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# The impact of fire and fire extinguishing method on the corrosion behavior of the steel bars in concrete pore solution

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## ABSTRACT

Exposure of reinforced concrete structural elements to high temperatures, e.g. fire, remains one of the serious potential risks to such structures. This exposure can lead to losses in concrete structural capacity, possible plastic deformation of embedded steel and loss of bond between reinforcing steel and concrete. The level of temperature and the method of extinguishing the fire alter the microstructure of reinforcing steel bars. This microstructure alteration changes the corrosion behavior of steel in such structures, when exposed to chloride ions. The present study was undertaken to determine the impact of exposure of steel to high temperature and the method of extinguishing the fire on its corrosion behavior in alkaline environment of concrete in presence of chloride ions. Results indicated that exposure of steel to high temperatures, regardless of its level; made steel more susceptible to corrosion compared to the reference case, when steel was kept at room temperature. The worst case happened for the steel exposed to 850 °C for an hour, then cooled rapidly in water, where the corrosion rate increased approximately 60% in chloride contaminated concrete pore solution.

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## 1. Introduction

During the past few decades, many researchers have studied the effect of elevated temperature on the performance of steel reinforced concrete structures. The exposure of steel reinforced concrete structures to high temperatures during an aggressive fire leads to significant losses in its structural capacity [1–4]. One of the earliest works has been performed by Kasami et al. where they observed a significant decrease of bond strength with increasing temperatures [5]. Malhotra and Stevens tested the fire resistance of encased steel columns subjected to axial loads and found that the thicker the concrete cover was, the higher the fire resistance of column was [6]. It was shown that exposure of concrete to temperatures in excess of 400 °C would have a detrimental impact on its strength and integrity [7]. In general, the effects of high temperature fire on concrete components include: reduction in compressive strength; micro-cracking within the concrete microstructure; color changes consistent with strength reductions; reduction in the modulus of elasticity; various degrees of spalling; loss of bond between concrete and steel; possible loss of residual strength of steel reinforcement and possible loss of tension in prestressing tendons [8,9]. Elevated temperatures can also have a

negative impact on the mechanical properties of the reinforcing steel. Generally, both the yield strength and the modulus of elasticity of steel decrease with increasing temperature [10].

Experience from real fires shows that it is rare for a concrete building to collapse due to fire, and most fire-damaged concrete structures can be successfully repaired [11]. Awoyera and his colleagues showed that steel reinforced concrete elements subjected to temperature up to 500 °C are still safe for use, but the buildings subjected to temperatures above 600 °C are structurally unsafe [12].

Steel reinforced concrete structures could be exposed to de-icing salts, mainly sodium chlorides. Depending on the degree of damage, some concrete members may need no repair due to overdesign, some may only need minor repairs, and others may have to be strengthened or removed and replaced [13]. Standard practice for fire-damaged steel reinforced concrete requires that all the severely fire affected concrete be removed from behind the steel reinforcement to a depth of at least one bar diameter [14,15]. The removed concrete is then replaced with cementitious repair materials [13,16,17].

Two examples of covered concrete structures that may experience high temperatures in the case of fire incident are tunnels [18,19] and parking garages [20,21]. In areas with cold winters, tunnel tubes, specifically their entrance, are exposed to de-icing salts. In addition, vehicles transport the de-icing salts from the road outside into the tunnel tubes [22]. Damage in tunnels

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resulting from the infiltration of groundwater containing chlorides was also reported [23]. In rail tunnels, where stray currents from the traction supply may occur, the rapid migration of the chloride ions to the steelwork attracting the current was also observed [23]. Parking structures in cold climates are exposed to more severe conditions than most other structures. Vehicles bring in rainwater, snow, and deicing salts. Roof-level areas are directly exposed and perimeter areas of open parking structures are indirectly exposed to windblown rain and snow. Unlike bridges, however, which are washed by spring rains, parking garages are rarely washed down in the spring. As a result, the de-icing deposited in the winter remains all year. Thus, when comparing concrete chloride contents of bridge decks and parking garage decks in the same location, and all other parameters being equal, the garage decks usually show a higher chloride content at all slab depths [24].

Therefore, if a steel reinforced concrete, such as a tunnel or a parking garage, experiences fire, such structure might also be exposed to de-icing salts. As far as the authors are concerned, all previous studies on the fire-damaged steel reinforced concrete structures were focused on the mechanical performance of the damaged structure. No study was found on the effect of elevated temperatures on the corrosion behavior of the reinforcing bars. Exposing the steel bars to high temperatures and the cooling method can significantly increase the corrosion activity and corrosion rate of steel. Since the steel in fire-damaged concrete usually is not replaced during the repair process, this change in corrosion behavior can decrease the remaining service lives of such structures significantly. This paper discusses the corrosion behavior of steel treated at different elevated temperatures and cooling methods.

