



RILEM TC 154-EMC: ELECTROCHEMICAL TECHNIQUES FOR MEASURING METALLIC CORROSION

Test methods for on site measurement of resistivity of concrete

Prepared by R. Polder, with contributions from C. Andrade, B. Elsener, Ø. Vennesland, J. Gulikers, R. Weidert and M. Raupach

Recommendations

The text presented hereafter is a draft for general consideration. Comments should be sent to the TC Chairlady: Dr Carmen Andrade, Instituto de Ciencias de la Construcción "Eduardo Torroja", Serrano Galvache s/n - Apto 19.002, 28033 Madrid, Spain; e-mail: andrade@ietcc.csic.es, by 30 June 2001.

TC MEMBERSHIP: Chairlady: C. Andrade, Spain; Secretary: B. Elsener, Switzerland; Members: C. Alonso, Spain; R. Cigna, Italy; J. Galland, France; J. Gulikers, The Netherlands; U. Nürnberger, Germany; R. Polder, The Netherlands; V. Pollet, Belgium; M. Salta, Portugal; Ø. Vennesland, Norway; R. Weidert, Germany; Corresponding members: C. Page, UK; C. Stevenson, South Africa.

PREFACE

Reinforcement corrosion is the major threat to the durability of reinforced concrete structures. Although many structures perform very well, various types of structures in particular in the infrastructure, need significant maintenance due to the impact of aggressive environments. Environmental actions are irreversible and aggressive substances build up over the years. Due to adverse combinations of poor design, inadequate execution and aggressive environments, the world-wide spending on maintenance and the impact on the performance of structures are increasing.

RILEM committees have studied reinforcement corrosion in concrete since 1960, which resulted in a successful State-of-the-Art report by TC 60-CSC (1988) and in a Draft Recommendation on Strategies for the Repair of Concrete Structures Damaged by Steel Corrosion by TC 124 (1994). In this document, the importance of condition assessment was pointed out as the first step in the repair process and as a basis for further decisions. Decisions on repair strategies should be based on knowledge of:

- the cause of damage or loss of protection
- the degree and amount of damage
- the expected progress of damage with time
- the effect of damage on structural behaviour and serviceability.

The most widely used assessment method is visual inspection, which at best allows to describe and quantify the damage. Traditionally, intrusive testing is used to reveal the causes of corrosion with a normally limited possibility to take samples. Non-destructive test methods have become valuable additions to the repertoire. They should work rapidly and allow to cover the complete surface of a concrete member. They should detect the main causes of corrosion, the condition of the steel, the sensi-

tivity for loss of protection or the severity of corrosion. Most non-destructive tests are electrochemical methods: potential mapping, polarisation resistance testing, concrete electrical resistance measurement. Embedding probes allows to monitor various factors involved in corrosion and environmental influences. To address these items, RILEM has set up TC 154-EMC on Electrochemical Techniques for measuring Corrosion of Steel in Concrete. Through its existence, TC 154 has set out to prepare RILEM Technical Recommendations on:

- Half cell potential measurements
- Test methods for on-site corrosion rate measurement of concrete reinforcement by means of the polarisation resistance method
- Test methods for on site measurement of resistivity of concrete
- Embedded probes for corrosion.

The present document intends to describe methods to assess concrete resistivity on site for various purposes related to corrosion and protection of steel reinforcement.

1. SCOPE

This RILEM Technical Recommendation intends to give a general description of methods to assess concrete resistivity on site for various purposes related to corrosion and protection of steel reinforcement. In addition, it provides background, technical details and a guideline for the execution and interpretation of measurements of concrete resistivity on site.

When new structures are designed and built, resistivity probes may be embedded. In addition to monitoring chloride content, steel potential or corrosion rate, the resistivity is measured periodically during the lifetime; together they may indicate the risk of corrosion of the

embedded steel. However, this is beyond the present scope. For structures without embedded probes, the resistivity can be measured non-destructively using electrodes placed on the concrete surface. Together with other information the corrosion risk can be determined. This Recommendation describes in detail methods to determine concrete resistivity on site.

