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Time-Domain Reflectometry of Water Content in Portland Cement Concrete

Charles J. Korhonen, Vincent C. Janoo, and
Christopher M. Berini

November 1997

Abstract: Time-domain reflectometry is useful for measuring the moisture content of solids. However, little information exists on its use with portland cement concrete. By monitoring the response from TDR sensors embedded in concrete as the concrete dried, we developed a second-order polynomial equation that relates dielectric constant to moisture content. The study is valid for the specific concrete studied.

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PREFACE

This report was prepared by Charles J. Korhonen and Dr. Vincent C. Janoo, Research Civil Engineers, and Christopher M. Berini, Civil Engineering Technician, Civil Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Funding was provided by the Office of Aviation Research, Federal Aviation Administration, U.S. Department of Transportation.

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EXECUTIVE SUMMARY

The time-domain reflectometry probes that were installed in the Denver International Airport concrete pavement several years ago have been indicating that the concrete is wetter than it possibly could be. Topp's equation for soils, used to reduce the Denver TDR data, was suspected as being the problem. This study showed that TDR measures lower water contents in concrete than what is predicted by Topp's equation. Thus, the problem at Denver was with the way the data were analyzed and not with the probes. A second-order polynomial equation was subsequently developed to predict water contents in concrete. However, until additional testing is done to define the effects of mixture proportions on TDR readings, the equation developed in this study is considered valid for only the Denver concrete.

Time-Domain Reflectometry of Water Content in Portland Cement Concrete

CHARLES J. KORHONEN, VINCENT C. JANOO, AND CHRISTOPHER M. BERINI

INTRODUCTION

During construction of the new Denver International Airport, portions of the portland cement concrete pavement were instrumented with time-domain reflectometry (TDR) probes to monitor water content within the concrete. Though installing the probes into the concrete was easy, data taken with the probes were confusing. At times the probes were indicating that the concrete was wetter than it could possibly be. A likely reason for this problem seemed to be with the method used to analyze the data rather than with the probes themselves. Data analysis is necessary because the probes do not measure water content; instead, they measure the dielectric constant of a material from which the water content must then be derived.

At the time of their installation, little information existed on the use of TDR probes in concrete. The best information came from studies of soils. Notably, Topp et al. (1980) developed a mathematical relation between the dielectric constant and volumetric water content for soils. Since both soil and concrete are porous and are geologic materials, it was reasoned that Topp's relations might be applicable to concrete. They were not. Thus, the purpose of this study was to establish in the laboratory a relationship between water content and dielectric constant of concrete.

EXPERIMENTAL PROGRAM

The experimental program consisted of embedding TDR probes in specimens of fresh concrete and mortar, curing the specimens for a minimum of 28 days in water, and then measuring their dielectric constants at known water contents (see App. A). The program was divided into two parts: part I tested both concrete and mortar, and part II tested only concrete. We pretested the probes in concrete and related materials before starting the main experimental program.

In addition to studying the relationship between water content and dielectric constant of concrete, we looked at shrinkage as a function of moisture content. Preliminary results are shown in Appendix B.

TDR overview

The TDR method as applied to the measurement of dielectric properties is given by Fellner-Feldegg (1969) and Topp et al. (1980). Briefly, the TDR method calculates a material's relative dielectric constant by comparing the velocity of an electromagnetic signal propagated through that material to one propagated through free space.

The TDR system used in this study was a Tektronix model 1502B metallic cable wave generator controlled by a Campbell Scientific CR10 datalogger. This system operates by sending electromagnetic signals into a coaxial cable to a probe (Fig. 1) at the end of the cable. The instrumentation measures the time that it takes the signal to travel down the length of the probe and to reflect back to its source, which gives signal velocity:

$$\nu = {}^{2L}\!/_{t} \tag{1}$$

where ν = signal velocity
L = probe length
t = transit time.

This velocity is related to the dielectric constant of the material in which the probe is embedded:

$$\nu = {}^{c}\!/_{\varepsilon^{0.5}} \tag{2}$$

where c is speed of light in free space, and ε is

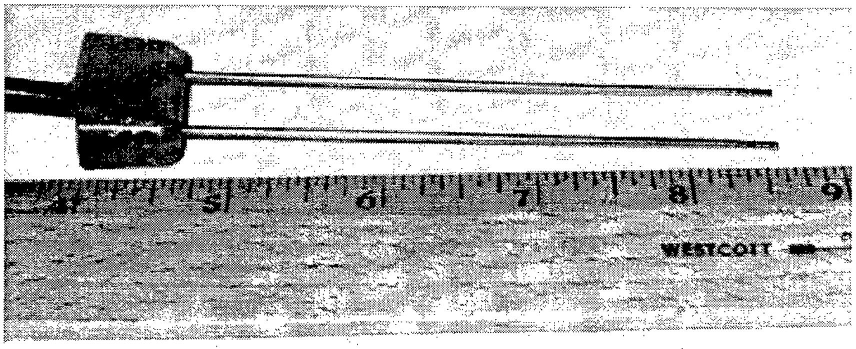

Figure 1. TDR probe. Each probe consists of two parallel stainless steel rods, each 1.6 mm in diam. and 100 mm long, spaced 12.7 mm apart. The rods are held in a plastic handle, where they are connected to a coaxial cable that is attached to a 50-ohm multiplexer, capable of supporting eight probes.

relative dielectric constant of the material surrounding the probe.

Thus, signal velocity should be affected by changes in the dielectric constant of the material surrounding the probe. If the dielectric constant of the material increases, signal velocity should slow down. Water, having a relatively high dielectric constant of about 80, should affect signal velocity much more greatly than would most geologic materials, such as soil, sand and stone, which have dielectric constants between 2 and 7, or air that has a dielectric constant of 1. Concrete's dielectric constant is derived from the separate constituents of air, cement paste (a calcium silicate hydrate), aggregate, and water. Because the dielectric constant of bulk water is high, its effect on the composite dielectric constant of concrete should be significant, and should be easily detectable, even in small amounts.

