Merlin

Purpose

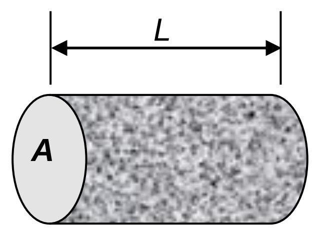
Merlin is used to measure the **bulk electrical resistivity,** or its inverse, the **bulk electrical conductivity,** of saturated specimens or cores. This test is governed by **ASTM C1876** "Standard Test Method for Bulk Electrical Resistivity or Bulk Conductivity of Concrete". The operation is simple and a measurement is obtained within two seconds. The conductivity of a saturated concrete specimen provides information on the resistance of the concrete to penetration of ionic species, chloride ions for instance, by diffusion. The term **bulk** is used to indicate that the measurement is made through the specimen as opposed to a surface-based measurement.

Merlin can be used for the following purposes:

- Research and development to characterize the influence of new materials on the electrical resistivity of concrete.
- Optimizing mixture proportions and blends of supplementary cementitious materials to increase concrete service life.
- On-site durability quality control and quality assurance.
- Evaluation of in-place concrete (using cores).

Principle

The electrical resistance ***R*** of a conductor of length ***L*** and uniform cross-sectional area ***A*** is given by the equation shown in the figure to the right. The quantity **ρ** is the **electrical resistivity** and is a material property, with units of resistance multiplied by length, such as ohm·m. If the electrical resistance ***R*** of a specimen of length ***L*** and area ***A*** is measured, the resistivity can then be calculated as **ρ = *R A/L***. The inverse of electrical resistivity is the electrical conductivity, **σ = 1/ρ**. The inverse of ohms is a unit called siemens (S). Therefore, electrical conductivity has units of S/m. For concrete, it is convenient to express electrical conductivity in millisiemens per meter or mS/m.



$$R = \rho \frac{L}{A}$$

In assessing the ability of a concrete mixture to resist penetration of a particular type of ion, one of the key properties is the **diffusivity**, which defines how readily that ion will migrate through saturated concrete in the presence of a concentration gradient. For a saturated porous material, such as concrete, the diffusion coefficient of a given type of ion can be related to electrical conductivity through the **Nernst-Einstein equation** as follows (Snyder et al. 2000; Nokken and Hooton 2006):

$$\frac{\sigma}{\sigma_p} = \frac{D}{D_w} \qquad (1)$$

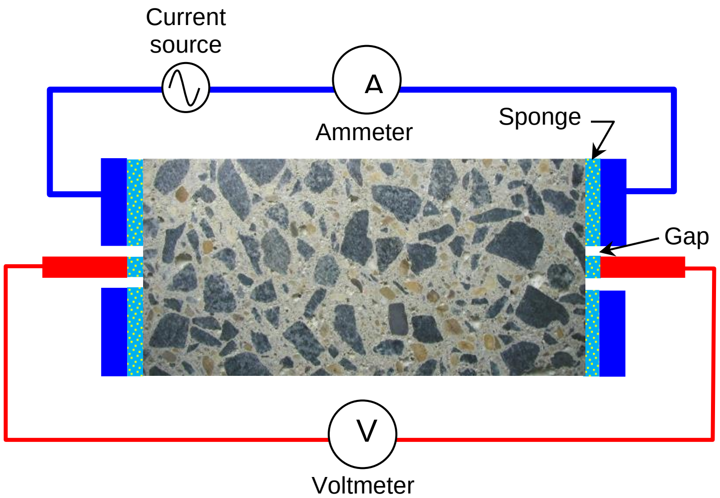
where σ = bulk electrical conductivity of the saturated porous material
σ_p = conductivity of the pore fluid
D = bulk diffusion coefficient of the specific type of ion through the porous material, and
D_w = diffusion coefficient of the specific ion through water (Mills and Lobo 1989).

If the conductivity of the pore fluid is assumed to be similar among different concretes, the measured bulk electrical conductivity is related directly to the bulk diffusion coefficient (Berke and Hicks 1992). Measurement of the bulk diffusion coefficient of a particular type of ion through concrete is a time-consuming process, while electrical conductivity can be measured with **Merlin** in a matter of seconds.

