MATEC Web of Conferences **199**, 11016 (2018) https://doi.org/10.1051/matecconf/201819911016
*ICCRRR 2018*

# Electrical Resistance Tomography for Assessing Water Movement in Cracked Cementitious Mixtures

*Keiyu* Kawaai[1,*], and *Isao* Ujike[1]

[1]Civil and Environmental Engineering, Ehime University, Matsuyama, Ehime, Japan

**Abstract.** Electrical resistance tomography (ERT) has been studied for visualizing variations of conductivity in concrete specimens. In recent years, unsaturated water flow through pores formed in concrete has been intensively examined though ERT systems to visualize the permeation front that gradually changes with elapsed time. This study examines water movement through internal cracks which are typically not observed on the surface of mortar or concrete specimens via ERT systems. The results indicate the gradual increase of saturated region owing to the ingress of water through cracked surface up to 120 hours. And, the region with higher conductivity estimated in uncracked parts is evidently in good agreement with higher moisture content measured by moisture meter on the split surface. In addition, the presence of crack in concrete specimen subjected to water ingress is clearly visualized via ERT images owing to rapid water movement in cracked zones. This study has provided the important insight that the ingress and the movement of water through pores and cracks formed in cementitious mixtures could be assessed via electrical measurements.

## 1 Introduction

The durability of reinforced concrete (RC) structures is dominantly controlled by the resistance against the ingress of harmful substances including chloride ions, carbon dioxide, and water containing dissolved oxygen. The corrosion of steel bars taking place especially under marine environment is likely to be severe depending on the availability of dissolved oxygen and moisture consumed by the cathodic reactions. It is widely known that the durability performance of RC structure is adversely affected by the presence of cracks owing to early age cracking, bending moment, drying shrinkage and etc., which leads to less resistance against ingress of corrosive substances. Many studies have been carried out for examining the effects of such cracks on the corrosion processes in concrete [1]. Besides such cracks appeared on the surface of cover concrete, Goto and Otsuka (1980) reported that internal cracks tend to arise from the edge of knots present in deformed steel bars owing to tensile stresses increased up to 100 N/mm$^2$ when loaded under service conditions [2]. This may have a significant impact on the durability performances pertaining to corrosion processes of steel bars if present. This study is aimed at developing a new technique for assessing the water movement through such cracks in cementitious mixtures. In particular, electro-chemical properties in partially saturated concrete which could be modified by the presence of cracks and water ingress are of great interest.

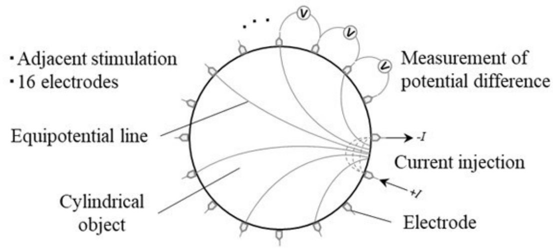


**Fig. 1** ERT set-up and measurement pattern.

Electrical resistance tomography (ERT) is a technique which allows us to assess the changes of electrical conductivity. This has been extensively used in medical, geophysical applications [3, 4]. The ERT has been studied for visualizing variations of conductivity in concrete specimens [5]. The ERT system is typically carried out in such a way that DC or AC current is injected to a pair of electrodes among 16 electrodes equally apart located in cylindrical object, and potential differences are measured between each adjacent electrode as shown in Figure 1. More recently, unsaturated water flow through pores formed in relatively porous concrete has been examined though ERT systems to visualize the permeation front that gradually changes with elapsed time [6]. The results showed that the permeation front inferred by distributions of conductivity estimated through the inverse analysis was reasonably consistent with dividing lines between the presence of water and dried pores analysed via neutron radiography. This study examines ERT assessment for water movement through internal cracks which are not observed on the surface of mortar specimens.

