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Highway IDEA Program

Development of Time Domain Reflectometry Instrument for QA/QC of Fresh and Early Stage Concrete

Final Report for Highway IDEA Project 126

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January 2010

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Final Report

NCHRP-IDEA-126

Development of Time Domain Reflectometry Instrument for QA/QC of Fresh and Early Stage Concrete

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Abstract

The project developed a new instrument based on Time Domain Reflectometry (TDR) for measuring properties of fresh and early age concrete as an alternative to traditional quality control methods that rely heavily on the slump value and compressive strength and do not always produce durable concrete. Work in the first stage focused on the design and development of a prototype sensor system for use on fresh and early age concrete. An experimental program systematically evaluated the sensor system's ability to measure the performance properties of concrete. The program tested several representative concrete specimens used in highway pavement, bridge, and industrial and residential structures. TDR signals were collected on concrete specimens subjected to different curing conditions, including early freezing, and the results were correlated with data obtained by standard test methods. The results indicated that the TDR sensor system could reliably measure or estimate concrete properties, such as free water content, density, air void content, initial and final setting times, and mechanical strength. New test results also showed promise of advancing this technology to estimate the thermal properties of concrete, such as the thermal conductivity and heat capacity. We have conducted experiments in a few types of soils to verify the testing methodology. The results were encouraging. The technology was found not only suitable to measure the physical and thermal properties of materials at a common temperature but also works non-destructively under freezing-thawing cycles. The system is being refined to measure the thermal properties in a non-intrusive fashion. The work on thermal properties of construction materials also led to the idea of smart coatings with modulated optimal properties for effective solar energy management. Efforts are underway to integrate the sensor data as input for Building Information Systems, an emerging area with significant potential to improve the energy efficiency. The researchers received a U.S. patent on the technology and have filed for a new patent on a flat strip design, in addition to submitting several invention disclosures to the University for review. Discussions are underway with several vendors who have expressed commercial interest in the TDR technology.

Key Words: Time Domain Reflectometry, TDR, dielectric constant, electrical conductivity, water content, water-cement ratio, dry density, compression strength, freeze-thaw, ultrasonic

Distribution Statement

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TABLE OF CONTENT

Executive Summary 1

1. General Description 2
1.0 Introduction 2
1.1 Technology Background 8
1.2 Current Engineering Practice 10
1.3 Rationale of Time Domain Reflectometry for Fresh and Early Stage Concrete 11
1.4 Preliminary Study of TDR for Concrete 11
1.5 Scope of Work 13

2. Description of Project Work 14
2.1 Development of TDR Sensor and Monitoring System 14
2.2 Experimental Design and Procedures 17

3. Summary of Experimental Discoveries 22
3.1 Experimental Observations 22
3.2 Validation of Concrete Mix Proportion 23
3.3 Estimation of the Degree of Hydration 26
3.4 Estimation of Setting Times 27
3.5 Estimation of Concrete Strength 28
3.6 Assistance in Winter Curing Decisions 30

4. Other Related Explorations 33
4.1 Measurement of the Thermal Properties of Concrete 33
4.2 Characterizing Pore Structure by Advanced Ultrasonic Technology 35
4.3 Strength of Concrete from Ultrasonic Testing 37

5. Summary and Plan for Implementation 41
5.1 Summary of Research Discoveries 41
5.2 Recommendations for Future Research 42
5.3 Plan for Implementation 42

Appendix 44
References 45

EXECUTIVE SUMMARY

The goal of this project is to develop and demonstrate the application of a new instrument based on Time Domain Reflectometry (TDR) (a guided radar) for measuring properties of fresh and early age concrete as an alternative to traditional quality control methods. Traditional techniques, which heavily rely on the slump value and compressive strength, do not always produce durable concrete. Work in the first stage focused on the design and development of a prototype sensor system for use on fresh and early age concrete. An experimental test program was undertaken for a systematic evaluation of the sensor system for measuring the performance properties of concrete. The program involved several representative concrete specimens used in highway pavement, bridge, and industrial and residential structures. TDR signals were collected on concrete specimens subjected to different curing conditions, including early freezing, and the results were correlated with data obtained by standard test methods. The results indicate that the TDR sensor system can accurately measure or estimate the properties of fresh and early stage concrete such as free water content, density, air void content, initial and final setting times, and mechanical strength. New test results also showed promise of advancing this technology to estimate the thermal properties of concrete, such as the thermal conductivity and heat capacity. Potential applications of this new technology include:

- concrete mix proportion verification;
- initial and final setting times determination;
- air content estimation;
- guidance on temperature curing for preventing early freezing damage;
- warning of bleeding and segregation and ensuring uniformity in paving (a new flat cable design helps integration with paving operations);
- density estimation for ultrathin pavement topping;
- thermal properties of concrete.

The technology was found not only suitable to measure the physical and thermal properties of materials at common temperature but also works non-destructively under freezing-thawing cycles. The system is being refined to measure the thermal properties in non-intrusive fashion. The work on thermal properties of construction materials also led to the idea of smart coatings with modulated optimal properties for effective solar energy management. Efforts are underway to integrate the sensor data as input for Building Information Systems, an emerging area with significant potential to improve the energy efficiency.

A U.S. patent on the technology has been issued to the researchers, and a new provisional patent application on flat strip design has been filed. Several invention disclosures have also been submitted to the university for review. A few vendors expressed interest in this technology.

1. GENERAL DESCRIPTION

1.1 Introduction

Concrete is one of the most widely used construction materials for buildings, roads, dams, etc. It achieves excellent mechanical properties if properly mix design and curing procedures are followed. It has been widely accepted that the behaviors of concrete in the early stage determines its long term performance. The current acceptance of production concrete relies on the slump value and compressive strength, which has been observed not to always produce durable concrete. Successful application of concrete materials requires innovative tools to assist in the study of early stage concrete behaviors and ensure proper construction control. Given the huge quality of concrete placed annually in the U.S. and over the world, innovative tools are needed to assist the study of early stage concrete behaviors and ensure proper construction control. The improvements in the performance of concrete mean better durability and reduced life cycle cost. All of these contribute to the sustainable development strategy for transportation infrastructure.

This study explores the application of a guided Electromagnetic Wave technology (TDR) to study the early stage concrete behaviors and provide QA/QC of fresh concrete and early stage concrete. In addition, the study investigates the unique issue of concrete pouring in the cold regions under freezing-thawing conditions.

1.2 Technology Background

1.2.1 Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) is an established technology used by electrical engineers to locate discontinuities in electrical cables. Previous research indicated that TDR was also a useful tool for characterizing material dielectric properties. Since the pioneering work by Topp et al. (1980), TDR has been a topic of extensive research in soil sciences, agriculture and civil engineering. ItI has become widely used in civil and transportation engineering practice.

A TDR system for field measurement generally includes a TDR device (which consists of a pulse generator and a sampler), a connection cable, and a measurement probe (Fig. 1.1). The pulse generator sends out a pulse (which generally is a fast rising step pulse) and the sampler records the response from the system. The typical TDR signal and information content for TDR measurement in a soil is shown in Fig. 1.2. In this figure, we can see a “peak” and a “valley”, which are caused by reflections and are characteristic of TDR signals measured in geomaterials. The “peak” is caused by the first reflection, which occurs when the electromagnetic pulse crosses the air/material interface. The “valley” is caused by the second reflection, which occurs when the electromagnetic pulse arrives at the end of the measurement probe.

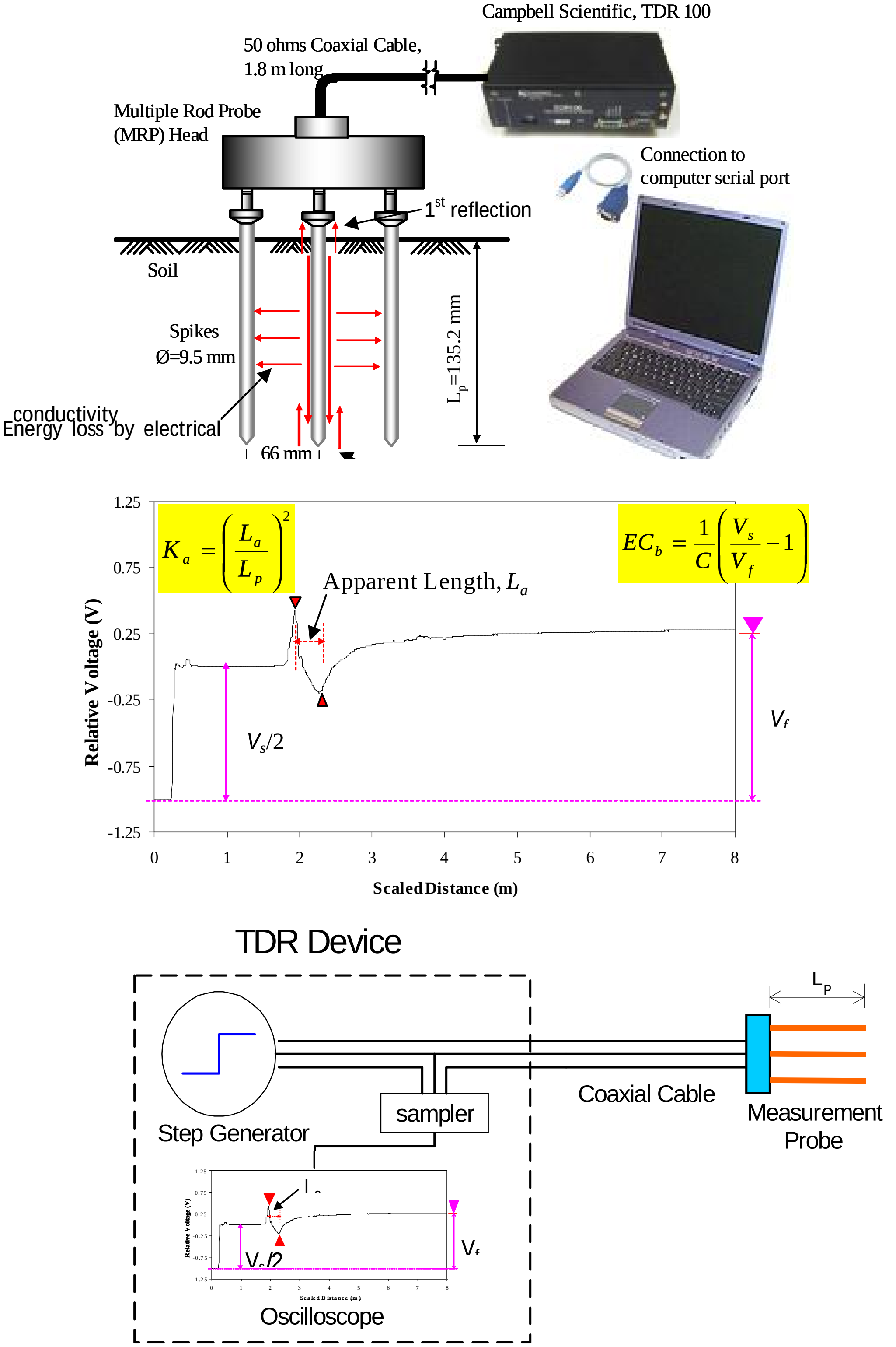


Fig. 1.2 Typical TDR signal and information content

Dielectric constant and electrical conductivity are two important pieces of information that can be obtained from analysis of a TDR signal. Material dielectric constant is analogous to Young's modulus in that it determines the wave speed (electromagnetic wave rather than stress wave). It can be determined from travel time analysis and is generally called apparent dielectric constant (denoted Ka in this paper). According to the theory, Ka represents the real part of the frequency dependent dielectric permittivity. Equation (1.1) gives the mathematic expression for computing dielectric constant from TDR measurement.

$$K_a = \left(\frac{L_a}{L_p} \right)^2 \qquad (1.1)$$

where L_p is the length of the probe in the material and L_a is the scaled horizontal distance between the two reflections (called apparent length, see Fig. 1.2).

The electrical conductivity (denoted ECb in this paper) causes attenuation of the TDR signal and is another important piece of information that can be obtained from TDR waveforms. Different approaches can be used to obtain electrical conductivity from a TDR signal. The approach based on analysis of the long-term response of a TDR system10 is used in this paper to determine electrical conductivity (Eq. (1.2)).

$$EC_b = \frac{1}{C} \left(\frac{V_s}{V_f} - 1 \right) \qquad (1.2)$$

where V_s is the source voltage, V_f is the long term voltage level (a method to locate these two characteristic voltages are shown in Fig. 1.2, and C is a constant related to probe configuration, which can be obtained by calibration.

For coaxially configured probes,

$$C = \frac{2p\, L_p R_s}{\ln \left(\frac{d_0}{d_i} \right)} \qquad (1.3)$$

in which L_p equals the length of the probe in the material, R_s the internal resistance of the pulse generator (typically 50 ohms), and d_0 and d_i are the diameters of outer and inner coaxial conductors, respectively.

TDR measured dielectric constant is widely applied for measuring moisture content in a variety of materials and TDR measured electrical conductivity is widely used in agriculture science to estimate soil salinity and pore fluid electrical conductivity.

1.2.2 Measuring Water Content by Time Domain Reflectometry

TDR has been extensively applied to estimate the water content in soils from the measurement of soil dielectric constant. The strong correlation between TDR-measured dielectric constant and the amount of water in the soil is attributed to the much larger dielectric constant of free water (around 81 at room temperature) as compared with the dielectric constant of air (around 1) or soil solids (around 3 to 7). In freshly mixed concrete, where chemical reactions are just starting, the multiphase system resembles soil mixtures. The behavior of water in fresh concrete mixture resembles that in soils. As time goes on, more water becomes chemically bound by hydration reactions. Thus, the established TDR technology for soil water content measurement is a candidate for measuring the water content in concrete.