## 2. Experimental procedures

### 2.1. Steel specimens

All steel specimens prepared from a #4 ( $\phi=0.5$  in.  $\approx 12.7$  mm) structural steel bar, meeting the requirements of ASTM A615 [25]. Specimens with a length of 101.6 mm (4 in.) were cut, and after exposure to different degrees of high temperatures and cooling the specimens with different rates, the surface of each specimen was merely cleaned by wire brush and 25.4 mm (1 in.) of each two ends were coated with epoxy. Epoxy coating provided a 25.4 mm (1 in.) exposure length and prevented extraneous effects (Fig. 1). Concrete simulated pore solution, with the composition outlined in Table 1 (similar to that for Type I cement) with a pH of 13.1 [26], was used to simulate the concrete environment.

The specimens were immersed in pore solution, and the container was sealed, to avoid carbonation. The advantage of performing the experiments in the solution is that the surface of the steel bars can be visually examined during the test period, and the results can be obtained in a relatively short period of time. For each temperature and cooling method, a cell with three identical steel specimens in pore solution was prepared.

### 2.2. Elevated temperatures and cooling methods

Simplistic heating and cooling steps were used in this study to simulate different of scenarios, from mild to severe elevated temperatures [1]. Three specimens were used for each scenario. The air-circulated furnace was programmed to increase the temperature to the target value at the rate of 5 °C/min. After reaching the target temperature, the steel specimens were kept at that temperature for an hour and then removed and cooled to room temperature. To mimic two different extinguishing approaches,

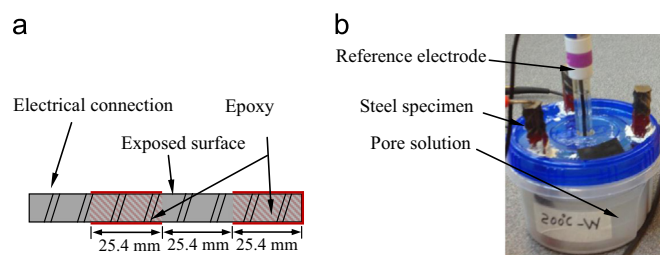


Fig. 1. (a) Schematic illustration of one of the steel specimens, showing the epoxy coated portions (hatched areas) and exposed surface area. (b) One of the measurement cells with three identical steel specimens.

Table 1

Chemical composition of the simulated concrete pore solution.

Compound	Mol/L
NaOH	0.1
KOH	0.3
Ca(OH) <sub>2</sub>	0.03
CaSO <sub>4</sub> · H <sub>2</sub> O (Gypsum)	0.002

Table 2

Temperatures and cooling methods using to prepare specimens.

Specimen code	Temperature (°C)	Cooling method
25	25	Reference
200A	200	Air
200W	200	Water
500A	500	Air
500W	500	Water
850A	850	Air
850W	850	Water

specimens were cooled using two methods: slowly cooled in the open air and quenched rapidly in water. The details of specimens and temperatures are shown in Table 2.

### 2.3. Electrochemical measurements

Electrochemical measurements were started 24 h after immersing the specimens into the pore solution. Steel specimens were kept in pore solution, three weeks before adding chloride to the solution to ascertain passivity [26]. After immersion in a chloride-free pore solution for three weeks, NaCl was added to the pore solution. Chloride additions were made by replacing a certain amount of the pore solution with a solution of the same composition but with the addition of the sodium chloride. The volume replaced was selected so that the chloride concentration in the solution was increased to 0.5 M ( $\sim 3\%$  NaCl).

The corrosion potential of all steel specimens was measured daily, using a Saturated Calomel Electrode (SCE). A typical three-electrode system, including the steel specimen as the working electrode, SCE as the reference electrode, and 316 stainless steel sheet as the counter electrode, were used for other electrochemical tests. The Potentiostatic Linear Polarization Resistance (PLPR) method was used to determine the corrosion current density of the embedded steel bars. In the PLPR test, a constant potential for a certain period of time is applied, during which the current reaches a stable state and at which point the polarization resistance,  $R_p$ , and corrosion current  $i_{corr}$  can be calculated [27]. In this study a constant potential of  $\pm 10$  mV for 120 seconds versus the open-circuit potential was applied, and 0.052 V and 0.026 V were used as the Stern–Geary constant [28] to calculate the  $R_p$  value in passive and active corrosion, respectively. The ohmic

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