The resistivity of cement-based materials (concrete) is a function of porosity (inherent, time dependent materials property), the chemical composition (conductivity) of the solution in the pores and the number and distribution of pores filled with solution as a result of the interaction with the environment. Based on these three aspects, the electrical resistivity of a given concrete structure or element may give information related to corrosion of embedded steel in the initiation as well as in the propagation period.

2. SIGNIFICANCE AND USE

The electrical resistivity of concrete is a materials property that may be useful for monitoring and inspection of concrete structures with regard to reinforcement corrosion in combination with other non-destructive techniques, *e.g.* potential mapping and corrosion rate.

The resistivity of a given structure exposed to chloride load gives information about the risk of early corrosion damage, because generally a low concrete resistivity is correlated to rapid chloride penetration and to a high corrosion rate. In addition resistivity mapping may show the most porous spots, where chloride penetration is likely to be fastest and future corrosion rates will be highest; preventive measures may be taken accordingly. After damage occurs, resistivity is relevant for possible maintenance actions as well: electrochemical repair methods are influenced by concrete resistivity and its variation over the structure.

Resistivity does not show whether steel in concrete is in an active state of corrosion or not. That information must be obtained in another way: from chloride analysis, carbonation depth measurement, potential mapping, polarisation resistance measurement and visual inspection of the steel. If the steel is actively corroding, resistivity measurements may give additional information: it may show where in the structure corrosion may be strongest. In general terms and within one structure, relative corrosion rates can be predicted. The choice between local or more general repair measures can be related to the variation of the corrosion rate, as deduced from resistivity measurements.

Resistivity measurements (from the concrete surface) can be performed on all parts of concrete structures that are exposed to air. It cannot be measured on buried or submerged parts. Resistivity measurements can be used at any time during the service life of a concrete structure and under any circumstances, provided the temperature is higher than 0°C.

Resistivity measurements may be useful for the following purposes:

- to assess the (range of) value(s) of the concrete resistivity of a particular structure, in order to estimate the risk of corrosion in case passivation will be (or has been) lost
- to locate the most permeable parts of a structure, in order to define further investigations or protective measures
- to locate spots with the most severe exposure to water and dissolved aggressive species
- to help design systems for cathodic protection and other electrochemical treatments
- quality control of concrete in the production phase.

3. DEFINITIONS

Concrete resistivity is the ratio between applied voltage and resulting current in a unit cell that is a specific geometry independent material property, which describes the electrical resistance. The dimension of resistivity is resistance multiplied by length, its unit is usually Ω m (ohm meter).

Conductivity is the inverse of resistivity.

4. THEORETICAL BACKGROUND

4.1 General

The electrical resistivity of concrete may vary over a wide range, from 10^1 to 10^6 Ω m, mainly influenced by the moisture content (environment) and the composition (material) of the concrete, as was shown by Gjorv & Vennesland [20] and Tuutti [42]. In concrete, electrical current is carried by ions dissolved in the pore liquid. More pore water (wet concrete) as well as more and larger pores with a higher degree of connectivity and a lower tortuosity (high w/c) cause a lower resistivity. For a constant relative humidity and in stationary conditions, resistivity is increased by a lower water to cement ratio (w/c), longer curing times (hydration) or by the addition of reactive minerals such as blast furnace slag, fly ash and/or silica fume. The resistivity of concrete increases when the concrete is drying out and when the concrete carbonates (in particular in Portland cement concrete). Carbonation reduces the amount of ions available for carrying the current and may densify the concrete. For non-carbonated concrete, the effect of the penetration of chloride ions on the resistivity is relatively small.

Because the current is transported only by the ions of the pore liquid in the cement paste, concrete is not a homogeneous conductor. Aggregate particles are essentially isolating bodies. The coarse aggregate may have a similar size as the concrete cover to the steel or the spacing of measuring electrodes. Consequently, on the scale of centimetres, the current flow is non-homogeneous. With measuring electrodes far apart, the current flow will be more homogeneous. Local disturbances of homogeneous current flow may be also due to a different resistivity of the surface concrete layer and to the presence of steel bars.

