Concrete Conductivity: Effects of temperature, saturation and air content

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Background

- Joint deterioration manifested itself as cracking and spalling of concrete in the vicinity of both longitudinal and transverse joints (Fig. 1 (a)).
- Under service conditions, the temperature, pore solution concentration, and degree of saturation of concrete near the joint vary continuously
- Electrical conductivity, which also depends on the aforementioned parameters, might offer a means of monitoring changes in those parameters over time and improve our understanding of the cause of deterioration.
- This study examined how temperature, saturation level, and air content individually affect the electrical conductivity of concrete.

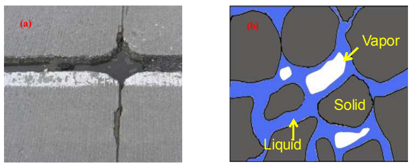


FIGURE 1 (a) Examples of Concrete Pavement Joints Deterioration and (b) schematic of conductive path

Electrical Conductivity

- In concrete, conduction occurs predominantly through the pore solution (blue region in Fig 1 (b)).
- Increase in the degree of hydration or level of drying increase the tortuosity of the conductive path which then reduces electrical conductivity of the sample.
- Electrical conductivity of concrete depends on:
  - Temperature
  - Moisture Content
  - Pore solution concentration

General Approach

- Concrete cylinders (4" x 8") were cast using mixture proportions(see Table 1).
- The cylinders were cured at 23°C and 100% RH for at least 28 days.
- 2" thick disks were cut, vacuum saturated and exposed to different conditioning as described in the following sections.
- After conditioning electrical resistance was measured and electrical conductivity calculated.

Electrical Conductivity and Temperature

- Arrhenius relationship can be used to model the effects of temperature on conductivity (Eq. 1).
- Other researchers have verified this relationship for concrete at temperatures ranging between 0°C to 50°C.
- This research evaluates the applicability of Arrhenius relationship for temperature ranging between -18°C to 23°C.

$$\sigma = Ae^{-\left[\frac{E_a}{RT}\right]}$$

EQUATION 1 Arrhenius Equation

- σ is conductivity of concrete (S/m)
- A is the nominal conductivity at infinite temperature (S/m)
- Ea is activation energy (kJ/mole)
- R is the universal gas constant (8.314 kJ/mol/K)
- T is the absolute temperature (K)

Mixture Proportions and Sample Conditioning

- Mixture proportions used to study the effects of temperature are summarized in Table 1, column (I)
- After vacuum saturation, samples were conditioned to temperatures of 23°C, 15°C, 10°C, 5°C, 0°C, -5°C, -10°C, and -18°C.
- The temperature was monitor using embedded temperature sensors (I-buttons ®).
- The sample conductivity was calculated from electrical resistance which was measured after each of the aforementioned temperatures was attained.

Table 1 Mixture proportions

Constituents	Effect of temperature (I)	Effect of saturation (II)	Effect of air content (III)			
			AC 4	AC 5	AC 6	AC 7
Cement	586*	586*	586*	586*	586*	586*
Water	252*	264*	264*	264*	264*	264*
F.A.	1370*	1440*	1440*	1400*	1360*	1320*
C.A.	1670*	1760*	1760*	1700*	1660*	1610*
AEA		0.7**	0.7**	0.8**	1.1**	1.45**
Air Content (ASTM C231)	6%	4%	4%	5.3%	6.7%	8.5%

* in lb./cu. yd. ** in oz./cu. yd.

Results

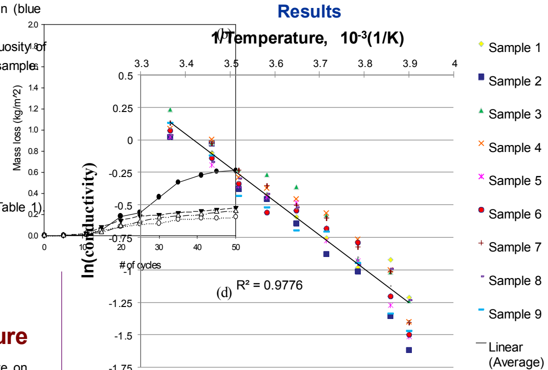


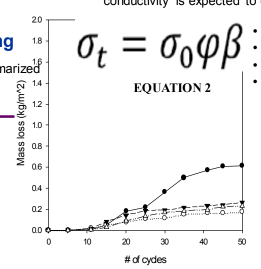
FIGURE 2 Plot of ln(conductivity) vs. 1/Temperature for nine specimens tested

- The plot between natural logarithm of conductivity and the inverse of absolute temperature is a straight line for temperatures ranging from -18°C to 23°C.

Electrical Conductivity and Saturation Level

- Conductivity has a one-to-one relationship with its moisture content.
- This relationship can be modelled using Eq. 2.
- [illegible] path becomes more tortuous and therefore the conductivity is expected to decrease (β decreases).