Pretest

To verify that our TDR system functioned properly, we pretested it in various concrete and mortar components and compared those measurements to known or calculated values. We measured the dielectric constant of air and water, for which the dielectric constants are well known, and concrete, mortar and their individual components, for which the dielectric constants had to be calculated (App. A explains the calculations). The pretest results in Table 1 show that the measured value agreed with the textbook value of 1 for air and was within 5% of the textbook value for water. For the other materials, for which there were no textbook values, the results were mixed. The measured value was within 10% of the calculated value for all but the coarse aggregate, concrete (ssd) and mortar (od). Those three measurements differed by 13 to 36% from the calculated values. Nevertheless, we were satisfied that the TDR system functioned as expected.

Table 1. Comparison of measured to known and calculated dielectric constant.

	Dielectric constant	
Material	*Measured*	*Known/calculated**
Air	1	1
Tap water, 10°C	80	83.83
Sand, od†	2.9	3.02
Coarse aggregate, od	2.2	3.45
Unhydrated cement	2.7	2.83
Hydrated cement paste, ssd†	31.2	33.64
Concrete, od	5.4	5.49
Concrete, ssd	12.0	10.61
Mortar, od	3.9	4.99
Mortar, ssd	13.0	14.03

* Air and water obtained from *Handbook of Physics and Chemistry* (1977); the rest are derived in Appendix A.

† od and ssd stand for oven-dry and saturated surface-dry, respectively.

Mixture proportions

Table 2 gives the mixture proportions, slumps, air contents, and specific gravities for the concrete and mortar used in this study. The concrete for part I was patterned after the concrete used for the TDR test section at the Denver airport*. Though it did not contain flyash, the part I concrete was designed to contain the same aggregate-to-paste ratio as the Denver concrete. This assured that the

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*Personal communication with M. Hovan, FAA William J. Hughes Technical Center, 31 October 1995.

Table 2. Mixture proportions (units are kg unless noted).

	Part I		*Denver*	*Part II*	
Ingredients	*Concrete (6 Feb 96)*	*Mortar (6 Feb 96)*	*Airport Mix 10*	*Concrete (18 April 96)*	*Concrete (18 April 96)*
Cement	14.75	25.65	10.47	14.75	14.75
Flyash	—	—	3.49	—	—
Coarse agg.	47.51	—	44.69	47.51	47.51
Fine agg.	34.51	62.60	33.80	34.51	34.51
Plasticizer (mL/kg)*	—	—	1.74	9.8	9.8
Air entrainer (g)	12	10	12	12	12
Water	6.07	10.26	5.82	6.07	6.07
w/cm (water/ cemetitious ratio)	0.41	0.40	0.41	0.41	0.41
Slump (mm)	12.7	—	38.1	25.4	38.1
Air content	3.5%	1.05%	5.4%	3.0%	3.75%
C. agg.— s.g.	2.89	—	2.72	2.89	2.89
F. agg.— s.g.	2.67	2.67	2.64	2.67	2.67
Flyash— s.g.	—	—	2.63	—	—
Cement— s.g.	3.15	3.15	3.15	3.15	3.15

* Rheobuild 1000 used for the Part II mixes. The plasticizer for the Denver mix is unknown. Dosage is per kg of cement.

Dates denote time of mixing. All mixtures are based on a 0.045-m^3 batch size.

TDR probe would be exposed to the same dielectric mix in the lab as in Denver. The mortar was designed to duplicate the mortar fraction of the Denver concrete.

Two concrete mixtures were used for part II. The first mixture duplicated the mixture used in part I, except that it contained a plasticizer to achieve more workability. The part I concrete mixture was very stiff; its slump was 12.7 mm. With the plasticizer, the slump was improved to 25.4 mm without the aggregate-to-paste ratio being changed. The second mixture also duplicated the part I concrete, except it was made with a smaller-sized coarse aggregate. The purpose of using a smaller aggregate was to determine if aggregate size could affect dielectric readings.

Sample preparation

The concrete and mortar were mixed at room temperature in separate batches in a 0.1-m^3 rotary-drum mixer following standard laboratory mixing procedures. The mixing procedure for the concrete followed ASTM C192. Mixing procedures for the mortar followed ASTM C305. Once the concrete or mortar was mixed, it was placed into 76- × 152-mm cylindrical plastic molds. For part I, the molds were filled and then the TDR probes were jiggled into the fresh concrete or mortar. For part II, the concrete was carefully placed around each probe as it was held in place. The purpose of using two methods of embedding the probes into the specimens was to determine if the tips of the probes, during the jiggling process, might rearrange the coarse aggregate ahead of the probe. The coarse aggregate arrangement should not be affected with the second method.

Material properties

The cement used for the concrete and mortar was an ASTM Type I portland cement. The aggregate were obtained from a source local to CRREL (it was impractical to ship aggregate from Denver). The coarse aggregate, a crushed ledge (amphibolite), had a bulk specific gravity, saturated-surface-dry (ssd), of 2.89 and an absorption of 0.52%. The fine aggregate, a natural sand, had a bulk specific gravity (ssd) of 2.67 and an absorption of 1.1%. Tables 3 and 4 list the particle size distributions, specific gravities, and absorptions for the aggregates used in each mixture, including the Denver mixture. The mineralogical type for the coarse aggregate used in Denver was unknown, but Table 3 shows that the specific gravity and absorption are similar to those of the ledge. This suggests that the ledge should be dielectrically similar to the coarse aggregate at Denver. The sand used in this study was essentially identical to the Denver sand.

Sample curing

Once the probes were embedded in the concrete or the mortar, the plastic molds were sealed to prevent moisture loss and stored at 20°C for 24 hours. After this, the molds were removed and the specimens were placed in 20°C lime-saturated water for a minimum of 28 days before any TDR readings were taken.