4.2 Temperature dependence

Temperature changes have important effects on concrete resistivity. A higher temperature causes the resistivity to decrease and vice versa (for a constant relative humidity). This is caused by changes in the ion mobility in the pore solution and by changes in the ion-solid interaction with the cement paste. As a first approach an Arrhenius equation can be written to describe the effect of temperature on conductivity:

$$\sigma(T_i) = \sigma(T_0) * \exp(b [T_0^{-1} - T_i^{-1}]) \quad (1)$$

with

σ the conductivity	[1/ Ω m]
T_0 the reference temperature	[K]
T_i the actual temperature	[K]
b an empirical factor	[K].

For steady state conditions, b was found to be in the range of 1500 to 4500, [7, 8, 11, 16], and:

- to increase with decreasing relative humidity for a given cement paste, mortar or concrete
- to decrease with w/c ratio of the mix for a given relative humidity.

The temperature dependence of the conductivity of bulk pore solution differs significantly from that of cement paste or mortar with the same ion concentration in the pores [7]. This is due to strong ion-solid interactions. The humidity dependence of the temperature exponent in cement paste or concrete can be explained by the fact that at lower RH the pore solution becomes more concentrated and is present in more narrow pores, so the ratio of pore wall surface area to liquid increases and consequently the degree of interaction between ions and solid increases. These interactions may be different for cements with different chemical compositions (slag, fly ash cement).

From the foregoing, it will be clear that accurate temperature correction of resistivity data is very complex. The concrete composition and the moisture content both influence the resistivity itself and its temperature dependence. For simplicity, it may be assumed that in the range of 0°C to 40°C, doubling of resistivity takes place for a 20°C decrease, or that a change of 3% to 5% per degree occurs.

4.3 Concrete resistivity and corrosion rate

From the electrochemical nature of the corrosion process, a relationship may be expected between the resistivity of concrete and the corrosion rate of reinforcement after depassivation. In the corrosion cell circuit, the (hydroxide) ion transport between anode and cathode is one of the rate controlling factors [21, 37]. An alternative view is that a low resistivity increases the anodic (dissolution) process [21]. Using a simplified approach based on the work of Bazant [6], the corrosion rate of depassivated steel in concrete should be inversely proportional to the resistivity of the concrete. This was confirmed in a general sense [1, 3, 21]. Further work has shown indeed that this relationship may be dependent on concrete composition [7, 19]. In any case, within a

given structure (after passivation has been lost), it is likely that areas with low resistivity will have a higher corrosion rate than areas with high resistivity.

4.4 Concrete resistivity and chloride penetration

From theoretical and experimental work there appears to be a relationship between resistivity of and chloride diffusion in a particular concrete composition [2, 33, 35]. For example, concrete with a high percentage of blast furnace slag has a high resistivity and a low chloride diffusion coefficient. Complete quantitative evaluation may require knowing the pore water conductivity [5] and information on chloride binding (and other ion-solid interactions).

In practical terms:

- within a particular existing structure, more permeable areas will have a comparatively lower resistivity and stronger chloride penetration
- for a new structure to be exposed to chlorides, a minimum resistivity can be specified based on the empirical relationship between resistivity and chloride penetration and when the concrete is produced, the resistivity may be measured of each day's production as part of the quality control system.

4.5 Concrete resistivity and carbonation

In OPC concrete, carbonation induces a significant increase of resistivity. When exposed to sufficiently wet conditions, the corrosion rate of steel in carbonated concrete may be comparatively high, following the general correlation between inverse resistivity and corrosion rate [21].

4.6 Concrete resistivity and electrochemical maintenance methods

Concrete resistivity is an important factor in the effectiveness and durability of cathodic protection (CP) systems applied to chloride contaminated structures [23, 30, 34]. Similarly resistivity is important for electrochemical chloride removal and realkalisation [31]. For a large variation in resistivity within a structure it is more difficult to obtain uniform protection (CP) or a well-predicted result (chloride removal, realkalisation). In practice, parts of structures with different resistivities (either due to different concrete composition or different exposure conditions) should be placed in separate electrical zones in order to achieve sufficient control of current flow. Theoretical work in this area was reported by Hunkeler and Holtzhauer [24]. Repair mortars used in connection with electrochemical techniques should have a similar resistivity to that of the old concrete [9, 36]. Differences in resistivity in the material or different resistance between anode and reinforcement can be accepted to a certain degree; the resulting difference in current density may have a positive effect: where conditions are more corrosive, a stronger current will be flowing.

