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Effects of electric arc furnace dust on susceptibility of steel to corrosion in chloride-contaminated concrete

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HIGHLIGHTS

- ▶ Chloride-induced corrosion of steel in concrete is highly temperature-dependent.
- ▶ Crevices enhance susceptibility of steel in concrete to chloride-induced corrosion.
- ▶ Crevice corrosion in EAFD-free mortars occurred at low critical chloride contents.
- ▶ In mortars with small additions of EAFD this occurred at higher chloride contents.

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ABSTRACT

Small additions of electric arc furnace dust (EAFD) are currently being made to reinforced concrete in Saudi Arabia as a means of exploiting this waste material. To elucidate the possible effects of these additions on the susceptibility of reinforcing steel to corrosion, a series of laboratory tests was conducted on steel bars in mortar specimens containing 0%, 2% and 3.5% of EAFD by weight of cement, exposed to chloride ingress at 20 and 40 °C. Effects of deliberately induced crevices at the steel/mortar interface on corrosion initiation were also investigated. The results showed that the above additions of EAFD caused no increase in the susceptibility of the embedded steel to chloride-induced corrosion and tolerance to chloride was actually enhanced by the presence of EAFD under the conditions investigated.

1. Introduction

EAFD is an industrial by-product of the electric arc steel making process, its estimated annual rate of production being around 3.7 million tons [1]. It consists of a very fine powder which commonly contains heavy metal contaminants at varying concentrations and this makes its disposal at landfill sites problematic owing to environmental concerns. It may also contain a significant amount of chloride which restricts its potential for use as an addition to reinforced concrete partly because of the possibility that this may lead to an increased risk of corrosion of embedded reinforcing steel. Nevertheless, the incorporation of small quantities of EAFD (up to 2% or 3% by weight of cement) in reinforced concrete has been practised for several years in Saudi Arabia and it would appear, from the limited evidence available in the literature, that no adverse effects on durability have been reported [2–4].

To seek further information regarding the influence of small additions of EAFD (corresponding to 0%, 2% and 3.5% by weight of cement) on the susceptibility to corrosion of steel in concrete, the laboratory investigations to be described in this paper were performed. They were designed to incorporate the effects of some of the many factors that are believed to affect 'threshold chloride levels' for initiation of corrosion of steel in concrete [5,6]. In particular, the influences of the following variables were investigated: (i) the presence of crevices at the steel surface that cause occluded cell formation and disrupt the local buffering capacity of the steel/concrete interfacial zone; (ii) the temperature of the exposure environment that affects the pitting susceptibility of steel in alkaline media such as concrete.

The aim was to provide improved understanding of the effects of the particular EAFD material that is currently used in Saudi Arabia where concrete structures may often be exposed to the combined aggressive actions of chloride ingress and a hot climate with substantial diurnal temperature variations.

2. Experimental

2.1. Materials and specimen preparation

Saudi Arabian ordinary Portland cement (conforming to ASTM C150/C150M-09, Type I) and EAFD used throughout the experimental work were supplied by Saudi Basic Industries Corporation. The manufacturer's analysis of the cement is presented in Table 1 and compositional details of the EAFD, obtained by XRF analysis,

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are shown in Table 2. The fine aggregate used was clean quartzite sand supplied by Tarmac Roadstone Ltd. Mortars were mixed by hand using distilled water with fixed proportions of water:cement:sand (0.5:1:2.1) and variable additions of EAFD (0%, 2% and 3.5% by weight of cement).

Thirty-six mild steel bars, 100 mm in length and 8 mm in diameter, were prepared for electrochemical measurements by abrasion with P800 emery paper, rinsing with acetone then ethanol and exposure to dry air in a desiccator for at least 1 week before masking at both ends was performed to leave an exposed surface area of 10.1 cm^2. The masking technique involved application of a duplex coating of an SBR-modified cement paste overlaid with an air-curable epoxy resin, as described elsewhere [7], to eliminate spurious effects of end-crevice corrosion. Half of the steel bars, however, had three 2 mm thick plastic ties wrapped around them at positions near the middle of their exposed lengths, as illustrated in Fig. 1. This was done so that the influence of crevices of a kind that were representative of commonplace interfacial defects on reinforcing bars in actual concrete structures could be studied in a reproducible manner. The eighteen bars without these artificial defects were designated Type A and those with the defects were designated Type B.

The bars were all positioned vertically along the axes of cylindrical moulds so that mortars of the above compositions could be cast around them and lightly compacted on a vibrating table. After being removed from the moulds, the specimens were of the form illustrated schematically in Fig. 2. They were cured for 7 days in a fog room at 20 ± 2 °C before being subjected to exposure testing as described below.

2.2. Exposure tests

Prior to commencement of the exposure tests, the electrochemical condition of the steel bars in each of the specimens was assessed by means of corrosion potential (E_{corr}) and linear polarisation resistance measurements of corrosion rate (i_{corr}) conducted using the cell arrangement shown in Fig. 3. The potentiodynamic scan rate, use of IR-compensation and application of the Stern–Geary equation (assuming $B = 26$ mV/decade) were as in previous researches [7,8].

