



Replication studies paper

The impact of sandblasting as a surface modification method on the corrosion behavior of steels in simulated concrete pore solution

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HIGHLIGHTS

- Increasing sandblasting time enhanced the corrosion resistance of the steel rebar in chloride-contaminated pore solution.
- The passive layer on all specimens was a highly disordered n-type semi-conductor.
- Sandblasting treatment can improve the formation of the passive layer.
- Sandblasting treatment increased the surface roughness of the specimens.
- A dense calcium-rich crystalline structure was formed on the surface of the sandblasted specimens.

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ABSTRACT

This investigation aimed to study the passivation and corrosion performance of sandblasted steel in a concrete environment. The surfaces of the steel specimens were modified using sandblasting method for three durations: 5, 10, and 15 min. The specimens were immersed in the chloride-free concrete pore solution for 14 days and then 3% by weight of chloride ions were added to the solution. The specimens were then kept in the chloride-contaminated pore solution for 60 days. Results from the electrochemical tests indicated that the passive layer formed on the surface on all specimens exposed to a simulated concrete pore solution were highly disordered n-type semi-conductors. In all specimens, except the 15 min sandblasted ones, the presence of chloride ions decreased the slope of the Mott-Schottky plots and increased the donor density which indicated formation of a thinner passive layer and corrosion. The results of electrochemical experiments on steel rebar exposed to chloride-contaminated pore solution showed significant improvement in corrosion resistance of the sandblasted specimens. This improvement was proportional to the increase in the sandblasting time. Microscopic analysis of the steel specimens at the end of the experiment showed the formation of a dense calcium-rich crystalline structure on the surface of sandblasted specimens. The density and the uniformity of the calcium-rich layer increased by increasing the sandblasting time. It was hypothesized that the formation of this layer combined with the enhanced passive layer in sandblasted specimens were the reasons for the improvement in corrosion resistance of the sandblasted steel specimens.

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1. Introduction

At potentials and pH levels normally measured in the concrete, a protective passive layer forms on the surface of the carbon steel [1–3]. This layer decreases the anodic dissolution rate of steel to negligible levels. Partial or complete loss of the passive layer, known as depassivation, (mainly by chloride ions [4–6]) leads to active corrosion of the steel bars.

Studies showed that alteration of the surface structure of a metal can lead to improvement of its mechanical properties as well as corrosion resistance due to enhancing its passive layer performance [7–10]. It has been shown that the surface condition of the carbon steel has a major influence on its corrosion in the concrete environment [11]. A study by Ghods et al. indicated the importance of mill scale of the surface of steel on the corrosion initiation [12]. Their results showed that as-received rebars are more susceptible to chloride-induced depassivation than rebars without mill scale. Song et al. investigated the influence of wire-brushing on the corrosion resistance of the rebar in the concrete environment [13]. Results of their work indicated the formation of a continuous

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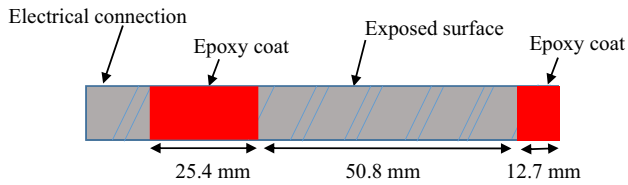


Fig. 1. Schematic illustration of one of the epoxy coated steel specimens.

surface nano-crystalline structure resulted from wire-brushing led to the rapid formation of the passive layer and enhancement of its stability. Sandblasting was used for surface strengthening [14], surface modification [15], surface cleaning and rust removal purposes [16]. In this process, the surface of specimens is blasted repeatedly by sand particles with high speed. Sandblasting can remove the oxide scale (mill scale), generate a local plastic deformation and grain refinement in the surface layer [17] and often results in a compressive residual stress in the subsurface region [18]. An investigation by Wang and Li [9] showed that nano-crystalline surface layer was formed after sandblasting on the surface of 304 stainless steel [19]. However, their results indicated a significant decrease in corrosion resistance of the sandblasted compared to the as-received 304 stainless steel exposed to a 3.5% NaCl solution. Geng et al. study on the impact of sandblasting on the corrosion of 316 stainless steel showed similar results [18]. Hou et al. reported an increase in corrosion resistance of carbon steel in concrete due to sandblasting treatment [20]. It should be noted just half-cell potential measurements were used in that study and the main focus of that study was the impact of sandblasting on the bonding between steel and concrete.

