

### Purpose

The **Merlin** is one of the newest developments by Germann Instruments. It is used to measure the **bulk electrical conductivity**, or its inverse, the **bulk electrical resistivity**, of saturated 100 by 200 mm concrete cylinders or cores. The test is simple to perform and a test result 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 by diffusion.

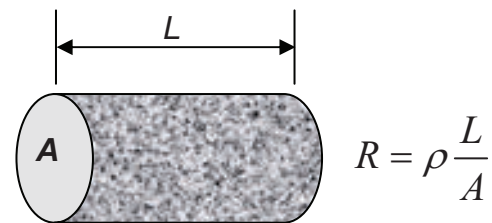


**Merlin** can be used for the following purposes:

- Research and development to characterize the influence of new materials on the electrical conductivity of concrete
- Optimizing mixture proportions and supplementary cementitious materials to increase concrete service life
- On-site 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  $\rho$  is called 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 is measured, the resistivity can be calculated from the relationship  $\rho = R A/L$ . The inverse of electrical resistivity is the **electrical conductivity**,  $\sigma$ . 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 conductivity in millisiemens per meter or mS/m.



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 the given type of ion will migrate through saturated concrete in the presence of a concentration gradient. For a saturated porous material, such as hardened concrete, the diffusion coefficient of a give type of ion can be related to electrical conductivity through the **Nernst-Einstein equation** as follows (Snyder et al. 2000; Nokken and Hooton 2006):

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

where  $\sigma$  = bulk electrical conductivity of the saturated porous material

$\sigma_p$  = 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).

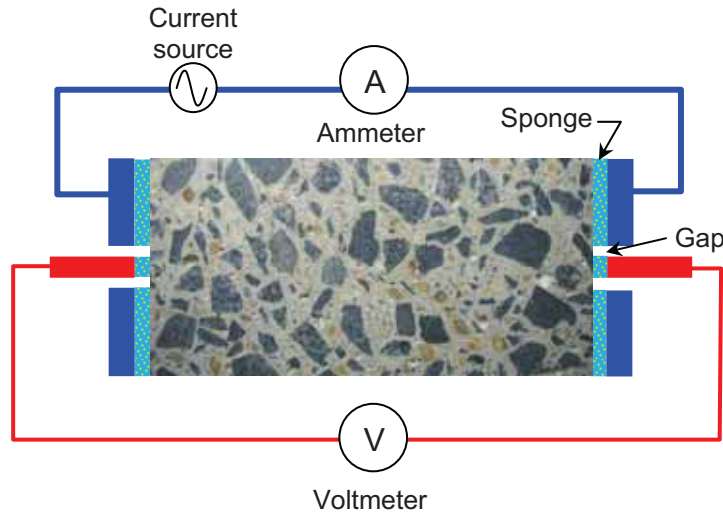
If the conductivity of the pore fluid is assumed to be similar among different concretes, the measured bulk electrical conductivity is related directly to the bulk diffusion coefficient (Berke and Hicks 1992). Measurement of the bulk diffusion coefficient of a particular type of ion through concrete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

The electrical conductivity of saturated cement paste is related to the paste porosity (volume of pores and how they are connected). The paste porosity is in turn related to the degree of hydration, the types of cementitious materials, and the water-cementitious materials ( $w/cm$ ) ratio. If electrical measurements are made at a fixed degree of hydration for a given system of cementitious materials, the measured conductivity is related to the  $w/cm$ .

# Merlin

## Method of operation

The following is a schematic of the measurement method incorporated in **Merlin**. 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. The specimen must be in a water-saturated condition to obtain a meaningful measurement.



An alternating current source is used to apply current through the saturated cylinder or core. A voltmeter is used to measure the voltage drop across the specimen, and an ammeter measures the current. From the measured current  $I$  and voltage  $V$ , the bulk conductivity is calculated as follows:

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

where,  $L$  is the specimen length and  $A$  is the specimen cross-sectional area. The bulk resistivity is the inverse of the bulk conductivity, that is,  $\rho = 1/\sigma$ .

A 100 by 200 mm verification cylinder is provided to check that the **Merlin** system is operating correctly. The cylinder includes a push button switch than can be used to select one of several precision resistor from 10  $\Omega$  to 1 M $\Omega$ . For example, if the 1000  $\Omega$  resistor is selected and the system is functioning correctly, the conductivity reading of the verification cylinder should be 25.46 mS/m and the resistivity should be 39.27  $\Omega \cdot m$ .