Table 3. Coarse aggregate gradation. The 13.2- and 9.5-mm headings indicate the nominal size of the gradation.

	Percent passing		
Sieve size	*Denver Mix 10*	*CRREL Part I & II (13.2 mm)*	*CRREL Part II (9.5 mm)*
9.5 mm	—	—	—
38.1 mm	100	100	100
26.5 mm	100	100	100
19.0 mm	75	100	100
13.2 mm	38	69.8	100
9.5 mm	4	37.3	93.6
4.75 mm	1	3.2	17
2.26 mm	0.6	—	—
75 µm	0.2	—	—
Specific gravity	2.724	2.89	2.89
Absorption	0.76%	0.52%	0.52%

Table 4. Fine aggregate.

	Percent passing	
Sieve size	*Denver Mix 10*	*CRREL Part I & II*
9.5 mm	100	100
4.75 mm	100	100
2.36 mm	91	89
1.18 mm	66	66.3
600 µm	38	41.5
300 µm	16	8.6
150 µm	5	6.5
75 µm	2.4	3.3
Specific gravity	2.638	2.67
Absorption	1.1%	1.1%

Measurements

The relation between dielectric constant and water content was developed by taking a TDR reading each time a specimen was dried a small amount. The initial TDR readings were taken when the specimens were removed from the curing water and their surfaces were towel-dried to saturated surface-dry (ssd) conditions. At that point the specimens were also weighed. The specimens, along with the embedded TDR probes and coaxial cables, were then placed into a 60°C drying oven, being careful not to kink the cables. The specimens were dried at 60°C, for all but the final drying, to prevent any possibility of melting the coaxial cable. The final drying was conducted at 105°C. During the 60°C drying, the specimens were periodically removed from the oven, sealed in plastic bags until the moisture evenly distributed itself in the specimens, measured with the TDR system, and weighed. (See *Results* for a description of how drying times were determined and of how an even moisture distribution was determined.) The weights were converted into moisture contents after the specimens reached a constant weight in the 105°C oven.

RESULTS

Figure 2 presents the drying curves for dummy specimens of concrete and mortar. As previously mentioned, the specimens instrumented

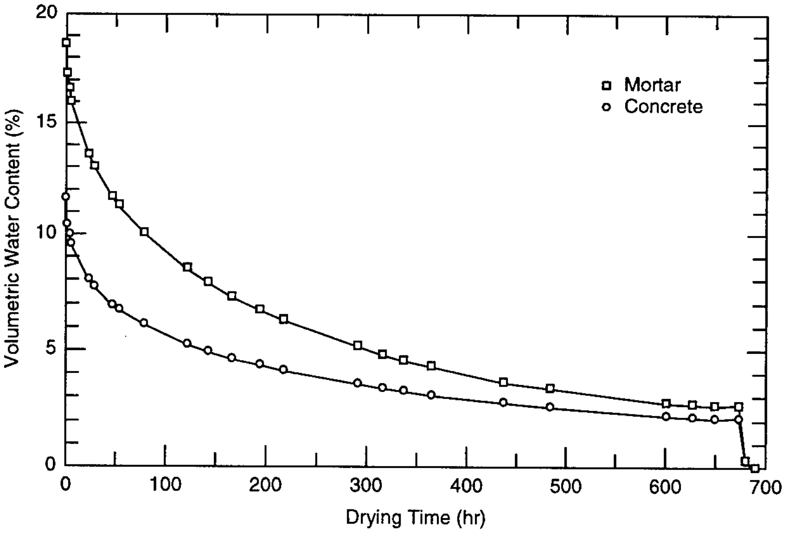

Figure 2. Drying curves for 76- × 152-mm mortar and concrete cylinders at 60°C. The oven-dry condition (final data point) was achieved by drying the cylinders at 105°C.

with TDR probes were dried from a saturated-surface-dry condition to an oven-dry condition, a small amount at a time. It was important to not dry the specimens too much at any one time (to create too few opportunities for TDR readings) or too little (to create unnecessary work). About 1% moisture loss per drying time seemed appropriate. Thus, Figure 2 helped us to determine how long to keep a specimen in the drying oven. For example, to cause the initial 1% moisture loss required only 3 hours of drying, whereas it took up to 1 week of drying to cause the same moisture loss during the latter stages of drying. The final (oven-dry) condition was attained by keeping the specimens in a 105°C oven for 24 hours.

Table 5 shows how soon a specimen of mortar or concrete will attain a uniform moisture content after it has been removed from the drying oven. The specimens were sealed inside individual plastic bags while the moisture equilibrated within the specimens. A specimen was defined to be of uniform moisture content when the moisture content at its center was within a half percent of the moisture content at its surface. We arrived at this definition because the TDR system was able to detect moisture only to within $\pm{}^{1}/_{2}$% during this study (see *Discussion*). Thus, we considered moisture to be equilibrated when the differences across the specimens were no greater than this amount. To determine when concrete or mortar would reach this condition, dummy specimens, at various moisture contents, were placed into the 60°C oven. Specimens were removed from the oven at various times, placed in plastic bags, and periodically tested for moisture by crushing the specimens with a laboratory compression tester and obtaining small samples from the outer and center portions of each specimen. The samples retrieved from each specimen were then immediately weighed and dried to constant weight in a 105°C oven. The data (Table 5) show that mortar reaches a uniform moisture condition within 1 day after being removed from the oven, whereas concrete requires up to 9 days. In our testing, all specimens were kept in individual plastic bags for 9 days before TDR readings and weights were obtained.

Table 5. Time for moisture to become evenly distributed within 76- × 152-mm concrete and mortar cylinders after they were removed from the 60°C oven.

	Time out of oven (days)	*Difference center-to-surface (%)*
Concrete	2	1.59
Concrete	5	1.24
Concrete	9	0.24
Mortar	1	0.16
Mortar	2	0.11

Figure 3 shows a plot of dielectric content vs. water content for concrete and mortar specimens. A plot of Topp's equation for soils is shown for comparison. The specimens were subjected to six drying cycles in the 60°C oven. In those six cycles, the concrete dried from a volumetric moisture content of about 11% to about 4%, while the mortar dried from about 18% to about 8%.