One of the most popular equations used to relate TDR measured soil dielectric constant to volumetric water content is a third order polynomial called Topp's equation (Eq. 1.4). It is currently widely used in field practice.

$$q = 4.3\times10^{-6} K_a^3 - 5.5\times10^{-4} K_a^2 + 2.92\times10^{-2} K_a - 5.3\times10^{-2} \tag{1.4}$$

where Ka is dielectric constant, and q is volumetric water content.

A simplified square root type equation (Eq. (1.5)) was proposed later and was found to provide similar accuracy.

$$q = \bar{b}\sqrt{K_a} + \bar{a} \tag{1.5}$$

Jones et al. recommend values of $\bar{b} = 0.125, \bar{a} = -0.1875$ from a dielectric mixing model.

Volumetric water contents (θ) in Eqs.(1.4) and (1.5) may be converted to gravimetric water contents (w) as conventionally used with soil and concrete by use of the relationship provided in Eq.(1.6) below:

$$w = q\frac{r_w}{r_d} \tag{1.6}$$

where r_d is the dry density of soil, r_w is density of water and w is the gravimetric water content.

Siddiqui and Drnevich and Siddiqui et al. related gravimetric water content and soil dry densities to soil dielectric constant using Eq. (1.7).

$$\sqrt{K_a}\frac{r_w}{r_d} = a + bw \tag{1.7}$$

where a and b are soil specific constants obtained from calibration tests.

For rapid determination of water content of concrete using this equation, a batch sample can be obtained and put into a cylindrical mold of known volume, from which total density of concrete in the mold, r_t, can be determined. The relationship between total density and dry density is given by Eq. (1.8)

$$r_d = \frac{r_t}{1+w} \tag{1.8}$$

Substituting Eq. (1.8) into Eq. (1.7) and solving for the water content gives:

$$w = \frac{\sqrt{K_a}\frac{r_w}{r_t} - a}{b - \sqrt{K_a}\frac{r_w}{r_t}} \tag{1.9}$$

Equation (1.9), with appropriate values of a and b for concrete, can be used to obtain the free water content of concrete.

1.2.3 Relationship between TDR Measured Electrical Conductivity and Cement Content

Electrical conductivity is another important piece of information that can be obtained from a TDR signal. For freshly mixed concrete, which consists of cement paste, sand, and coarse aggregate, the major contribution to electrical conductivity is from the cement paste. The conductivity in mixtures consisting of a highly conductive phase and low conductive phases has been investigated in previous research. This included studying of the influence on bulk electrical conductivity by the amount of carbon black added to two-phase composite materials; in another study, the effects of percent graphite addition on the bulk electrical conductivity of a graphite-sand mixture was investigated. Both works showed that bulk electrical conductivity was linearly dependent on the concentration of the highly conductive phase (defined as ratio of mass of high conductive phase to nonconductive solids). In addition, both works showed that once a conduction network of a highly conductive phase was formed in the mixture, conductivity was relatively independent of the amount of added water.

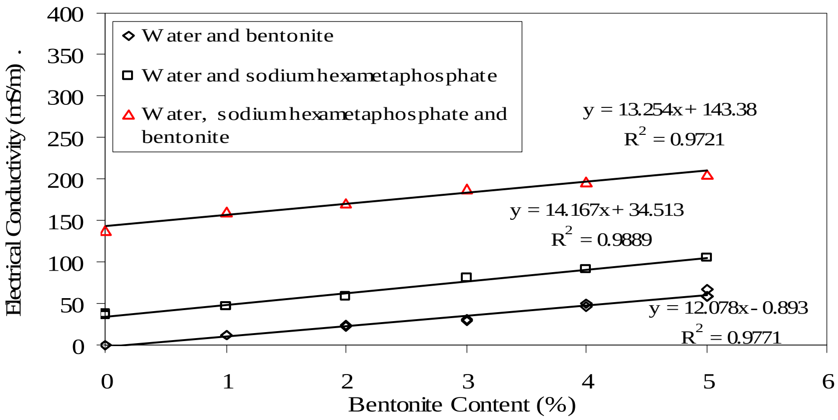


Fig. 1.3 Relationship between TDR measured electrical conductivity and bentonite content

Similar phenomena were observed in research that used bentonite to increase the seismic resistance capability of clean sand. Figure 1.3 shows the TDR measured bulk electrical conductivity versus percent bentonite (defined as ratio of mass of bentonite versus mass of sand) using water with different salt additives. The plot indicates that there is a linear relationship between TDR electrical conductivity and percent bentonite content. The slope of this relationship is independent of a dispersant (sodium hexametaphosphate in this case), which only affects the intercept.

In view of the similarity between the fresh concrete mixtures and the mixtures investigated in previous research, a linear relationship is proposed between TDR-measured electrical conductivity of the fresh concrete mixtures and the cement content (defined as mass of cement to mass of sand plus aggregate) as shown in Eq. (1.10):

$$c(\%) = \frac{1}{b}\left(EC_b - a\right) \tag{1.10}$$

where a (units of ms/m) is a constant related to the amount of chemical additives in fresh concrete; b is a property related to cement properties and aggregate geometry.

For a given concrete mixture design, a group of calibration tests can be performed on samples with different cement contents to determine the calibration constants in Eq. (1.10). Amounts of water, sand, coarse aggregate, and the type and amount of admixtures used in the calibration should be similar to those used in the field.

1.2.4 Physicochemical Reactions During Curing

Extensive physicochemical changes take place in a concrete mixture as it cures. While chemical reactions are the most important process occurring during concrete curing, the exact nature of the entire hydration process is complicated and not fully understood. Different models are proposed to describe the behavior of concrete at different stages of curing and hydration. Generally speaking, hydration reactions take place between cement powder and water upon mixing and theoretically, the process continues forever. Major products of the reactions include calcium silicate, calcium aluminate, ettringite, etc. Calcium silicate is the major component affecting concrete strength and calcium aluminates predominantly determine the time of the initial setting. A significant amount of heat is generated during the hydration process.

A direct consequence of the hydration process is a change in the microscopic structure. This results in the increase of modulus and strength. Beek et al. found that there is a strong linear correlation between concrete strength and the degree of hydration. The hydration process, which significantly changes the microstructure of concrete, changes the electrical behavior of concrete as well. Bulk water becomes chemically bound water, which shows significantly different dielectric behavior compared with bulk free water. The formation of solid structures by hydration reactions reduces the amount of free ions in pore solution, which results in a decrease of electrical conductivity. Thus, concrete electrical behavior can be a strong indicator of the progress of the hydration process. As the hydration process directly results in the increase of concrete strength, electrical properties can thus be used to monitor strength development.

1.3 Current Engineering Practice

1.3.1 The status of free water content and water-cementitious ratio measurement

The free water content and water-cement ratio are among the most important factors for concrete strength and durability (Powers and Brownyard (1948), Mindess et al. (2003)). The current field practice is to estimate water-cementitious ratio from the batch mixture quantities. The estimated results are not generally accurate because the quantities do not accurately account for factors such as moisture contained in the aggregate or water added at the job site. Alternative approaches have been investigated based on analytic instruments (Hime (1990), Howdyshell (1991)), Near-Infrared (NIR) (Fateley and Chaffin (1999)), ultrasonic waves (Popovics and Popovics (1998), Philippidis and Aggelis (2003)), nuclear methods (HITEC (1996)) and microwave ovens (Naik and Ramme (1987), Nagi and Whitting (1994), AASHTO-T318 (TP-23)). Among the various approaches investigated, only the microwave oven and nuclear methods meet the requirements for a practical field instrumentation tool (i.e., easy to perform the test and analyze the data and the equipment is cost effective). However, they both still present a number of problems.

The nuclear water-cement ratio gauge, which is a modification of the one used for soils, was found to be very sensitive to factors such as the air content in concrete, the aggregate type, and the fly ash used in the mix (HITEC (1996)). These, together with the extensive training and strict license and handling requirements make it undesirable for field applications (Dowell and Cramer (2002)).

The microwave oven method provides a relatively rapid method to measure the water content in concrete. The method involves a simple test procedure, inexpensive equipment, and can be performed in about a half hour (Nagi and Whiting (1994)). However, it has been found that the amount of coarse aggregate can have an appreciable influence on the results (Nantung (1998)). A possible explanation is that entrapped water is not removed during the test. Evaluation by the Wisconsin DOT indicates that the microwave method is “marginally useful” for quality control (Dowell and Cramer (2002)). Shortcomings of the microwave method include the destructive characteristics of the test (nothing else can be measured from the sample) and its inability to provide information on concrete strength.

1.3.2 The status of concrete strength measurement

The strength of the concrete is the factor that is strongly related to the performance and service life of concrete structures. The laboratory compression tests are destructive and might not be representative of the actual concrete behaviors due to differences in curing and boundary conditions. Alternative approaches such as calorimetry, thermal techniques, nuclear magnetic resonance spectroscopy are generally expensive and require sophisticated methods of data analysis.

The maturity method based on thermal measurements (Saul (1951), Carino (1991)) has been identified as a promising approach to gauge the concrete strength development and is currently being introduced in field practice (Carino and Lew (2001), ASTM C1074). The method is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of maturity index. The maturity index is based on an integration of temperature history which can be easily measured.

The ultrasonic wave has been increasingly used for monitoring the hardening process and estimating the initial setting of concrete (Garnie et al. (1995), Rapoport et al. (2000)). Efforts have also been made to estimate concrete strength using ultrasonic waves (Akkaya et al. (2003), Voigt et al. (2003), Matusnović et al. (2004)). It generally requires sophisticated signal analysis. In addition, the undefined boundary of the concrete sample tends to compromise the accuracy and the reliability of the measurement results (Popovics and Popovics (1998)). With special designed testing configuration, Voigt et al. (2003) developed an ultrasonic “maturity meter” which is promising for fresh concrete applications.

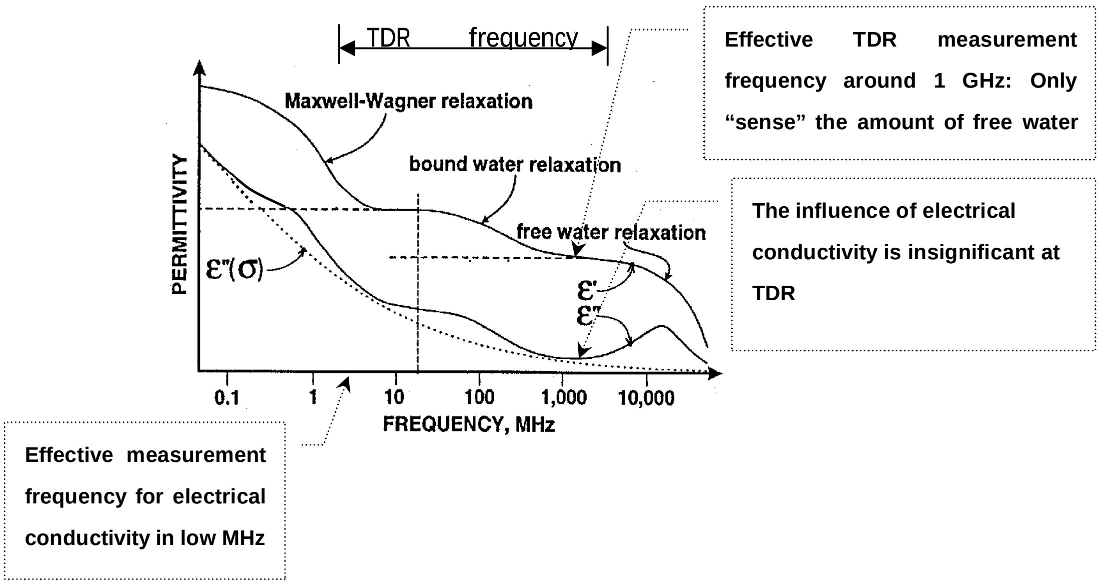
Hydration causes the change of concrete microstructure and the increases of the strength of concrete. It also simultaneously changes the electrical properties of concrete. Thus, the electrical properties of concrete, especially conductivity, are strongly related to strength. Previous research has investigated the application of electrical conductivity for monitoring the initial set and curing progress (Boast (1936), Tamás (1982)); assessing the water content of fresh concrete (McCarter and Curran (1984)), studying the influence of additives (Perez-Pena et al. (1989), EI-Nein et al. (1995)), and evaluating the corrosion of concrete reinforcement. Efforts have also been made to develop advanced models relating the bulk concrete electrical conductivity to microscopic mixture components (Garboczi, et al. (1995)). Van Beek et al. (1997) found that there is a strong linear correlation between concrete strength and degree of hydration. The formation of solid structures by hydration reactions reduces the amount of free ions in pore solution, which results in a decrease of the electrical conductivity (EI-Enein et al., 1995, Xu et al., 2000, Princigallo et al., 2003).

1.4 Rationale of Time Domain Reflectometry for fresh and early stage concrete

TDR is an established technology for soil instrumentation in geotechnical engineering. It can be used to determine volumetric water content (ASTM D6565) as water has a much larger dielectric constant (around 81) than that of the air (around 1) or soil solids (around 3 to 5). The researchers of this proposal have developed new procedures and equipment that significantly improved the accuracy of the method for water content determination and extended it to include estimation of in situ soil density (Siddiqui et al. (2000), Drnevich et al. (2001), U.S. Patents: 5,801,537 (Sep. 1, 1998), 5,933,015 (Aug. 3, 1999), 6,215,317 (April 10, 2001), others pending). Recent research by the PI has further simplified the test procedures by incorporating the use of the electrical conductivity in addition to the dielectric constant (Yu and Drnevich (2004)). The previous research resulted in a newly established ASTM standard D6780.

In addition to instrumentation for soils, TDR was found to be a low cost alternative to NMR and x-ray for studying the moisture variation in hardened concrete (Korhonen et al. (1997), Hansen E.J. de P. and Hansen (2002)). The TDR-based dielectric spectroscopy was developed to study the transition from free water to bound water and the microstructure of cement paste (Hager and Domszy (2004)). However, currently the research and application of TDR for fresh or early stage concrete is limited.

