



Influence of cementitious binder on chloride removal under electrochemical treatment in concrete



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HIGHLIGHTS

- Chlorides at the steel depth were more extracted at the higher current density.
- GGBS-mixed concrete were beneficial in extracting chlorides under electric charge.
- Chlorides adsorbed on hydrates could be released into mobile under electric charge.
- Electrochemical treatment mitigated corrosion rate of steel, but not re-passivated.

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ABSTRACT

The present study concerns electrochemical treatment to extract chloride ions and to re-passivate the corroded steel in chloride-contaminated concrete. As binder, ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS) and pulverised fuel ash (PFA) were used to produce different concrete mixes: OPC, GGBS and ternary mix containing the three binders, respectively. After 56 days of curing, a DC was supplied to the concrete specimens, ranging 250, 500 and 750 mA/m² for 4 weeks. Then, the corrosion rate was measured by the anodic polarisation. In fact, an increase in the current density applied to the specimens resulted in a decrease in the corrosion rate, imposing a reduction of the corrosiveness of steel in concrete. For a change in the chloride profile, a removal of chlorides at the depth of the steel was more significant in GGBS and ternary mixes, presumably due to a release of adsorbed chlorides on the hydration surface into free, which was further removed under electric charge. However, all chlorides could not be removed by the immobility of chlorides chemically bound into chloroaluminate and chloro-ferrite hydrates; a mostly half of chlorides in cast were, in fact, present even after the treatment.

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1. Introduction

Electrochemical chloride extraction method was developed in the 1970's for the repair of reinforced concrete structures subject to chloride-induced corrosion [1]. Its principle is to apply a high voltage DC current between the steel reinforcement and an external anode in order to force chloride ions away from the steel. The anode is usually a titanium mesh that is placed on the outside of the concrete surface and is in contact with an electrolyte solution. The current density used in chloride extraction typically exceeded 1–2A/m² and the duration of application varies from 6 to 10 weeks. Due to the high current density applied to concrete, the electrochemical chloride extraction method more or less achieved a chloride removal at the depth of the steel and thus mitigating corrosion

of steel, depending on the current density and voltage [2], for example, found that chloride-induced corrosion was arrested after applying a current of 8.37A/m² for 8 weeks, resulting in the removal of chloride ions at the steel–concrete interface. Orellan et al. [3] reported a significant removal of chloride at the steel–concrete interface with 50% extraction of chloride in the cover concrete after 7 weeks treatment.

However, the high current density in electrochemical treatments may reduce the bond strength between the steel and concrete. A reduction of 30–60% in bond strength has been reported in the majority of previous studies [4–6]. Moreover, the high current densities used appeared to be unrealistic to apply in in-situ. More currently, Buenfeld and Broomfield [7] showed a relatively lower reduction in bond strength compared to previous studies, ranging from 11% to 25%, when the current density applied was in the range of 100–750 mA/m²; in fact, the reduced bond strength was recovered in 24 h. Thus, it can be advisable to optimise the

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current density for chloride extraction to achieve a chloride removal with no adverse effect, presumably as being lower than 1000 mA/m^2 .

Despite removing chlorides from cover concrete under electric charge, the reduction of chlorides has been rarely quantified at different depths in concrete [8]; only a change in the chloride concentration in a bulk concrete has been often determined rather than profiling of chloride ingresses after the treatment. This is attributed to a destructive chloride profiling method. With no non-destructive methods for measuring the chloride concentration at different depths of cover concrete, a large number of replications must be manufactured for chloride profiling both for untreated and for treated specimens to determine the change in chloride profile arising from the treatment at a statistically high confidence level. Moreover, the influence of concrete mix design on chloride removal was not mostly identified. For example, the pore structure of the cement matrix may directly affect ionic transport under the treatment, as being governed by a free water/binder ratio, binder type and aggregate portion in the mix.

In the present study, the effect of electrochemical treatment in re-passivating the steel embedded in concrete was evaluated by measuring the corrosion rate and potential after the treatment at 250, 500 and 750 mA/m^2 for 4 weeks to avoid potential risk of the adverse effect. Simultaneously, the influence of binder type on the treatment in terms of concrete mix containing pozzolanic materials was determined by the corrosion behaviour and chloride removal. In particular, chloride ingresses at different depths after the treatment was measured with four replicating specimens to quantify the effect of a chloride removal within a bulk concrete in the absence of anodic solution on the surface of concrete specimens.

2. Experiments

2.1. Specimen preparation

Concrete specimen was manufactured with a centrally located steel rebar located in a prism mould ($70 \times 70 \times 150 \text{ mm}$) to produce 30.0 mm of the cover depth. To investigate the influence of binder type on electrochemical treatment, the portion of pozzolanic materials were maximised in concrete mix within guidelines. Ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS) and pulverised fuel ash (PFA) were taken as binders for three different mixes: (1) OPC solely mixed for control, (2) binary mix of 40% OPC and 60% GGBS (hereinafter GGBS), and (3) ternary mix of 20% PFA, 40% GGBS and 40% OPC (hereinafter Ternary), respectively. The chemical oxide composition of binders is given in Table 1. For the mix proportion of concrete, the ratio of binder, water, sand and gravel (10 mm) was 1.00: 0.40: 2.09: 3.14 by mass to produce a normal strength concrete. To accelerate the corrosion process, 3.0% of chlorides (i.e. NaCl) was admixed in mixing water to all specimens.