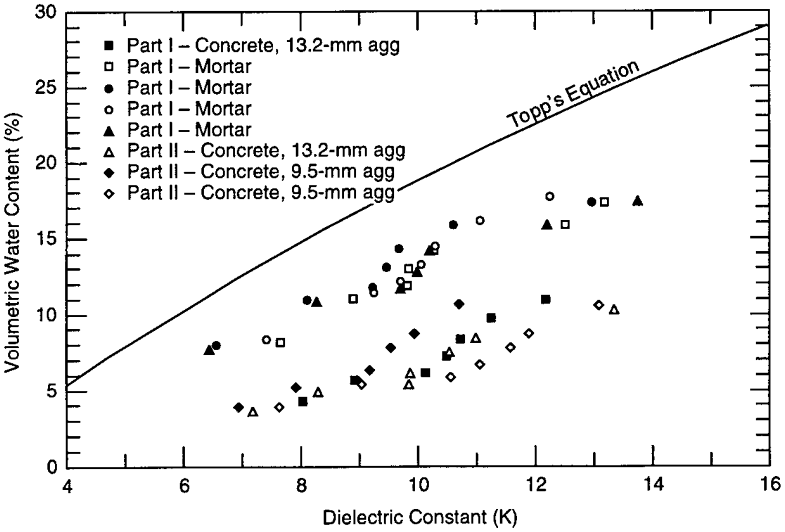

Figure 3. Dielectric constant vs. water content for all concrete and mortar specimens.

DISCUSSION

The objective of this study was to develop a relationship between the dielectric constant and the moisture content of hardened concrete proportioned similarly to the concrete used for the Denver International Airport pavement. Figure 3 shows that time-domain reflectometry can measure dielectric constants for concrete and mortar that are predictably influenced by moisture content—the higher the moisture content the higher the dielectric constant. However, neither concrete or mortar results could be mathematically described using Topp's equation for soils. When compared to Topp's predictions (Fig. 3), the test results show that TDR will predict a lower moisture content for concrete and for mortar than for a soil of equal dielectric constant. This finding agrees with the problem experienced in the field where TDR, when related to Topp's equation, indicated that the Denver pavement was wetter than it could possibly be. Thus, a separate relation between dielectric constant and water content had to be developed for concrete.

There may not be a unique relationship for all types of concrete. We say this because the results for concrete were different from those for mortar. The data (Fig. 3) for mortar were closer to Topp's equation predictions than were those for concrete, with mortar having a lower dielectric constant than concrete at any water content. The primary differences between the mortar and the concrete of this study (Table 2) were that the mortar contained no coarse aggregate and that the mortar contained more paste (cement plus water). It is known that hardened cement paste has a specific surface area that is several orders of magnitude greater than that of unhydrated cement, sand, or coarse aggregate. Since adsorbed water has a lower dielectric constant than bulk water, a material with a higher surface area, such as the mortar, would be expected to have a lower dielectric constant than a material possessing a lower surface area, such as the concrete, for equal water contents. We see this trend in the Figure 3 data. This suggests that the dielectric constant of concrete is a function of coarse aggregate and paste content in addition to water content. We did not investigate these combinations of variables, but the relation between dielectric constant and water content might consist of a family of curves dependent on paste, aggregate, and moisture content.

Besides moisture content, the two variables that we did investigate were the method used to embed a probe into concrete and the size of the coarse aggregate. The findings (Fig. 3) show that it did not matter if the TDR probes were jiggled into the fresh mix or if the mix was carefully placed around the probes. The size of the coarse aggregate did seem to have some effect on the results; Figure 3 shows that the smaller aggregate produced different results from those of the larger aggregate. However, the results from the smaller aggregate bracketed those from the larger aggregate; thus, we are uncertain what effect aggregate size has.

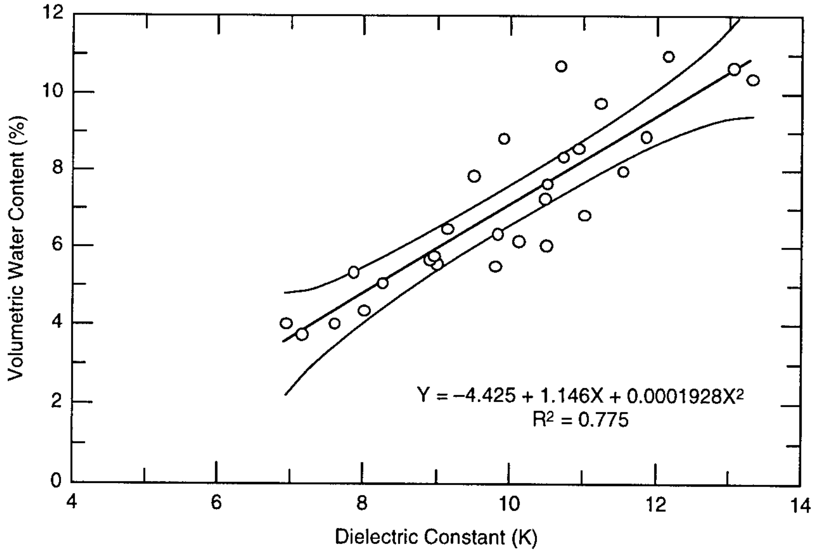

Figure 4. Second-order polynomial equation for concrete. A 95% confidence band is provided.

A second-order polynomial equation was fitted to the concrete data as shown in Figure 4. Also shown is a 95% confidence band. This band suggests that we can be confident that 95% of the time a dielectric constant measured with TDR will be within this envelope. At best, this band is within ±$^1/_2$% of the curve fitted to the data. The curve for concrete covers a range of water contents from 4 to 11%. However, until studies on other concretes are conducted, the following equation is considered usable only for the particular concrete used in this study:

$$\omega = 0.0001928K^2 + 1.146K - 4.425 \qquad (3)$$

where ω is volumetric water content (%), and K is the dielectric constant.