Fresh concrete is a very complex system. Water exists in concrete in the form of free water or bound water. Both types of water have dielectric relaxation behaviors. Dielectric relaxation is a phenomena where the real part of dielectric permittivity (or dielectric constant) reduces from a large value (around 81 for water) to a very small value (around 3~4) after passing the relaxation frequency. Free water has a large dielectric permittivity which is flat until around 17GHz (relaxation frequency of free water). Because of the strong restraints by the chemical bond, bound water has a much lower relaxation frequency (in the low megahertz range). This means if we look at concrete using a frequency larger than the bound water relaxation frequency and smaller than free water relaxation frequency, free water will show dielectric constant of around 81 while bound water will show dielectric constant of only 3 to 4. Using the current TDR system, the effective measurement frequency for dielectric constant is around 1 GHz (Fig. 1.4). This makes TDR responsive only to the amount of free water in concrete. The bound water is spectrally invisible. In addition, because of the use of high frequency the electrical conductivity has negligible effects on the measured dielectric constant (Fig. 1.4). TDR signal provides condensed information on the complex microscopic mechanism, from which the dielectric constant can be easily obtained (Fig. 1.2).



Effective TDR measurement frequency around 1 GHz: Only "sense" the amount of free water

The influence of electrical conductivity is insignificant at TDR

Effective measurement frequency for electrical conductivity in low MHz

Fig. 1.4 Qualitative representation of dielectric permittivity as a function of frequency. Notations: ε': real part of dielectric permittivity or dielectric constant, ε'': imaginary part of dielectric permittivity, $\varepsilon''(\sigma)=\sigma/(i2\pi f\varepsilon_0)$ is contribution of the imaginary part of dielectric permittivity by the electrical conductivity σ, f is the frequency, ε_0 is the dielectric permittivity of free space which equals 8.85×10^{-12} Faraday/meter. (modified from Yu et al. (2005))

In summary, TDR measures the complex systems of fresh and early stage concrete from two very clear angles. It extracts important information on their behaviors. The advantages of TDR over other electrical methods include: 1) TDR determines the dielectric properties and electrical conductivity simultaneously on a well defined sample; 2) The information can be easily and accurately obtained. The high sensitivity of TDR to the hydration in concrete together with the fast signal acquisition and automatic data analyses make it a very promising tool for quality control and proper curing of fresh concrete and early stage concrete.

1.5 Preliminary Study of TDR for Concrete

Using a low cost TDR sensor similar to that used for soils, Yu et al. (2004a) found that TDR can accurately determine the free water content in fresh concrete. This, combined with the cementitious content from batch tickets provides improved estimation of the water-cementitious ratio. In addition, the calibration constants, while different from those of soils, were not found to be strongly influenced by the types of cement or chemical additives. This will be helpful in developing the reference database for field applications. Due to its nondestructive characteristics, TDR can provide real-time monitoring of the evolution of free water content during concrete curing (Fig. 1.5).

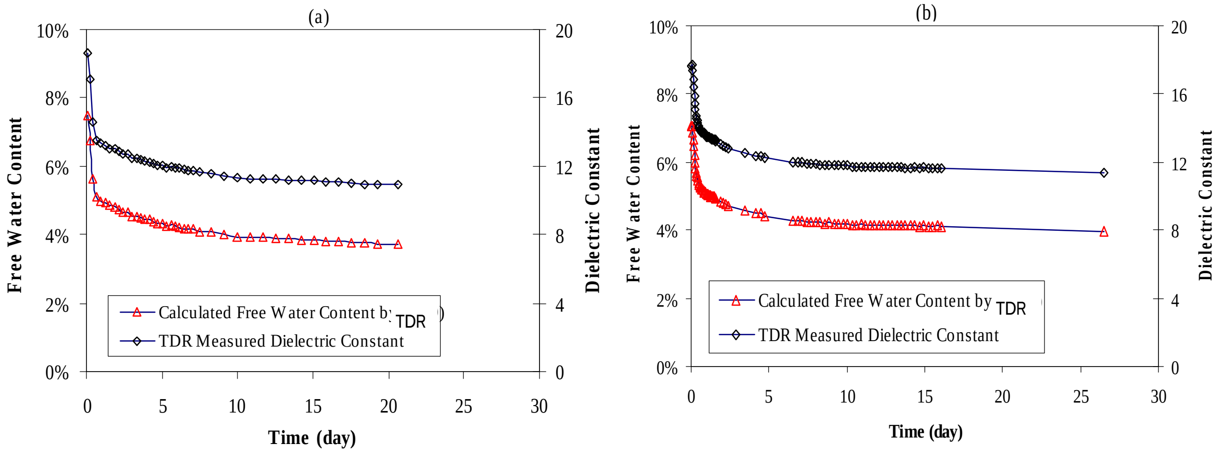


Fig. 1.5 TDR monitored evolution of dielectric constant and free water content in concrete: left) an ordinary concrete; right) a self-consolidating concrete (Yu et al. 2004a)

Yu et al. (2004b) also found that the evolution of electrical conductivity of concrete is a sensitive indicator for various stages of hydration reactions. Besides, the strength of early stage concrete can be accurately estimated from TDR measured electrical conductivity. From the trend of electrical conductivity evolution, the long term strength of concrete can be predicted within one day (Fig. 1.6).

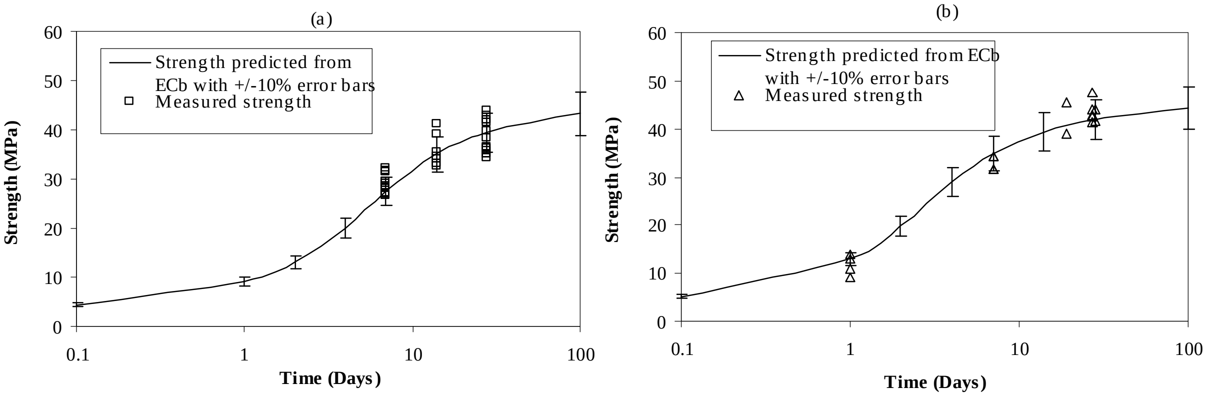


Fig. 1.6 Compressive strength of concrete predicted from short term TDR measurements (1 day) vs. measured values: left) an ordinary concrete; right) a self-consolidating concrete (Yu at al. 2004b)

While the results are encouraging, the conclusion is not inclusive due to the limited scope of the preliminary investigation. A more complete research is needed to refine the sensor design, validate the discoveries, generate reference databases and guidelines for field applications.

One distinctive advantage of the proposed TDR sensor system when compared to existing technologies is that the same system can be used to measure a variety of properties related to the performance of fresh and early stage concrete. These include the measurement of the free water content of fresh concrete (this together with the cementitious content from batch ticket can provide improved estimation of water-cementitious ratio), the monitoring of the evolution of the amount of free water during hydration, the estimation of the times of the initial setting and final setting, and the estimation of the strength of early stage concrete. The TDR sensor and system will be inexpensive and rugged[1]. The measurements are accurate as they provide large definite sampling volumes and well-behaved wave-fronts. The test procedures can be performed in a few minutes. The signal acquisition and analyses can be automated.

1.6 Scope of Work

The purpose of this NCHRP-IDEA study was to further validate the conclusions of the preliminary study. Four tasks were involved in the project: 1) Design a TDR sensor suitable for laboratory and field instrumentation of concrete; 2) Conduct an experimental program to validate the framework of free water content measurement, setting times estimation, strength prediction and establish a reference procedure for field application; 3) Develop guidelines for practical use; and 4) Implement research results.

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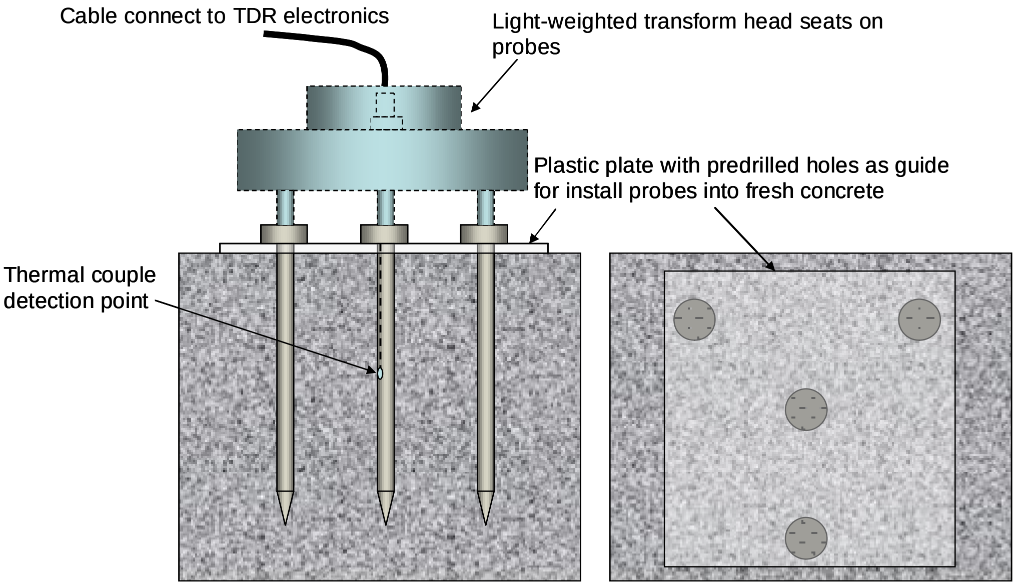
[1] The sensor probe used in our preliminary investigate consists of four ordinary spikes available from local grocery stores (cost around $0.15 each). The total cost of the sensor probe is less than $1.

2. DESCRIPTION OF PROJECT WORK

2.1 Development of TDR Sensor and Monitoring System

The first task was to design a sensor suitable for instrumentation of fresh concrete. A rugged TDR sensor that provides a high quality signal was developed. The new sensor could be similar to the one developed for soils but is modified to address the special requirements for installation in fresh concrete (Fig. 2.1). Fresh concrete has low bearing capacity, high ionic strength, and a large portion of coarse-grained materials. These characteristics require the sensor to be lightweight, highly corrosion resistant, and capable of providing sufficient sampling volume. For soils with a maximum particle size of around 19.00mm, standard (ASTM D2216) recommends a minimum sample of 2.5kg to achieve a water content measurement accuracy of ±0.1%. Larger samples are needed for materials with larger particles. Since fresh concrete generally contains significant portion of large-sized aggregates, the new TDR sensor was designed to have effective sampling volume of at least 3000 cm^3. This provided an effective sampling mass of around 7.5 kg for accurately measuring the water content and dry density of fresh concrete. The geometry of the sensor (including the number of spikes in the array, probe size, and spacing) was optimized to insure high quality signals.



Side View   Top View

Fig. 2.1Schema of TDR sensor for installation in fresh concrete (geometry of the sensor will be optimized in this task)

The new TDR sensor design was carried out in two stages. The first stage used numerical simulations. The computation code developed in previous research (Yu et al. (2005a)) was used to simulate the response of the TDR system to the sensor material, geometry and configuration. From the simulation the optimal design was identified. In the second stage, the sensor is manufactured according to the optimized design. The TDR signals measured on reference materials was compared with those predicted by numerical simulations. Performance of different types of materials and sensor configurations applied to corrosive conditions of fresh concrete were evaluated.

The measurement sensor was made of four common spikes arranged in coaxial configuration (the spikes cost 20 cents each and can be obtained in most local hardware stores). Prior to testing, the spikes were cleaned to remove burrs and oil films. Before installing the sensor in the field or in a sampling mold, a plastic template was first placed on the surface of the fresh concrete. Spikes were pushed in through the predrilled holes in the plastic plate. The use of the plastic plate was to align the spikes and provide support for the weight of TDR measurement head. In this study, the net length of the portion of the spikes submerged in concrete was 135.2 mm (the length of spikes used can vary depending on need) and the distance between center spike and outer spike was 66 mm. This gave a sufficiently large sampling volume, which was necessary to obtain accurate measurements in the coarse grained mixtures.

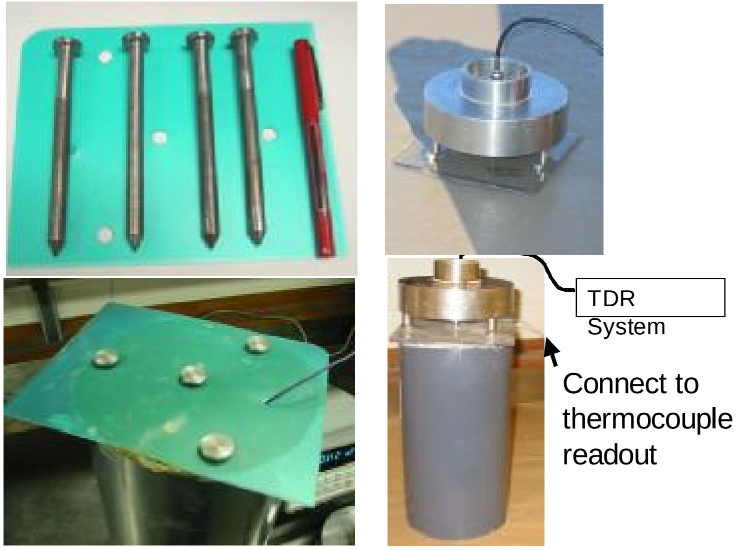


Fig. 2.2 Photo of TDR probe for concrete

Different sensor designs were explored, including a tube sensor arrangement to accommodate cast concrete specimens and a strip sensor to install in the field (Fig. 2.3). This further simplifies the testing system and accommodates real-scale specimens.

