Evaluation of Saturation Techniques for In-situ Surface Electrical Resistivity Measurements

By Dr. Michelle Nokken and Jose Sanchez Marquez

1. Basic Definitions

**Resistivity** - an intrinsic property that describes how resistive the material is to the flow of electric current,\[ V = IR \]

Resistivity, \( \rho \), is the Resistance normalized by the length, \( L \), and cross sectional area, \( A \).

\[ \rho = \frac{R A}{L} \]

Conductivity, material’s ability to conduct an electric current.

**Agenda**

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  - 1. Basic Definitions
  - 2. Resistivity Background
  - 3. Methods of measuring Resistivity
  - 4. Why Resistivity is related to Permeability
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- Saturation Effect
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2. Resistivity Background

- 1980 FWHA study (Whiting)
- 1983 AASHTO T277
- 1991 ASTM C1202
- 2002 FDOT study for alternate methods
- 2004 FM5-578
- 2011 AASHTO T95
- 2012 ASTM C1760
3. Methods of measuring Resistivity

- ASTM C1202
- ASTM C1760
- AASHTO TP-95

4. Why Electrical Resistivity is related to Permeability?

When a voltage is applied, it creates an electric potential gradient that drives the flow of electrons through the concrete. More tortuous path more difficult for the electrons to pass through, higher electrical Resistivity.

Water contains ionic species such as chlorides or sulfates with a more tortuous path more difficult for the fluids to pass through, low permeability.

5. Pore network

- Connected
- Not Connected

6. According to Previous Research

- SCMs tend to have a more complex and refined pore networks giving the concrete a higher tortuosity and a lower permeability.
- Increasing w/cm generates greater porosity, fewer interruptions to flow, and concrete tends to have a lower tortuosity and higher permeability.

7. Factors Influencing Resistivity

- Tortuosity / Pore structure
  - Water to cement ratio
  - SCM (amount and type)
  - Age and curing
- Chemical Admixtures
- Temperature (~2%/°C)
- Saturation
8. Effect of Saturation

- At low levels of saturation, resistivity cannot be measured, usually is zero, but after a minimum period of immersion (5 min), it is possible to obtain resistivity values.
- AASHTO T95 requires a minimum of 7 days at 100% humidity.
- ASTM method is considering 7 days in a limewater tank maintained at 23°C ± 2°C.
- Limewater reduces resistivity by 10% (Kessler et al., 2008).
- However, it is important to know how much time is necessary to saturate the sample or element in order to achieve a reliable value?

**Objectives**

1. Understand how the moisture (saturation) content influences the overall measured resistivity response.
2. Investigate differences between geometry (cylinders, cores, slabs and structures (columns)).
3. Develop an adequate method to saturate in-situ concrete in order to achieve reliable Surface Resistivity Values.

**Methodology**

1. For the first 7 days samples were stored in limewater solution (calcium hydroxide) at room temperature ~23 ± 2°C.
2. Stored in high humidity (90%+) until testing.
3. Removed at 28, 56 and 91 days.
4. Measured resistivity for 3 days at each age. (Returned to moist curing until next test time).
5. During 72 hours the resistivity of every sample was measured 7 times at different saturation degrees (0 – 1 – 3 – 6 – 24 – 48 – 72 hours).
Comparison between Mixes at 28 Days

Mix 100TI
- Significant decrease up to 6 hours.
- Stable after 6 hours.
- Average difference of -2.2 % was observed between the first measurement and the last one.

Mix 50L-50S
- Significant decrease up to 6 hours.
- Increases observed after 6 hours.
- Average difference of -0.7 % was observed between the first measurement and the last one.

At 28 days 3 Kind of different behavior were observed during the time test was conducted at different times (hours) for the total 5 mixes.

Comparison between Mixes at 28 Days

Mix 50TI-20FA-30S
- Loss decrease up to six hours.
- Increases observed after 6 hours.
- Average difference of +3.5 % was observed between the first measurement and the last one.

Mix 100T1
- Most changes observed up to 6 hours.
- Stable after 24 hours.
- Average difference of +3.5 % was observed between the first measurement and the last one.

