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A new method for *in-situ* measurement of electrical resistivity of reinforced concrete

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ABSTRACT

A new method is described for the *in-situ* measurement of electrical resistivity of concrete structures. The method is based on the early work of J. Newman who calculated the electrolyte resistivity between a disk and a counter electrode located at infinity. This method has the advantage compared with Wenner's of using a single small electrode for the measurements. In this paper, results are presented comparing this method with Wenner's and with results carried out using a conductivity cell in electrolytes. Finally, values of resistivity are compared to corrosion intensity, and a threshold for active corrosion is suggested.

RÉSUMÉ

On décrit une nouvelle méthode de mesure de la résistivité électrique du béton dont la technique est basée sur un travail ancien de J. Newman qui avait calculé la résistivité entre un disque et une électrode auxiliaire placée à l'infini. Comparée à la méthode de Wenner, cette méthode présente l'avantage de n'utiliser, pour les mesures, qu'une petite électrode. Dans cet article, on présente les résultats de la comparaison établie avec la méthode de Wenner et avec les résultats obtenus avec une cellule de conductivité placée dans les électrolytes. Enfin, on compare les valeurs de la résistivité du béton avec celles de l'intensité de la corrosion et on suggère un seuil de corrosion active.

1. INTRODUCTION

The measurement of concrete electrical resistivity started relatively early [1-5]. Properties, such as the amount of water in concrete, pore size distribution or setting rate, were the focus of monitoring by means of this technique. However, in spite of the very promising early expectations, the measurement of resistivity has not achieved its complete development.

The methods most widely used in these experiments at the laboratory level have been: a) specimens with electrodes for direct application of Ohm's law [1- 4]; b) specimens with well-defined geometries where the resistivity is obtained in deriving particular mathematical expressions [5,6], and c) through calculation of the "cell constant" by means of electrolytes of known resistivity [7-11]. Regarding the calculation of concrete resistivity in specimens by direct application of Ohm's law, the need of having a well-defined cross sectional area and distance between electrodes must be constantly stressed. Completely embedded electrodes may not be suitable as they enable a multiple current path (front and back of the electrodes).

In addition to laboratory experiments for testing hydration rates or pore water content, the concrete electrical resistivity has also been subjected to the on-site indirect measurement of corrosion of reinforcements. Stratfull was the first [12] to suggest a relationship between resistivity and risk of corrosion. He established as a threshold value for active corrosion 65 kΩ cm.

Later on, other researchers published results on this subject [7, 13-17] and at present, a scale, given in Table 1, is used for relating the severity of corrosion to resistivity [13-15].

With respect to the on-site methods used in real structures, the most common is the one related to Wenner's [18,19] formula applied to measuring soil resistivity. The application of this method to concrete has had to overcome several difficulties [15], which include: 1) the carbonation of the concrete surface which may

Editorial note
Carmen Andrade and Maria-Cruz Alonso are working at the Instituto Eduardo de Torroja which is a RILEM Titular Member. Dr. Andrade, who was the 1986 RILEM Medallist, have had all these years great responsibilities within RILEM. Chairlady of the Advisory Technical Committee until 1993, she is now a member of the Coordinating Committee. She is active in 116-PCD Technical Committee on Permeability of Concrete as a Criterion of its Durability and has been appointed chairdlady of 154-EMC Technical Committee on Electrochemical Techniques for Measuring Metallic Corrosion. Carmen Andrade has been appointed RILEM Fellow in 1995.

Table 1 – Resistivity values for corrosion risk (kΩ.cm)

Resistivity kΩ.cm	Risk level
> 20	Low corrosion rate
10-20	Low to moderate corrosion rate
5-10	High corrosion rate
< 5	Very high corrosion rate

introduce an additional resistivity; 2) the distance between electrodes and lengths have to be sufficient to refer the measurement to a certain cover depth, and 3) the distance of the measuring point to the rebars, since if they are in the current path, an error is introduced. Modern equipment usually takes into account the first two of these inconveniences, while the third one depends upon each particular structure.