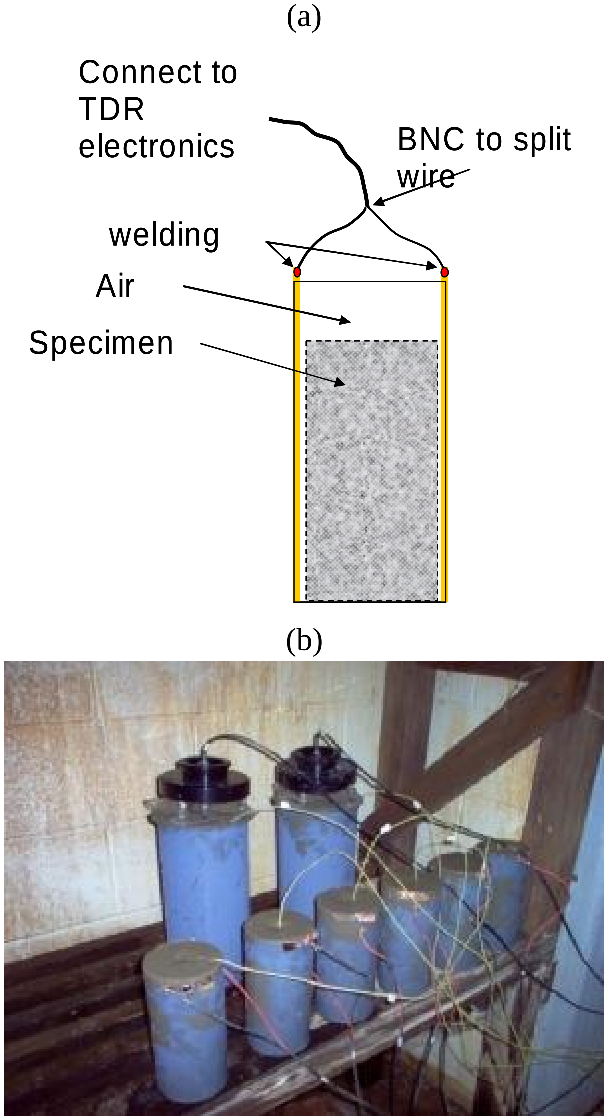


Fig. 2.3 a) schematic of tube sensor accommodating the cylinder specimen; b) photo of monitoring channels

A thermocouple was integrated into the sensor probe to measure the temperature (Fig. 2.3). The data of temperature history together with TDR measured free water content evolution intended to provide complete information on concrete curing conditions. The recorded temperature evolution could also be used to compare the strength predicted by TDR measured electrical conductivity and those by the maturity method.

Fig. 2.4 monitoring station for curing concrete

A monitoring station was developed to automate the data acquisition (Fig. 2.4). This includes in-house developed computer software with user-friendly interface. The system is capable of simultaneously controlling eight channels of TDR concrete sensors through the use of a multiplexer. The operation parameters can be set for the station to take TDR signals at preset time intervals.

2.2 Experimental Design and Procedures

The experimental design tried to mimic the actual production process. Three representative types of concrete used in Ohio DOT projects were used in the experiment. Concrete from commercial suppliers The Collinwood-Horning Concrete Company (http://www.collinwood-horning.com) were used in the study. The concrete mixes were designated as ODOT Class C (Ordinary pavement concrete of 4000 psi), High Strength (8000 psi) and Self-consolidating concrete (6000 psi). A list of concrete properties is shown in Table 2.1.

Table 2.1 Concrete Mixes Used in the Experimental Program

	ODOT Class C	High strength	Self-consolidating
Designed 28-day strength (psi)	4000	8000	6000
Slump (inch)	4	6	6
Designed Water-cement ratio	0.53	0.26	0.31
Actuall w-c ratio	0.648	0.552	0.33
Sand (lb)	1380	1140	1438
Gravel(lb)	1480	1660	#57 Limestone 738 #8 Limestone 783
Cement(lb)	Type 1-5 650	Type 2-3 665	648
Admixture(oz)	AE-260 4	AE-260 7 3500N 32 Super 84	Duraflux33 (SCC Admixture) 10
Water(lb)	76	102	240

The concrete was delivered by the manufacture and was immediately validated for the acceptance criteria using commonly used slump test (Fig.2.5)

Fig. 2.5. Photo of concrete delivery, slump test and penetration test

For each concrete recipe, 60 of 4 inch specimens and 30 of 6 inch specimens were cast. Sufficient numbers of specimens were prepared to ensure at least three repetitive tests could be conducted for each testing conditions. All of these samples were kept in the curing room before they were subjected to different freezing processes. These specimens were divided into groups and were subjected to different curing conditions. The physical and mechanical properties of concrete were measured at different curing ages

TDR Tests: In TDR test, 7 specimens were monitored in each group of experiments; each subjected to a different curing process. Among these, there were 4 different freezing processes produced by placing the specimens into a temperature controlled freezer on the 1st, 2nd, 4th and 6th day of curing. The remaining 3 specimens were cured under normal curing conditions but with different types of TDR probe design, including a parallel strip design, a four-spike probe design and an insulated four-spike probe design (Fig. 2.3).

Upon installation of the sensor, a measurement head was seated on the caps of the spikes, which was connected to the TDR by a coaxial cable. A specially developed computer program was used to take data and obtain the initial dielectric constant and electrical conductivity. Multiple readings were taken and averaged to obtain improved accuracy. This process took less than one minute. The monitoring module of the computer program was then activated, which automatically took TDR readings at specified time intervals to monitor the change of dielectric constant and electrical conductivity with time. TDR sensor monitors the electrical conductivity (ECb) and dielectric constant (Ka) of concrete specimens subjected to different curing processes. For each of these specimens, a thermocouple wire was also installed to monitor the temperature with time, whether due to hydration reactions or changes in ambient temperature. The 7 thermocouples installed inside the specimen were used to monitor the internal temperature process (Fig. 2.3). A monitoring system was built to monitor 8 channels of TDR signals as well as 8 channels of thermocouples. The assignment of the monitoring channels is shown in Table 2.2.

Table 2.2 Distribution of Monitoring Channels

TDR Channel No.	TDR sensor type	Sample	When was it frozen	Thermocouple No.
1	Parallel	4-inch	1st day	5
5	Parallel	4-inch	2nd day	2
3	Parallel	4-inch	w/o	3
4	Parallel	4-inch	4th day	4
6	Parallel	4-inch	6th day	6
7	Uninsulated spikes	6-inch	w/o	7
8	Insulated spikes	6-inch	w/o	8
				1 (Environment Temp)

In conjunction with TDR monitoring, the mechanical and physical properties of concrete subjected to different curing procedures were also measured. The tests included the compressive strength, water content (by over dry), ultrasonic wave speed at different curing ages. The details of the experimental plan are shown in Table 3. For example, the virgin concrete specimens (those subjected to normal curing conditions) were tested for the strength, water content and ultrasonic wave velocity at 1, 2, 3, 4, 5, 6, 7 and 28 days.

In addition to investigate the function of TDR for concrete physical and mechanical properties, a special curing condition considered was the freezing-thawing effects on curing concrete. This intends to simulate the conditions of concrete construction in cold regions. The specimens were placed in a freezer of -15°C at curing ages of 1 day up to 6 days. The specimens were then thawed on the 7th day and subjected to regular curing conditions. For the specimens subjected to freezing, the strength and water content at 3rd day, 7th day and 28th day are measured. The frozen specimens were tested before and after defrost.

Table 2.3 Test Schedule of Different Types of Concrete

Sample\Curing ages	1	2	3	4	5	6	7	28
Virgin	*	*	*	*	*	*	*	*
1st frozen			*				*	*
2nd frozen			*				*	*
4th frozen			*				*	*
6th frozen			*				*	*

Note: * indicates when comprehensive physical and mechanical tests were conducted

Over Dry Water Content: Water content is measured by a destructive oven dry method (Fig. 2.6), which provides reference values of free water content in concrete.

Fig. 2.6 Oven dry method

Ultrasonic Test: The ultrasonic system includes a high power pulse generator, 0.5MHz ultrasonic transducers, and a PC-oscilloscope (Fig. 2.7). The high characteristic frequency ultrasonic transducer ensures a high resolution in determining the ultrasonic wave velocity. Water is used as a couplant to the concrete specimens.

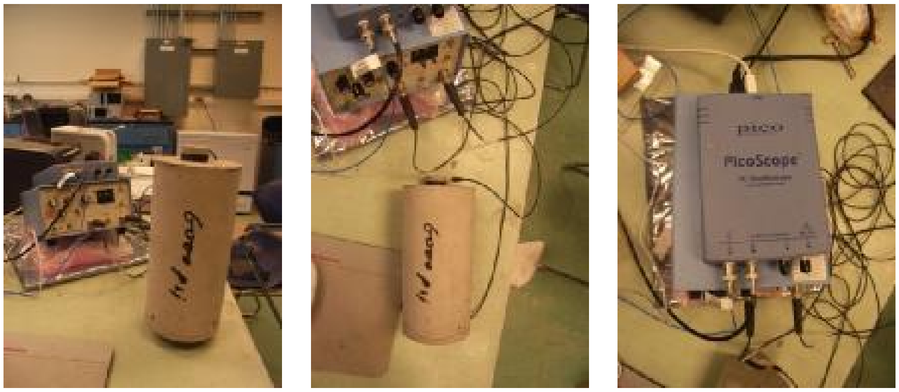


Fig. 2.7 Ultrasonic testing device and example photos of testing concrete specimen

Compressive Strength Test: A MTS machine is used to test the compressive strength of concrete at different curing ages. The machine and destructive samples are shown in Fig. 2.8

Fig. 2.8 MTS machine and destructive concrete sample

3. SUMMARY OF EXPERIMENTAL DISCOVERIES

3.1 Experimental Observations

Figure 3.1 shows examples of TDR monitored signals at different curing ages. As time proceeds, more free water turned into bond water, which subsequently causes the significant change in the TDR signal responses. It can be noticed that 1) the dielectric constant K_a decreases with increasing curing time; and 2) the long term signal levels increase with curing time, which indicate the electrical conductivity (or reverse of electrical resistivity) decreases with time. The first phenomenon is attributed to the fact that the increasing amount of liquid water in the concrete specimen becomes ice. As ice has much a smaller dielectric constant (i.e. around 3) compared with water (around 81), conversion of water into ice reduces the bulk dielectric constant of concrete. The decrease of electrical conductivity during the freezing process is probably due to the reduced amount of free ions available and their reduced mobility.

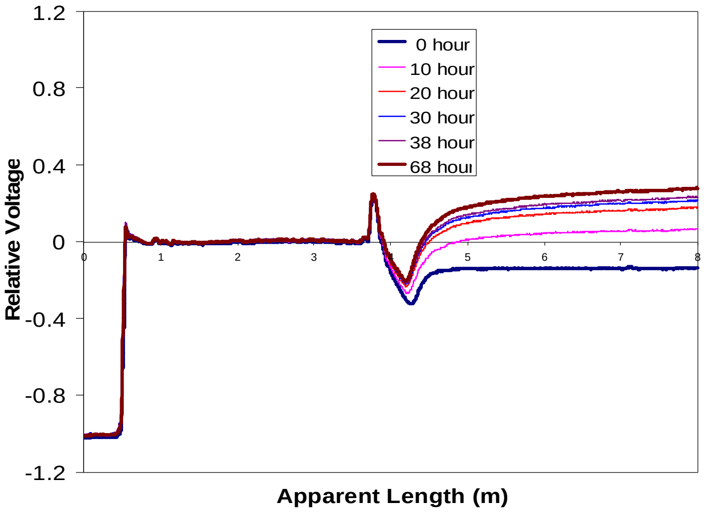


Fig. 3.1 Variation of TDR signals with curing time for TDR channel 2

The water content at different curing ages were measured by oven drying the concrete specimen. Figure 3.2 shows an example of the evolution of free water content with time. The water content at different curing ages were measured by oven dry method conducted on the concrete specimen. As can be seen from this figure, the water content decreases at a high rate at the first few days. The speed became slow after about 7 days. As hydration is the process that water is being consumed, the amount of water content variations is a direct indictor for the hydration rate. The information of this figure indicates concrete hydration is faster at the initial curing stage; the hydration rate becomes slower and slower with the curing ages.