A mild steel rebar ($\text{Ø}10 \times 150 \text{ mm}$) was masked on the ends by cement rich paste and then a heat shrink band to avoid corrosion under masking materials. One end of the steel rebar was protruded for an electric connect with wire. Thus, unprotected length of the steel rebar was kept 100 mm in concrete. To complete the electric circuit for electrochemical treatment, titanium mesh was placed along the surface of inner mould before casting of concrete, as seen in Fig. 1. However, electrolytic solution was not placed on the concrete surface so that chlorides in a bulk concrete could only migrate under electric charge rather than diffusion and absorption, which would occur in the process of diluting chlorides moved from concrete body in the electrolyte. The concrete specimens were demoulded 24 h after casting of concrete, and then wrapped in a polythene film for 56 days at $20 \pm 2 \text{ °C}$ to avoid ionic intrusion or/and extrusion on the surface of specimen in the process of concrete curing, which would otherwise often occur in wet curing.

Table 1
Oxide composition of binders.

	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	Mn ₂ O ₃	TiO ₃	SO ₃
OPC	64.70	20.70	4.60	3.00	1.00	0.13	0.65	–	–	3.00
GGBS	41.20	34.20	11.70	1.43	8.81	0.29	0.31	0.30	0.58	–
PFA	5.26	46.47	30.09	5.07	0.87	0.38	0.71	0.03	1.71	0.64

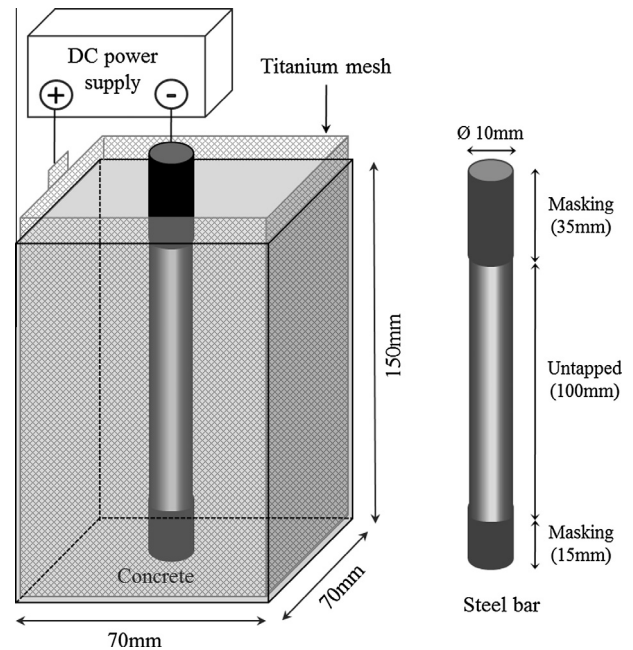


Fig. 1. Schematic for electrochemical chloride extraction to concrete contaminated by chloride ions.

Table 2
Applied current densities and voltages for electrochemical treatment.

Applied current density (mA/m^2)	Voltage (mV)	Charge (Coulombs)	Duration of treatment (days)
250	7853	3800	28
500	15,708	7600	
750	23,562	11,400	

Then, electrochemical treatment was applied to the specimen at different current densities and voltages. The applied current density ranged 250, 500 and 750 mA/m^2 to the area of unprotected steel surface at a given resistance, in order to be in the more realistic range for in-situ, beyond which adverse effect to concrete properties such as a debondment of steel from the concrete body arising from the evolution of hydrogen gas at the interface. Simultaneously, the voltage was accordingly increased. The duration of treatment was always 28 days for all specimens to produce the variation in the charge passed throughout the specimen as given in Table 2. The replication of each series was four, and their average values were taken to represent the corrosion resistance.

2.2. Corrosion behaviour

Immediately after electrochemical treatment, the corrosion rate was measured by the anodic polarisation technique. The potential was swept at a low scan rate of 0.1 mV/s to a potential of 25.0 mV above the corrosion potential to achieve the polarisation resistance of the steel in concrete. The titanium mesh was again used for an auxiliary electrode, while the reference electrode (i.e. standard calomel electrode) was placed close to the steel rebar protruded on the top of the concrete specimen through a salty wet tissue. The electrical resistance of concrete, in terms of IR drop, was automatically compensated by using a current interruption technique. Then, the corrosion rate was calculated by the Ohm's law as given in Eq. (1).

$$I_{\text{CORR}} = \frac{B}{R_p} \quad (1)$$

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