In the present paper, a new method for the on-site measurement of concrete resistivity is described which simply uses the rebar as a counter-electrode and therefore makes the location of the measuring point irrelevant provided a certain cover thickness exists. The method uses a small metallic disc placed on the concrete surface and calculates the cover resistivity by means of a simple equation. Results are also given for the relationship found on-site between resistivity and corrosion rate which does not fit into the scale presented in Table 1, but more closely follows Stratfull's previous work.

2. MEASUREMENT (DISC) METHOD AND CALCULATIONS

This method is based on the work of Newman [20] who estimated the ohmic drop from the resistance, R, between a small disc, WE, of radius a placed at the surface of an electrolyte and a much larger counter electrode, CE, placed at infinity. He demonstrated theoretically that the electrical resistance measured between WE and CE is a function of the resistivity of the electrolyte:

$$R = \rho/4a \qquad (1)$$

This expression is only valid if the contribution of the CE resistance to the total resistance is negligible. This is achieved when the CE surface (rebar) is much larger than that of the WE (disc). The WE can be built with any conductive material and must have a disc shape. This circular geometry requirement has been thoroughly studied in its current flow for different applications: rotating disc [20], anodes for cathodic protection and earth drains [21,22].

Fig. 1 depicts the equipotential lines calculated from Newman's work where the percentages of ohmic drop from the disc, WE, are indicated. Thus, at a distance equal to the disc diameter, the ohmic drop is already at 71%. This means that the ohmic drop is concentrated very near the disc surface and, therefore, the bulk resistance can be accurately measured if the CE (rebars) is placed far enough from the WE (disc).

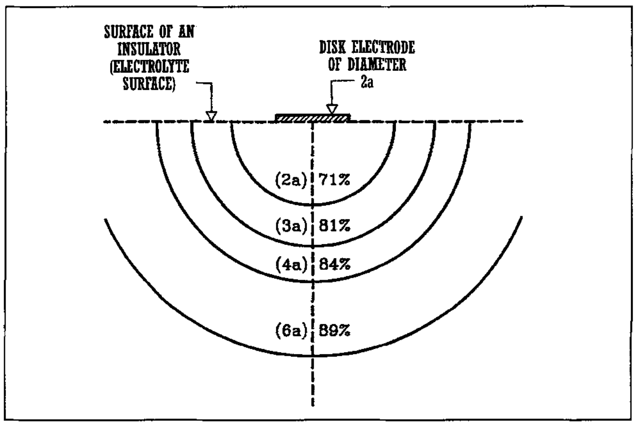

Fig. 1 – Potential lines for a disc electrode. Percentage of ohmic drop between the disc and the equipotential lines at different distances from the electrode.

Although the reinforcement network has not the ideal shape of an equipotential surface, it has been assumed in principle that the method could be applied to measure concrete resistivity if the cover depth is thicker than about twice the diameter of the disc being used as WE.

3. EXPERIMENTATION

The suitability of the disc method for measuring concrete resistivity has been tested by comparing its results with those obtained in liquids or in concrete.

In the *liquid* electrolytes (tap water), the reference value was obtained by means of (see Fig. 2): a) a conductimetric cell connected to a CRISON conductimeter, or b) Wenner's method. For the latter method, a sensor with four electrodes equally separated by 5 cm and of 5 cm in length was built. For the measuring device, a loaded (d.c.) simple-circuit battery was also built. The four electrodes were placed to barely touch the surface of the liquid.

For *concrete* measurements, slabs of 50 x 50 x 7cm in size, with embedded rebars of 8 mm in diameter, were used (Fig. 3). The reference resistivity values were obtained by means of: a) Wenner's method tested on the concrete surface between rebars, or b) the direct application of Ohm's law to the resistance values obtained between the extreme rebars of the slabs (Fig. 3). This resistance was measured by means of the positive feedback of an AMEL potentiostat or through the current interruption technique.