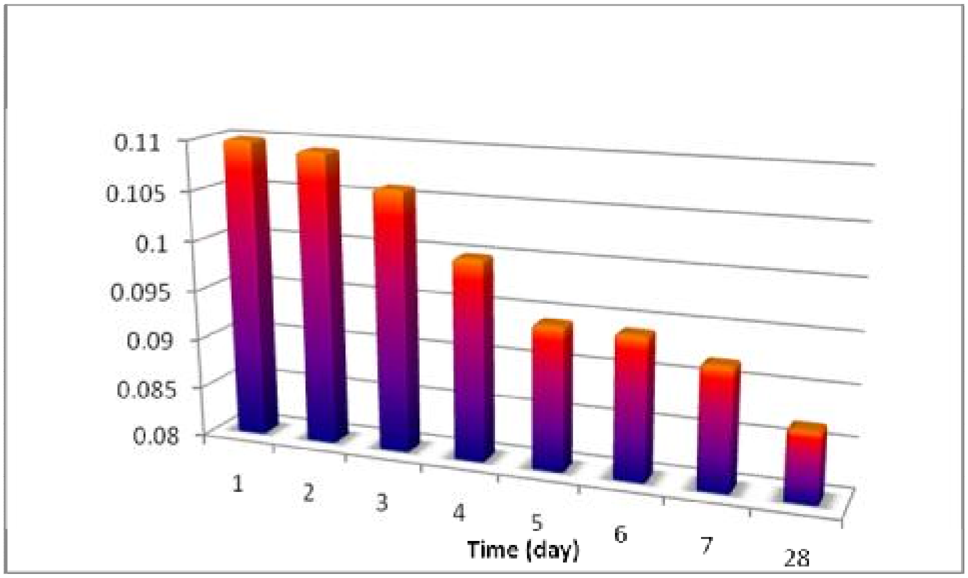


Fig. 3.2 Measured water content at different curing age by over dry method

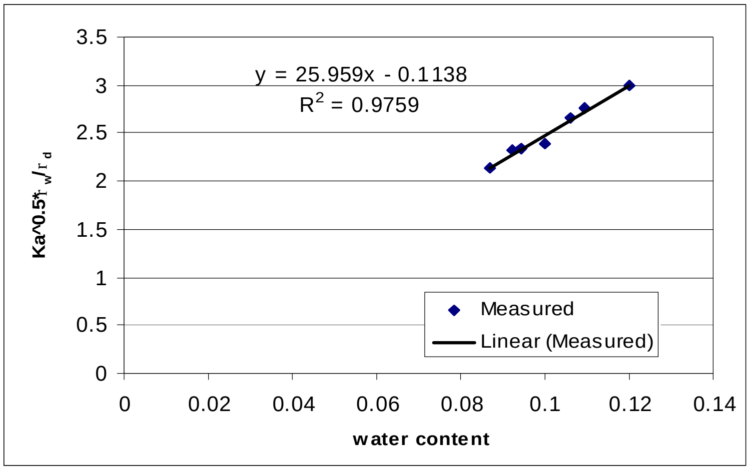
3.2 Validation of Concrete Mix Proportion

Concrete needs to be properly mixed and placed to ensure it is durable. It has been found that the concrete proportional information (e.g. water-cementitious ratio) from batch tickets does not necessarily implies the actual proportions of concrete poured in the field. For example, water is frequently added to ensure the flowability on site. One potential application of this new technology is to provide direct validation of the mix proportions. As shown in Table 2.1, the actual w-c ratio can be quite different from the ticket values.

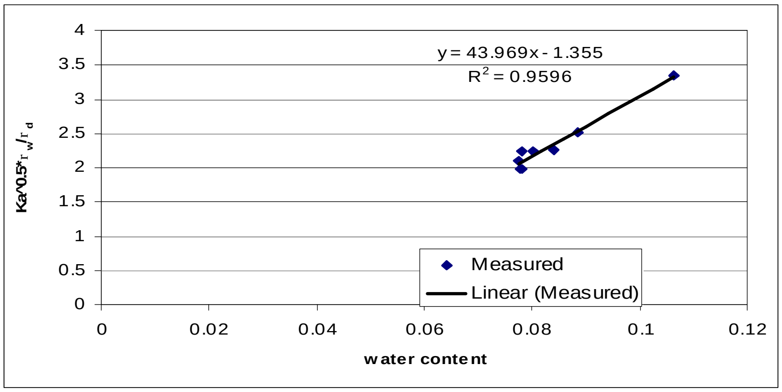
Water Content and Density of Curing Concrete

The ASTM D6780, which is for measuring the water content and density of soils, is evaluated for application on concrete. Figure 3.3 shows the calibration curves for each type of concrete by using the calibration equation of ASTM D6780, i.e., Eq. (1.7). Experimental data indicated the format of the calibration for the TDR measured dielectric constant versus free water content and density applies very well to curing concrete, as indicated by the good linear relationships (Fig. 3.3).

(a)



(b)



(c)

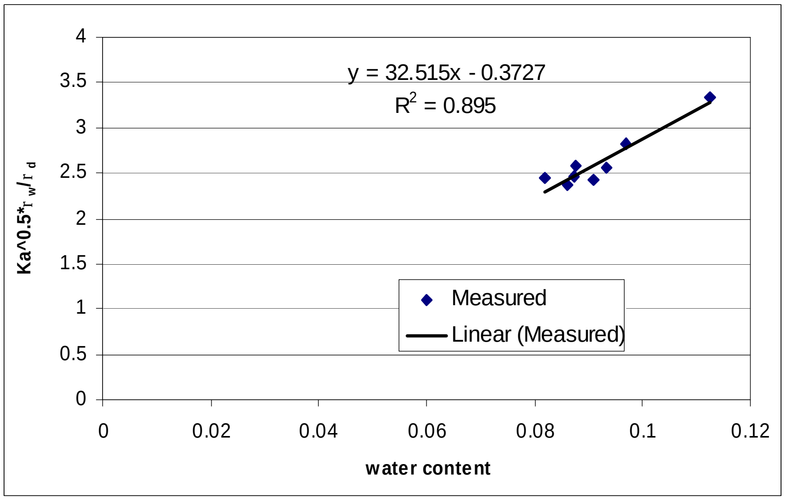
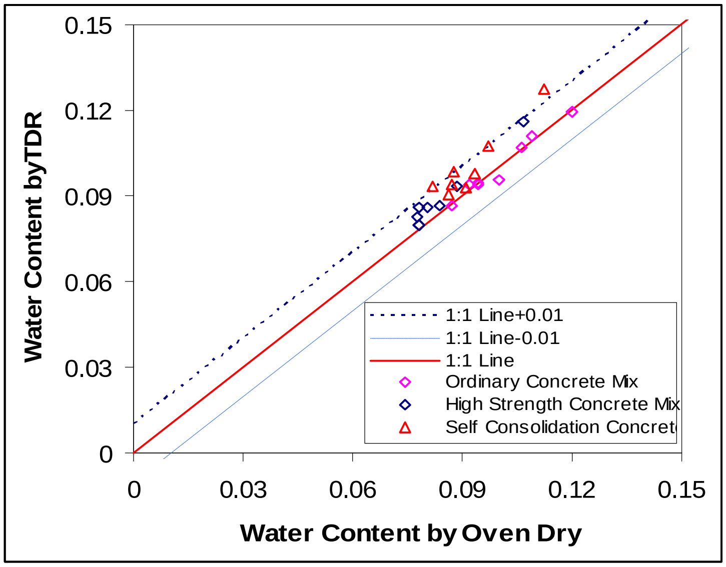


Fig. 3.3 Relationship between TDR dielectric constant and concrete physical properties (water content and density) for a) ordinary paving concrete, b) high strength concrete and c) self-consolidation concrete

Using the procedures by ASTM D6780, the water content and density of concrete at different curing ages can be calculated. The results are shown in Fig. 3.4. Good accuracy was found between TDR results and those of physical measurements. The comparison shows the water content estimated from TDR generally falls within ±0.01 of actual water content. Good accuracy was also found for dry density of concrete. As TDR is nondestructive, it provides a convenient way to measure the mixing proportions such as free water content and density in concrete.

(a)



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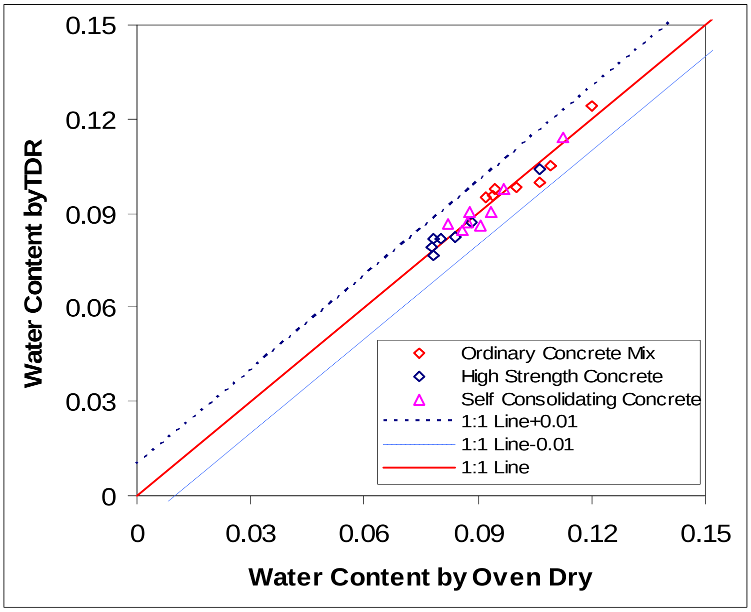


(c)

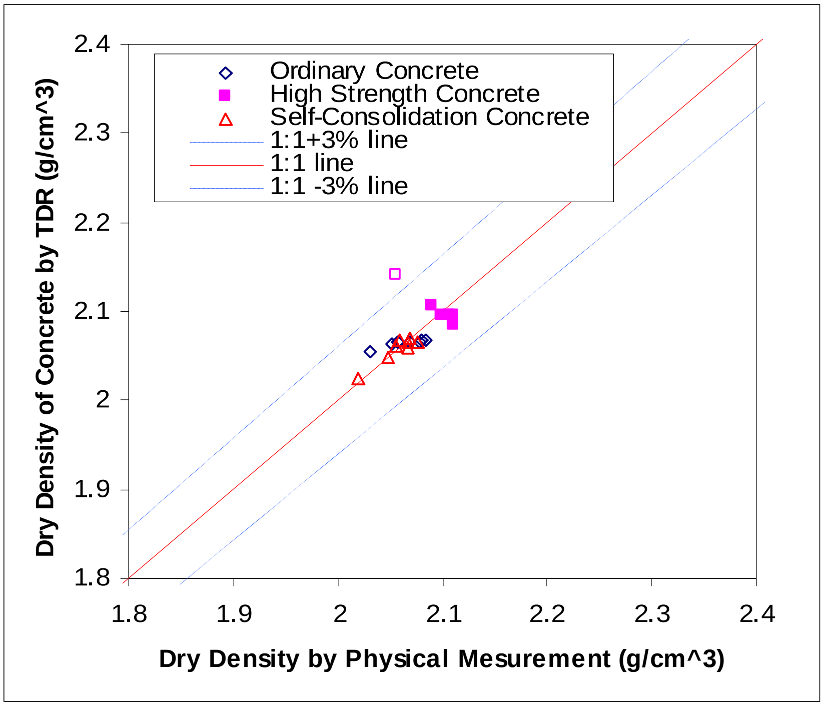


Fig. 3.4 Estimated water content and dry density of curing concrete using standard procedures a) two step method; b) one step method; c) dry density by one step method

3.3 Estimation of the Degree of Hydration

With the accurately measured free water content by TDR, the degree of hydration in curing concrete can be estimated. An example is shown in Fig. 3.5. The degree of hydration here is defined as the percentage of free water consumed by hydration reactions versus the total amount of free water available for hydrations. The degree of hydration can be related to a variety of concrete mechanical properties via the vast number of empirical relationships that have been developed over the years for different types of concrete.

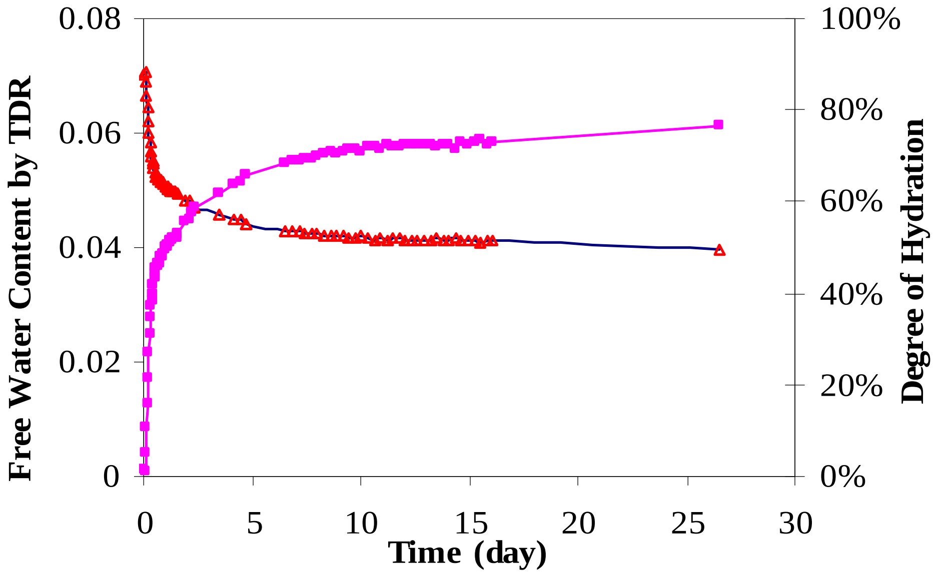


Fig. 3.5 Estimated degree of hydration by TDR

3.4 Estimation of Setting Times

TDR measures the electrical conductivity with high sensitivity and accuracy. The evolution of electrical conductivity was found to be informative for the various stages of concrete hydration. The trend of electrical conductivity evolution is a direct indicator on the extent and speed of concrete hydration reactions. From this, important curing stages such as initial setting time and final setting time can be determined. Besides, the trend of evolution is a strong indicator for the mechanism of hydration reactions occurring in concrete at different curing conditions (Fig. 3.6).

From Fig. 3.6, due to heat released during dissolution and hydration, temperature rises in the first 10 hours. After about 200 minutes from the beginning, there is a peak of EC_b which indicates the end of dormant period and the start of initial setting. The reflection point of the EC_b curve means the end of final setting which happened after 10 hours of hydration. At the same time, the process determining concrete hydration changed from convection controlled process to diffusion controlled process. The setting times estimated by TDR monitored electrical conductivity variations closely match that by traditional penetration method.