5. METHODS FOR ON SITE MEASUREMENT OF CONCRETE RESISTIVITY

5.1 Basic aspects of on site measurement of resistivity

All methods for on site measurement of concrete resistivity involve at least two electrodes, of which one may be a reinforcing bar. A voltage is superimposed between the electrodes and the resulting current is measured (or vice versa). The ratio gives a resistance (in Ω). The resistivity is obtained by multiplying the measured resistance by a geometrical conversion factor, called the cell constant (in m). For a given test geometry the cell constant can be obtained in various ways, either from theoretical considerations or from calibration using either standard concrete samples or electrolytes of known resistivity. For comparative purposes such as monitoring changes in time, using the resistance is sufficient.

The assumption of converting the measured resistance to a resistivity value is valid only for a homogeneous material. Instead, concrete usually contains steel rebars and may show different resistivity distributions as a function of the depth to the surface. The surface layer may be carbonated or strongly dried out, resulting in a higher resistivity than the concrete bulk. On the other hand, shortly after rain, a surface layer may have a lower resistivity than the bulk. When using a four-probe method, these effects may be minimised by placing the measuring electrodes at a larger distance. However, this is less favourable with regard to the influence of rebars. The effect of a carbonated surface layer is not very large, provided its depth is less than the electrode spacing, in practice if it does not extend beyond the reinforcement [26]. Possibly more strict boundary conditions apply [22].

5.2 Four-point method

On site, the resistivity can be measured using a probe according to Wenner, consisting of four equally spaced point electrodes that are pressed onto the concrete surface (4-point method), illustrated in Fig. 1. The two outer point electrodes induce the measuring current (usually AC with a frequency between 50 and 1000 Hz, normally sinusoidal) and the two inner electrodes measure the resulting potential drop in the electric field. The resistance is the ratio of the voltage and the current. This method has long been known and used for determining soil resistivities [44], and was studied for the application to concrete structures by Stratfull [40] and Naish and co-workers [28].

The resistance R calculated from the four-point measurement can be converted to resistivity ρ using a cell constant based on theoretical considerations by:

$$\rho = 2 * \pi * a * R \quad (2)$$

with a the electrode spacing. This formula applies in principle only for homogeneous semi-infinite volumes of concrete and infinitely small electrode points. The

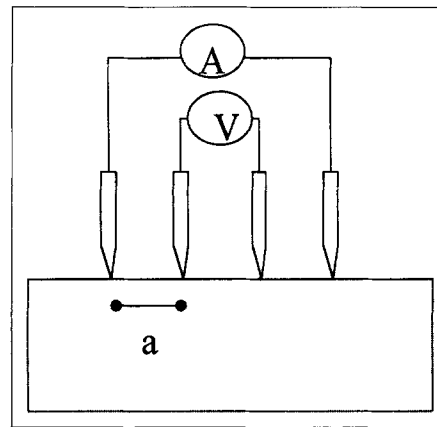


Fig. 1 – Setup of four-electrode measurement of concrete resistivity.

applicability of this formula has been shown by Millard [26] and Elsener [12]. Elsener studied concrete blocks with 200 mm thickness using electrodes with a spacing varying from 20 to 100 mm. Electrode spacing from 20 to 80 mm gave the same resistivity with a maximum error of 20%. A good correlation was found between calibrated data measured with cast in electrodes and 4-point resistivity obtained from the surface over a wide range of values. From laboratory tests on various specimens [43, 45] it was shown that the “true” resistivity was obtained within an error of 25%.

Because rebars conduct current much better than concrete, they will disturb homogeneous current flow. In extreme cases (four probes on top of one rebar), an artificially low resistivity is measured. Measuring over bars at 10 or 20 mm depth, errors can be made of a factor 2 to 6 [45]. However, even if only one of the four electrodes is near a bar, current flow will be far from ideal and erroneous results may be produced. The measured result may be artificially low or high, depending on which electrode is near a rebar. To minimise this effect, none of the measuring electrodes should be placed above or near rebars. With the usual rebar spacing this causes the need to place the measuring electrodes quite close. This may be conflicting with the objective to have the electrodes far apart in order to avoid effects of aggregate particles. Measuring errors resulting from the contact resistance between the electrodes and the concrete is discussed by Ewins [17] and several other sources of error by Millard [26]. A practical compromise appears to be an electrode spacing of 30 to 50 mm.

