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Stray current induced corrosion of steel fibre reinforced concrete

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ABSTRACT

Stray current induced corrosion is a major technical challenge for modern electric railway systems. The leakage of stray current to surrounding reinforced concrete structures can lead to steel reinforcement corrosion and the subsequent disintegration of concrete. Steel fibre reinforced concrete has been increasingly used as the railway tunnel lining material but it is not clear if discrete steel fibres can still pick up and transfer stray current in the same way as conventional steel reinforcement and lead to similar corrosion reactions. The corrosion behaviour of steel fibres was investigated through voltammetry tests and electrochemical impedance spectroscopy. The presence of high concentration chloride ions was found to increase the pitting corrosion tendency of steel fibres in simulated concrete pore solutions and mortar specimens. The chloride threshold level for corrosion of steel fibres in concrete is approximately 4% NaCl (by mass of cement) which is significantly higher than that of conventional steel reinforcement.

1. Introduction

Railway electrification represents an important carbon strategy in the UK. It is estimated that an electric train consumes at least 20% less power (per passenger per mile) compared to a diesel-powered train [1]. In the UK, only 39% of the national rail network is electrified and it comprises 600 V/750 V direct current (DC) and 25 kV (50 Hz) alternating current (AC) traction power systems [2]. The UK government is committed to promote railway electrification and thus provide more sustainable and comfortable services for the public. Major work has been carried out for the Crossrail project which is expected to be delivered in 2018 and the construction of High Speed 2 (HS2) is expected to begin in 2017. In addition, the planning stages for HS3 and Crossrail 2 projects are both underway. For a modern electric train traction system, the transmission of power is normally provided by an overhead wire or a conductor rail. The return circuit is usually through the running tracks which are connected to nearby substations. Stray current refers to the current which disperses directly to the ground through the return path. Niasati and Gholami [3] proposed a simplified electronic circuit of the electric railway system, as shown in Fig. 1(a), to model the stray current leakage. In this circuit, stray current (i_S) can be determined according to railway traction current (i_T), resistance of the running tracks (R_R) and the track-earth resistance (R_T) based on Eq. (1). The resistance of the overhead catenary wire (R_C), in comparison to that of the running tracks (R_R), is negligible and it has not been taken into account in Eq. (1).

$$i_S = \frac{R_R i_T}{R_T + R_R + R_S} \tag{1}$$

Considering a more general condition that more than one leakage of stray current occurs along the running tracks, as shown in Fig. 1(b), Eq. (2) can be used to quantify stray current (i_S). r_R represents the resistance of the running tracks and r_T represents the track-earth resistance [4].

$$i_S = \frac{1}{12} i_T \frac{r_R}{r_T} L^2 \tag{2}$$

Both Eqs. (1) and (2) indicate that reduced track-earth resistance (R_T or r_T) will encourage traction current leakage or stray current (i_s). The leakage of stray current to surrounding structures, e.g. reinforced concrete sleepers and tunnel linings (Fig. 2), can lead to steel reinforcement corrosion and the subsequent disintegration of concrete which eventually reduces the service life of the entire railway system [5–7]. Stray current also accelerates the corrosion of underground service cables, water mains and gas pipes. Approximately £550 million is required per annum for the rehabilitation and repair of the stray-current induced corrosion damage to the UK infrastructures [8]. It is engineering practice to mitigate against stray current by providing sufficient insulation between the running tracks and earth, i.e. to increase R_T or r_T. The use of a separate rail (or the fourth rail) as the return circuit as used by some London underground subway lines can also effectively reduce the magnitude of stray current, but the cost of installing and maintaining the fourth rail over the entire design life of a railway system is significant. It should be noted that increased resistance of running tracks (R_R or r_R) can also lead to an increased stray

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List of notations

α_a, α_c	Constant values (V)
A	Exposed anode area (cm^2)
β_a, β_b	Anodic and cathodic Tafel constants/gradients
C_f	Capacitance of mortar ($S\cdot s^n\cdot cm^{-2}$)
C_{dl}	Capacitance represents the layer between the solution and the steel surface. Faradaic charge transfer reaction on the steel surface ($S\cdot s^n\cdot cm^{-2}$)
CR	Corrosion rate (mm/year)
EW	Mass of metal that will be oxidized by the passage of one Faraday of electric charge (27.925 for steel)
$E_{e,a}$, $E_{e,c}$	Anodic and cathodic equilibrium potentials (V)
E_{corr}	Corrosion potential (V)
I	Measured current from the circuit or the net electron flow (A)
I_a, I_c	Anodic and cathodic currents (A)
$I_{0,a}$, $I_{0,c}$	Anodic and cathodic exchange currents (A)
I_{corr}	Corrosion current (A)
i_{corr}	Corrosion current density (A/cm^2)
K	Constant value: 3.27×10^{-3} (mm g/μA cm year)
L	Distance between substations (km)
$\eta_{e,a}$, $\eta_{e,c}$	Anodic and cathodic overpotentials (V) from the equilibrium potential $E_{e,a}$ and $E_{e,c}$
ρ	Density (7.8 g/cm^3 for steel)
r_R	Resistance of the running tracks (Ω/km)
r_T	Track-earth resistance (Ω·km)
R_S	Resistance of the solution ($k\Omega\cdot cm^2$)
R_f	Resistance of mortar layer ($k\Omega\cdot cm^2$)
R_{ct}	Charge transfer resistance of the steel ($k\Omega\cdot cm^2$)
θ	Phase shift (radian)
W	Warburg diffusion element ($S\cdot s^{1/2}\cdot cm^{-2}$)