All the above-mentioned studies clearly showed the impact of surface modification on the corrosion of metals, including corrosion of steel bars in concrete. Nonetheless, to the best of the authors' knowledge, there is no in-depth study on the impact of sandblasting on formation of the passive layer and the consequent corrosion of carbon steel in the high alkaline environment of concrete, which is the objective of this work. In this study, the surface of steel was treated by sandblasting for 5, 10 and 15 min. The impact of these treatments on the formation and breakdown of the passive layer in the presence of chloride ions was investigated. In addition, the impact of sandblasting on the semi-conductive behavior of the steel surface was studied.

2. Experimental procedures

2.1. Steel specimens

All steel specimens were prepared from a #4 ($\phi = 0.5$ in. ≈ 12.7 mm) structural steel bar, meeting the requirement of ASTM A615 [21]. Specimens with a length of 101.6 mm (4 in.) were cut and their surfaces were treated by particles with an

approximately 750 μm diameter under 350 kPa of air pressure. Four sets of steel specimens were prepared as follows: as-received (AS), sandblasted for 5 min (SB5), sandblasted for 10 min (SB10) and sandblasted for 15 min (SB15). Then, 25.4 mm (1 in.) of one end and 12.7 (0.5 in.) of another end were coated with epoxy as shown in Fig. 1. Epoxy coating provided a 50.8 mm (2 in.) exposure length and prevented extraneous effects.

Fig. 2 shows the surfaces of one rebar in each group, before exposure to the pore solution.

Concrete simulated pore solution, with the composition given in [22] with a pH of approximately 13.1, was used to simulate the concrete environment. For each set of specimens, a container with three identical steel specimens was prepared. The specimens were immersed in pore solution and the container was sealed to minimize diverse effects of atmospheric carbonation [22]. Specimens were immersed in chloride free pore solution for 14 days to ascertain formation of passive layer on the surface of rebars. Then, pore solution in each measurement cell was partially replaced with a 3 wt% chloride contaminated pore solution. Electrochemical measurements were started 24 h after immersing the specimens in the pore solution and continued for 60 days.

2.2. Electrochemical measurements

A typical three-electrode measurement cell setup, including a specimen as the working electrode, a saturated calomel electrode (SCE) as the reference electrode, and a 316 stainless-steel sheet as the counter electrode, was used for the electrochemical tests.

To evaluate the probability of corrosion of the specimens, the corrosion potential of all specimens was measured using an SCE. However, the results were converted to the values versus Cu/Cu(SO)₄ reference electrode to ease the using of the ASTM C876 guideline [23].

The cyclic polarization technique was used to evaluate the susceptibility of the specimens to pitting corrosion. For all cyclic polarization tests, the potential scanned from -50 mV against open circuit potential to $+500$ mV versus against the reference electrode and reversed to -100 mV versus the reference electrode with the scan rate of 0.1 mV/s.

The Potentiostatic Linear Polarization Resistance (PLPR) method was used to determine the corrosion current density of the steel specimens [24]. In this study, a constant potential of ± 10 mV versus the half-cell potential was applied, and 0.052 V and 0.026 V were used as the Stern-Geary constant to calculate the R_p values in passive and active corrosion, respectively [25].

Electrochemical Impedance Spectroscopy (EIS) was carried out to study the passivation and depassivation processes. A 10 mV alternating potential perturbation over the frequency range from 10^6 Hz to 10^{-2} Hz was used for the EIS tests.

When a semi-conductor contacts an electrolyte, electrical charges are transferred between the semi-conductor phase and the solution phase. For the two phases to be in equilibrium, their electrochemical potential must be the same [26]. The electrochemical potential of the solution is determined by the redox potential [27] of the electrolyte solution, and the redox potential of the semi-conductor is determined by the Fermi level, which is defined as the energy level at which the probability of occupation by an electron is 50 per cent [28,29]. If the redox potential of the solution and the Fermi level do not lay at the same energy level, a movement of charge between the semi-conductor and the solution is required to equilibrate the two phases. For a metallic electrode, the excess charge lays at the surface. However, for a semi-conductor, this charge extends into the electrode for a significant distance [29]. This region is referred to as the space charge region, and an electrical field is associated with it.

Doped semi-conductors, in which the majority of charge carriers are electrons, are referred to as n-type semi-conductors, whereas those in which holes are the majority of charge carriers are referred to as p-type semi-conductors, the density of the donors/acceptors are called donor/acceptor density [26].



Fig. 2. The surface of steel specimens, before exposure to the pore solution.

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