5.3 Methods involving the rebar network as one electrode

A possible method is to place one metal electrode on the concrete surface and to measure the resistance between this electrode and the reinforcement. This requires a connection to the reinforcement cage and full steel continuity. The method is illustrated in Fig. 2 and is actually a 2-electrode type of measurement.

The conversion of the measured resistance between disc electrode and steel bar, $R(\text{disc-bar})$, into resistivity ρ according to:

$$\rho = k * R(\text{disc-bar}) \quad (3)$$

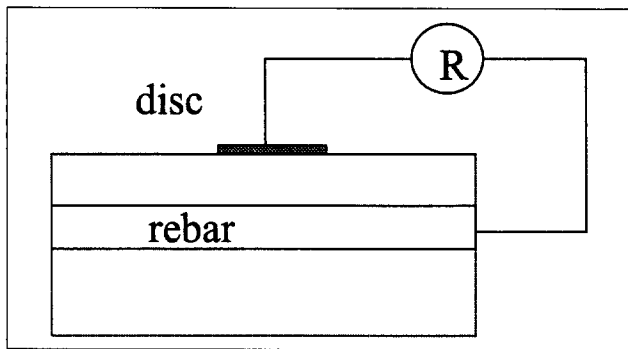


Fig. 2– Setup of one electrode (disc) measurement of concrete resistivity.

is more complex than for the four-point measurements, because the cell constant k depends on disc size, concrete cover, rebar spacing and rebar diameter. For disc sizes smaller than the distance to a large electrode (the rebar system), Feliu *et al.* [18] have shown that the resistivity is given by:

$$\rho = 2 * a * R(\text{disc-bar}) \quad (4)$$

with a the diameter of the disc (in m).

In practice, this may require that the disc is not placed immediately over the rebars, but at some distance, for instance in the middle of the rebar mesh. This is particularly necessary if the cover depth is low or the disc diameter is more than 10 to 20 mm.

For large disc electrodes the magnitude of the cell constant is different. Using a disc of 200 mm diameter, calibration with the four-point method was carried out [13] on a reinforced concrete wall with quite homogeneous cover and rebar network. For resistivities in the range from 200 to 1500 Ω m, the cell constant was about 1.5 m.

5.4 Other arrangements

Concrete resistance can be measured also using two electrodes placed on the concrete surface. Compared to the one-electrode method, this will avoid the need to make electrical contact to the reinforcement. The presence of rebars will disturb this measurement as described for the four-point method above. Because the amount of current running (for a fixed voltage) depends on the size of the contact between electrode and concrete [26], the method is more sensitive to variations in the execution than other methods described above. For a given electrode diameter and precise operation, this method may give good resistance results. Conversion to resistivity is not recommended.

6. PRACTICAL EXECUTION

6.1 Apparatus

The apparatus consists of a measuring instrument, one or more probes and cables to connect them.

6.1.1 Measuring instruments

Instruments for measuring concrete resistivity on site may be:

- earth resistance meters (for 4-electrode methods)
- regular resistance meters (for 2-electrode methods)
- parts of other instruments, like ohmic drop compensation circuits in potentiostats or frequency analysers.

The resistance meters shall apply sinusoidal current of frequencies between 50 Hz and 1 kHz, or other signal forms if their suitability is demonstrated. The electrolytical resistance of concrete does not seem to depend significantly on frequency in this range.

One manufacturer uses a square waveform with 13 Hz and fast sampling at a particular point in the cycle, based on advanced circuit analysis [17].

DC instruments (like simple multimeters) shall not be used, because the direct current will induce electrode polarisation which may cause serious errors.

6.1.2 Probes (electrodes)

According to the measuring method, a probe consists of one or more electrodes. For one-electrode measurements, the instrument shall have a good electrical contact to the reinforcement (less than 1 Ω). For four-electrode probes, the electrodes shall be firmly fixed to keep their spacing constant.

