ON-SITE ASSESSMENT OF CURING EFFICIENCY BY MEANS OF ELECTRICAL RESISTIVITY MEASUREMENTS

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Abstract

The strong dependence of concrete electrical resistivity with the saturation degree of the concrete provides a practical tool to assess the drying behaviour of concrete by means of electrical measurements and thus, this technique may be used to monitor curing efficiency.

As concrete resistivity is also influenced by other factors, such as cement type, w/c, type and content of mineral admixtures, it is required to uncouple their influence to accurately assess the drying behaviour through the use of a new parameter defined as “relative resistivity”, which has been presented in earlier works.

This paper analyses the suitability of standard Wenner probes, with an electrode spacing of 50 mm, to detect early drying of the exposed concrete, because the current lines can reach deeper and wetter layers.

Different concretes, in the range 20 to 65 MPa, have been exposed to drying conditions at early ages and the respective drying behaviours were characterised by multiple techniques, such as mass loss and electrical resistivity by Wenner technique using different electrode spacing.

From the results, it is clearly shown that a closer electrode spacing is much more sensitive to identify the drying behaviour of the cover concrete, thus providing a practical tool to on-site assessment of curing efficiency. Complementary aspects such as the variability of the measures and the need for a shape and size factor definition have been also dealt with.

1. Introduction

Curing of concrete is important for many reasons, in particular, to prevent early cracking and to achieve the desired quality of the cover concrete to provide a suitable barrier effect against external attack [1] [2].
Curing comprises all specific actions aimed at providing the cement the humidity and temperature conditions for it to continue hydration at the desired rate. In common situations curing activities are focused on preventing the concrete from early drying.

The strong dependence of concrete electrical resistivity with the saturation degree of the concrete provides a practical tool to assess the drying behaviour of concrete by mean of electrical measurements and thus, this technique may be used to monitor curing efficiency.

As concrete resistivity is also influenced by other factors, such as cement type, w/c, type and content of mineral admixtures, it is required to uncouple their influence to accurately assess the drying behaviour through the use of a new parameter defined as “relative resistivity”. The relative resistivity is the ratio between the resistivity of the concrete under drying and the resistivity of the same concrete cured under standard conditions, at the same age [3].

In a previous paper, it was shown the suitability of the relative resistivity to assess the drying rate of concrete in a non-destructive manner [4].

It is common for the commercial resistivity meters based on Wenner probes to have a spacing of 50 mm between electrodes. The spacing determines the depth of the current flow [5] and thus, the depth of the concrete layers where the humidity content is assessed.

Actually, under drying conditions, outer layers of concrete are drier than deeper ones and the current flow is altered, as it tends to follow a less resistive path. As a result, the concrete resistivity measured by the instrument corresponds to layers located at deeper depth than the cover concrete.

As far as early drying is concerned, the critical layers of the concrete are the exposed ones and the resistivity measure should involve these layers. Moreover, drying kinetics is faster for exposed layers so the earlier the premature drying is detected, the more effective the remedial measures to increase the humidity content for the hydration to evolve.

The use of a smaller spacing of the electrodes in the Wenner array could be a reasonable manner to force the electrical current to flow through shallow layers. If this modification were effective, the measure will involve mainly the cover concrete, and the drying will be detected earlier than using 50 mm spaced electrodes.

2. Objectives

The objective of the testing program was to validate the assessment of concrete drying by means of smaller electrode spacing in the Wenner arrangement of a commercial resistivity meter.

In addition, the results obtained with the shorter spacing are compared to the standard-spacing ones, i.e.50 mm to determine their variability and mean values.

3. Testing program

Different concretes, in the range 20 to 65 MPa, have been prepared and cured under different regimes. Some of the samples were kept under standard curing (20ºC, RH > 90 %), while others were exposed to different drying conditions at early age; some of the drying regimes were mild, protected from the sun in laboratory ambient and others were severe, such as 35ºC, RH < 50 %.

The respective drying behaviours of cylindrical samples were characterised by different techniques, such as mass loss and electrical resistivity (Wenner probe) using different electrode spacing.
The electrode spacing was set at 20 mm and 50 mm (standard spacing) and the results were compared, taking into consideration that the absolute resistivity value depends on the relationship between the electrode spacing and the sample size and shape, according to Morris et al. [6].