FIGURE 2 Mass loss of the *late* age salt scaling mixtures: (a) 20FA/5SF; (b) 20FA/7SF; (c) 30FA/5SF; (d) 30FA/7SF



$$\sigma_t = \sigma_0 \varphi \beta$$

EQUATION 2

- σ_t is conductivity (S/m) of concrete sample
- σ_0 is pore solution conductivity (S/m)
- φ is total liquid filled porosity
- β is the factor representing moisture connectivity

Mixture Proportions and Sample Conditioning

- Concrete mixture proportions used in this task are summarized in Table 1 column (II).
- The initial resistance was measured immediately after vacuum saturation,.
- The samples were then allowed to dry to desired mass to attain saturation levels of 95%, 90%, 85% and 80%.
- Resistance was measured when each of those saturation levels was attained.

Results

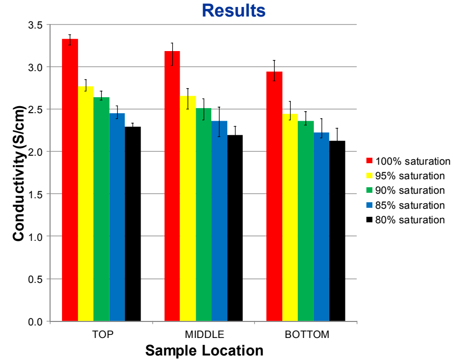


FIGURE 3 Changes in conductivity with changing saturation level and sample location

- Figure 3 shows that the conductivity of concrete decreases with decreasing moisture content.
- Conductivity decreases by 30% when saturation level is reduced from 100% to 80%. 15% of this decrease occurs during the first 5% decrease in saturation level.
- 7 – 11% decrease in conductivity is observed between samples extracted from the top and the bottom of the cylinder (at similar saturation levels). This difference in conductivity can be attributed to segregation.

Electrical Conductivity and Air Content

- Formation factor (1/φβ) is defined as the inverse of the product of pore connectivity (β) and total liquid filled porosity(φ).
- In other words, formation factor can be interpreted as a measure of the volume of the pores and their connectivity.
- Therefore, we could use the formation factor to quantify the microstructure of the concrete and hence use that relationship to describe the effect of air content on conductivity of concrete.
- The present study will model the conductivity of concrete to its air content using formation factor and pore solution conductivity (σ_0).

Mixture Proportions and Sample Conditioning

- Mixture proportions for this task are summarized in Table 1, column (III).
- After vacuum saturation, the resistance was the samples was measured.
- Paste samples with w/c similar to concrete were cast and squeezed after curing for 28 days to extract pore solution and to measure its conductivity (σ_0).
- Using Eq. 3 (modified form of Eq. 2) the formation factor was calculated.

$$\frac{\sigma_t}{\sigma_0} = \frac{1}{F} f(S)$$

EQUATION 3

- f(S) is a function of saturation. For saturated samples, f(S) = 1
- F is the formation factor

Results

Table 2- Conductivity and formation factor values

Mixture	Air Content (ASTM C457)	Average concrete conductivity, σ_t (S/cm)	Pore solution conductivity, σ_0 (S/m)	Formation Factor, F
A.C. 4	3.6%	1.26	4.7	**0.037**
A.C. 5	4.5%	1.39	4.7	**0.034**
A.C. 7	6.1%	1.66	4.7	**0.028**
A.C. 9	8.6%	1.30	4.7	0.036

- As air content (A.C.) increases, the formation factor decreases (implying that conductivity increases) except for the mixture with the highest air content (8.6%).
- The lower conductivity (higher formation factor) for mixture with air content of 8.6% may be due to the fact that at such high air content there might exists smaller air voids which are isolated and therefore are difficult to saturate completely. Empty air voids impede conductivity by increasing the tortuosity of the sample.
- The aforementioned explanation was verified by calculating the amount of empty air voids in the concrete sample. The calculations are summarized in Table 3.
- Mixture with 8.6% air was saturated only 64% as opposed to 80% for other mixtures.

Table 3 Calculation of percentage saturation of air voids

Air Content ASTM C457) (1)	Volume of the sample (cm3) (2)	Measured (actual) Evaporated Water (g) (3)	Theoretically calculated Evaporable Water (g) (4)	Water filling air voids (g) (5)=(3) – (4)	Theoretically calculated amount of water in air void at complete saturation (g) (6) = [(1)x(2)]/100	% of air voids actually saturated (7)=[{(6) - (5)}/(6)]*100
4.53%	720.74	79.35	52.6	26.75	32.65	**81.92**
6.06%	720.74	89.10	52.6	36.5	43.68	**83.56**
8.64%	**720.74**	**92.40**	**52.6**	**39.8**	**62.27**	63.91

Conclusions

- Concrete conductivity follows Arrhenius relationship for temperatures ranging between -18°C to 23°C.
- The concrete conductivity reduces by 30% when its saturation level is reduced from 100% to 80%.
- Segregation can effect the concrete conductivity.
- Concretes with higher air contents are difficult to saturate compared to concretes with lower air content. Therefore increasing air content might postpone the deterioration of joints by freeze-thaw damage.
- When saturated, concrete with higher air content demonstrates higher conductivity.

Future Work…

- The results of this preliminary testing will be used to design experiments which will attempt to quantify the microstructural deterioration, using conductivity, occurring in concrete when exposed to freezing and thawing in presence of deicing salt solutions.
- Comparing conductivity information from laboratory testing with conductivity values obtained while testing samples extracted from cores drilled out of deteriorated and non deteriorated joints of concrete pavements might provide us further understanding of the reason of premature joint deterioration.