* Corresponding author: kkawaai@cee.ehime-u.ac.jp

# 2 Experimental

This section reports on experimental procedure for ERT measurements developed in this study. First, experimental set-up including materials, specimen details and measurement methods is described. Subsequently, the inversion analysis based on FEM is presented according to past research [7].

## 2.1. Materials and specimens

Mortar mixture with a water to cementitious ratio of 0.5 was used in this study. Cement was high early strength Portland cement (specific gravity: 3.14 g/cm$^3$) in accordance with JIS R 5210. And tap water was used as a mixing water. Fine aggregate was crushed limestone with specific gravity, F.M., and water absorption of 2.66 g/cm$^3$, 2.47, and 0.58% respectively. Cylindrical specimens were cast with a diameter of 150 mm and a height of 100 mm as shown in Figure 2. It is noted that hollow core was made by inserting PVC pipe with a diameter of 32 mm before casting. Electrodes comprising stainless steel $\phi$3mm in the specimens were partially embedded using conductive epoxy (< 0.001 Ω cm) up to the depth of 10 mm.

Two types of specimens were prepared with and without cracks. Cracks were induced by loading machine in such a way that the steel plate was pushed down and internal pressure in the hollow core was adjusted to make internal cracking in the cross section of the specimens.

## 2.2. Measurement methods

AC current (30V, 100Hz) was injected to a pair of electrodes selected among 16 electrodes. And then, potential differences were measured using tester in each pair of electrodes i.e. 16 cases. Thus, 16 x 16 = 256 measurements were totally carried out. Current injected to the specimens was measured using shunt resistance connected to the electrical circuit.

The moisture content was measured using portable moisture tester on the split surface of mortar specimens after water ingress was assumed to reach steady state. This was conducted immediately after the specimens were split.

## 2.3. FEM inversion analysis

ERT is a non-invasive technique based on the distribution of the electrical conductivity in an object which is estimated via surface measurements. The inversion analysis employed in this study is essential to estimate the distribution of conductivity/resistivity in the object based on the potentials measured on the surface of the object. It is well known as an ill-posed problem, thus indicating that there are some possible solutions to be feasible. In this study, difference imaging method according to past research [7] was employed for the inversion analysis. It requires two sets of data obtained in two timings. It should be noted that temporal changes of conductivity in the two conditions are highly desirable. Then, the data obtained for the first measurement serves as a reference data, and the changes from the reference conditions are estimated as conductivity changes and distributions. The methodology is more tolerant to the measurement noises and experimental errors including electrode dimensions and positions modelled by FEM, however the results only give qualitative information. The detail information about the accuracy and limitation of the technique can be found elsewhere [e.g. 8].

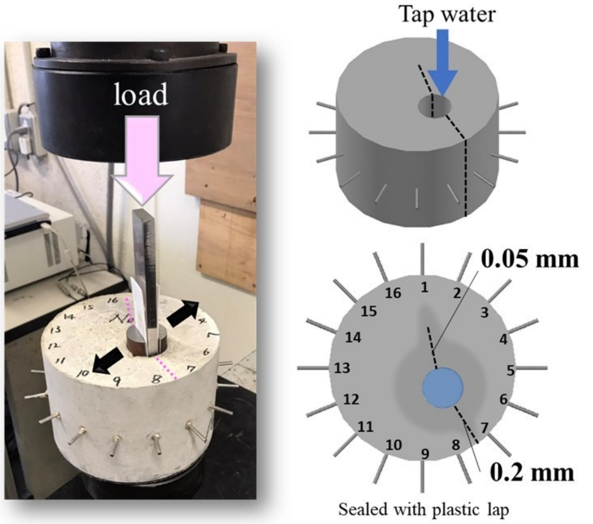


**Fig. 2** Cracking in mortar specimens and water flow through internal cracking from hollow core.

# 3 Results and discussion

This section reports on the results of ERT measurements and reconstructed images. In particular, water movement from the hollow core and internal cracking are analysed in detail. The changes of resistivity owing to water movement are discussed with respect to measured potential differences. And then, this study examines ERT assessment for water movement in cracked mortar specimens based on reconstructed images and moisture distribution measured on the split specimen.