## Application

From the theoretical basis of the **Merlin**, it can be seen that measurement of the bulk electrical conductivity of a saturated concrete specimen 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 bulk electrical 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, 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 that current is constant during a **PROOVE'it** 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:

$$\sigma = \frac{QL}{VtA} \quad (3)$$

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

The bulk resistivity limits can also be calculated by taking the inverse of the above equation.

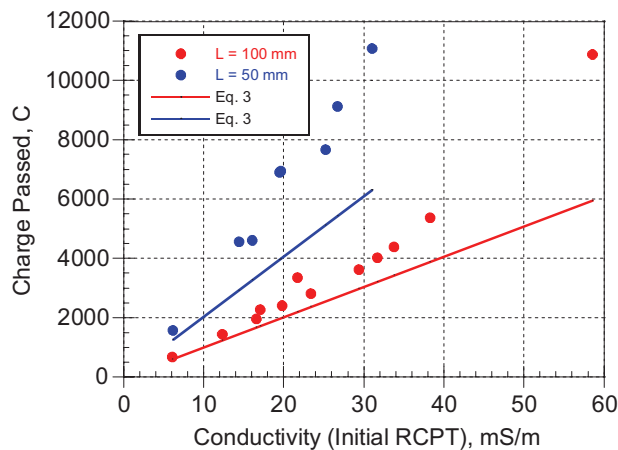
For a specimen length of 50.8 mm and a diameter of 95 mm (the reference dimensions specified in ASTM C1202), the conversion from charge passed using ASTM C1202 to bulk conductivity (Eq. 3) and bulk resistivity values is as follows:

Charge passed using <b>PROOVE'it</b> , Coulombs <sup>†</sup>	<b>Merlin</b> Bulk Conductivity mS/m	<b>Merlin</b> Bulk Resistivity Ω·m
50	0.28	3636
100*	0.55	1818
1,000*	5.50	181.8
2,000*	11.00	90.89
4,000*	22.00	45.45
10,000	55.01	18.18

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

\*Limiting values in ASTM C1202 used to define different categories of "chloride ion penetrability" (see page 101)

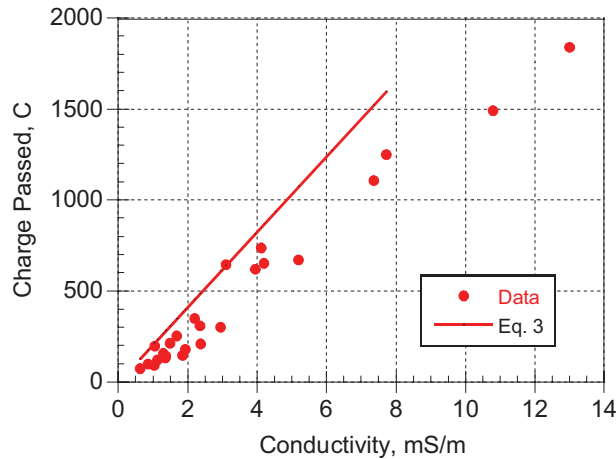
### Test Data



Snyder et al. (2000) measured the charge passed through 100 mm diameter cylindrical specimens in accordance with ASTM C1202 and used the initial current during the test to calculate the bulk conductivity according to Eq. 2. This calculated bulk conductivity is based on the same principle as used by **Merlin**. The cylinders had lengths of 50 and 100 mm. The graph on the left shows the charge passed versus the bulk conductivity. The solid lines represent the theoretical relationships between charge passed and bulk conductivity as given by Eq. 3. It is seen that there are approximately linear relationships between charge passed and bulk conductivity. The measured charges passed are,

however, greater than predicted by Eq. 3. This can be explained, in part, by heating of the specimens. The concretes used by Snyder et al. (2000) had relatively high conductivities. As explained above, specimens with high conductivity will heat up during the ASTM C1202 test. As specimen temperature increases, the conductivity of the pore fluid increases and the current increases. This leads to instability and a higher charge passed compared with a specimen kept at a constant temperature.