current according to Eqs. (1) and (2). The rail track joints are therefore required to be either welded or using low resistance joint bonds, complying with BS EN 50122-2 [9]. Reducing the distance between adjacent substations (L) can effectively reduce stray current although this has a cost consequence too. A stray current collection system, complying with BS EN 50122-2:2010 [9], can capture the stray current and return it back to substations through a return earth wire [10]. This can also be taken as an effective stray current mitigation method.

The corrosion of conventional steel reinforcement in concrete is often of an electrochemical nature. The corrosion process consists of at least two half-cell reactions, i.e. an oxidation reaction at the anode (loss of electron) and a reduction reaction at the cathode (gain of electron) [11]. The anodic reaction is normally iron dissolution:

$$Fe \rightarrow Fe^{2+} + 2e^- \tag{3}$$

The cathodic reaction can be oxygen reduction:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{4}$$

The cathodic reaction can also be water reduction, in the absence of oxygen:

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \tag{5}$$

Negatively charged electrons released from the anode travel to the cathode through the steel reinforcement. The formation of electrochemical cells also requires a continuous path for ions between the anode and the cathode which normally occurs through the concrete pore solution. Steel corrosion or oxidization is primarily a result of the anodic current (I_a) according to Faraday's laws of electrolysis, i.e. the amount of substance which reacts or literates is directly proportional to the quantity of electric charge passing through it. Corrosion normally occurs at an equilibrium state between the two half-cell reactions, upon which anodic and cathodic currents are both present and equal to each other, namely the corrosion current (I_{corr}) [12]. The steel corrosion rate (CR) can be determined according to Eq. (6) [13]:

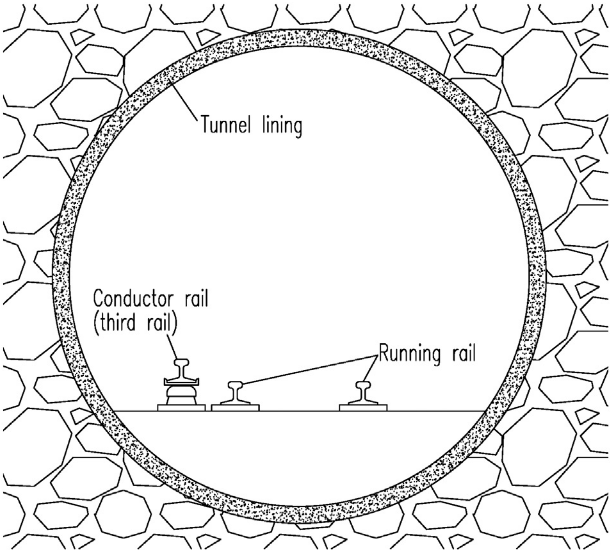
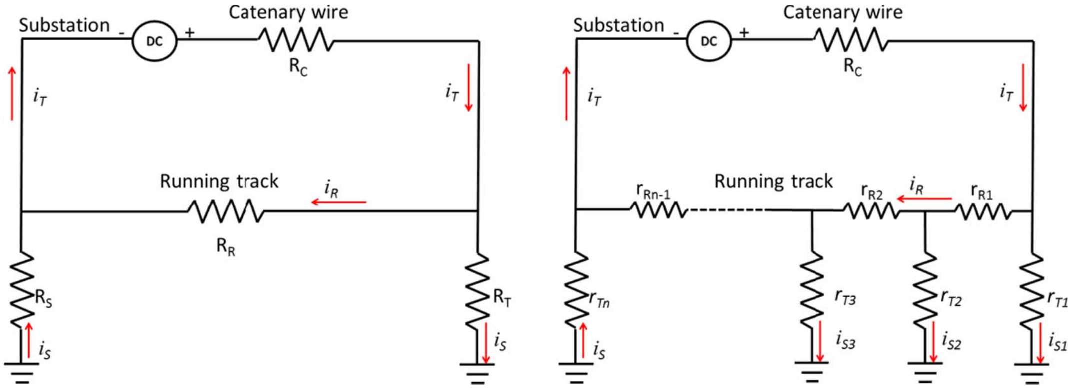


Fig. 2. Schematic of the railway tunnel section.



(a) Single leakage of stray current (b) Multiple leakages of stray current

Fig. 1. Equivalent electronic circuits of stray current formation.