## 3.1. Visualisation of water movement in uncracked mortar specimen

Figure 2 shows ERT images obtained for the specimens without cracks after tap water was poured into the hollow core. The images are shown based on the results of potential measurements up to 480 hours. It is noted that lower resistivity is shown as blue colour and higher resistivity is shown as red colour in the images. The results indicate the gradual increase of saturated zones owing to the ingress of water from the hollow core up to 216 hours. When the pores are fully saturated with water, the conductivity is likely to increase in the presence of calcium hydroxide and etc., thus suggesting that electrical circuit is well formed via ion conduction in the region. It is noted that the pH in the water remained in the hollow core was changed to 10.9 from 8.41, which is caused by the calcium leaching from the hardened mortar matrix.

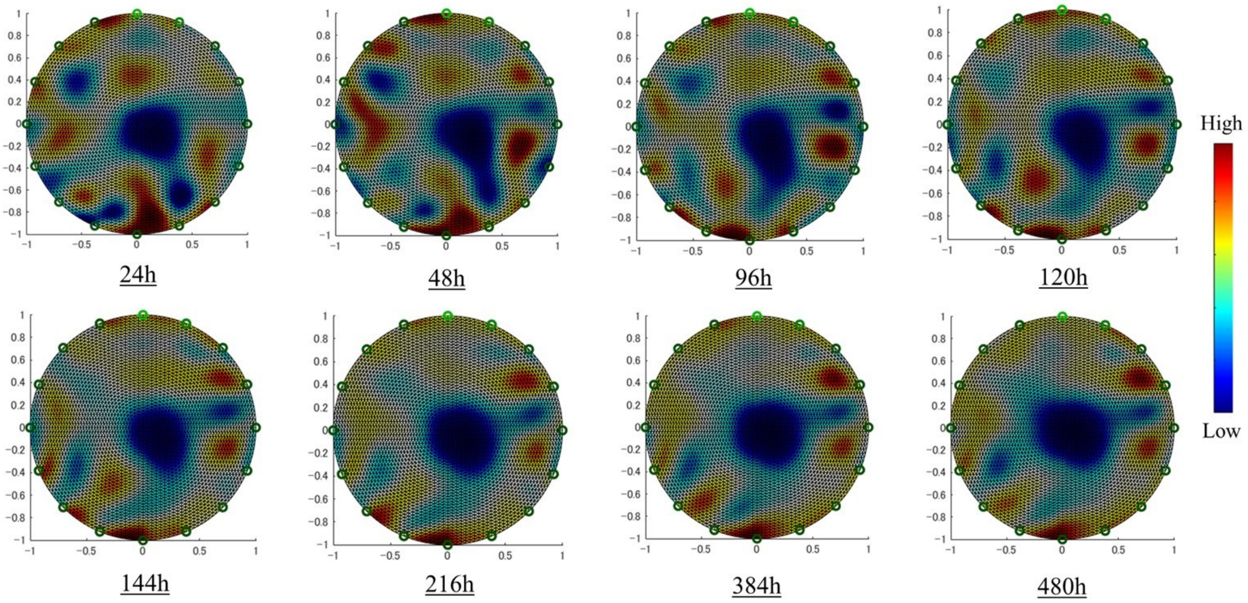


**Fig. 3** ERT images obtained for mortar specimens without cracks and water movement from hollow core.

The region highlighted in blue colour subsequently seems to reach steady state after 216 hours. This is attributed to the friction forces generated in the pores which could counteract suction forces associated with the water ingress.