Berke and Roberts (1989) also measured charge passed (AASHTO T-277, which is similar to ASTM C1202) and specimen resistivity based on a polarization method. In this case the concretes that were



used had relatively low conductivities. The graph to the left shows the Coulomb values reported by Berke and Roberts (1989) plotted versus the inverse of the reported resistivity values (conductivity) and the prediction based on Eq. 3. Again there is an approximately linear relationship between conductivity and charge passed. In this case, however, the data fall below the prediction based on Eq. 3. This difference is likely due to the method used to measure resistivity. In summary, these studies confirm the expected strong relationship between bulk conductivity and charge passed using ASTM C1202.

### Specimen Conditioning and Test Interpretation

An electrical conductivity test will provide an indication of the diffusivity of the concrete only if the specimen is saturated. Thus it is essential that cylinders be kept under water from the time of molding until time of testing. Reusable steel molds are available to provide specimens of consistent dimensions and to facilitate storage under water. Except for the ends, the cylinder should be in a surface dry condition at time of testing. Special caps are available to keep the cylinder ends wet while the surface is allowed to dry. Because of the high sensitivity of the measurement method, the cylinder must be supported on an insulated stand during the measurement. The conductivity of the pore solution affects the measured bulk conductivity of concrete. Thus comparisons should not be made between concretes with very 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 diffusivity. 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 diffusivity may not be reduced (Liu and Beaudoin 2000).

### References

- Berke, N.S. and Hicks, M.C., 1992, "Estimating the Life Cycle of Reinforced Concrete Decks and Marine Piles Using Laboratory Diffusion and Corrosion Data," *Corrosion Forms and Control for Infrastructure*, ASTM STP1137, pp. 207-231, [http://www.astm.org/DIGITAL\\_LIBRARY/STP/SOURCE\\_PAGES/STP1137.htm](http://www.astm.org/DIGITAL_LIBRARY/STP/SOURCE_PAGES/STP1137.htm)
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- Liu, Z. and Beaudoin, J. J., 2000, "The Permeability of Cement Systems to Chloride Ingress and Related Test Methods," *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 22, No. 1, June, pp. 16-23. [http://www.astm.org/DIGITAL\\_LIBRARY/JOURNALS/CEMENT/](http://www.astm.org/DIGITAL_LIBRARY/JOURNALS/CEMENT/)
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- Nokken, M,R, and Hooton, R.D., 2006, "Electrical Conductivity Testing," *Concrete International*, October, pp. 58-63, <http://www.concreteinternational.com/pages/index.asp>
- Snyder, K.A., Ferraris, C. Martys, N.S. and Garboczi, E.J., 2000, "Using Impedance Spectroscopy to Assess the Viability of the Rapid Chloride Test for Determining Concrete Conductivity," *J. Res. Natl. Inst. Stand. Technol.* 105, pp. 497-509, <http://nvl.nist.gov>

### Merlin Specifications

- Specimen diameter 90 to 110 mm
- Specimen length up to 200 mm
- 325 Hz AC current supply
- Measurement time: approximately 2 seconds
- Sampling rate 5 Hz
- Test results in terms of bulk conductivity or resistivity
- Test results can be stored for preparing test reports

### Merlin Ordering Numbers

Item	Order #
<b>Merlin</b> bulk conductivity cell	MRLN-1001
Netbook computer with software installed	MRLN -1002
<b>Merlin</b> software	MRLN-1003
<b>Merlin</b> verification cylinder	MRLN-1004
Insulating specimen support	MRLN-1005
Caps to prevent drying of ends of cylinders	MRLN-1006
Spray bottle	MRLN-1007
Carrying case	MRLN-1008
Precision steel mold, reusable	MRLN-1009

### Precision steel mold

The MRLN-1009 precision steel mold produces cylinders with a diameter of 100 mm and a length of 200 mm with an accuracy of 0.02 mm on the cylinder dimensions.

The steel mold is reusable and mold removal is simple. To remove the mold, the top and bottom lids are removed first. Then, the container is opened slightly by applying a small pressure with the screws in the welded flanges.

The mold allows specimens to be produced within the tolerances stated and with plane end faces that are perpendicular to axis of the specimen. This minimizes test variability due to specimen geometry.

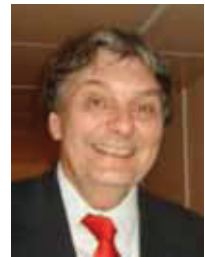


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