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Long-term performance of concrete surface coatings in soil exposure of marine environments

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HIGHLIGHTS

- Durability of concrete in soil exposure of marine environment is investigated.
- Various types of surface coatings are evaluated.
- Chloride ion diffusion and surface chloride buildup is monitored up to 88 months.
- Time to corrosion initiation is determined to rank the performance of coatings.

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ABSTRACT

The present research addresses the performance of coated concrete samples after 88 months of natural exposure to coastal soil of the Persian Gulf. A concrete mixture proportioned with water-to-cement ratio of 0.5 was used for casting the reference and all coated specimens. Five types of surface coatings were investigated. Samples were extracted at different ages of 9, 36, and 88 months to monitor carbonation depth and chloride ion penetration into concrete. Slight signs of carbonation are observed for the reference concrete and specimens coated with cementitious coatings. Chloride ion concentration profiles are analyzed during the exposure period. Chloride ion diffusivity is investigated for each sampling time. Surface chloride build-up is also monitored. Time to corrosion initiation is calculated and incorporated as a means of ranking coating efficiencies. Among all studied coatings, aliphatic acrylic and polyurethane are proved to reduce chloride ion concentration most effectively. This resulted in increasing the simulated time required for corrosion initiation in soil exposure at marine environments.

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1. Introduction

Reinforcing bars embedded in concrete are covered by a thin oxide layer which is formed and maintained in highly alkaline environment of concrete. Formation of hydroxide ions as a result of cement hydration process is the main source for this alkalinity and passive state of the oxide layer on steel rebar. However, this layer will be depassivated under two main circumstances: (1) drop in pH of the surrounding concrete to values lower than 9.0 [1]; (2) increase in chloride ion concentration on rebar surface to values higher than certain threshold values.

Several methods are investigated and proposed for enhancing the durability of reinforced concrete (RC) structures, including production of high performance concrete mixtures with low

water-to-cementitious materials ratio (w/cm), using corrosion inhibitors, cathodic protection systems, stainless steel and/or coated rebars, and concrete surface coatings. Given the fact that both aforementioned deterioration mechanisms are governed by ingress of harmful substances into concrete, incorporation of protective surface coatings can hinder the initiation of structural deterioration. This means that surface coatings can be categorized as economic choices for enhancing corrosion resistance in aggressive environments by decreasing the rate of moisture, gas, and aggressive ions transfer into concrete [2,3]. The outcome of this process is to increase the service life of the structures which is a function of corrosion initiation time. Impermeability against water, thermal stability, adequate adhesion, crack-bridging ability, and adequate elasticity are known as the main characteristics of a coating to create a barrier on the surface of concrete [4]. This technique is applicable for the new construction and repair of the existing damaged elements [5].

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Zhang et al. [6] studied the performance of geopolymers as protective coatings for concrete exposed to marine environments. The authors reported beneficial effects of employing these coatings on anti-corrosion properties. Shi et al. [7] investigated the effect of polymer coatings on properties of concrete. It was observed that the capillary absorption of coated concrete specimens decreased by 87% compared to the reference specimens. It was reported that the chloride ion diffusion coefficient also decreased from 7.8×10^{-6} to 5.9×10^{-6} mm²/s as a result of incorporating the surface coating. However, up to 1.5 mm increase in carbonation depth was observed in the case of coated specimens after 28 days of accelerated carbonation. Dong et al. [8] studied the effect of chemically activated surface coatings on properties of rubber modified concrete. It was observed that the chloride ion penetration of uncoated specimens was 20–40% higher than the coated ones. Diamanti et al. [5] investigated the effect of polymer modified cementitious coatings on water and chloride ion permeability of concrete. Authors reported that investigated coatings effectively hindered the chloride ion diffusion by decreasing the chloride diffusion coefficient of concrete mixture with w/cm of 0.65 from 8.0×10^{-6} to 0.2×10^{-6} mm²/s. It was also observed that employing surface coatings can highly enhance the resistance to water penetration into concrete. Brenna et al. [9] studied the long-term chloride penetration into concrete specimens coated with polymer-modified mortars. In the case of the concrete specimens made with w/cm of 0.55, it was reported that incorporation of the surface coatings reduced the chloride diffusion from 10.9×10^{-6} to 8.8×10^{-6} mm²/s. The surface chloride content also decreased from 4.2% to 0.6% (by cement weight). Impact was more significant for the specimens made with w/cm of 0.65. The chloride diffusion coefficient was decreased from 29.8×10^{-6} to 2.3×10^{-6} mm²/s while decreasing the surface chloride build-up from 4.4% to 0.6% (by cement weight).

