

Pitfalls in Using Electrical Conductivity to Monitor the Chloride Ingress of Concrete

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Abstract. Chloride ingress in the field structure is influenced by many factors. A non-destructive monitoring is a useful tool for assessing the health of reinforced structures. This study used array sensors to measure the temperature and electrical conductivity of concrete at depths from 10 mm to 140 mm. The electrical conductivity in concrete showed a continuous decrease during the exposure to 3% NaCl solution. A numerical modelling of multi-ion species migration in pore solution can explain the evolution of conductivity profile over exposing time. By comparing with several previous investigations, this study identified the pitfalls in using electrical conductivity or resistivity to monitor the chloride ingress in the exposed concrete. To obtain a correct information from the electrical monitoring system, the experimental and analysing process should consider the saturation degree of concrete, the hydration induced structure change, the leaching of ions, the ingress of chloride and composition of binders.

Keywords: Chloride Ingress, Reinforced Concrete, Non-destructive, Health Monitoring, Durability.

1 Introduction

Chloride ingress is one of the primary causes of reinforcement corrosion in concrete structure, which will result in cracking and spalling. This poses a significant durability problem for the bridges and other marine infrastructure. The methods commonly-employed to determine chloride content in concrete are invasive, intricate, and require a considerable amount of time (Li et al., 2022). Therefore, many investigations tried to design non-destructive method to monitor the chloride ingress by testing the electrical response of concrete. It has been confirmed that electrical conductivity can well indicate the chloride migration coefficient of concretes (Huang et al., 2022).

However, some previous investigations reported contradict findings for the correlation between the change of electrical conductivity and the profile or concentration of chloride in the exposed concrete. Basheer et al. found that the resistance of concrete containing various supplementary cementitious materials (SCMs) increased during their ponding in chloride solution up to 1 year (Basheer et al., 2002). After exposed to wetting-drying cycles of chloride solution, Portland cement concrete with a higher amount of chloride had a lower resistivity, but concrete with fly ash presented an increase in resistivities despite with increase of chloride content (Angst et al., 2011). Another previous investigation reported that the resistivity at corresponding depth decreased as the chloride content increased (Du Plooy et al., 2015). The monitoring of resistivity profile in concrete showed that resistivity at each depth of concrete decreased as the exposure time increased, so the authors concluded that resistivity decreased as concentration of chloride increased during exposure (Fares et al., 2018). A study measured the resistivity change of the concrete composites containing carbon nanotubes and carbon fibers

during the exposure to chloride solution, and it was found that resistivity of the composites increased as the chloride penetrated the specimens (Tafesse et al., 2022).

There seem to be conflicting conclusions from different publications on how the electrical conductivity of concrete changes with the penetration of chloride ions. This is mainly due to the complexity of physicochemical reaction in concrete during the exposure, which is mixed with hydration and multi-ion species transport processes. Therefore, the experimental settings and the analysis of electrical conductivity data need to be handled with caution to avoid falling into the pitfalls. This study will identify the main pitfalls in using electrical conductivity to monitor chloride ingress in order to ensure a correct application of the related technique.

2 Experiments and Modelling

2.1 Experimental Procedure

Concrete specimen was cast in a container as shown in Figure 1. It was mixed with a water-to-binder ratio of 0.45 and cement:sand:stone of 1:3:1.5 by mass. The chemical composition of cement is shown in the Table 1.

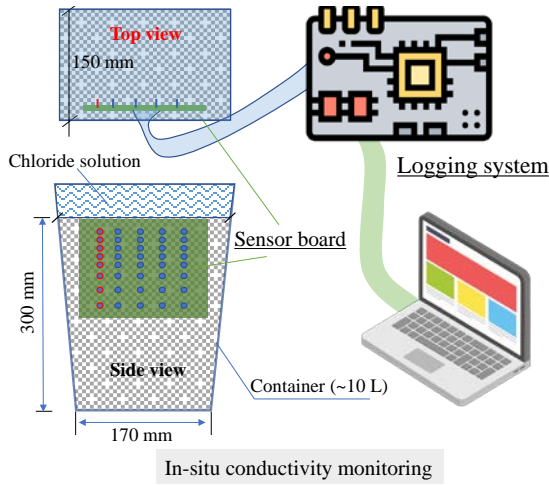
Table 1. Chemical composition of cement.