The 20 mm spacing was selected because this spacing would keep most of the current flow through the cover zone, i.e., 30 mm, as it is shown in Fig. 1, while only about 55.5 of the current flows through the cover layers when for the standard spacing of 50 mm.

Curves in Fig. 1 correspond the eq. (1), from [7], resized for the electrode spacings.

\[
I_{x,z_{1}} = I \left[ 1 - \frac{2}{\pi} \tan^{-1} \left( \frac{2z_{1}}{L} \right) \right]
\]  
(1)

Where:

\( I_{x,z_{1}} \) = fraction of the electrical current at the plane XZ flowing at depths deeper than \( z_{1} \).

\( \frac{z_{1}}{L} \) = Dimensionless variable composed by depth \( z_{1} \) and spacing \( L \) between electrodes of the Wenner array.

![Fig. 1: Fraction of electrical current passing vs. depth, for different spacing.](image)

Both Wenner spaced probes were used in many different samples, mainly cylinders, and measurements were made according to RILEM TC 154 recommendations [8] but the saturation under vacuum as the measurements were aimed at assessing the drying behaviour. The results have been grouped according to the electrode spacing and the coefficient of variation of each measure was calculated as the ratio between the standard deviation to the mean value.

The evolution of the apparent resistivity over time during the standard curing period was also recorded as its value is required to calculate the relative resistivity, which has proven to perform as a suitable indicator for concrete drying [3][4].
4. Test results

The percentage in mass loss over time of concretes with compressive strength ranging from 20 to 60 MPa is shown in Fig. 2. These data represent the kinetic of drying, measured on 150 x 300 mm cylinders exposed to the same ambient (21 ± 2)°C and (65 ± 5)% RH.

Table 1 shows the apparent resistivity of 150 x 300 mm concrete samples made of a 60 MPa concrete under standard curing, using 50 mm and 20 mm spacing, while Table 2 shows the increase in relative resistivity of 150 x 300 cylinders exposed to drying (same conditions as samples in Fig. 1). The relative resistivity was calculated according to the definition proposed by the authors in [3][4], as the ratio between the apparent resistivity measured under drying and the apparent resistivity of identical samples submitted to standard curing at the same age, measured with the same probe arrangement. As an alternative, the same value can be reached by dividing the corresponding absolute resistivity.

The absolute resistivity can be calculated from the apparent resistivity by applying a shape-and-size correction factor, as proposed by Morris et al. [6]. Indeed, the absolute values can be compared, as it is shown in Fig. 3, where the evolution of the absolute resistivity over time, measured with 50 mm and 20 mm spacing for standard cured samples, is sketched. In Fig. 3, only the fitting curve for the 50 mm spacing has been drawn, as it was taken as reference. Values obtained for 20 mm spacing are in good agreement with the 50-mm fitting curve.

The size and shape factors used are 1,65 for 150 by 300 mm sample, 50 mm spacing, while the factor is 2,7 for 20 mm spacing applied on 100 by 200 cylindrical samples.

![Fig. 2: mass loss by drying for concretes of 20, 50 and 60 MPa in compression.](image)

Table 1: $\rho_{app}$ vs. time for standard cured 150 x 300 mm samples (60 MPa concrete)

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>$\rho_{app}$ [Ω.m]</th>
<th>$\rho_{app}$ [Ω.m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5,0</td>
<td>3,71</td>
</tr>
<tr>
<td>5</td>
<td>7,1</td>
<td>5,02</td>
</tr>
<tr>
<td>7</td>
<td>7,2</td>
<td>4,85</td>
</tr>
<tr>
<td>a=20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2: relative resistivity over time for 60 MPa air-dried concrete cylindrical samples, measured with probe spacing of 50 mm (a=50) and 20 mm (a=20).

<table>
<thead>
<tr>
<th>Days of drying</th>
<th>a=50</th>
<th>a=20</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.87</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>0.93</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>0.97</td>
<td>0.92</td>
</tr>
<tr>
<td>9</td>
<td>1.07</td>
<td>1.11</td>
</tr>
<tr>
<td>15</td>
<td>1.14</td>
<td>1.26</td>
</tr>
<tr>
<td>22</td>
<td>1.06</td>
<td>1.28</td>
</tr>
<tr>
<td>28</td>
<td>1.08</td>
<td>1.86</td>
</tr>
<tr>
<td>55</td>
<td>1.19</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Fig. 3: Absolute resistivity evolution for standard cured 60 MPa concrete.