A wide range of concrete surface coatings such as the acrylic based, epoxy resin, polyurethane, cementitious based, etc. have been used during the last years. However, considering the effect of exposure condition on durability and performance of the coating itself, it is a necessity to completely understand the long-term performance of concrete surface coatings before employment in construction projects. Limited investigation exists on durability of concrete exposed to soil exposure at Persian Gulf region. High salinity and considerable relative humidity together with the large fluctuations in daily and seasonal temperatures make the structures encounter with an extraordinary aggressive environment in such a harsh marine environment [10]. Increasing concentration of atmospheric carbon dioxide due to petro-chemical activities in the Persian Gulf area might be another factor that inversely affects the durability of RC structures [11]. Underground structures and foundations are vulnerable to serious risk of corrosion in this environment. Technical difficulty of structural health monitoring and repair of embedded elements necessitates the incorporation of proper techniques to improve durability in such conditions.

This paper addresses the hindering effect of concrete surface coatings on diffusion of carbon dioxide and chloride ions into concrete specimens buried at the northern coasts of the Persian Gulf. Long-term in-situ performance of five different surface coatings is studied in this research. Samples are extracted at various time intervals to investigate durability. It should be noted that the present work is a part of an ongoing project concerning the durability of concrete structures conducted at the Construction Material Institute (CMI), University of Tehran [12,13].

2. Experimental program

The following section discusses incorporated materials, mixture proportions, test methods, curing, and exposure condition.

2.1. Mixture properties

The concrete mixture properties are presented in Table 1. The water-to-cement ratio (w/c) of 0.5 is selected to magnify the protective effect of surface coatings. The cement incorporated in preparing the mixture is Portland cement equivalent to ASTM type II qualifications. Concrete was proportioned with 400 kg/m³ of cement. The aggregates used are crushed limestone graded according to ASTM C33 [14]. Coarse aggregate had maximum size of 12.5 mm, absorption of 1.9%, and bulk specific gravity of 2.79. Fine aggregate with maximum size of 4.0 mm presents absorption of 3.2%, bulk specific gravity of 2.59, and fineness modulus of 3.29.

Five concrete surface coatings are compared in this study as described in Table 2. The selection was made in order to cover almost all types of compounds commercially available in the area. Coating application procedures and dosages were based on manufacturer instructions and recommendations. In the case of aliphatic acrylic (AA) coating, a low viscosity primer was recommended, which is the typical practice of applying acrylic based coatings to enhance the adhesion between the base coat and substrate [15]. As the carbonation depth and chloride penetration may be affected by various factors such as the mixture properties, curing conditions, and consolidation etc., specimens were prepared with the same mixture, consolidation method, and curing conditions. This way, it may be concluded that the differences in carbonation depth and penetrated chloride concentration may be traced in the performance of the coatings.

2.2. Casting and curing of specimens

Specimens were prepared in the CMI Laboratory, University of Tehran. The concrete was batched in a 0.1 m³ pan mixer. The fresh concrete was tested for air content according to ASTM C231 [16] together with controlling the slump according to ASTM C143 [17]. The unit weight of concrete was determined in accordance with ASTM C138 [18]. Properties of the fresh and hardened concrete are reported in Table 3. Cubes of 150 × 150 × 150 mm and prisms of 150 × 150 × 600 mm were cast in steel molds. A vibrating table was used to consolidate the fresh concrete in molds. The specimens were covered under wet burlap and plastic sheet for 24 h. The specimens were then demolded and cured in lime-saturated water of 21 °C. The 150 mm cubes were used to determine the compressive strength of specimens in accordance with DIN 1048 at 7 and 28 days [19]. Other samples were cured for 28 days before being transported to the site.

After the curing period, specimens were removed to the investigation site of the CMI, in Bandar-Abbas coast, north of the Persian Gulf. Prisms were sealed on four sides for ensuring one-dimensional diffusion of chloride ion and CO₂. Because of its acceptable performance which is determined during previous studies [4], thick layer of epoxy polyurethane coating was used for sealing the sides of specimens as shown in Fig. 1.

2.3. Exposure conditions

After sealing the four sides of the specimens, five types of coatings (that are going to be evaluated here) were employed for covering the remaining top and bottom sides of the prisms. The coated specimens were embedded in the soil of the coast where chloride ion could penetrate into the specimens. An approximately 1-m deep hole was prepared at a minimum distance of 10 m from the sea water to ensure that the soil, in which the specimens are embedded, will not be saturated by the sea water. The average chloride ion concentration of the soil was 1.25% (by weight).

3. Sampling and testing procedures

3.1. Chloride ion concentration

With the aim of studying the time dependant performance of surface coatings, sampling was conducted at 9, 36, and 88 months, each time cutting a 100-mm thick slice from the prisms, coating the cut surface of samples and moving the remaining parts to the exposure condition for future samplings. All of the slices were carried to the laboratory for testing purpose.

At laboratory, a nominal 45-mm diameter core was taken from each slice to provide chloride ion concentration profiles. Each core was grinded in eight depths from the finished surface to an

Table 1
Mixture proportions (kg/m³).

Water	Cement	Fine aggregate	Coarse aggregate	Superplasticizer (polycarboxylic based)
200	400	778	956	1.2

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