Chemical composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	K ₂ O	Na ₂ O	Cl	Sulfide	LOI
Weight (%)	62.2	19.6	4.5	3	3.5	3.5	1.01	0.27	0.07	-	2.5

Before casting, the sensor board was fixed in the container for the monitoring of electrical conductivity of concrete. After the container was filled with concrete, it was sealed with a cap to avoid moisture loss in early hydration. After curing for 7 d, the top layer of the container was then filled with tap water for 2 days. Afterwards, the tap water was replaced by 3% NaCl solution and the solution would be renewed every two weeks. The electrical conductivity at each depth was measured by four electrodes with Wenner configuration (Wenner, 1916), as shown in Figure 1. The blue circles represent the electrodes and the red circles mean the temperature sensors. The two outer electrodes are used for giving a instant current (I) and the two inner electrodes for collecting the voltage (V). Data were recorded by a computer connected to the logging system. The conductivity at each depth is calculated by Eq. (1).

$$\sigma_c = \frac{I}{2\pi V W^\gamma} e^{\frac{E_a}{R} \left(\frac{1}{273.15+T} - \frac{1}{298.15} \right)} \quad (1)$$

where σ_c is electrical conductivity of concrete normalized to 25 °C, I is the applied constant current between the outer two electrodes, V is potential difference between the two inner electrodes, E_a is the activation energy for conductivity change, R is the gas constant, W is the distance between two inner electrodes and γ is the dimension factor at different depths.



Illustrations:

The red circles are temperature sensors

The blue circles are electrodes

The electrodes were arranged with a configuration of horizontal distance 40 mm at depths of 10, 20, 30, 40, 50, 65, 80, 100, 120 and 140 mm

Figure 1. Electrical conductivity monitoring system for concrete specimen.

2.2 Numerical Modelling of Multi-ion Species Transport

The movement of ionic species under a gradient of external electrical potential can be described by the Nernst–Planck equation (Newman & Balsara, 2021). When there is no external potential, the diffusion of ion species in concrete follows Fick's law as Eq. (2).

$$J_i = -\frac{D_i}{f} \times \frac{\partial c_i}{\partial x} \quad (2)$$

where J_i is the flux of ions, D_i denotes the diffusion coefficient of specie i , c_i is the molarity of ion, x is the distance to the exposure surface, and f is the friction factor that describes the concrete resistance to ions diffusion.

Moreover, the sum of ions movement in the pore solution is the migration current in matrix, as shown in Eq. (3). The value of current (I) should be zero in a system without external electrical potential.

$$I = AF \sum_i z_i J_i = AF \sum_i z_i \left(-D_i \frac{\partial c_i}{\partial x} \right) \quad (3)$$

where A is the cross-sectional area of specimen, z_i is the valence of ions and F is the Faraday constant

The initial boundary of the specimens can be assumed as: the ponding solution with a constant concentration of 0.5 mol/L or 2.82 mol/L NaCl, and concentration of all the other ions in ponding solution with zero. The concentration of ions in pore solution at different hydration degree was estimated by use of the evaporable water content and the chemical composition of binders, which was described in the previous publication (Huang et al., 2022). Given with these boundaries, the redistribution of ions in concrete during its exposure to the chloride solution can be modelled. A previous publication had a detailed description about how to simulate the multi-ion species migration in concrete (Tang et al., 2012), and the numerical simulation in work referred to that paper. Afterwards, the electrical conductivity of pore solution can be

calculated according to procedures in a previous paper (Huang et al., 2022).