And, the regions estimated with higher conductivity in the uncracked parts were then tested in determining the moisture distribution. Figure 3 shows the moisture distribution measured on the split surface of mortar specimens tested after 100 days. The results are shown with respect to the depth from the hollow core in the mortar specimen. The permeation front was observed to be around 20 to 30 mm from the edge of hollow core. The results are evidently in good agreement with lower resistivity estimated via ERT analysis on the split surface as shown in Figure 4. Therefore, there is a good possibility that water movement through pores in cementitious mixtures can be visualized and assessed via the ERT analysis in this study. The water movement through internal cracks in the mortar specimen is presented in Section 3.3.

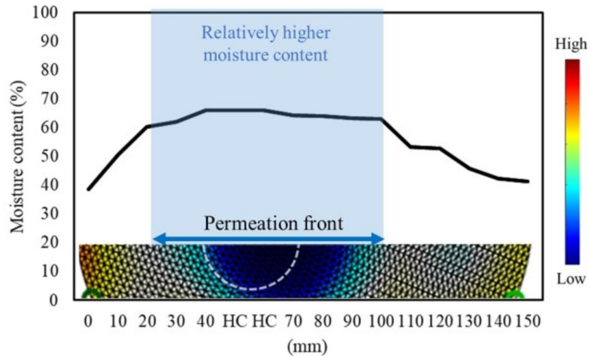


**Fig. 4** Moisutre distirubtion on the split surface of mortar specimen after 100 days of testing periods.

## 3.2. ERT assessment of water movement through cracks in mortar specimen

Figure 5 shows results of potential distribution measured in the cracked specimen after tap water was poured into the hollow core. To illustrate the changes of potential measurements, the results obtained after 6 and 120 hours of the monitoring were shown, which was normalized based on the potentials measured at initial condition. It is noted that the measurement data obtained for a pair of electrodes e.g. 1-2, 7-8, 16-1 electrodes located in the vicinity of cracks is separately shown. As can be seen, the potential measured in those electrodes was lowered as the water penetrated through the cracks. This is attributed to the presence of water spread from the cracked surface which is highly conductive compared to the uncracked region. The water movement owing to the suction forces may stabilize and tends to penetrate through the cracks in the direction parallel to the cracks

ERT images in each measurement were constructed as shown in Figure 6. For the case of images obtained after 6 hours measurement, the presence of hollow core is not observed. This can be explained by the fact that the difference imaging methodology is largely dependent on temporal changes of conductivity measured in two different timings. Although the conductivity is likely to increase in the vicinity of cracks which are gradually saturated, the changes of conductivity in the hollow core may not be large after the tap water is poured.

The results obtained after 24 hours indicate that the gradual increase of saturated region highlighted in blue colour is clearly observed. This is attributed to the ingress of water through cracked surface which led to higher conductivity i.e. larger amount of calcium hydroxide available for the ion conduction. The average potentials measured between electrodes 1-2, 7-8 and 16-1 are summarised in Table 1.

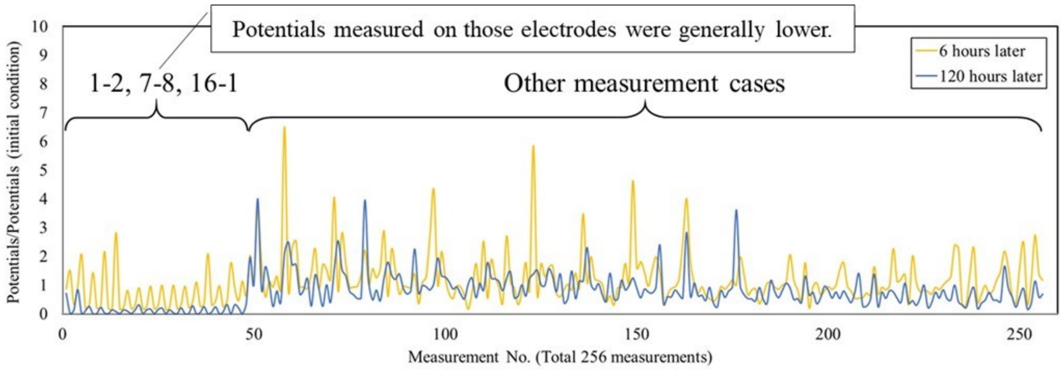


**Fig. 5** Results of potential measurements obtained for the specimen after tap water was poured into the hollow core and 120 hours. (NOTE : Measurement data obtained for a pair of electrodes located in the vicinity of cracks was separately shown.)