The apparent resistivity was calculated as the mean value from 3 and 4 measurement performed by positioning the Wenner probe along different generatrices of the cylindrical samples. For each case, the coefficient of variation (CV) was calculated and the complete data are shown in Fig. 4. These data correspond to different concretes in the range 20 – 60 MPa, exposed to different situations: early-age, standard curing and different drying regimes, and are grouped by electrode spacing.
5. Analysis and discussion

Electrical resistivity measurement using the 4-points method with the Wenner probe is commonly performed using the 50 mm spacing. This value is reasonable because it comprises a dimension about 2.5 times the maximum size of the coarse aggregate and provides a reliable measure with low dispersion.

Nevertheless, when the measure is aimed at assessing drying of concrete, this spacing seems to be too wide to catch what happens to the outer layers of concrete, as predicted in Fig. 1.

The internal distribution of relative humidity is non-linear, following a profile “similar” to the one predicted by Fick’s law, although the analytical solution of water diffusion cannot be applied as the diffusivity is a function of the humidity content [7]. As a result, drying phenomena are located mainly at the more exposed layers, while internal layers maintain a high humidity content long after curing is finished [8].

When 50 mm spacing is used, only a small portion of the current flows through the outer layers of concrete (the ones that dry-out first) and this effect is intensified by the lower resistivity of the deeper layers, that modifies the current pattern flow [9].

Drying kinetics of concrete strongly depends on its pore structure; in general, the higher the strength, the lesser the porosity and capillary connectivity, thus decreasing the rate of drying. Data shown in Fig. 1 are in agreement with this situation and it is clear that the 60 MPa concrete dries at a lower pace than the others.

Based on these results, the 60 MPa sample was selected to compare whether the closer spacing may provide an earlier assessment of drying. Fig. 5 represents the values shown in Table 2.
The red line in Fig. 5, corresponding to the 20 mm spacing measurements, goes up at about 22 days of drying, while the blue line only shows a slight slope up to 56 days. This difference confirms that reducing the spacing of the electrodes in the Wenner probe provides a tool to increase the sensitivity of the technique to identify the drying of the exposed layers, i.e., the cover zone.

As far as the resistivity measurement is concerned, it is evident from Table 1 that the apparent values measured with different spacing are not comparable. Nevertheless, provided that the specimen shape is cylindrical, the absolute value of electrical resistivity can be calculated from the apparent value by applying a size-shape constant. The application of the constants proposed by Morris et al. [6] for cylinders, leads to very comparable results of electrical resistivity $\rho$, as can be seen from Fig. 3. The curve that represents the evolution of electrical resistivity over time is almost the same for 20 mm and 50 mm spacing.

The use of closer spacing increases the variability of the measurements thus affecting its repeatability, as can be seen in Fig. 4, which shows that red dots, representing the 20 mm spacing measures exhibit a higher coefficient of variation.

Nevertheless, going into more detail in Fig. 4, a centred zone, corresponding to measurement numbers between 28 to about 50, shows a very low dispersion for both 50 mm and 20 mm spacing. These values correspond to measurements made on saturated samples at age greater than 28 days, while the others values, with higher CVs, represent drying samples and earlier stages of cement hydration (early-age measurements). For the latter, heterogeneity in hydration degree and water content through the sample are expected, this issue may also contribute to increase the CV.

Nevertheless, for all cases the CV remains is less than 0.1 (10 %), which is reasonably good for a non-destructive technique.

6. Conclusions

From the results, it is clearly shown that a closer electrode spacing is much more sensitive to identify the drying behaviour of the cover concrete, thus providing a practical tool to on site assessment of curing efficiency.
The use of different spacing than the customary 50 mm requires the identification of the corresponding shape and size factor to determine the absolute resistivity. The abacus proposed by Morris et al [6] has proven be suitable for cylindrical shaped samples. The variability of the measurement increases when decreasing the spacing of the electrodes, but the CV is well kept below 0.1. The use of a reduced spacing may be helpful for on-site measurements where steel bars under the place of testing must be avoided.

7. References

[1] American Concrete Institute, ACI Committee 308 – Concrete Curing