3 Results

3.1 Evolution of the Electrical Conductivity over Time

Figure 2a shows the electrical conductivity of concrete at different depths after an exposure to tap water. It is so clear that the conductivity in depth above 50 mm increases sharply in the first two days. This implies that the adsorption of water will induce a significant increase in electrical conductivity or reduction in resistivity. Some publications used the unsaturated specimen to perform the monitoring, which stated that the ingress of chloride will reduce the resistivity (Basheer et al., 2002; Du Plooy et al., 2015; Fares et al., 2018). However, the resistivity at early exposure time is mainly controlled by the moisture change instead of chloride ingress.

Figure 2b shows the evolution of electrical conductivity after replacing tap water with 3% NaCl solution for ponding. It induces a sudden increase in the conductivity at depth above 30 mm, which can be ascribed to the change of dimension factor induced by the high conductive surface layer. The most interesting phenomenon is that the electrical conductivity values at all depths present continuous decrease during the exposure until 101 d. The reduction of conductivity in the inner part (deeper than 120 mm) is mainly due to the hydration of cement, resulting in the change of pore structure. The next section will focus on revealing the reason for the change of conductivity at the near surface part.

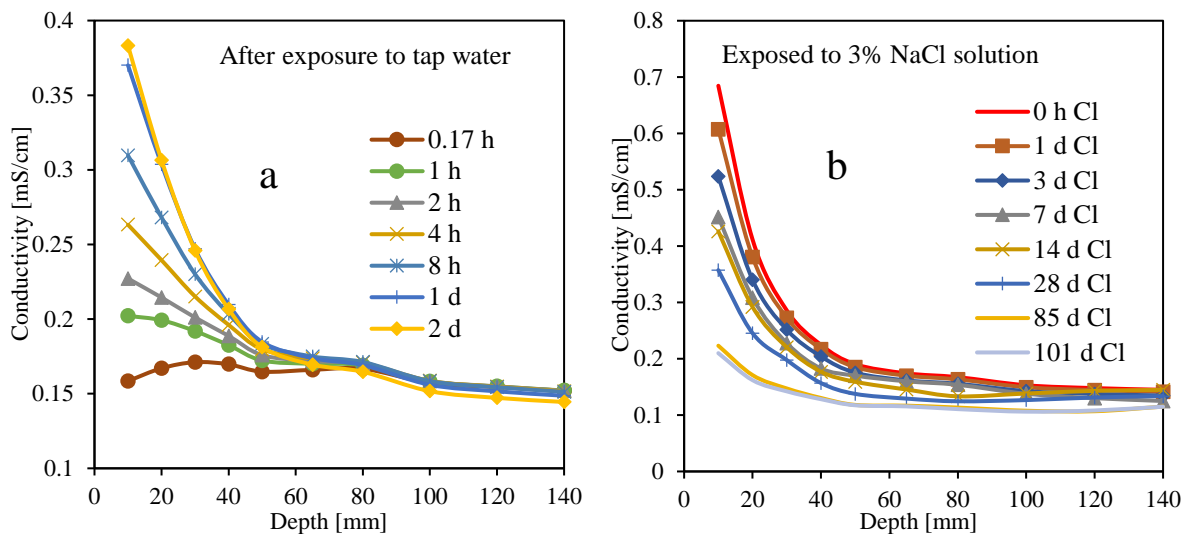


Figure 2. Electrical conductivity at various depths after exposure to tap water (a) and chloride solution (b).

3.2 Change of Conductivity Due to Ion Transport

3.2.1 Exposed to a normal concentration chloride solution

To eliminate the effect of hydration and sample dimension, the relative conductivity (C) is calculated by Eq. (4).

$$C = \frac{\sigma_{t,d}/\sigma_{t,140}}{\sigma_{0,d}/\sigma_{0,140}} \quad (4)$$

where $\sigma_{t,d}$ (mS/cm) means the conductivity in the depth d (mm) at exposure time t .