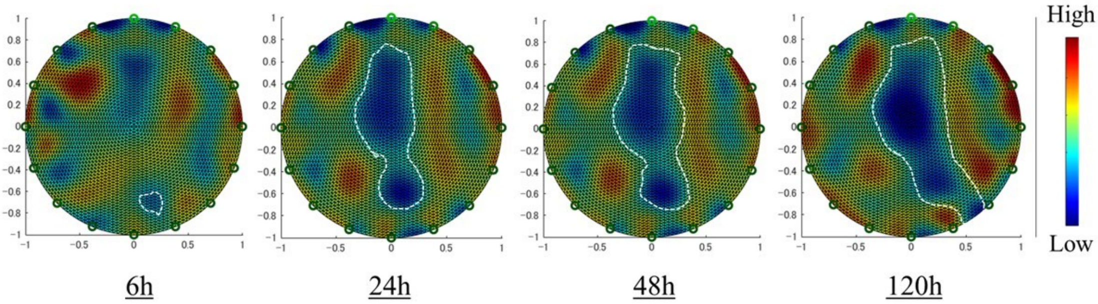


**Fig. 6** ERT images of cracked mortar specimens after tap water was poured into the hollow core up to 120 hours later.

**Table 1.** Average potentials measured on the electrodes in the vicinity of cracks (1-2, 7-8, 16-1).

| Time (hours) | 6 | 24 | 48 | 120 |
|---|---|---|---|---|
| Average potentials (V) | 0.68 | 0.52 | 0.14 | 0.09 |

As can be seen, the potentials are likely to decrease during the monitoring periods. In particular, a sudden drop was observed between 24 to 48 hours of the monitoring. This indicates that the water could reach to the edge of cracks or exposed surface through the cracks. In addition, the water permeation may stop in uncracked parts as mentioned in Section 3.1. Therefore, the widespread saturated pore zones are found to be along the cracks up to 120 hours monitoring. Although the saturation degree is supposed to be varied in the locations far from the cracked surface, the gradual decrease in the saturation degree may not be clear in the ERT images. However, fully saturated cracks should have higher conductivity in the presence of ions leached out from the cement matrix, the difference in terms of ion mobility depending on the types of ions present could be further investigated. This could contribute to give more quantitative information via the current approach. Finally, the regions with higher conductivity estimated in the vicinity of cracks are found to be good indicator for assessing the presence and movement of water through the cracks.

## 4 Conclusions

The water movement in cracked mortar specimen is clearly visualized via ERT images based on surface potential measurements. This study has provided the important insight that the ingress and the movement of water through pores and internal cracks formed in cementitious mixtures could be assessed via electrical measurements.

## References

1. A.W. Beeby, Concrete International, **5**, 2, (1978)
2. Y. Goto, and K. Otsuka, J. of JSCE, 294, (1980)
3. W. Daily, A. Ramirez, D. LaBrecque, J. Nitano, Water Resour. Res. **28**, 5, (1992)
4. R. Stacey, Tech. Rep. SGP-TR-182, Stanford University, (2006)
5. K. Karhunen, A. Seppänen, A. Lehikoinen, P.J.M. Monteiro, and J.P. Kaipio, Cem. Conc. Res., **40**, 1, (2010)
6. M. Hallaji, A. Seppänen, and M. Pour-Ghaz, Cem. Conc. Res., **69**, (2015)
7. A. Adler, and R. Guardo, IEEE Trans. Med. Imaging, **15**, 2, (1996)
8. A. Adler, and W.R.B. Lionheart, Physiol. Meas., **27**, 5, (2006)