The disc method was applied to the same liquid electrolytes and concrete slabs as before. For the first trials in

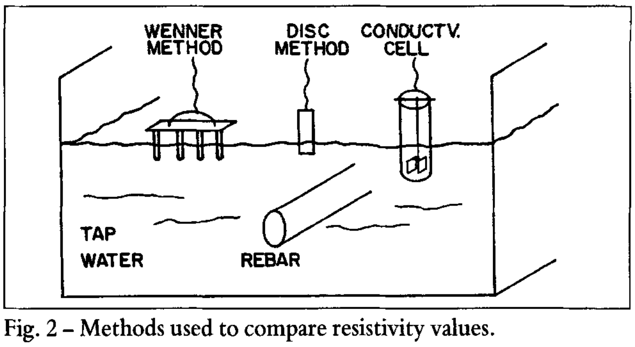

Fig. 2 – Methods used to compare resistivity values.

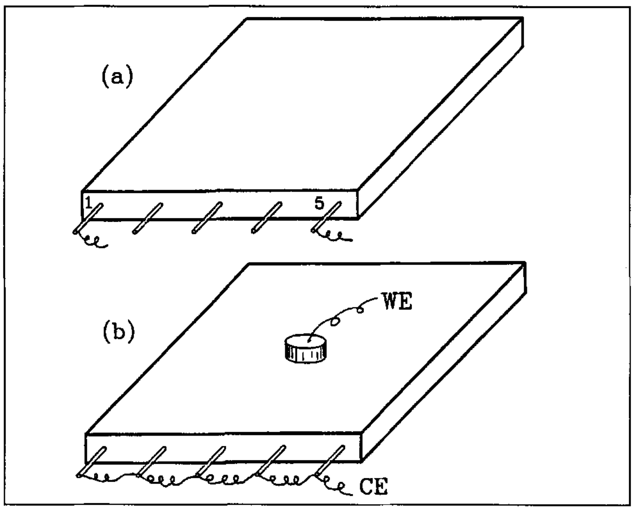

Fig. 3 – Reinforced concrete slab with five steel rods: forms of measuring ρ with a small metallic disc.

the slabs, a metallic disc of different diameters was used. An a.c. current of 1-5 KHertz or the current interruption (d.c.) technique was applied [23].

As soon as the first trials gave promising results, a special electrode was developed and implemented in the GECOR-6 and labelled "Sensor B" [24]. It has a disc of stainless steel of 2 cm in diameter with, in its center, a Cu/SO_4Cu reference electrode in order to obtain an accurate value of the electrical resistance from a galvanostatic pulse by the current interruption technique.

The disc is always placed to barely touch the surface of the liquid or at the concrete surface through a wet sponge. Rebars always act as the counter electrode (Figs. 2 and 3).

4. RESULTS AND DISCUSSION

4.1 Comparative trials on concrete resistivity values

Fig. 4 presents the values obtained in the concrete slabs for different disc diameters. In general, the disc size results are irrelevant. Even with the 5-cm diameter disc (much higher than the cover depth of 3.1 cm), the ρ values obtained by applying equation (1) seem to be correct.

Table 2. Resistivity values (kΩ.cm) obtained through different methods

Test conditions	Conductivimeter	Wenner's method	Ohm's law application	Disc method
Tap water	13	15.2	13.4	14.5
Concrete, no admixtures, very dry	–	4700	–	6500
Concrete with chlorides, wet.	–	22	–	37
Concrete, no admixtures, wet	–	–	26	29
Concrete, no admixtures, very wet	–	–	8.1	7.2
Concrete with Cl^-, very wet	–	–	3.3	3.8

No difference was found either between the measurements using an isolated rebar or when all the rebars were short-circuited.

Table 2 presents the comparative results obtained in both the solutions and the slabs. Only the mean values of several trials are given. The resistivity values obtained by means of the disc method are very similar to the reference values obtained from other sources, thereby showing the ability of this new method in its application to on-site measurements.

4.2 Relation between resistivity and corrosion intensity

As was mentioned earlier, resistivity values are of importance in assessing the residual life of corroding concrete structures. In laboratory experiments, it has already been established that there is a straight-line relationship [9-10] of slope -1 in a log-log plot of Icorr *versus* ρ. The corresponding value for a corrosion rate of 0.1-0.2 $\mu A/cm^2$, considered the boundary between active and negligible corrosion, is around 200kΩ.cm. Above this value the concrete is too dry to enable active corrosion.