At 28 days also 3 Kind of different behavior were observed during the time test was conducted at different times (hours) for the total 5 mixes.

## Agenda

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### Saturation Effect

- According to Previous Research
- Factors Influencing Resistivity
- Saturation at 28 – 91 Days

### Objectives

- Mixtures Design
- Experimental Program
- Observations
- Conclusion
- Recommendations

- Identifying saturation in samples
- Surface characteristics
- Results observed at 20 – 90 Days
- 91 days
- Ensuring the saturation between dry and full saturation
- Methods
  - Mix 50TI-20FA
  - Mix 100L-50S

### Observations

- Average difference of -2 %.
- Increases observed after 24 hours.
- Average difference of -2.2 % was observed between the first measurement and the last one.

### Conclusion

- Mix 50L-50S
- Similar for Mix 50TI-50S and 50TI-30FA-20S

### Recommendations

- 1. Partially Saturation Elements
- 2. In w/c, Saturation Difrect

### Saturation time Differences - Mixes w/c 0.40 at 28 – 91 Days

- 28 days
  - The average difference between 1 hour saturation and full saturation was only ~2%.

- 91 days
  - The average difference between humidity air conditions was only ~3%.
Saturation time Differences - Mixes w/c 0.50 at 28 – 91 Days

28 days: The average difference between 1 hour saturation and full saturation was only ~2%.

91 days: The average difference between humidity air conditions was ~7%.

Saturation time Differences - Mixes w/c 0.60 at 28 – 91 Days

28 days: The average difference between 1 hour saturation and full saturation was only ~2%.

91 days: The average difference between humidity air conditions was ~3%.

Agenda

Resistivity
- Basic Definitions
- Resistivity Background
- Methods of measuring Resistivity
- Methods of measuring Reliability
- Post Research

Saturation Effect
- According to Previous Research
- Factors influencing Resistivity
- Effect of Saturation

Objectives

Mixture Design

Experimental Program
- Increasing saturation between moist cured and lime saturated samples
- Methodology
- Comparison between Mixes
- Saturation time Differences

Observations

Conclusion

Recommendations

Mix 100TI shows what happen when the W/Cm is increase (0.4 to 0.60) generates greater porosity, concrete tends to have a lower tortuosity for the electrons are easy to pass trough the pore network (higher permeability).

Mix 50TI-20FA-30S Resistivity values don’t decrease when the W/Cm increase.

Mix 50TI-50S shows also a contradictory behavior, the resistivity values don’t decrease when the W/Cm increase.

It seems that the effect of using SCMs generates a more complex and refined pore networks and it is not affected by the increase of w/cm. At the end the concrete is going to have higher tortuosity and a lower permeability.
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  2. Resistivity Background
  3. Methods of measuring Resistivity
  4. Why Electrical Resistivity is related to Permeability

Saturation Effect
  5. According to Previous Research
  6. Factors in Measuring Resistivity

Objectives
  Mixture Design
  Experimental Program
  7. Comparing Saturation between moist cured and lime saturated samples
     a. Methodology
     b. Comparison between Mixes
     c. Saturation time Differences
     d. Comparison all ages

10. Increasing saturation in slabs
   a. Methodology
   b. Sensor’s characteristics
   c. Slab’s characteristics
   d. Geometry results at 28 – 56 Days
   e. RH results

11. Increasing saturation between dry and lime saturated
   a. Methodology
   b. Mix 75Ti-25FA
   c. Mix 100Ti

Observations

Conclusion

Recommendations

1. Partially Saturated Elements
2. In-situ Saturation Method

Methodology

1. Two mixtures were selected (100T1 and 50Ti-20FA-30S) with same w/cm equal to 0.40. The main idea was verify if the same influence of saturation was observed in the slabs.

2. Similar curing as previously (7 days limewater)

3. Sensors (Temp/RH) installed at various depths, five in total were installed and located in order to measure the internal relative humidity and temperature in concrete laboratory specimens

Sensor’s characteristics

The sensor has a range of 0-100% RH with an accuracy of +/- 2%.

Sensor locations, every 20, 40, 65, 95 and 115 mm depth

Geometry Results – 28 days

Mix 100T1
After applying the cell constant correction factor modified for circular concrete slabs K=1.32 (Morris et al, 1996) Slab was 13% less than the cylinder samples.