The electrical conductivity of saturated cement paste is related to the volume of pores and how they are connected within the paste. The paste porosity is related to the water-cement ratio (w/cm), the types of supplementary cementitious materials (SCMs), and the degree of hydration. For the same *w/cm* and degree of hydration, the use SCMs reduces pore size and increases the tortuosity of the pores and, thereby, reduces electrical conductivity and the ease of fluid penetration.

Method of operation

The **four-point** measurement method that is used provides an accurate measure of specimen resistance by minimizing the effects of the conductive sponges and the pressure applied to the electrodes.



An alternating current (325 Hz) is applied through the saturated specimen or core. A voltmeter measures the voltage drop across the specimen, and an ammeter measures the current through the specimen. From the measured current *I* and voltage *V*, the bulk conductivity is calculated as follows:

$$\sigma = \frac{I}{V}\frac{L}{A} \qquad (2)$$

The bulk **resistivity** is the inverse of the bulk conductivity, $\rho = 1/\sigma$.

A 100 by 200 mm verification cylinder is supplied to check that the **Merlin** system is operating correctly. The cylinder includes a switch to select one of several precision resistors from 10 Ω to 1 MΩ and the **Merlin** should display the right conductivity and resistivity values for each of these resistors.

Application

Measuring the bulk electrical conductivity also provides an indication of the diffusivity properties of the concrete. If the test is conducted at a consistent degree of hydration for a given combination of cementitious materials, the variation in measured bulk electrical conductivity can be used as an indicator of variation of *w/cm* using a pre-established correlation. If the conductivity of the approved concrete mixture for a project is known, that value can be used for quality control and quality assurance. Thus **Merlin** can be considered as a **surrogate test** to verify the *w/cm* of a specimen.

The bulk conductivity measured with **Merlin** is related directly to the charge passed through a specimen as measured by ASTM C1202 using the **PROOVE'it** system (see data sheet), provided that the current remains constant during the 6 h test duration. This is typically not the case for highly conductive concretes due to electrical heating of the specimen, which increases the pore fluid conductivity and the current. If we assume, however, that current is constant during the test, we can convert the ASTM C1202 coulomb limits for the different categories of "chloride ion penetrability" into bulk conductivity limits using the following relationship:

$$\sigma = \frac{Q\,L}{V\,t\,A} \qquad (3)$$

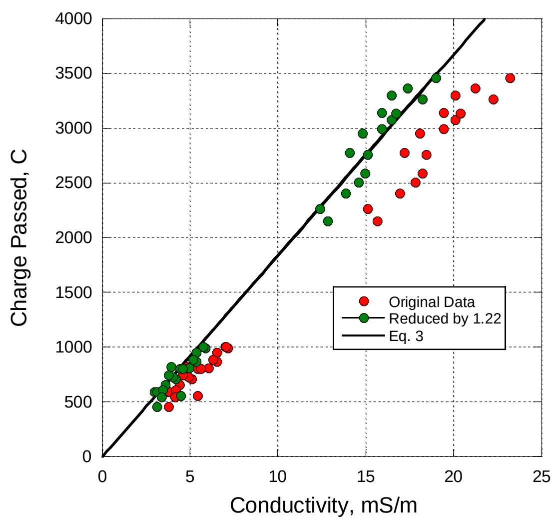
where Q = charge passed in the **PROOVE'it** test
V = applied voltage in the **PROOVE'it** test (60V)
L = length of the **PROOVE'it** specimen
A = area of the **PROOVE'it** specimen
t = measurement time (6 h = 21,600 s) of the **PROOVE'it** test

For a specimen length of 50 mm and a diameter of 95 mm (the reference dimensions specified in ASTM C1202), the conversion from charge passed using ASTM C1202 to bulk conductivity values (Eq. 3) and bulk resistivity values is as follows:

Permeability Class (ASTM C1202)	Charge passed using **PROOVE'it**, Coulombs†	**Merlin** Bulk Conductivity, mS/m	**Merlin** Bulk Resistivity, Ω·m
High	> 4,000	> 21.8	< 45.9
Moderate	4,000 – 2,000	21.8 – 10.9	45.9 – 91.9
Low	2,000 – 1,000	10.9 – 5.4	91.9 – 183.7
Very Low	1,000 – 100	5.4 – 0.54	183.7 – 1,837
Negligible	< 100	< 0.54	> 1,837