Figure 3a shows the evolution of relative conductivity at different depths over the ponding time. Apparently, the value at depth above 50 mm has a continuous decrease. The interesting increase in 50–120 mm at 7 d may be due to the pore structure change. According to the multi-ion transport modelling (Figure 3c), although the Na^+ and Cl^- concentration in pore solution has evident increases, the sever leaching of K^+ and OH^- during the exposure will result in the reduction of pore solution conductivity (Figure 3b). The evolution of pore solution conductivity over exposure time can match with the monitored electrical conductivity of concrete.

The increase in resistivity of the composites concrete was ascribed to the clogging of the carbon nanotube network as the chloride penetrated the specimens under external electrical potential (Tafesse et al., 2022). Several publications also ascribed the continuous increase in resistivity at a given depth to the hydration of supplementary cementitious materials during the long-term exposure (Basheer et al., 2002; Angst et al., 2011). These investigations used the solution with a similar NaCl concentration as this study, so there would be a strong leaching of conductive ions during the exposure, especially with a external electrical potential. According to the modelling results, the leaching effect is probably the main factor for reduction in conductivity (increase in resistivity) at the cover zone of concrete (depth < 30 mm).

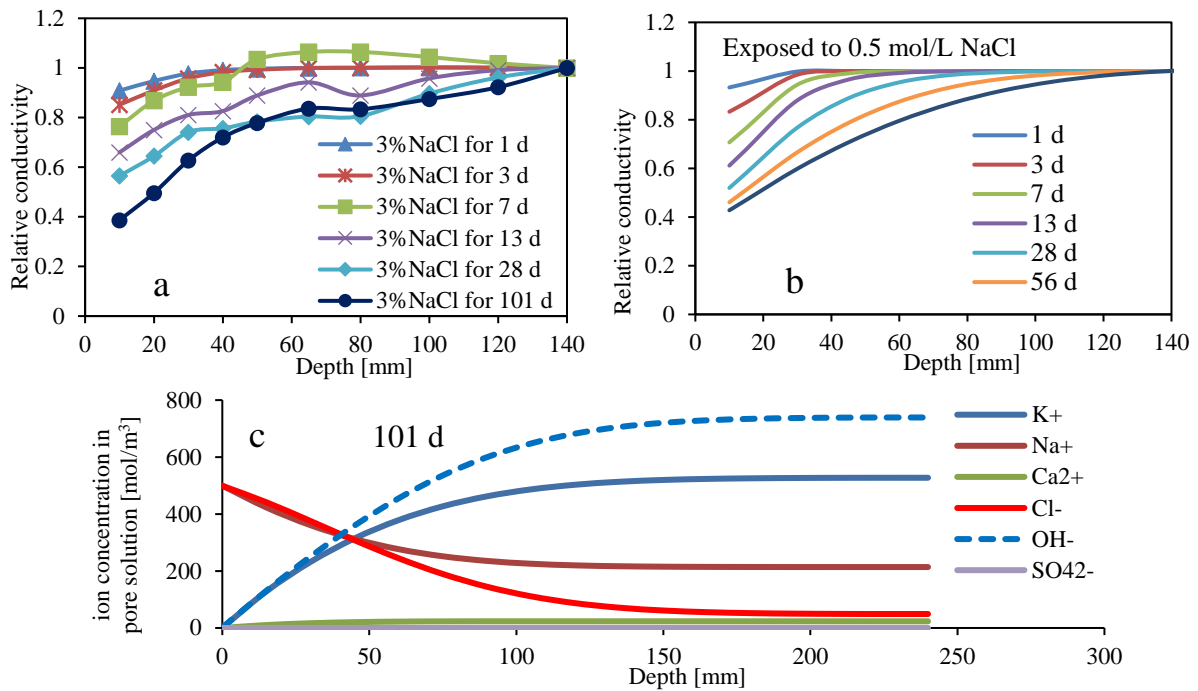


Figure 3. Relative electrical conductivity of concrete specimen (a) and the simulated pore solution (b) in relation to the ion concentration (c) while exposed to 3% NaCl.