Mix 50T1-20FA-30S
Slab was 17% less than the cylinder samples.

Geometry Results – 56 days

Mix 100T1
Slab was 12% less than the cylinder samples.

Mix 50T1-20FA-30S
Slab was 11% less than the cylinder samples.
Methodology

Two mature mixtures were tested,

1. Mix 2 - 75% Portland Cement and 25% Fly ash (3 cylinders). Saturated with tap water

Cylinders were mature (~5 years) and stored in air during this period of time.

The test cylinders were immersed in solution. At different times the surface resistivity was measured.

Mix 100TI – 1 hour:
- The first measurement was made after 9 min.
- Average difference of -12% between the first measurement and the last one.

Mix 100TI (0 to 72 hours)
- Increases observed after 24 hours
- Average difference of -44% between the first measurement and the last one.

Mix 75TI-25FA – 1 hour:
- The first measurement was made after 5 min.
- Average difference of -18% between the first measurement and the last one.

Mix 75TI-25FA (0 to 72 hours)
- After 24 and until 72 hours the resistivity values remain constant.
- Average difference of -78% between the first measurement and the last one.
Using the Wenner four-probe device

1. Requires the storage of samples in limewater solutions or 100% humidity.
2. Low permeability concretes may not obtain saturation even after long immersion times, owing to self-dessication (internal drying). Also observed in samples with high permeability properties.
3. Storage in limewater may provide additional curing and/or leaching that is not representative in actual field structures.

Conclusions

- Saturation for 24 hours appears to be sufficient.
  - Differences between 1, 24 and 72
- Differences observed between cylinders and slabs (even with correction)
- Tap water may be feasible for saturation purposes.

Agenda

Observations

- Resistivity
  1. Basic Definitions
  2. Resistivity Background
  3. Methods of measuring Resistivity
  4. Effect of Saturation
  5. Post-hardened
- Saturation Effect
  1. According to Previous Research
  2. Factors influencing Resistivity
  3. Effect of Saturation
- Objectives
  1. Mixture Design
  2. Experimental Program
  3. Increasing saturation between moist cured and lime saturated samples
  4. Comparison between Mixes
  5. Analysis of Data

Recommendations

1. Resistivity measurements on partially saturated elements.
2. Develop an adequate method to saturate in-situ concrete elements.

The cost of testing (in terms of time and money) could be significantly reduced if reliable measurements can be made on it.

Partially Saturated Elements

Once the degree of saturation changes, the pore solution conductivity and the solutions connectivity also change.

An universal expression was developed to characterize the pore structure of concrete (formation factor) plus an empirical expression for the effects of partial saturation.

\[
\sigma_c = \left( \frac{\sigma_p}{S} \right) \left( \frac{1}{F} \right) (S^n)
\]

Each term is independent and they are related to well defined properties of the matrix and the solution filling its pores.
1. Partially Saturated Elements

\( \sigma_C \)  
Concrete conductivity. A high concrete conductivity means that the pore network is less tortuous, more permeable and with a low resistivity value.

\( \frac{\Delta \mu}{S} \)  
Pore solution conductivity (attributable to the mixture design and subsequent concentration of water loss)

\( \frac{1}{F} \)  
Accounts the total pore space

\( S^n \)  
Accounts the connectivity of the fluid in the pore space, \( S \) is known as degree of saturation, \( n \) is known as saturation coefficient. According to (Weiss et al., 2013) the value of \( n \) for concretes is between (3.5 - 5)

2. In-situ Saturation Method

After that it was showed that a correlation existed between samples tested directly in the field and cores drill samples in the laboratory under wet conditions.

Now, using a combination of a number of anchored clamping pliers and a vacuum system plate to attach the device to the concrete element similar to principle used in the German Water permeation Test (GWT).

![Vacuum](image)

Figure xx, rapid saturation

In order to estimate an average water depth penetration is possible to follow these two graphic.

![Graph](image)

(Nokken and Mohammadi, 2013). Knowing the concrete humidity is possible to estimate the capacity of absorption of the element.
Thank you,