CONCLUSIONS AND RECOMMENDATIONS

A relationship between the dielectric constant and water content of a concrete has been developed. This relationship, a second-order polynomial, is considered valid for the Denver International Airport concrete pavement. The equation, shown above, is appropriate for volumetric water contents between 11 and 4% (5 to 2%, gravimetric), which encompass a wide range of pavement field conditions. Because the results showed that the TDR readings were different between mortar and concrete and that aggregate size may affect readings, a family of curves may be more appropriate for concrete. Thus, we hesitate to recommend these results for other concretes until additional studies are done on concretes of other mixture proportions.

We recommend that additional studies be done to evaluate the TDR response from a range of concretes. The concrete should include low to high paste contents and small to large aggregates.

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APPENDIX A: ESTIMATING DIELECTRIC CONSTANTS

Standard references list dielectric constants for a range of materials that are similar to the individual components found in concrete. For example, the *Handbook of Physics and Chemistry* (1977) lists calcium carbonate and quartz, of which sand, coarse aggregate, and cement can be partly or entirely composed of, as possessing dielectric constants between 4 and 7. Water and air, which also make up concrete, have dielectric constants of about 80 and 1, respectively. Since no dielectric constant is listed for concrete and since concrete consists of a mixture of dielectrics, individual values must be used to estimate the overall dielectric constant of concrete. To make this estimation, a mathematical weighting scheme of the different dielectrics must be applied based on the volume fraction of each in concrete. Ansoult et al. (1984), provides a convenient formula for estimating the overall dielectric response of a heterogeneous mixture such as concrete:

$$K_{\text{conc}} = \left[V_c K_c^{\alpha} + V_a K_a^{\alpha} + V_w K_w^{\alpha} + V_s K_s^{\alpha} + V_{ca} K_{ca}^{\alpha} + V_{uc} K_{uc}^{\alpha}\right]^{1/\alpha}$$

where V is the volume fraction, and K is the dielectric constant. α can be any value between –1 and +1. The +1 considers a situation where the dielectrics are being analyzed in a parallel configuration and –1 considers them to be in series. Since concrete ingredients are randomly distributed, being neither a parallel or a series configuration, we chose an intermediate value of 0.5. (Press et al. [1986] found $\alpha = 0.46$ to fit the situation for soil.)

The subscripts represent

conc = concrete
c = hydrated cement
a = air
w = water
s = sand
ca = coarse aggregate
uc = unhydrated cement.

The dielectrics that are listed in handbooks for geological material are for single pieces of material in an oven-dry condition. This does not represent how they are used in concrete. To more closely approximate in-situ dielectric constants, we analyzed each component of concrete independently before developing a dielectric constant for concrete. Estimates for individual concrete components and for 28-day old concrete are provided next.

SAND

Natural sand, which is mostly quartz, was used in this study. The *Handbook of Physics and Chemistry* (1977) lists quartz's dielectric constant as 4.34. We determined the sand to have an absorption (ASTM C 128) of 1.1%, bulk specific gravities (ASTM C 128) of 2.67, saturated surface-dry gravities, 2.64, oven dry, and a void ratio (ASTM C 29) of 0.32.

1. Since bulk sand consists of sand particles and interparticle void spaces, its overall oven-dry dielectric constant ($K_{\text{bs/od}}$) becomes

$$K_{\text{bs/od}} = \left[V_s K_s^{\alpha} + V_a K_a^{\alpha}\right]^{1/\alpha}$$

$$K_{\text{bs/od}} = \left[0.68 \times 4.34^{5} + 0.32 \times 1^{.5}\right]^{1/0.5}$$

$$K_{\text{bs/od}} = 3.02.$$

2. The void-free dielectric constant (K_{vf}) of sand was derived from the textbook value as follows:

$$K_s = \left[V K_{\text{vf}}^{\alpha} + V_a K_a^{\alpha}\right]^{1/\alpha}$$

$$4.34 = \left[0.989 K_{\text{vf}}^{0.5} \times 0.011 \times 1^{0.5}\right]^{1/0.5}$$

$$K_{\text{vf}} = 4.39.$$

3. When the intraparticle voids are water filled the dielectric constant of the individual sand particles ($K_{\text{is/wf}}$) becomes

$$K_{\text{is/wf}} = \left[V K_{\text{vf}}^{a} + V_w K_w^{a}\right]^{1/\alpha}$$

$$K_{\text{is/wf}} = \left[0.989 \times 4.39^{0.5} + 0.011 \times 80^{0.5}\right]^{1/0.5}$$

$$K_{\text{is/wf}} = 4.71.$$

4. Finally, the dielectric constant of bulk sand with its intraparticle voids water-filled and its interparticle voids air-filled ($K_{\text{bs/ssd}}$) becomes

$$K_{\text{bs/ssd}} = \left[V K_{\text{is/wf}}^{\alpha} + V_a K_a^{\alpha}\right]^{1/\alpha}$$

$$K_{\text{bs/ssd}} = \left[0.68 \times 4.71^{0.5} + 0.32 \times 1^{0.5}\right]^{1/0.5}$$

$$K_{\text{bs/ssd}} = 3.22.$$

CEMENT

A textbook value of dielectric constant for unhydrated portland cement was not found. A dielectric constant was developed from the known chemical composition of a general-purpose cement (Mindess and Young 1981). The primary components of such a cement are, in weight percentage, lime, 63; silica, 22; alumina, 6; ferric oxide, 2.5; sulfur trioxide, 2. The corresponding dielectric constants are calcite, 8.5; quartz, 4.34; aluminum oleate, 2.4; ferrous oxide, 14.2; sulfur, 4.0 (*Handbook of Physics and Chemistry* 1977). Weighting these dielectrics according to their percentages yields a dielectric of 6.9. The measured void ratio (ASTM C 29) of the cement used in this study was 0.58.