6.1.3 Contact between electrodes and concrete

Each electrode shall make contact with the concrete surface via a conducting electrolyte, usually in the form of a wetted sponge or a wetted wooden plug. If the concrete is dry, it will strongly absorb contact liquid and frequent wetting of the plugs is necessary. The presence of a water film on the surface should be avoided. Extensive pre-wetting the surface is not recommended because it may change the bulk concrete resistivity.

6.1.4 Cables and connections

All resistivity measurements are sensitive to poor conduction of cables and connections. All cables and connections shall be checked carefully before making measurements. A resistance of less than 1 Ω is usually taken as indicating good electrical connection.

6.2 Calibration and standardisation

6.2.1 Procedure

In the laboratory, four-electrode probes, disc probes and instruments must be calibrated by placing them with the electrode tips just in contact with liquids of known conductivity. The container shall measure at least 200 × 100 mm² surface area and at least 100 mm deep for electrode distance 30 mm and 200 mm deep for electrode distance 50 mm. Similarly, disc-electrode arrangements can be calibrated using a container filled with electrolyte solution.

True calibration is very difficult however to be performed in the field. A reasonable indication of good operation of the equipment can be obtained as follows.

Disc method (one electrode): the electrode is placed on a sheet of metal via the wetted sponge such as will be used on the concrete. The resistance is measured between the electrode and the metal sheet. The value shall be less than 10 Ω. If a higher resistance is measured, cables, connections and the wetting of the sponge shall be checked until < 10 Ω is measured.

Four-electrode method: the probe is placed with all four electrodes touching a metal sheet via their wooden plugs. The resistivity is measured in the normal way, and the reading shall be less than 1 Ω or 1 Ω m (depending on the instrument readout).

6.2.2 Standard reference measurement

Reference measurements shall be carried out on laboratory specimens of sufficient size. A possible procedure is as follows.

Concrete cubes are cast with a rib length not less than 150 mm and preferably 200 mm, with aggregate not larger than 32 mm. The current distribution should not be limited by the borders of the cube in order to have similar current distribution in the laboratory and when measuring on real structures. Cement type may be ordinary portland cement or different (see below). The cubes shall be stored in a fog room for at least four weeks. For calibration measurements, cubes are taken from the fog room, their surface is dried with a cotton cloth and they are exposed to dry laboratory air for 10 minutes to one hour, in order to have the surface loose its film of water. For calibration, the resistivity is measured in two steps:

- with metal plates pressed to two opposing (mould) surfaces via wetted cloth (see Fig. 3)
- with the four-point probe diagonally over the four vertical mould surfaces.

The “true resistivity” is calculated from the measurement with the two plates using a geometrically calculated cell constant (= area/length) by

$$\rho_{\text{concrete}} = R_{\text{measured}} * A / L \tag{5}$$

with ρ_{concrete} is the resistivity (in Ω m), R_{measured} the resistance between the plates (in Ω), A the area of the cube faces (in m²) and L the length of the cube (in m), and the four-electrode measurement is calibrated by equating A/L to 2 * π * a (Equation (1)).

For calibrating disc-electrode measurements the pro-

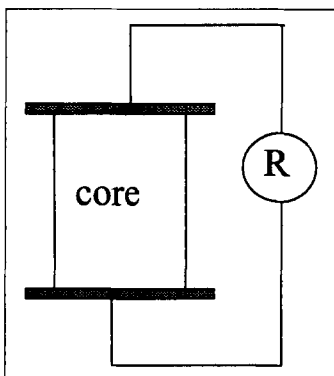


Fig. 3 – Resistivity determination of a concrete core or cube.

cedure may be as follows. Cubes are cast as described above. Resistivity is measured using steel plates as described above. Slabs are cast with reinforcing bars at two or more cover depths. The measuring electrode is placed on the concrete surface and resistance is measured. The “true resistivity” is calculated from the measurement on the cubes with the two plates. The disc-electrode device is calibrated by equating A/L to 2 * a (Equation (4)).

If measurements have to be carried out on concrete with particular high resistivity, it may be recommended to cast calibration specimens with high resistivity, for example by using cement with a high percentage of blast furnace slag (70%) fly ash (30%) or silica fume (10%).