The specimens were then placed in thermostatically controlled cabinets at 20 °C or 40 °C where they were subjected to repeated weekly cycles of immersion in 0.25 M NaCl solution for 5 days followed by exposure to air for 2 days. At the end of every cycle, E_{corr} and i_{corr} were re-measured until such time as depassivation of the steel was indicated by marked shifts in the values of these data, as illustrated in Fig. 4. When, for a given specimen, E_{corr} became more negative than −250 mV versus SCE and i_{corr} increased to a level in excess of 0.2 $\mu A/cm^2$ [9], it was assumed that chloride-induced corrosion had been initiated and the exposure test was terminated.

2.3. Determination of critical chloride levels

To estimate the critical chloride levels associated with the onset of corrosion for the various specimens, in which depassivation of the embedded steel was observed, the mortars were split longitudinally so that the steel bars could be removed. Dust samples were then obtained as rapidly as possible from a 2 mm wide annulus of material that had been in close proximity to the steel. This was done by drilling with a 12 mm diameter masonry bit inserted into the hole left after extracting the 8 mm diameter steel bar. The dust samples were ground to pass a 150 μm sieve and dried at 105 °C before being analysed to determine their total (acid-soluble) chloride contents and cement contents. The chloride contents were measured by a titrimetric method [10] and the cement contents were obtained from XRF measurements of the calcium contents of the dust since the aggregate was purely siliceous in nature.

3. Results and discussion

A summary of the results of the exposure tests, which were carried out over a maximum period of 321 days, is given in Table 3. This shows a number of features, illustrating in particular the importance of the exposure temperature and the presence or absence of interfacial defects (crevices) in determining the susceptibility of steel to chloride-induced corrosion. Thus, whilst none of the nine specimens containing Type A steel bars exposed at 20 °C showed signs of depassivation within the timescale of the experiments, all of the nine specimens containing Type B steel bars exposed at 40 °C had suffered corrosion initiation during this period. The temperature effect was as expected since previous research has shown that the critical chloride levels required for induction of pitting of Fe in mortars decrease with increasing temperature over the range 0–40 °C [11]. The influence of interfacial defects (crevices) was also in line with expectations since they disrupt the integrity of the buffering layer of cement hydration products that is believed to play an important role in restraining pit growth on embedded steel [6].

Table 1
Analysis of cement.

Constituent	Weight (%)
SiO_2	21.52
Al_2O_3	4.64
Fe_2O_3	3.09
CaO	65.31
MgO	1.59
SO_3	2.25
Tricalcium silicate (C_3S)	60.3
Dicalcium silicate (C_2S)	16.2
Tricalcium aluminate (C_3A)	7.1
Tetracalcium aluminoferrite (C_4AF)	9.4
Loss on ignition	1.12
Fineness (cm^2/g)	3540

Table 2
Analysis of EAFD.

Element	Weight (%)
Al	0.17
Ca	5.79
Fe	29.44
Mg	2.5
Mn	1.52
Pb	1.8
Si	1.31
Zn	18.78
K	3.24
Na	0.88
Cl	2.25
S	0.46
P	0.13
Cu	0.13

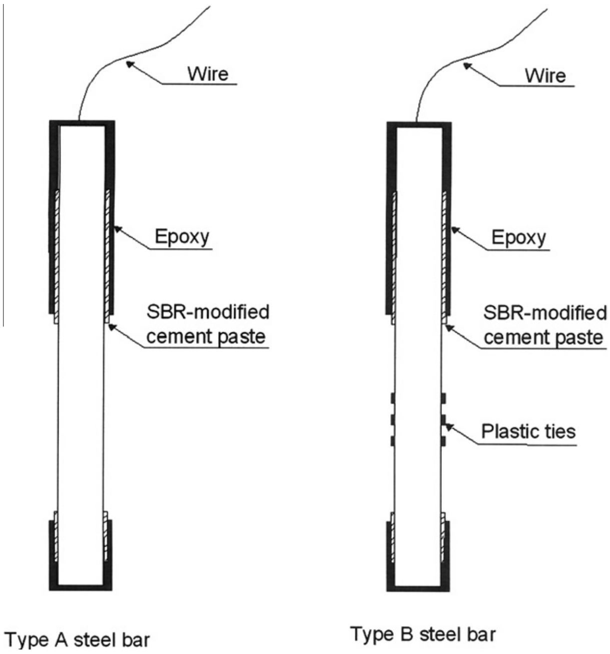

Fig. 1. Schematic features of steel bar electrodes of Types A and B.

Other significant findings were that the electrochemical response of the steel in specimens of plain cement mortars appeared somewhat more sensitive to the presence of interfacial defects (crevices) than that of steel in mortars containing 2–3.5% EAFD. Thus the steel bars in specimens A1, A2 and A3 all remained passive at both 20 and 40 °C throughout the entire exposure period of