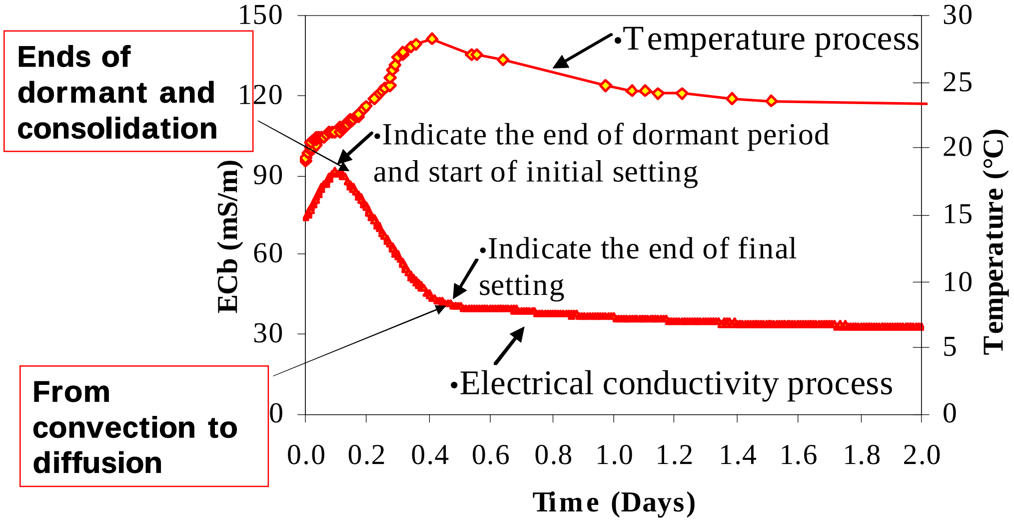


Fig. 3.6 Different stages of hydration from TDR electrical conductivity

3.5 Estimation of Concrete Strength:

With TDR measurement results, the strength of concrete can be estimated via different approaches. For example, by use of the estimated degree of hydration and the existing empirical relationships between the degree of hydration and concrete strength. It is also possible to directly relate concrete strength and TDR measurement data (i.e., the electrical conductivity), since both are products of the concrete hydration reactions. The amount of free ions reduces during hydration. The path of ions migrating through concrete increases. Both of these result in continuing decreases of electrical conductivity. Figure 3.7 shows the typical process of electrical conductivity evolution measured for concrete.

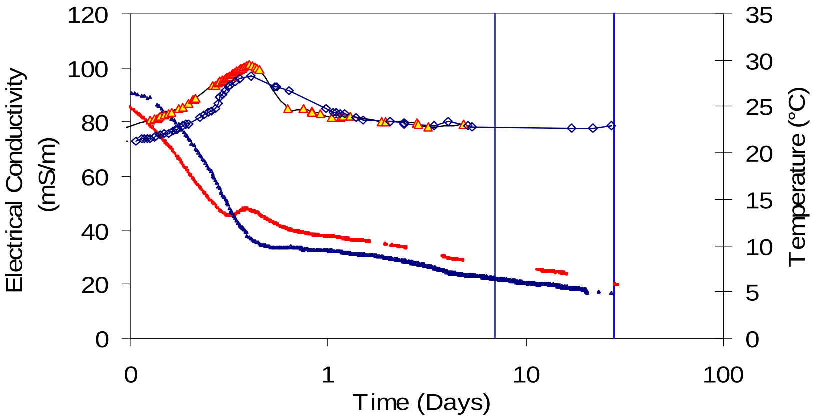


Fig. 3.7 Typical process of ECb evolution in log scale

There should be a relationship between the electrical conductivity versus hydration and then the strength of concrete. The electrical properties of concrete have long been used as indicators of concrete's physical properties. They were used to study moisture penetration, measure the thickness of concrete pavement, study concrete microstructure properties, and monitor the hydration process. The following is an equation obtained by Beek et al. to estimate strength of concrete based on measurement of electrical conductivity.

$$f_c(t) = R\left(\frac{s_{t=0}}{s(t)} - 1\right) \tag{3.1}$$

where: $f_c(t)$ is compressive cube strength; R is a constant based on mix properties in the same units as $f_c(t)$; $s_{t=0}$ is electrical conductivity shortly after mixing and $s(t)$ is electrical conductivity at time t.

A new relationship shown in Eq. (3.2) was used to analyze the measured data:

$$\frac{f_{c,t}}{f_{c,28day}} = A\exp\left(B\frac{EC_{b,\max}}{EC_{b,t}}\right) \tag{3.2}$$

where, $f_{c,t}$ is the strength at curing time t, $f_{c,28}$ day is the 28-day strength, $EC_{b,\max}$ is the maximum electrical conductivity, $EC_{b,t}$ is the electrical conductivity at time t. A and B might be dependent upon type of concrete mix.

Figure 3.8 shows the relationship of normalized electrical conductivity and normalized concrete strength. A "universal" relationship seems to apply and obtains reasonable accuracy.

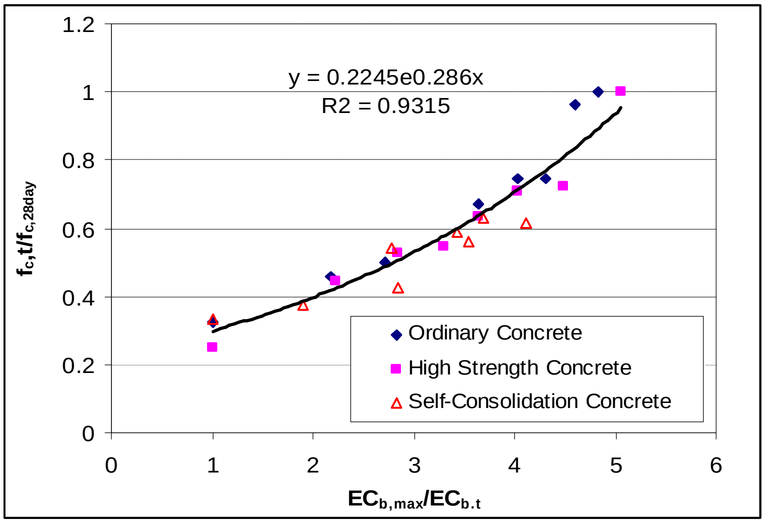


Fig. 3.8 The relationship between TDR measured electrical conductivity and strength of concrete

Fig. 3.9 shows the comparison of the compressive strength by TDR measured electrical conductivity versus those by breaking cylinders.

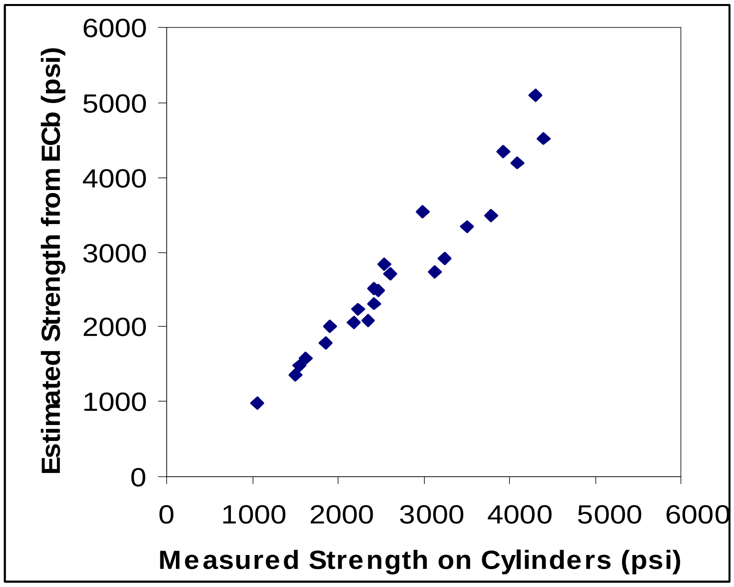


Fig. 3.9 Strength of concrete predicted using TDR versus those by breaking cylinders

3.6 Assistance in Winter Curing Decisions

A few states such as Ohio DOT has empirical 5-day curing imposed for cold weather concrete pouring. This is not optimized for durability and economic considerations. A mechanistic criterion can be developed from TDR measurements. The criteria proposed involved the determination of free water content and the volume of air voids at the initial mixing and at different curing ages. (A tool to provide such measurement will be important to implement such engineering measures.) Based on the trend of phase evolution, a criterion for preventing freezing damage can be developed, i.e., a requisite condition is to have sufficient amount of empty capillary pores to accommodate the volume expansion of ice. This can be mathematically described as in Eq. (3.3). This criterion is conservative and assumes the stress generated by volume expansion of ice exceeds that of bonding strength.

$$V_{empty,pore} \geq 10\% V_{free,water} \tag{3.3}$$

The fresh concrete is a mix of aggregates (fine and coarse), cement, water and air. The volumetric percentage by different phases can be determined from the mixing proportions. Based on the assumption which the total density of concrete specimens remain constant, the change of air volume during the curing process can be determined from the density and water content of concrete, incorporating the specific gravities of individual phases. Figure 3.10 plots the evolution of relative volume of water in concrete mix without/with air-entrain admix; also shown in this figure is the evolution of the relative volume of air. As can be seen from this plot, the volume of water continues to decrease as the results of hydration. The volume of the air, in the meanwhile, continues to increase as the results of reduction in the volume of water and decreases in the volume of hydration products compared with reactants. Comparison between Fig. 3.10a and 3.10b clearly demonstrate the effectiveness of the air entrain admixture in providing room to accommodate the volume expansion of icing.

(a)

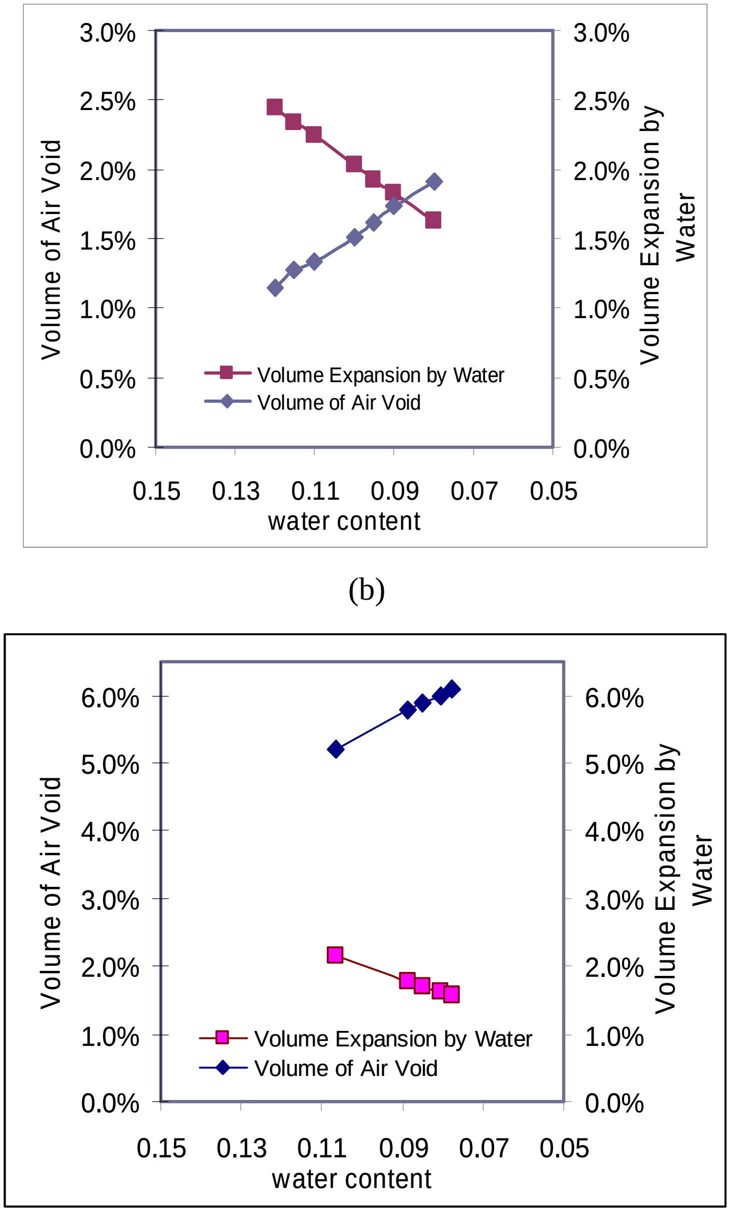
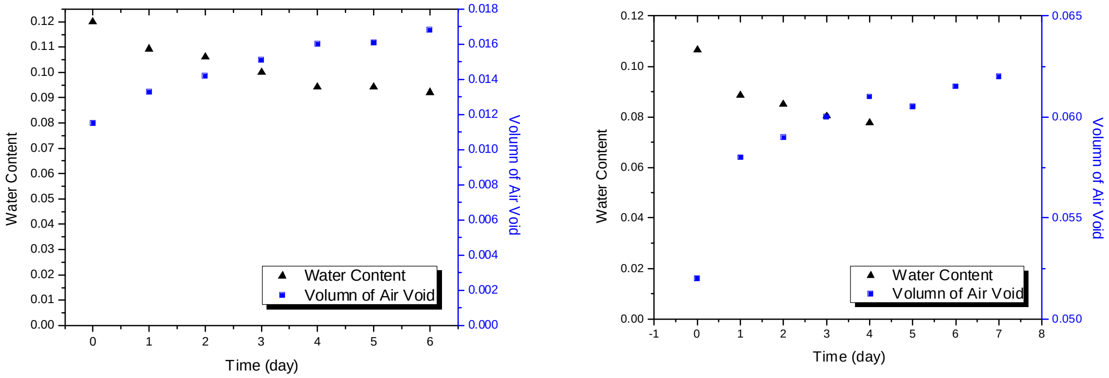


Fig. 3.10 Estimated volume of air void in concrete and trend of volume expansion of icing: a) concrete without air-entrain admixture; b) concrete with air-entrain admixture

Comparison of Fig. 3.10a and 3.11a shows it takes more than 6 days of curing for the volume of air voids to become large enough to accommodate the volume expansion of ice (at free water content of 0.09). For such cases, the 5-day thermal bath curing DOTs practice is not sufficient to prevent freezing damages of concrete.



a) Water content and air volume change of concrete without air entry admix

b) Water content and air volume change of concrete with air entry admix

Fig. 3.11 Air void content and water content during curing process

4. OTHER RELATED EXPLORATIONS

4.1 Measurement of the Thermal Properties of Concrete

The thermal properties of concrete play important roles in the thermal balance of roads. In fact, the coefficient of thermal expansion is one of the most important parameters determining concrete durability. Thermal properties of concrete can be measured by the fusion of thermal pulse technology with the TDR probe design. A prototype design of thermo-TDR was implemented and evaluated (Fig. 4.1). Example of thermal pulse responses is shown in Fig. 4.2.