It is emphasised that calibration measurements shall always be carried out on wet concrete (surface dry).

6.3 Precision and bias

Considerable scatter is present in most sets of resistivity measurements, even if they concern four-point data from laboratory specimens cast from the same mix and exposed to the same environment. In any set of measurements on the same concrete in the same conditions, coefficients of variation of 10% are good and 20% must be considered normal. In the field, a coefficient of variation of 30% is normal.

6.4 Measurement procedure

6.4.1 Concrete conditions and surface preparation

Concrete shall be clean and in particular free from oil and other types of contamination.

Before measurements are taken, the concrete surface may be wetted slightly to improve the contact, for instance by quickly moving a soaked sponge over the area to be measured. Strong wetting will influence the resistivity, which shall be avoided if the resistivity under the prevailing conditions must be obtained.

Sponges and wooden plugs shall be kept moist, which may require frequent wetting as the concrete may absorb the wetting solution (from wooden plugs in particular), thus preventing sufficient contact.

Because temperature has a significant effect on concrete resistivity, it is recommended to avoid measuring in very hot and very cold weather conditions. In all cases, the surface temperature of the concrete shall be measured and reported.

6.4.2 Procedure

For one-electrode measurements a simple procedure (with relatively poor precision) is as follows:

- locate the rebars (using a magnetic cover meter)
- expose rebars on at least two spots, check electrical continuity and make a firm connection to the reinforcement
- wet the surface if considered necessary
- measure the resistance with the disc electrode at 5 to 10 closely spaced spots, record the values and take the median as the reading for that position

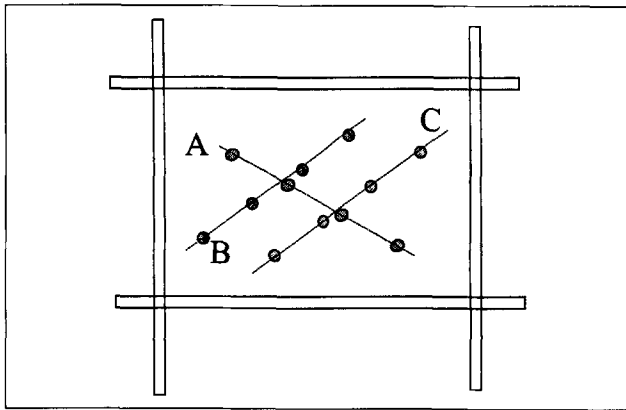


Fig. 4 – Taking resistivity (four electrode) at various spots in the same area to minimise influence of rebars.

– calculate the resistivity using the estimated cell constant using Equation (4).

For four-electrode measurements the procedure is as follows:

- locate the rebars using a cover meter and mark the rebar mesh
- wet the surface if considered necessary
- measure with the four electrodes as far from the rebars as possible, usual diagonally inside the rebar mesh (see Fig. 4), and take five readings from the same position, moving the electrodes at least a few mm between each reading
- record all five readings and take the median as the reading for that position
- calculate the resistivity using the theoretical cell constant from Equation (2).

6.4.3 Selection of measurement locations

Measurements shall be carried out on areas which are representative with regard to the following aspects:

- concrete composition
- exposure (wetting by rain and splash or sheltered, orientation to prevailing winds)
- importance of structural element.

Within each area, sufficient measurements must be taken to get a representative set of data. This may include the average resistivity but also the variation. For resistivity mapping with the four-electrode technique, a grid spacing of 1 m is usually suitable [26].

6.5 Complementary tests: additional samples for laboratory testing

It may be useful to take core samples from the structure and expose them in the laboratory in standardised saturation conditions to determine the resistivity. Furthermore, core samples can be analysed to determine the cement type and further compositional details.

Core samples taken from the structure are exposed in a fog room or saturated under vacuum and the resistivity is measured by using metal plates (see Fig. 3) to determine its value in saturated conditions. Obtaining saturation may require a long time, in particular for very dense concretes. However, imperfect saturation does not make a large difference, as long as the wider pores are filled. For cores the resistivity is calculated by:

$$\rho_{\text{concrete}} = R_{\text{measured}} * B / L \tag{6}$$

with ρ_{concrete} is the resistivity (in $\Omega \text{ m}$), R_{measured} the resistance between the plates (in Ω), B the area of the core face (in m^2) and L the length of the core (in m).