1. Thus, the dielectric constant of bulk cement becomes

$$K_c = \left[V_c K_c^{\alpha} + V_a K_a^{\alpha}\right]^{1/\alpha}$$

$$K_c = \left[0.42 \times 6.9^{0.5} + 0.58 \times 1^{0.5}\right]^{1/0.5}$$

$$K_c = 2.83.$$

COARSE AGGREGATE

The coarse aggregate used in this study was a crushed ledge classified as a metamorphic, amphibolite rock. We could not find a textbook dielectric constant for this rock type. Measurements show that this rock has bulk specific gravities (ASTM C 127) of 2.89 (ssd) and 2.87 (od), a moisture absorption (ASTM C 127) of 0.5 %, and, for the large CRREL gradation in Table 2, an interparticle void ratio (ASTM C 29) of 0.46.

We chose dolomite, of the rock-type minerals, as being most like amphibolite. The only justification for making this choice was that dolomite has an oven-dry specific gravity of 2.85 which is quite like that of amphibolite. The *Handbook of Physics and Chemistry* (1977) lists the dielectric constant (K_{ca}) of dolomite as 6.8.

1. Its bulk, oven-dry dielectric constant ($K_{\mathrm{bca/od}}$) becomes

$$K_{\mathrm{bca/od}} = \left[V_{\mathrm{ca}} K_{\mathrm{ca}}^{\mathrm{a}} + V_{\mathrm{a}} K_{\mathrm{a}}^{\mathrm{a}}\right]^{1/\alpha}$$

$$K_{\mathrm{bca/od}} = \left[0.54 \times 6.8^{0.5} + 0.46 \times 1^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{bca/od}} = 3.45.$$

2. Its void-free dielectric constant ($K_{\mathrm{ca/vf}}$) becomes

$$K_{\mathrm{ca}} = \left[V K_{\mathrm{ca/vf}}^{\alpha} + V_{\mathrm{a}} K_{\mathrm{a}}^{\mathrm{a}}\right]^{1/\alpha}$$

$$6.8 = \left[0.955 \times K_{\mathrm{ca/vf}}^{0.5} + 0.005 \times 1^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{ca/vf}} = 6.84.$$

3. Individual coarse aggregate particles in a saturated condition yields a dielectric constant ($K_{\mathrm{ica/wf}}$) of

$$K_{\mathrm{ica/wf}} = \left[V K_{\mathrm{ca/vf}}^{\alpha} + V_{\mathrm{a}} K_{\mathrm{a}}^{\mathrm{a}}\right]^{1/\alpha}$$

$$K_{\mathrm{ica/wf}} = \left[0.955 \times 6.84^{0.5} + 0.005 \times 80^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{ica/wf}} = 7.01.$$

4. The dielectric constant of bulk coarse aggregate at saturated surface-dry (ssd) condition ($K_{\mathrm{ica/ssd}}$) becomes

$$K_{\mathrm{ica/ssd}} = \left[V K_{\mathrm{ica/wf}}^{\alpha} + V_{\mathrm{a}} K_{\mathrm{a}}^{\mathrm{a}}\right]^{1/\alpha}$$

$$K_{\mathrm{ica/ssd}} = \left[0.54 \times 7.01^{.5} + 0.46 \times 1^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{ica/ssd}} = 3.57.$$

HYDRATED CEMENT

The following describes the procedure used to derive a dielectric constant for hydrated cement. Unless noted, Mindess and Young (1981) was referenced for the facts in this section.

- Portland cement (PC) evolves into a gel of constant 26% porosity.
- PC chemically combines with water equal to 24% of its unhydrated mass.
- Excess water is held in both capillary and gel pores.
- The total volume of gel equals 68% of the unhydrated cement mass.
- The fraction of cement that hydrates is time and temperature dependent.
- Mironov (1977) measured the degree of hydration after 28 days at 20°C as 0.66.
- All samples were made with a 0.41 water to cement ratio.

1. Each gram of cement will hydrate into volume of

$$V = 0.68\delta\, W_{\mathrm{c}}$$

$$V = 0.86 \times 0.66 \times 1$$

$$V = 0.449\ \mathrm{cm}^3.$$

2. Each gram of cement will remain 34% unhydrated. Its unhydrated volume is

$$V_{uc} = 0.34\ W_c\ /\text{specific gravity of PC}$$

$$V_{uc} = 0.34 \times 1/3.15$$

$$V_{uc} = 0.1079\ \text{cm}^3.$$

3. Each gram of cement will combine with an amount of water equal to

$$W_{wc} = 0.24\ W_c\ \delta$$

$$W_{wc} = 0.24 \times 1 \times 0.66$$

$W_{wc} = 0.158$ g (cm^3 assuming combined water is same as bulk water).

4. The gel produced by each gram of cement has a pore volume of

$$V_p = 0.26\ V$$

$$V_p = 0.26 \times 0.449$$

$$V_p = 0.1167\ \text{cm}^3.$$

5. The cement volume in the gel is

$$V_c = V - W_{wc} - V_p$$

$$V_c = 0.449 - 0.158 - 0.1167$$

$$V_c = 0.174.$$

6. The volume of mix water filling capillary pores, assuming gel pores are filled, is

$$V_{cap} = \text{w/c} - V_p - W_{wc}$$

$$V_{cap} = 0.41 - 0.1167 - 0.158$$

$$V_{cap} = 0.141.$$

7. The total volume of hydrated cement is

$$V_t = V_{uc} + W_{wc} + V_p + V_c + V_{cap}$$

$$V_t = 0.1079{+}0.158{+}0.1167{+}0.174{+}0.141$$

$$V_t = 0.6976\ \text{cm}^3.$$

8. The volume fractions of each component become

$$V_{uc}\,/\,V_t = 0.1079/0.6976 = 0.155$$

$$W_{wc}\,/\,V_t = 0.158/0.6976 = 0.226$$

$$V_p\,/\,V_t = 0.1167/0.6976 = 0.167$$

$$V_c\,/\,V_t = 0.174/0.6976 = 0.249$$

$$V_{cap}\,/\,V_t = 0.141/0.6976 = 0.203.$$

9. The water combined with the cement behaves differently from bulk water. The dielectric constant of ice (*Lange's Handbook of Chemistry* 1973) was selected for this bound water, K_{ice} = 0.40.