3.2.2 Exposed to the high concentration chloride solution

Some investigations exposed the concrete to a high concentration chloride solution for monitoring of the resistivity change, such as using solution with 2.82 mol/L NaCl (Fares et al., 2018). Figure 4a illustrates the simulated relative conductivity of pore solution under this exposure condition. The conductivity near surface zone increases after 7 d and the influential zone becomes deeper over time. This is mainly due to the fact that the increase in concentration of Na^+ and Cl^- outperforms the leaching of K^+ and OH^- (Figure 4b). However, this level of NaCl concentration is much higher than the real exposure condition, such as sea water.

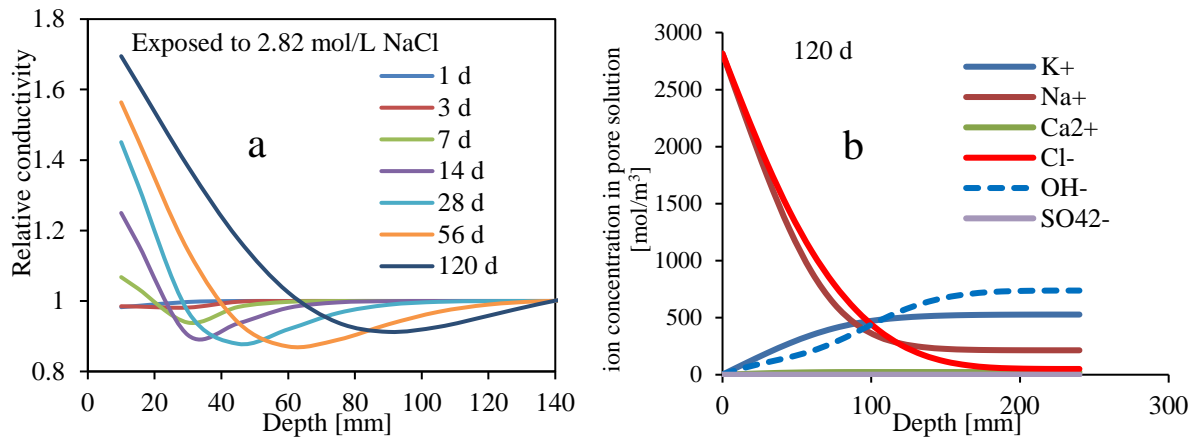


Figure 4. Relative electrical conductivity (a) and ion concentration in pore solution (b) after exposed to 2.82 mol/L NaCl.

3.2.2 Effect of binder type

As the solubility of alkali metal oxide in SCMs is usually much lower than those in cement, the replacement of cement with SCMs will induce a significant reduction in concentration of conductive ions in pore solution (Huang et al., 2022). Figure 5a presents the simulated pore solution conductivity of the blended concrete with 50% substitution of cement with limestone. After an exposure of 90 d, the relative conductivity at the cover zone starts to increase. The relative conductivity presents a similar tendency as chloride profile after 5 years of exposure. As figure 5b shows, the concentration of K^+ and OH^- in the blended concrete is much lower than the Portland cement concrete (see in Figure 3c). The effect of leaching on conductivity of blended concrete is weaker than the Portland cement concrete, and it will be covered by the ingress of Na^+ and Cl^- after a certain period.