In some cases, it has been useful to expose cores in a climate room with other than saturated conditions in order to obtain resistivity values representative of more sheltered conditions. This can be achieved by storing the cores in chambers with controlled humidity and temperature, for instance 20°C and 80% Relative Humidity. Over some time (preferably months or alternatively until constant weight is achieved) resistivity is measured as described in previous paragraphs.

Complementary tests can be carried out on cores, supporting the interpretation of resistivity values. For instance cement type and further compositional information can be determined using polarising and fluorescence microscopy (PFM).

7. INTERPRETATION AND USE OF RESULTS

7.1 General

To take full advantage of resistivity data measured on a structure, they should be compared to reference data of similar concrete types. In Table 1, some reference data are given, depending on cement type and exposure,

Table 1 – Global reference values at 20°C for the electrical resistivity of dense-aggregate concrete of existing structures (age > 10 years); conditions between [] are the comparable laboratory climates		
Environment	Concrete resistivity ρ_{concrete} ($\Omega \text{ m}$)	
	Ordinary Portland cement concrete (CEM I)	Blast furnace slag (> 65% slag, CEM III/B) or fly ash (> 25%) cement or silica fume (>5%) concrete
Very wet, submerged, splash zone, [fog room]	50 - 200	300 - 1000
Outside, exposed	100 - 400	500 - 2000
Outside, sheltered, coated, hydrophobised [20°C/80%RH], not carbonated	200 - 500	1000 - 4000
ditto, carbonated	1000 and higher	2000 - 6000 and higher
indoor climate (carbonated), [20°C/50%RH]	3000 and higher	4000 - 10.000 and higher

derived from various laboratory studies. The variations given within each group (e.g. CEM I, very wet: 50 - 200 Ω m), are caused by variation of water-to-cement ratio and chemical cement composition [10, 29]. In view of the discussion of temperature effects on resistivity, it is important to realise that these reference values have been obtained during exposure at 20°C.

7.2 Meaning of absolute values

The absolute value of resistivity measured on a structure can be interpreted as follows. If the cement type is known, the observed resistivity is compared to the reference value for that cement type and for the appropriate exposure conditions. If for example, a wet structure made with OPC has a mean measured resistivity of 50 Ω m, it means that the water-to-cement ratio must be quite high. The risk of corrosion is relatively high if factors for depassivation are present (e.g. exposure to de-icing salts).

As discussed before, resistivity data must be corrected for temperature effects. In general, a decrease in temperature of about 20°C doubles the measured resistivity, if all other factors remain constant (see 4.2). If concrete cores are taken and exposed in a laboratory, temperature correction can be made more accurately.

7.3 Mapping for moisture content, homogeneity, etc

If the concrete composition is relatively homogeneous, mapping resistivity may show wet and dry areas. If an OPC structure has resistivity values between 100 and 500 Ω m, the extreme values can be interpreted as indicating relatively wet and relatively dry areas.

If on the other hand, the exposure (so the moisture content) is homogeneously wet, variations in resistivity (say from 50 to 200 Ω m) can be interpreted as caused by local variations in water-to-cement ratio. Areas with 50 Ω m will be more susceptible to penetration of chloride from the environment than areas with 200 Ω m.

7.4 Relationship to corrosion rate measurements

The relationship between concrete resistivity and corrosion rate is still subjected to study. However, as a general rule some reference can be given. Table 2 shows

Concrete resistivity ρ_{concrete} (Ω m)	Risk of corrosion
< 100	high
100 - 500	moderate
500 - 1000	low
> 1000	negligible

suggested interpretation of resistivity values with regard to corrosion risk for OPC concrete. As before, it must be emphasised that the values refer to 20°C.

8. DATA PRESENTATION REPORT

The report must contain:

- date of testing
- description of the structure and individual measurement locations
- the weather conditions (temperature, humidity) at the time of testing and preferably over a few days before testing
- the measuring method used and calibration data
- the measuring grid used
- the results of the measurements, preferably with maps or location sketches.

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