative development of carbonation resistance with respect to coating aging through aging and carbonation experiments on concrete specimens with three typical organic film coatings. Moreover, it aims to predict the service life of a coating based on its carbonation resistance.

2. Materials and methods

2.1. Raw materials

Chinese standard P·O42.5R ordinary Portland cement produced by Zhonglian Cement Plant was used. Table 1 shows the chemical composition of the cement. Natural river sand with a fineness modulus of 2.5, crushed stone with a particle size of 5–20 mm, and ordinary tap water were chosen as fine aggregate, coarse aggregate, and mixing water, respectively. The concrete water/cement ratio was set to 0.6, and the detailed mixture ratio of concrete was cement: sand: stones: water = 360:730:1094:216 (in kg/m^3).

Table 1
Chemical composition of ordinary Portland cement (wt%).

Item	SiO_2	SO_3	Fe_2O_3	Al_2O_3	CaO	MgO	Loss
Cement	22.30	3.58	3.16	5.05	64.78	0.92	1.32

Three typical concrete organic film coatings available in the market, namely, PO, EP, and chlorinated rubber (CR) coatings, were adopted. The first two coatings are composed of two components, whereas the CR coating is composed of only one component.

2.2. Specimens

The size of each specimen is 100 × 100 × 300 mm^3. The specimens were fabricated at normal indoor temperature and demolded 24 h after casting. They were then transferred to a water tank for curing at a temperature of 20 ± 2 °C until the age of 28 d. Before the application of coatings, the specimens were stored in an oven for 48 h at 60 °C for drying.

According to the manufacturer's instructions, coatings were brushed on the surface of the specimens. One-layer and two-layer for each type of coating were applied, and the brushing interval was 24 h. After the completion of coating, specimens were placed in an indoor environment for at least 7 d before the experiments were initiated. The thickness of each dry coating film was measured using a USB digital microscope, and the measurements are listed in Table 2.

2.3. Experimental methods

The speed of coating aging is associated with the prevailing environmental climate conditions. Generally, more severe environmental climate conditions always correspond to a faster coating aging speed. Under natural climate conditions, the aging speed of organic coating is relatively slow [12,15]. Two kinds of artificial accelerated aging methods, namely, ultraviolet light radiation aging (ultraviolet aging) and coupled ultraviolet light radiation and moisture aging (coupled aging), were selected to shorten the experimental time. At the same time, natural outdoor exposure aging (natural aging) was used for comparison.

The ultraviolet aging and coupled aging experiments were all conducted in an artificial climate chamber, which was equipped with two 400 W ultraviolet lamps. The vertical distance from the ultraviolet lamps to the surface of the specimens was 20 cm. For the ultraviolet aging experiment, the internal temperature was set to 60 ± 0.5 °C, but the relative humidity (RH) was not controlled. For the coupled aging experiment, the same internal temperature was adopted, but the RH was set to $\geqslant$90%. The natural aging experiment was conducted on the roof of a three-story laboratory building, where the annual average temperature was 14 °C and the annual average RH was 68.8%.

Coated specimens under these three aging methods were retrieved periodically and subjected to accelerated carbonation experiments. Partial specimens were also examined by scanning electron microscopy (SEM). Accelerated carbonation experiments were performed according to the Chinese national standard (GB/T50082-2009). Specimens were put into an oven at 60 °C and dried for 48 h before carbonation, and then put into an accelerated carbonation chamber, in which CO_2 concentration was 20 ± 3%, RH was 70 ± 5%, temperature was 20 ± 2 °C, and carbonation time was 28 d. After carbonation, the specimens were split and then measured for carbonation depth with the use of 1% phenolphthalein ethanol solution. The measurement accuracy was 0.5 mm, and the average of the three specimens with the same coating was taken as the representative measurement of the carbonation depth of each coating type.

According to the experimental plan, a total of 216 pieces coated specimens were fabricated, and three pieces of specimens without coating were also fabricated and subjected to an accelerated carbonation experiment for comparison. The detailed coated specimens' making plan was shown in Table 3.

3. Results

3.1. Carbonation depth of coated concrete after ultraviolet aging

The CO_2 diffusion coefficients of the organic coatings before aging range between 10^{-12} and 10^{-10} m^2/s, whereas that of ordinary concrete is approximately 10^{-8} m^2/s [8]. Organic film coatings have higher densities than normal concrete; thus, the former can restrain the diffusion of CO_2 into concrete and enhance concrete carbonation resistance. Fig. 1 presents the accelerated carbonation

Table 2
Film thickness of the three types of coatings (μm).

Item	Coatings		
	EP	PO	CR
One-layer	45	29	34
Two-layer	88	63	67