10. The water-saturated dielectric constant is calculated:

$$K_{ssd} = \Big[W_{wc}K_{ice}^{0.5} + V_cK_c^{0.5} + V_pK_p^{0.5} + V_{uc}K^{0.5} + V_{cap}K_{cap}^{0.5}\Big]^{1/0.5}$$

$$K_{ssd} = \Big[0.226 \times 40^{0.5} + 0.249 \times 6.9^{0.5} + 0.167 \times 80^{0.5} + 0.155 \times 6.9^{0.5} + 0.203 \times 80^{0.5}\Big]^{1/0.5}$$

$$K_{ssd} = 33.64.$$

11. Oven-dry hydrated cement is

$$K_{od} = \Big[W_{wc}K_{ice}^{0.5} + V_cK_c^{0.5} + V_pK_p^{0.5} + V_{uc}K^{0.5} + V_{cap}K_{cap}^{0.5}\Big]^{1/0.5}$$

$$K_{od} = \Big[0.226 \times 40^{0.5} + 0.249 \times 6.9^{0.5} + 0.167 \times 1^{0.5} + 0.155 \times 6.9^{0.5} + 0.203 \times 1^{0.5}\Big]^{1/0.5}$$

$$K_{od} = 8.18.$$

CONCRETE

The dielectric constant of concrete was derived from the mixture proportions used in this study and from the dielectric constants developed above.

Mixture	
Cement	14,882 g
Coarse aggregate	47,924 g
Sand	34,808 g
Water	6,120 g
Percent air	3.9

1. Volume of hydrated cement:

$$V_c = 0.68\text{cd}\ W_c$$

$$V_c = 0.68 \times 0.66 \times 14{,}882$$

$$V_c = 6{,}679 \text{ cm}^3.$$

2. Volume of unhydrated cement:

$$V_{uc} = (\mathrm{W_c}\, 0.34)/\mathrm{SG}$$

$$V_{uc} = (14{,}882 \times 0.34)/3.15$$

$$V_{uc} = 1{,}606 \text{ cm}^3.$$

3. Volume of capillary water:

Chemically bound water

$= 0.23 \times 14{,}882 \times 0.66 = 2{,}259$ g

Free water = 6,120 – 2,259 = 3,861 g

Water held in gel pores

= Vol. Hyd. cement × 0.26 = 6,679

× 0.26 = 1,736 cm^3

Capillary water = 3,861 – 1,736 = 2,125 cm^3.

4. Volume fractions:

Component	*Volume (cm^3)*	*Volume fraction*
Hydrated cement	6,679	0.161
Coarse aggregate	16,583	0.40
Sand	13,037	0.31
Capillary water	2,125	0.05
Air	1,655	0.039
Unhydrated cement	1,606	0.04
TOTAL	41,685	1.000

5. The dielectric constant of water-saturated concrete (K_{ssd}) is

$$\begin{aligned} K_{ssd} = {} & [V_c K_c^{0.5} + V_{ca} K_{ca}^{0.5} + V_s K_s^{0.5} \\ & + V_{cw} K_{cw}^{0.5} + V_a K_a^{0.5} \\ & + V_{uc} K_{uc}^{0.5}]^{1/0.5} \end{aligned}$$

$$\begin{aligned} K_{ssd} = {} & [0.161 \times 33.64^{0.5} + 0.40 \times 7.01^{0.5} \\ & + 0.31 \times 4.71^{0.5} + 0.05 \times 80^{0.5} \\ & + 0.039 \times 1^{0.5} + 0.04 \times 6.9^{0.5}]^{1/0.5} \end{aligned}$$

$$K_{ssd} = 10.61.$$

6. Its oven-dry dielectric (K_{od}) is

$$\begin{aligned} K_{od} = {} & [V_c K_c^{0.5} + V_{ca} K_{ca}^{0.5} + V_s K_s^{0.5} \\ & + V_{cw} K_{cw}^{0.5} + V_a K_a^{0.5} + V_{uc} K_{uc}^{0.5}]^{1/0.5} \end{aligned}$$

$$\begin{aligned} K_{od} = {} & [0.161 \times 8.18^{0.5} + 0.40 \times 6.8^{0..5} \\ & + 0.31 \times 4.34^{0.5} + 0.05 \times 1^{0.5} \\ & + 0.039 \times 1^{0.5} + 0.04 \times 6.9^{0.5}]^{1/0.5} \end{aligned}$$

$$K_{od} = 5.49.$$

MORTAR

The dielectric constant of mortar was derived from the mixture proportions used in this study and from the dielectric constants developed above.

Mixture	
Cement	25,878 g
Sand	63,560 g
Water	10,397 g
Air, %	1.05

1. Volume of hydrated cement:

$$V_c = 0.68 \times \delta \times W_c$$

$$V_c = 0.68 \times 0.66 \times 25{,}878$$

$$V_c = 11{,}614 \text{ cm}^3.$$

2. Volume of unhydrated cement:

$$V_{uc} = (W_c \times 0.34)/\mathrm{SG}$$

$$V_{uc} = (25{,}878 \times 0.34)/3.15$$

$$V_{uc} = 2{,}793 \text{ cm}^3.$$

3. Volume of capillary water:

Chemically bound water = 0.23

× 25,878 × 0.66 = 3,928 g

Free water = 10,397 – 3,928 = 6,469 g

Water held in gel pores = 11,614

× 0.26 = 3,020 cm^3

Capillary water = 6,469 – 3,020 = 3,449 cm^3.