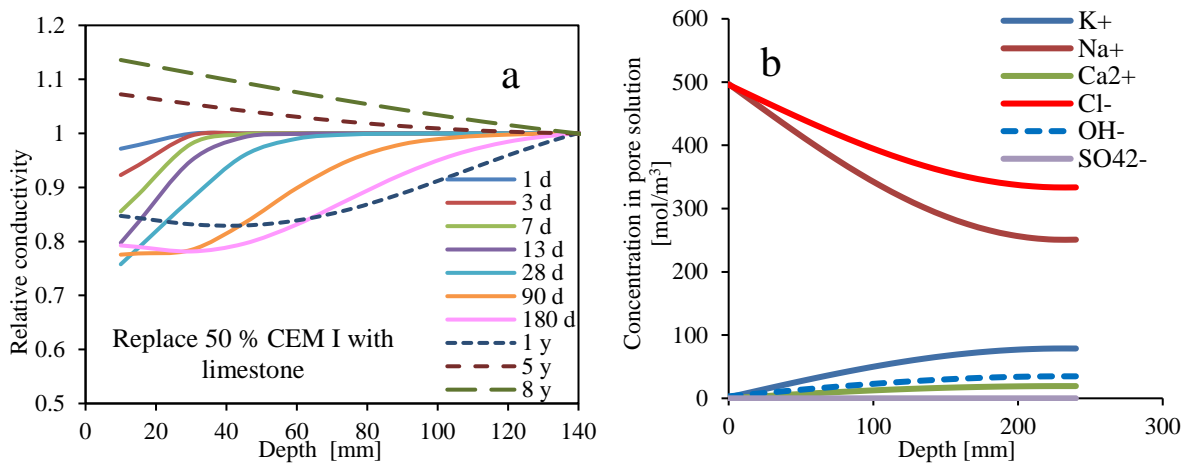


Figure 5. Relative electrical conductivity (a) and ion concentration in pore solution (b) of blended concrete exposed to 0.5 mol/L NaCl.

3.3 Pitfalls in Using Conductivity to Monitor the Chloride Ingress

The electrical conductivity of concrete during exposure is influenced by many factors, including the saturation degree, the hydration induced structure change, the leaching of ions, the ingress of chloride and the composition of binders. There are some pitfalls while studies try to monitor the ion ingress process by electrical conductivity or resistivity. The below points should be taken into consideration for a correct analysis of the electrical conductivity data from the exposed concrete specimens.

1. The electrical conductivity or resistivity of concrete is highly sensitive to the saturation degree, so the saturation degree of sample is an important parameter for analysis of the monitored results. The initial increase in conductivity of unsaturated sample after exposure is mainly due to the water adsorption. Even though the sample was saturated before exposure, the leaching of ions from pore solution will mix with the ingress of ions to influence the conductivity.

2. If the specimen was exposed to a high concentration NaCl solution, it is possible to obtain a profile of electrical conductivity similar as the chloride profile. However, this kind of experiments cannot represent the real exposure environment with a much lower ion concentration. The results based on high concentration exposure give a fake information that the increase in conductivity is only controlled by the ingress of chloride, but it actually is a mix of leaching and ingress.

3. The binder type is very important while extracting the information of ingress profile from conductivity test. The different solubility of conductive composition in alternative binders need to be considered, since it would change the ion concentration in pore solution to influence the leaching and ingress.

In general, it is very difficult to directly correlate the change of electrical conductivity to the profile or concentration of chloride in the concrete at the real exposure site. With a numerical modelling it may be possible to extract the information of chloride ingress. The monitoring of electrical conductivity is useful to indicate the diffusion coefficient and its time dependency (Huang et al., 2022), and it is also useful as an indicator of corrosion rate and initiation of steel corrosion (Morris et al., 2002; Andrade & Alonso, 1996; Alonso et al., 1988).

4 Conclusions

- The transport of ions in concrete can be monitored by the electrical conductivity, but the profiles of electrical conductivity at different depths are determined by the combining effects of the saturation degree, the concentration of exposure solution and the composition of binders. Therefore, there are some pitfalls in the analysis of electrical conductivity data in relation to ion ingress. To obtain a credible information, the numerical modelling is required to clarify the effect from other factors.
- The numerical simulation demonstrates well how chloride ingress and pore solution leaching impact the electrical conductivity. Experiments with high concentration exposure may provide misleading information for the application of conductivity monitoring in exposure site. The evolution of electrical conductivity also strongly depends on the binder types. The electrical conductivity data cannot be directly correlated to the chloride concentration in concrete during exposure.

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