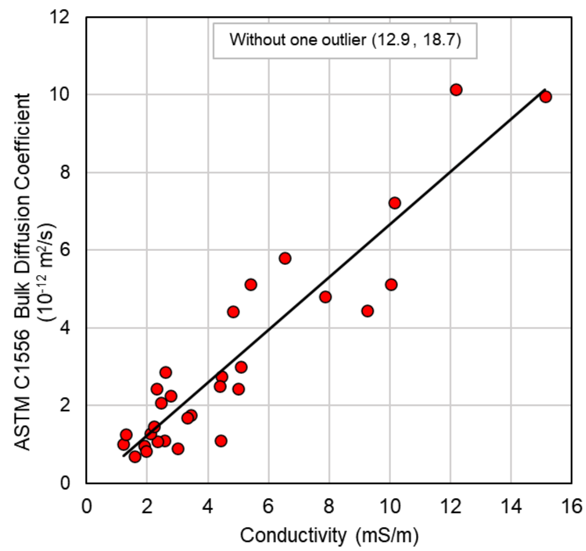
†It is assumed that current is constant during the 6 h test duration, which is typically not true for high conductivity concrete

Test Data

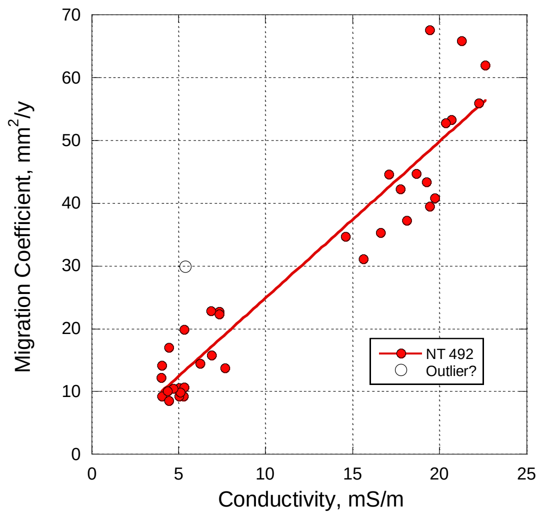


Data have been published on the relationships between bulk conductivity and other durability related properties, such as permeability, chloride diffusion, and charge passed. E. Karkar (2011) performed a study from which bulk conductivity can be compared with results of other test methods. The study involved nine concrete mixtures, made with different cementitious materials, and with *w/cm* values between 0.40 and 0.50. The specimens were tested at ages of 35 and 56 days. Bulk electrical conductivity was measured after applying current for 1 minute and 5 minutes using the ASTM C1202 apparatus and compared with bulk conductivity using the **Merlin**. Charge passed in accordance with ASTM C1202 was also measured. The graph on the left shows the Coulomb values measured by ASTM C1202 versus conductivity measured with **Merlin** on the same specimens. The straight line is the relationship given by Eq. (3) for a specimen diameter of 95 mm and length of 50 mm. It is seen that the bulk conductivity measured with **Merlin** is systematically greater than expected based on Eq. (3). Hence the measured values have been reduced by a factor of 1.22. The reduced values, which are plotted as green points, are now in agreement with Eq. (3). The reason for this discrepancy was not addressed by Karkar (2011), but the important conclusion is that a rapid measurement of bulk conductivity will provide the same information as the 6-h ASTM C1202 test.

According to the **Nernst-Einstein equation,** Eq. (1), the bulk chloride ion diffusion coefficient is expected to vary linearly with bulk electrical conductivity of concrete, assuming that the pore fluid conductivity is the same. The plot on the right shows data (Kessler et al. 2008) of mixes made with different cementitious materials and w/cm values between 0.29 and 0.45. The **chloride bulk diffusion coefficient** determined by ASTM C1556 after 1 year of chloride exposure is plotted as a function of bulk conductivity. While there is data scatter, it is clear that there is a consistent relationship between them.



The chloride ion migration coefficient determined by Nordtest Build 492 is not identical to the chloride diffusion coefficient, but it has been shown that the two are correlated to each other (Frederiksen et al. 1997). Thus we would expect the migration coefficient to also be a linear function of bulk conductivity assuming the same pore fluid conductivity. The data by Karkar (2011) also allow presenting the migration coefficient plotted as a function of bulk conductivity measured by **Merlin**.



