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Water repellent surface impregnation for extension of service life of reinforced concrete structures in marine environments: The role of cracks

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ABSTRACT

The enhancement of long-term durability of marine structures is a matter of interest to many researchers. The study presented in this paper examines the effectiveness of a water reducer and chloride barrier surface impregnation of the concrete cover of reinforced concrete (RC) structures, exposed to a marine environment. Specific focuses is on how surface cracks created (1) before impregnation and (2) after impregnation, affect the effectiveness of the surface treatment. The experiments are conducted in an environment which is as close as possible to the real humid subtropical marine environment.

A series of reinforced concrete (RC) prisms and concrete cylinders, each treated with various commercial surface impregnation agents, were exposed to cyclic sea water shower under an outdoor environment to accelerate the dry/wet cycles for 1 year. Six types of surface impregnation agents, including four types of silane-based water repellent agents and two types of sodium silicate-based pore blockers (water–glass) were applied. Three types of RC prisms were prepared to simulate the different cracking possibilities, which may occur in surface impregnated concrete structures, during their service life. No cracks were introduced in the first prism group, while cracks were introduced before and after surface impregnation, in the second and third groups, respectively. The time-dependent water absorption of all specimens was monitored during exposure to the dry/wet cycles. Finally the specimens were split open to measure the penetration depths of the surface impregnation agents and the chloride penetration profiles. The areas with corrosion evident in the steel reinforcement in the RC prisms were also measured.

Sodium silicate-based pore blockers were found to be inefficient in preventing chloride penetration of concrete under simulated marine exposures. The long-term efficiency of water repellent agents used for surface impregnation was found to be highly dependent on the type of agent and whether impregnation was carried out before or after crack formation.

1. Introduction

Chloride-induced corrosion of steel reinforcement is a major concern regarding the durability of reinforced concrete (RC) structures exposed to marine environments. In practice, the time taken for steel corrosion to occur in marine RC structures is short, in comparison with their designed service life. Thus, there is often a need for supplementary measures to protect such concrete or/and steel reinforcement in such an aggressive environment. Surface treatment is commonly used to improve the resistance of such concrete cover against the penetration of aggressive substances, both in new structures and existing structures, whenever the need for further protection becomes obvious. For instance, the surface of repaired structures is sometimes treated in order to extend the service life of repair measures [1,2].

In general, protective surface treatment can be classified into three categories: (a) surface coating, whereby in most cases a thin or thick polymer film is applied, (b) sealing, whereby the surface near the pores is blocked, and (c) surface impregnation, whereby the surface near zone is impregnated with a water repellent agent, leaving the pores open. Recently there has been an increasing acceptance of surface impregnation materials for buildings and highway bridges.

The protective surface treatment wins favor in that it does not interrupt construction work, and is hence cost-effective [3,4]. In recent years, two types of surface treatments are frequently used in the construction industry. One is a silane-based water repellent agent and the other is a sodium silicate-based pore blocker, which is a Sealant. Both can penetrate concrete pores and react with hydrated cement particles. In the former case, the reaction product, i.e. a silicon resin, can form a hydrophobic lining on the pore walls. The achievable penetration depth in concrete mainly depends on four factors: the type of hydrophobic agent applied, the water to

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cement ratio of the concrete substrate, the initial moisture content and the surface preparation of the concrete substrate [5–12]. In the latter case, the reaction product can block the pores, leading to a modest strengthening, but the penetration depth is usually minimal, apart from when the concrete is extremely porous [2].

Up to now test results on the performance of sodium silicate impregnated concrete is limited, and therefore little is known about its influence on the carbon-dioxide or chloride penetration resistance. In contrast, since 1980s, much research has been conducted on the durability of concrete, impregnated with silane-based water repellent agents. An early review of the assessment methods and reported performance of such hydrophobic impregnation and the corresponding mechanisms are found in Refs. [13,14]. Extensive laboratory tests [15–18] have verified that hydrophobic impregnation can establish an efficient barrier for concrete and postpone the corrosion initiation and reduce the corrosion rate of internal steel reinforcement. Some encouraging results from long-term field exposure tests have also been recently reported [19–21]. Although some of the recent studies indicated that hydrophobic impregnation may only have a minor influence on the diffusion mechanisms of chloride ions in concrete [22,23], its validity in decreasing the internal humidity and significantly suppressing the capillary water absorption has been well recognized [23–25]. The above properties, most certainly can be considered to improve the durability of marine RC structures, since the supply of water and chloride is a key factor influencing the corrosion of internal steel reinforcement.

In a structural design, the existence of cracks is usually allowed in flexural RC members. These cracks, however, may serve as easy paths for water penetration and the chloride ions dissolved in water. It is of utmost importance to know exactly when surface impregnation treatment is most effective: that is whether the water repellant agents or sealants are effective in concrete with cracks, which exist at the time of impregnation or which are formed after impregnation.