4. Volume fractions:

Component	*Volume (cm^3)*	*Volume fraction*
Hydrated cement	11,614	0.276
Sand	23,805	0.565
Capillary water	3,449	0.082
Air	442	0.0105
Unhydrated cement	2,793	0.0665
TOTAL	42,103	1.000

5. The dielectric constant of water-saturated mortar (K_{ssd}) is

$$K_{\mathrm{ssd}} = \left[V_c K_c^{0.5} + V_s K_s^{0.5} + V_{\mathrm{cw}} K_{\mathrm{cw}}^{0.5} + V_a K_a^{0.5} + V_{\mathrm{uc}} K_{\mathrm{uc}}^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{ssd}} = \left[0.276 \times 33.64^{0.5} + 0.565 \times 4.71^{0.5} + 0.082 \times 80^{0.5} + 0.0105 \times 1^{0.5} + 0.0665 \times 6.9^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{ssd}} = 14.03.$$

6. Its oven-dry dielectric (K_{od}) is

$$K_{\mathrm{od}} = \left[V_c K_c^{0.5} + V_s K_s^{0.5} + V_{\mathrm{cw}} K_{\mathrm{cs}}^{0.5} + V_a K_a^{0.5} + V_{\mathrm{uc}} K_{\mathrm{uc}}^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{od}} = \left[0.276 \times 8.18^{0.5} + 0.565 \times 4.34^{0.5} + 0.082 \times 1^{0.5} + 0.0105 \times 1^{0.5} + 0.0665 \times 6.9^{0.5}\right]^{1/0.5}$$

$$K_{\mathrm{od}} = 4.99.$$

APPENDIX B: SHRINKAGE MEASUREMENTS

A major weakness of concrete is that it shrinks with age, and much of this shrinkage is due to moisture loss. Inadequate allowance for the effects of shrinkage can lead to cracking, warping and twisting, all of which reduce the service life of concrete. We measured the shrinkage of concrete as a function of moisture content. However, we did not use a sealed specimen as a control. Thus our shrinkage measurements are due to two causes: moisture loss due to drying (evaporation to the atmosphere) and moisture loss due to self-desiccation (water consumed by hydration).

The samples used for this test were made with the same mixture proportions and materials used for the TDR specimens made with the larger coarse aggregate in Part II (see Tables 2 and 3). The samples were molded into 7.62- × 7.62- × 28.58-cm beams fitted with stainless steel gage studs in their ends. Measurements were taken according to ASTM C 490 each time the specimen was partially dried. The drying procedure described for the TDR samples was followed here. Figure B1 shows an individual shrinkage measurement being taken.

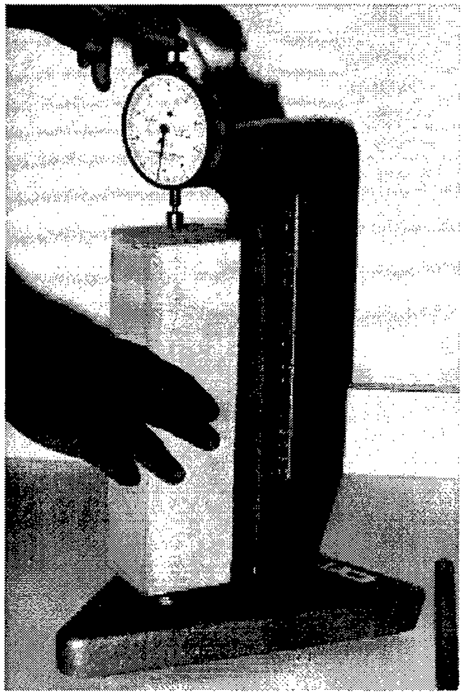

Figure B1. Extensometer used to measure length at the centerline of the concrete.

Current practices acknowledge that concrete will crack, and accommodate for this eventuality by making it crack at strategically located joints. Concrete can be designed to shrink less but little information is available on how to do this. A systematic study is needed to define the shrinkage characteristics of concrete. Drying-shrinkage of concrete (see Fig. B2) is largely a cement paste property that is modified by coarse aggregate. Thus, the study should investigate the effects of cement content, water content, and aggregate shape, size, and type on shrinkage. Also, certain chemicals admixtures can influence shrinkage in a positive way. These should be investigated as well.

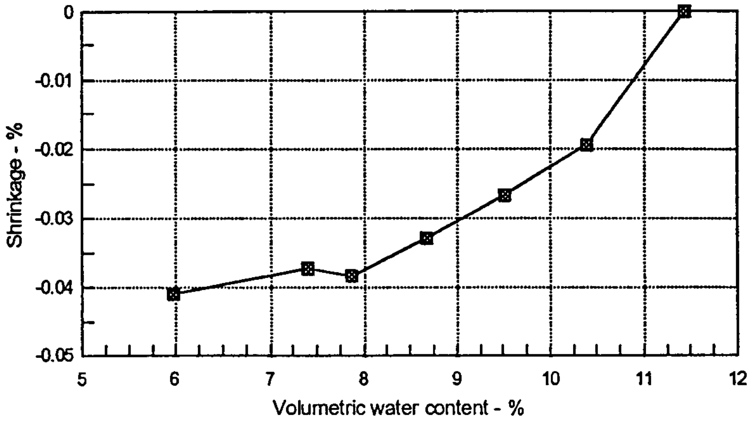

Figure B2. Shrinkage vs. water content of concrete.

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13. ABSTRACT (*Maximum 200 words*)

Time-domain reflectometry is useful for measuring the moisture content of solids. However, little information exists on its use with portland cement concrete. By monitoring the response from TDR sensors embedded in concrete as the concrete dried, we developed a second-order polynomial equation that relates dielectric constant to moisture content. The study is valid for the specific concrete studied.

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