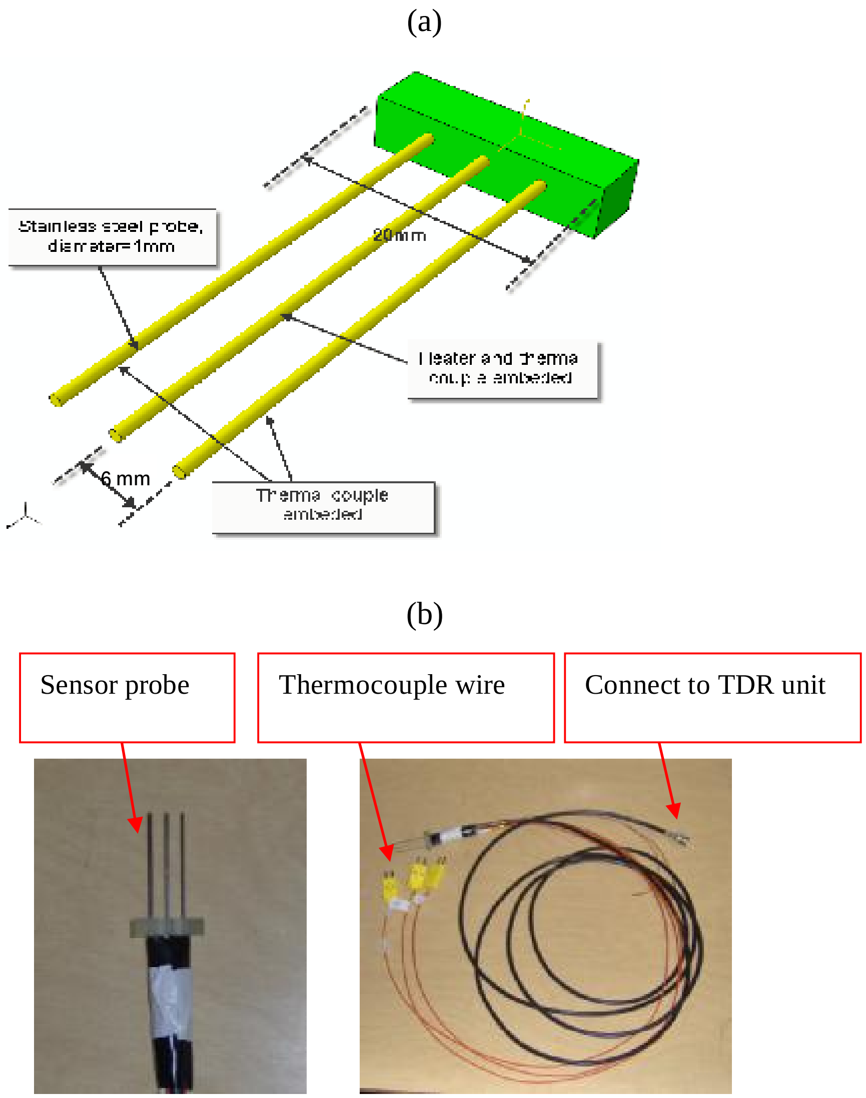


Fig. 4.1 a) Schematic design of the thermal-TDR probe; b) photos of the fabricated thermo-TDR probe

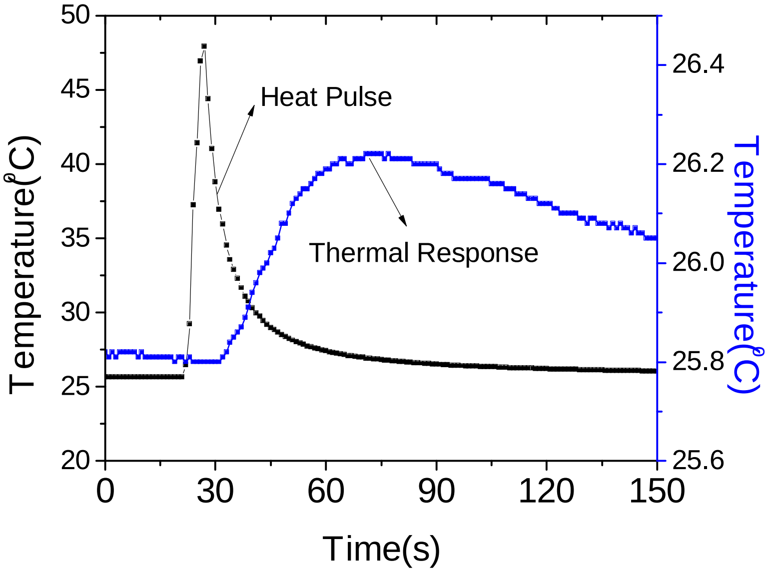


Fig. 4.2 Example of measured thermal pulse response in materials

Example of measured thermal conductivity variation with temperature for clay samples is shown in Table 4.1.

Table 4.1 Results of dielectric constant, thermal conductivity and volumetric heat capacity for clay samples

Water Content	*Dry Density (g/cm^3)*	*Dielectric Constant*	*Travel Time*	*Inversion Analyses*	
			Thermal Conductivity (W/(m·K))	*Thermal Conductivity (W/(m·K))*	*Volumetric Thermal Capacity(J/(m3·K))*
0 (0)	1.28	1.60	0.226	0.365	5.35e5
5% (6.1%)	1.35	4.69	0.329	0.457	1.01e6
10% (11.9%)	1.33	8.03	0.405	0.587	1.55e6
15% (15.8%)	1.31	10.03	0.478	0.602	1.55e6

With the ability of TDR to measure the physical properties of curing concrete and the ability of thermal pulse technology to measure the thermal properties. Fusion of both technology has the potential to address emerging problems such as energy conservation and heat island effects.

4.2 Characterizing Pore Structure by Advanced Ultrasonic Technology

The criteria for freezing damage established by TDR does not consider the distribution of air voids in concrete specimens. The use of advanced ultrasonic wave scattering was explored to estimate the pore structure in concrete. Ultrasonic technology using quantitative attenuation measurements may provide in situ measurements of both air void size and volume fraction in a rapid approach and at low cost. Previous studies have been successful in relating ultrasonic attenuation with grain size and porosity in ceramic and metallic materials. Ultrasonic waves have proven to be very effective to characterize the distributed voids in structural materials. A few scattering models have been developed in the literature (Evans et al. 1978, Papadakis 1965, Punurai 2006).

The model by Punuri et al. (2006) was extended to a distributed air void system. The cement matrix with the entrained air specimen was assumed to be a two-component system, i.e., cement paste matrix (which includes some intrinsic porosity) with a distribution of spherical air voids. The total attenuation coefficient, α, of this two component system is calculated as (Punurai et al. 2006):

$$\alpha = (1 - \emptyset)\alpha_{\mathbf{a}} + \alpha_s \qquad (4\text{-}1)$$

where αa is the absorption attenuation coefficient of the incident wave in the viscoelastic matrix (1/m or Neper/m) and α_s is the scattering attenuation coefficient.

The air void size distribution is assumed to follow a certain relationship. Estimation of the concrete pore structure from ultrasonic wave scattering requires inversion analyses. The mathematic description of inversion analyses from the scattering of ultrasonic wave is given in Eq. (4-2).

$$\arg\min(j, D_m, s) = \left\| g(j, D_m, s, f) - g'(f) \right\| \qquad (4\text{-}2)$$

where argmin is a function that minimizes its value by determining the optimal parameters, g and g’ are ultrasonic wave scattering (attenuation versus frequency) by models prediction or physically measurement respectively. $\|\cdot\|$ is the norm whose order is selected based on a specific problem. 2nd order norm is the commonly used root-mean-square criteria.

Figure 4.3 shows the schematic illustration of the inversion analyses procedures. The forward models for wave attenuation include the viscoelastic model for cement matrix and the attenuation due to wave scattering by the air voids. The inversion algorithm results in model parameters that minimize the difference between the model-predicted wave scattering and that from the measured signals. The results of inversion analyses determine the parameters such as pore volume, φ, and pore size distribution (i.e. the mean pore size, D_m, and the standard deviation, σ.)

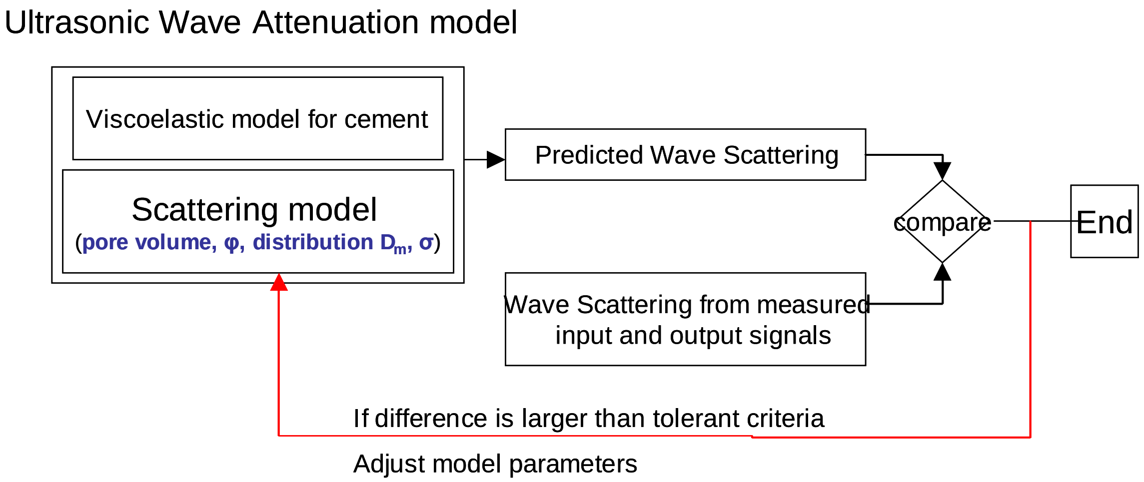


Fig. 4.3 Schematic of inversion analyses procedure

An example of inversion results are shown in Fig. 4.4. The parameters from inversion analyses converged to the true values.

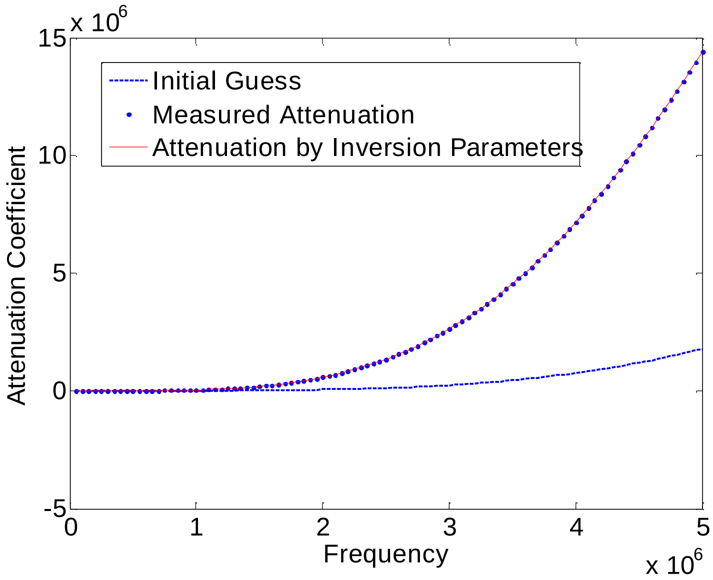


Fig. 4.4. Example results of inversion analyses

A schematic diagram of the experimental setup for the attenuation measurements is shown in Fig. 4.5. One pair of contact ultrasonic transducers (Labeled T for transmitting and R for receiving) were placed on the opposite sides of the specimen. The ultrasonic transducers used in our experiment have a central frequency of 0.5 MHz. The vibration produced by the transmission transducer for multiple round trips is picked up by the receiver transducer. The signals were then processed to determine the signal attenuations. This is subsequently used in the inversion analyses. Preliminary results indicate it is promising to estimate the air void distribution using the inversion analyses of the ultrasonic wave scattering model.

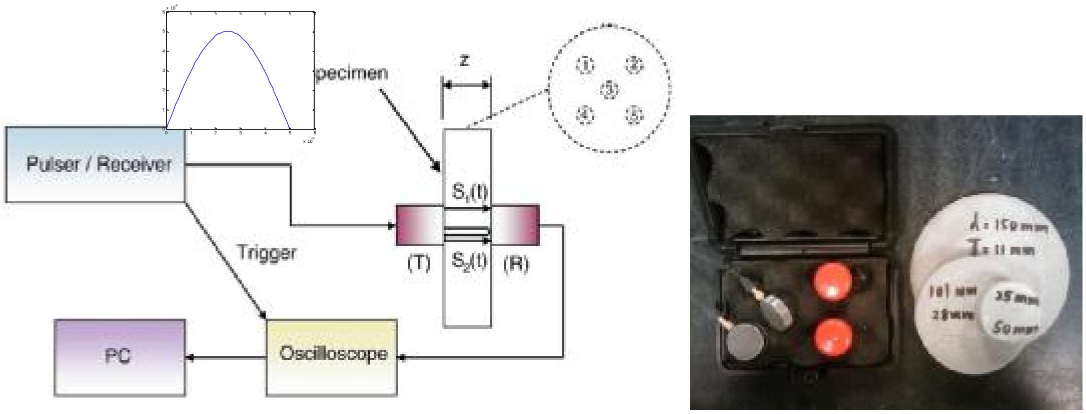


Fig. 4.5 a) schematic diagram of the experimental setup; b) cement paste specimens

4.3 Strength of Concrete from Ultrasonic Testing

4.3.1. Ultrasonic velocity versus strength for concrete with normal curing procedures

plots the strength of concrete versus ultrasonic wave velocity for concrete subjected to normal curing conditions. As seen from this plot, there are reasonably linear relationships between both factors. This confirms the observations in many existing literatures. Such relationships can be used to estimate the compressive strength of concrete from ultrasonic measurements.