However, despite the above-reviewed extensive research work, to date little is known of the extent to which the presence of cracks in concrete structural elements, occurring in surfaces (1) before application of sealants or other surface treatments (2) after application of sealants or other surface treatments, influence the long-term efficiency of these measures and the subsequent durability of structures in a marine environment. Recently, Tittarelli and Moriconi [26] applied one type of silane-based hydrophobic admixture to concrete and studied its influence on the corrosion of reinforcing steel. They found that the addition of silane substantially reduced the rate of corrosion of steel reinforcement in un-cracked specimens. However, it was also found that the corrosion of steel reinforcement in cracked concrete hydrophobic specimens was unexpectedly more severe. The reason suggested was that oxygen diffused faster through the open concrete porosity in the hydrophobic concrete, as compared to the slow diffusion through the water filled pores of the saturated concrete. Concerning this situation, it must be mentioned that the crack width in their study was 1 mm, which is unrealistic in RC structures under service conditions. It is also important to note that Tittarelli and Moriconi added aqueous silane emulsion of an alkyl-triethoxy-silane to the fresh concrete mix; meaning that they had prepared an integral water repellent material. Hence their findings cannot be compared directly with observations found on surface impregnated water repellent concrete in the real case.

In order to avoid misapplications, further studies, under realistic service conditions, are needed to understand how the chloride penetration of surface impregnated concrete and the subsequent corrosion of internal steel reinforcement and durability of structures in a marine environment are influenced by the presence of cracks. Therefore, this project aims to study the long-term effectiveness of different surface impregnation materials after treatment of cracked and un-cracked concrete specimens during a well-controlled outdoor exposure program and to determine which surface treatment material provides the most significant improvement in the durability of marine RC structures with and without cracks.

2. Experiment

2.1. Materials

For the experiment, concrete was made with a cement content of 248 kg/m^3, a water–cement ratio (*W/C*) of 0.68, and a fine-to-coarse aggregate ratio of 0.49. The compressive strength of concrete at 28 days curing was 34.0 MPa. A relatively high *W/C* ratio was chosen for several reasons. Firstly, the penetration depth of silane-based water repellent agents increases with the *W/C* ratio [7,10]. A relatively high *W/C* ratio results in a deeper penetration and therefore provides a better comparison with the performance of different surface impregnation materials. Secondly, in practice, concrete, which needs protection or repair usually has poor quality owing to such as an error in *W/C* at the construction site. Thirdly, a high *W/C* ratio is better suited to show how different surface impregnation materials influence the corrosion of internal steel reinforcement, within a relatively short exposure period (1 year in this study) because chloride ions can penetrate easily. In total, six types of surface impregnation materials are applied in this study (see Table 1). They are listed as A, B, C, D, E and F and form two surface treatment sets, namely silane-based water repellent agents (A, B, C and D), and sodium silicate-based pore blockers (E and F). Their properties and dosage are further described in Table 1. The moisture content of the side surfaces of RC prisms was about 4.0% when the surface impregnations were applied.

2.2. Details of specimens

Two types of specimens were prepared including forty RC prisms ($150 \times 100 \times 100$) mm and 14 concrete cylinders (ϕ 100×65 mm) as shown in Fig. 1. The concrete cylinders were prepared, mainly to investigate the chloride penetration profiles in un-cracked concrete when different surface impregnation materials were applied. The RC prisms were prepared to enable an investigation into how surface impregnation influences the chloride penetration of cracked concrete and the subsequent corrosion of internal steel reinforcement. The RC prisms had two layers of steel bars (ϕ10) at a depth of 17.5 mm and 45 mm, respectively (see Fig. 1), to monitor the status of steel bars at different cover depths, after exposure. Two side surfaces of each RC prism were treated with surface impregnation agents while the remaining four sides were sealed by an epoxy resin (see Fig. 1). As seen in Table 2, which provides a compilation of all specimens, there were three types of RC prisms. The first type of prism had no cracks, the surface of the second type was impregnated after the cracks were introduced, and the surface of the third type was impregnated before the cracks were introduced. The test specimens corresponding to the three types, mentioned above, are identified by the symbols "NC", "AC" and "BC", respectively (see Table 2). The presence of steel bars in the prisms contributed to the ease with which cracks were introduced into concrete through splitting tests.

During the splitting tests, the crack widths were controlled using two displacement transducers to bridge the cracks (see Fig. 2a). After the splitting tests, crack widths at the two side surfaces of each RC prism were measured under a microscope (see Fig. 2b). The crack width was measured at five locations of each side surface and their mean value was then taken as the crack