Specimen Conditioning and Test Interpretation

For an electrical conductivity test according to ASTM C1876, it is essential that the specimens obtained from cores or cast in molds, the ends are submerged in a simulated pore solution prepared with NaOH, KOH, and $Ca(OH)_2$ for at least 6 days, or from time of demolding in the case of molded cylinders.

The purpose of this conditioning is to bring the specimen to a level of near-complete saturation of the capillary and gel pores and to prevent leaching of ions from the pore solution of concrete as this is known to affect measured conductivity values.

The conductivity of the pore solution affects the measured bulk conductivity of concrete. Thus comparisons should not be made between concretes with widely different pore solution conductivities. For example, the use of calcium nitrite as a corrosion inhibitor will increase the conductivity of the pore fluid, and the measured bulk conductivity of the concrete will be higher than for another concrete without calcium nitrite but with a similar chloride ion diffusion coefficient. On the other hand, concrete with supplementary cementitious materials may have a reduced pore fluid conductivity, which will reduce the measured bulk conductivity while the actual diffusion coefficient may not be reduced (Liu and Beaudoin 2000).

Variability

The single-operator variation is reported to be 4.3 % in ASTM C1876 and the multi-laboratory variation was found to be 13.2 %.

Merlin Specifications

- 220 VAC / 60 Hz or 110 VAC / 50 Hz power supply
- Measurement time: ≈ 2 seconds
- Frequency: 325 Hz AC
- Sampling rate: 5 Hz
- Precision: ± 0.1 % for 20 to 4,000 Ω·m at 23°C
- Test results displayed in terms of bulk resistivity or conductivity
- Test results can be stored for preparing test reports
- USB connection
- Compatible with Windows 7 / 8 / 10 operating systems

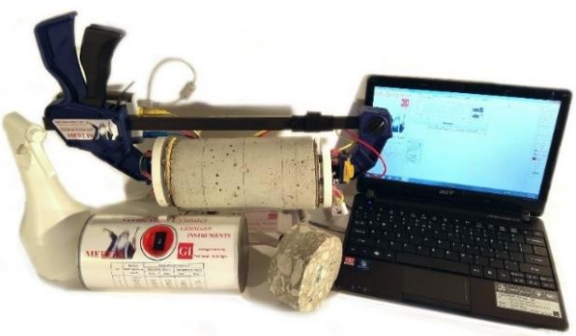
Two versions of the **Merlin** system are available:

	Merlin	**Merlin Grande**
Size of specimens	For 200 mm long and 100 mm diameter cylindrical specimens.	For up to 300 mm long and 150 mm wide specimens, **cylinders or cubes**.
	Minimum length = 25 mm Minimum diameter/width = 75 mm	

Merlin Ordering Numbers

Merlin, MRLN-1000 Kit

Item	Order #
Merlin unit	MRLN-1001
Netbook computer	MRLN -1002
Merlin software	MRLN-1003
Merlin verification cylinder	MRLN-1004
Insulating specimen support	MRLN-1005
Spray bottle	MRLN-1007
Carrying case	MRLN-1008



Merlin Grande, MRLN-2000 Kit

Item	Order #
Merlin Grande unit	MRLN-2001
Netbook computer	MRLN -1002
Merlin software	MRLN-1003
Merlin verification cylinder	MRLN-1004
Spray bottle	MRLN-1007
Carrying case	MRLN-1008

Optional Items

Item	Order #
Precision steel mold, reusable	MRLN-1009
CORECASE for 100 mm cores	CEL-100
Drilling machine, 1150W	CC-29
Diamond saw for trimming cores	PR-1060

References

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Nokken, M,R, and Hooton, R.D., 2006, "Electrical Conductivity Testing," *Concrete International*, October, pp. 58-63.

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Kessler, Powers, Vivas, Paredes, Virmani, 2008, “Surface Resistivity as an Indicator of Concrete Chloride Penetration Resistance,” 2008 Concrete Bridge Conference, St. Louis MO, United States. Transportation Research Board (TRB), TRID database, Accession Number: 01104992.