The disagreement between this result and the ranges given in Table 1 is interpreted as being due to the lack of real data for on-site corrosion rates. In fact, rebar corrosion rates have started to be measured on-site only recently, since the GECOR-6 device became available [25] and therefore, a reliable scale could not have been established beforehand.

The scale proposed from the present results is given in [24] and shown in Table 3. The values have been derived from Fig. 5, which assembles the results of numerous trials carried out on real-size structures.

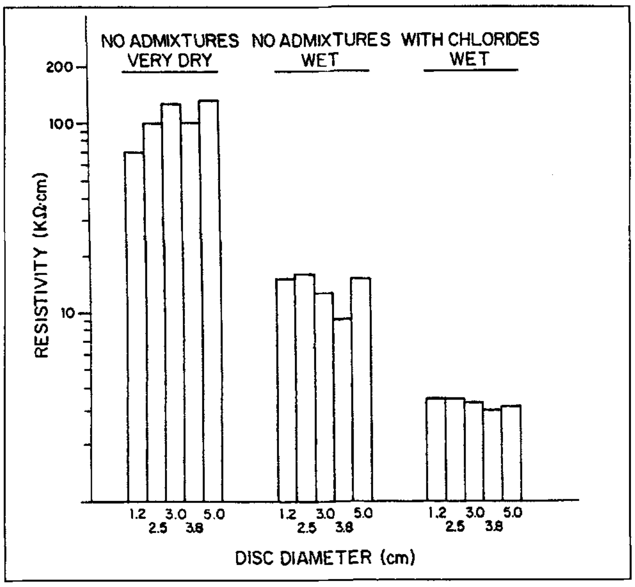

Fig. 4 – Influence of disc diameter on the electrical resistivity values obtained from high-frequency impedance measurements for different concrete conditions.

Table 3. Resistivity values and risk of corrosion

Resistivity kΩ.cm	Risk levels
> 100-200	The corrosion rate values will be very low even if the concrete is carbonated or the chloride contaminated
10-100	Low to high corrosion rate
< 10	Resistivity is not the parameter controlling the corrosion rate.

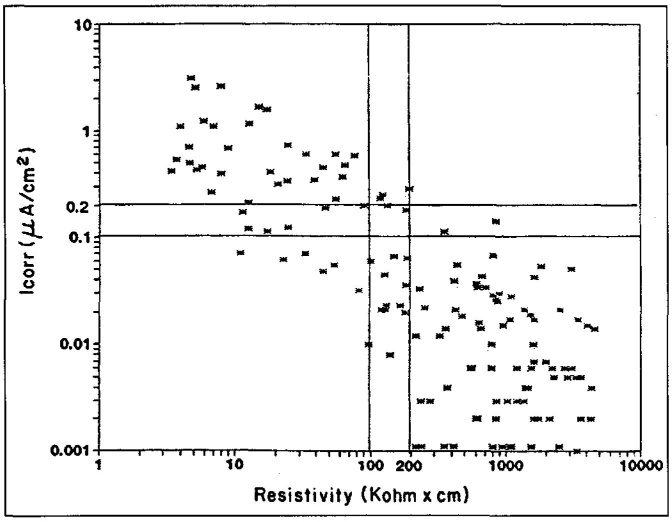

Fig. 5 - Plot of Icorr against concrete resistivity for a great number of real structures examined [25].

5. CONCLUSIONS

The feasibility of using Newman's formula for on-site concrete resistivity measurements by means of a small disc electrode has been presented.

The disc method displays the advantage of using the rebar network as a counter electrode, in addition to being a simple method.

A comparison of resistivity values obtained from real structures, together with corrosion rates, has shown that the threshold between active and negligible corrosion results around 100-200 kΩ.cm, not far from the Stratfull limit given only for chloride contaminated structures.

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