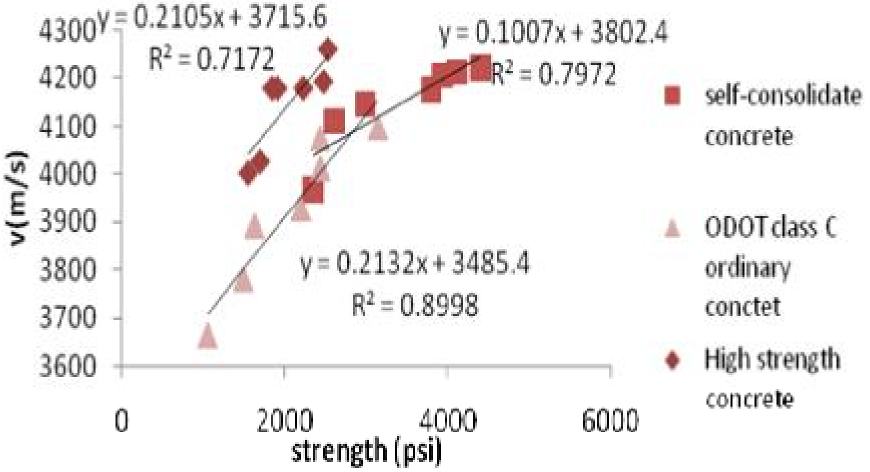


Fig. 4.6 Relationships between ultrasonic velocity and strength of concrete

4.3.2 Ultrasonic velocity (after-thaw) versus strength (after-thaw) for concrete subjected to freezing during the curing process

In this experiment, concrete specimens were placed in the freezer at different curing ages (2-day, 3-day, 4-day, 5-day etc). At the end of the 7th day, the specimens were taken out of the freezing room. Ultrasonic tests and compression tests were then conducted on each specimen either in complete frozen status or in complete thaw status. The frozen status is ensured by compressing the specimens immediately after being taken out of the freezer; the complete thaw is ensured by subjecting the specimens to rapid thawing procedures. Figure 4.7 shows the plots of ultrasonic wave velocity and strength relationship for concrete specimens that are completely thaw. This figure indicates there exist reasonably linear relationships between ultrasonic velocity (after thaw) and strength of concrete (after thaw) subjected to freezing during the curing process. The implication is that the strength of concrete can be estimated on the frozen concrete, under the condition they are thawed before the test is conducted. The thawing can be achieved by methods such as heating.

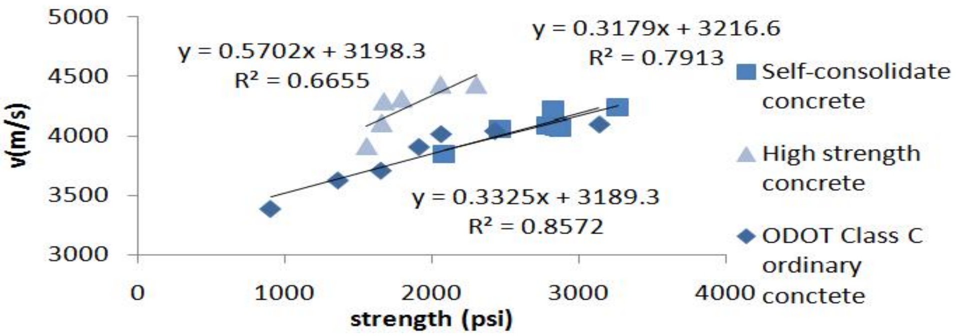


Fig. 4.7 Relationships between ultrasonic velocity (after thaw) and strength of frozen concrete (after thaw)

4.3.3 Ultrasonic velocity (before-thaw) versus strength (before-thaw) relationship for concrete subjected to freezing during the curing process

Figure 4.8 plots the ultrasonic velocity (before thaw) versus strength of frozen concrete specimens (either before thaw or after thaw). The large scattering in the data indicates there are no reliable relationships between the compressive strength and ultrasonic velocity for frozen concrete, whether it is frozen or completely thawed. This implies if NDT testing is conducted on concrete while it is frozen, the measured wave speed can not be used to reliably predict the strength of concrete.

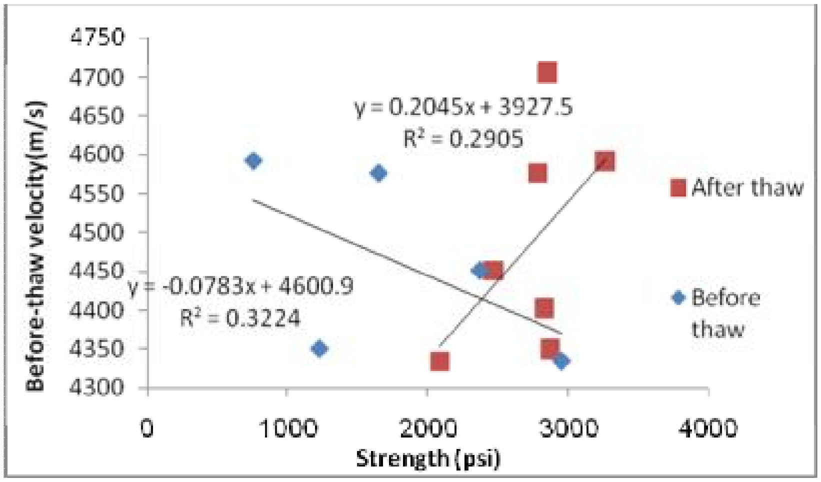


Fig. 4.8 The ultrasonic wave velocity of frozen concrete versus strengths of concrete specimens

4.3.4 Estimation of Frozen Concrete Strength

A plot of the differences in the strength of concrete in the complete frozen or thaw conditions is plotted in Fig. 4.9. Also plotted on Fig. 4.9 is the evolution of free water content (or free ice content when the concrete is completely frozen). It is interesting to notice that both curves show similar trends. When plotting the free water content and the differences in the compressive strength of concrete in complete frozen or thawed status, a very good linear relationship appears (as shown in Fig. 4.10). This is probably due to the fact that when the free water in the sample freezes, the strength of ice contributes the bulk strength of frozen concrete specimens.

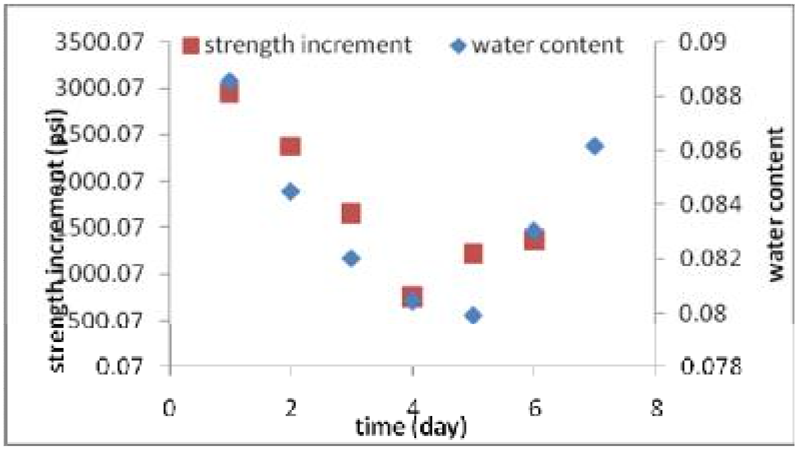


Fig. 4.9 Free water content and differences in strength of frozen and thaw concrete

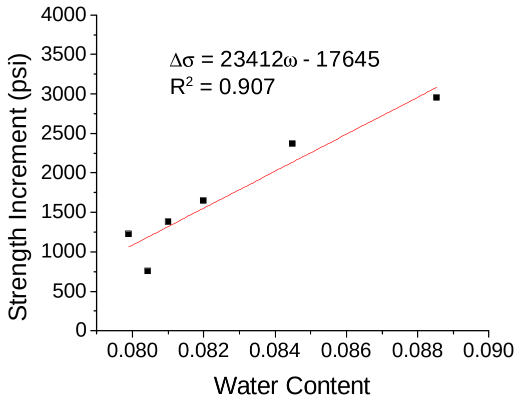


Fig. 4.10 Difference strength versus free water content (i.e. ice content in completely frozen concrete)

With the use of relationship such as in Fig. 4.10, an estimation of the strength of frozen concrete from seismic tests (such as ultrasonic measurement) can be performed in the following sequences:

1) Thaw the concrete specimen
2) Estimate the strength of thaw concrete from ultrasonic test
3) Use the free water content to determine the differences in the strength of concrete between complete freeze or complete thaw status
4) Estimate the strength of frozen concrete by adding the strength from steps 2) and 3).

TDR can provide information in Step 3) of the testing sequences.

5.0 SUMMARY AND PLAN FOR IMPLEMENTATION

5.1 Summary of Research Discoveries

This project explored the development and application of a new instrument based on Time Domain Reflectometry (TDR) for measuring the performance properties of fresh and early stage concrete. The test data were analyzed to determine the capabilities of the sensor system in measuring the properties such as the free water content, dry density, the times of initial and final setting and the long-term mechanical strength. We also established criteria to analyze the freezing-thawing damages of concrete in cold regions. The following summarizes the major discoveries of this research. These items illustrate the potentials of TDR instrument for ensuring the performance properties of concrete in the early stage.

1. Validation of fresh concrete mix proportion. Validation of the proper mix proportion, such as the free water content and water-cement ratio. These propertiesare important for the strength and durability of concrete. The much larger dielectric constant of water compared with the other ingredients in fresh concrete makes its bulk dielectric constant strongly dependent on its free water content. On the other hand, the high ionic content in the pore solution of fresh

concrete has a major effect its electrical conductivity. Both dielectric constant and electrical conductivity can be accurately measured by TDR. The study in this IDEA program showed that the free water content and dry density of curing concrete can be monitored using standard TDR procedures. The TDR data can be analyzed to estimate the volume development of different phases in curing concrete.

2. Predicting setting times of fresh concrete. The setting times of concrete are crucial pieces of parameters for construction decisions. When the setting time is known, the times of mixing, transporting, casting and finishing can be regulated and the necessity of various set-controlling admixtures can be assessed. Typically, the initial and final setting time of concrete is measured by the penetration method ASTM C 403 (1995). This research found that TDR can be used to determine the setting times of fresh concrete, based on the trend of bulk electrical conductivity development while curing.
3. Estimation of compressive strength. The strength of concrete is another important parameter for various construction decisions. It also plays a major role for the performance of concrete structures. This study found that the electrical conductivity of concrete has a strong correlation to its compressive strength. A relationship was found to be independent of the types of concrete investigated in this study. This implies that the strength of concrete could be estimated from the TDR measured electrical conductivity. The measurement is non-destructive on the same sampling zone in concrete.
4. Establishing criteria for cold weather curing to prevent freeze-thaw damage. Freezing-thawing damages are among the most detrimental factors on the durability of concrete in cold regions. The current cold weather curing control protocol is subjective. The uncertainty tends to either cause high winter construction cost or inferior concrete subjected to freezing-thawing damages. A physics-based criterion was established to allow for the development of sufficient amount of pore volume to accommodate the volume expansion when water freezes. The ability of TDR to measure the free water content and volume of different phases in concrete is an near ideal fit for this function.
5. Besides the original study plan, this study also conducted pilot investigations on multi-functionalization of TDR technologies. These include topics such as measurement of the thermal properties of concrete by fusion of the thermal pulse technology with TDR into thermo-TDR probe; characterization of the pore size distribution with ultrasonic wave scattering model; estimation of the strength of frozen concrete by combining TDR and ultrasonic technology, which includes procedures to correct the effects of freezing.

5.2 Recommendations for Further Research

This study validated the concept of TDR for measuring the performance properties of concrete. Due to the scope of this study, the types of materials tested are not exhaustive. The following recommendations are proposed to further validate the project discoveries and refine the instrument into a practice tool:

1) Employ field worthy design and explore the potential integration with the paving operation.
2) Conduct larger scale lab and field experimental programs to build up the application database
3) Further understand the fundamentals of cement hydration and the interactions of electromagnetic waves with concrete matrix. From these establish robust relationships between the physico-chemical and electrical properties of concrete.

Fig. 5.1 Potential of integration of a novel strip TDR sensor with paving operation

5.3 Plan for Implementation

One patent has been granted for this technology. Another preliminary patent has been filed. A few industry vendors including Durham Geo and Slope Indicator, a manufacturer and distributor of engineering testing equipment and instruments, expressed interest to commercializing the developed technology and was evaluating the feasibility of its use (Fig. 5.2). Discussions with state agencies and concrete contractors also elicited strong interest in this technological development. Application for federal assistance has been filed to commercialize this technology.

Fig. 5.2 (left) TDR package for field instrumentation (Courtesy Durham Geo Enterprises, GA); (right) Example of laboratory experiment.

APPENDIX

Table A Comparison of technologies for QA/AC of early stage concrete (*Malhotra and Carino 2004*)

	Water content	Dry density (segregation)	Air void	Degree of hydration	Setting times	Strength	Non destructive	Principle
Maturity method						X	X	Heat generation due to hydration
Microwave oven	X							Drying by microwave
Rebound method						X		Collision mechanics
Penetration resistance method					X	X		Mechanical resistance to penetration
Pullout test						X		Mechanical bonding strength
Ultrasonic shear wave					X	X	X	Ultrasonic wave propagation
Short pulse radar	X			X				Electromagnetic wave responses
TDR Instrument (guided radar, this study)	X	X	X	X	X	X	X	Responses to guided radar wave due to transition of water and mobile ions by hydration

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