INDIANA DEPARTMENT OF TRANSPORTATION
DIVISION OF MATERIALS AND TESTS

REAL-TIME IN-PLACE COMPRESSIVE STRENGTH OF CONCRETE USING ELECTROMECHANICAL RESONANCE TEST METHOD

ITM 408-22

1.0 SCOPE.

1.1 This test method covers evaluating the real-time, in-place compressive strength of normal weight concrete (≥ 140 pcf) with or without additional SCMs, in the field using the resonant peak of an electromechanical spectrum as a non-destructive test method for accepting, opening to traffic, and loading of structural concrete.

1.2 This ITM may involve hazardous materials, operations, and equipment, and may not address all safety problems associated with the use of the test method. The user of the ITM is responsible for establishing appropriate safety and health practices and determining the applicability of regulatory limitations prior to use.

2.0 REFERENCES.

2.1 AASHTO Standards:

R 9 Accepting Sampling Plans for Highway Construction
T 325 Estimating the Strength of Concrete in Transportation Construction by Maturity Tests

2.2 ASTM Standards:

C39 Compressive Strength of Cylindrical Concrete Specimens
C215 Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens

D3665 Random Sampling of Construction Materials
E105 Probability Sampling of Materials

2.3 ITM Standards:

402 Strength of Portland Cement Concrete Pavement (PCCP) Using the Maturity Method Utilizing the Time Temperature Factor Methodology

2.4 ACI Codes:

318 Building Code Requirements for Structural Concrete and Commentary

3.0 TERMINOLOGY. Definitions for terms and abbreviations shall be in accordance with the Department's Standard Specifications, Section 101 and as follows:

3.1 Concrete Sample Holder. An acoustically insulative container with an open end that receives and holds a sample of freshly poured concrete and may be fully embedded in a concrete structure.

3.2 Electromechanical Spectrum (EMS). A relationship between electrical properties of a piezoelectric disk and its frequency, such as the impedance spectrum, admittance spectrum, or conductance spectrum. The spectrum is influenced by both electrical and mechanical boundary conditions of the piezoelectric disk.

3.3 Resonance. The phenomenon of increased amplitude occuring when the frequency of a periodically applied force is equal to or close to a natural frequency of the system in which it acts.

3.4 Sensing Region of Concrete (SRC). The sampled region or volume of concrete that generates an EMS used to calculate the testing results of the Strength Meter.

3.5 Strength Meter. An apparatus comprised of a piezoelectric disk that is integrated into a Concrete Sample Holder. The piezoelectric disk actuates the SRC and measures its EMS, which is used to estimate the dynamic and static Young's moduli and compressive strength of the concrete. The Strength Meter functions as an acoustical resonator specially designed for real-time, in-place concrete testing.

4.0 SIGNIFICANCE AND USE.

4.1 This ITM shall be used to determine the real-time, in-place compressive strength of normal weight concrete ($\geq$ 140 pcf) with or without additional SCMs, for accepting, opening to traffic, and loading of concrete.

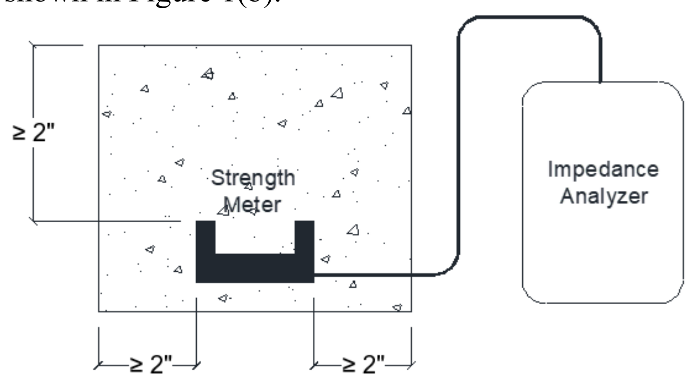
4.2 This test method does not require concrete mix design-specific calibration, but rather, directly determines the real-time, in-place dynamic and static Young's moduli and compressive strength of concrete.

4.3 The primary limitation of the procedures presented in this ITM is that compressive strengths below 300 psi are not measurable because the wave propagation is highly attenuated when concrete is in plastic condition.

5.0 APPARATUS.

5.1 Personal Protective Equipment. Personal safety equipment required by the field organization or OSHA, or both, for work shall be used in the concrete placement areas.

5.2 Strength Meter. Strength Meters suitable for embedment in the concrete structure shall be installed at a minimum of 2 in. from the top surface boundary of the concrete and each peripheral boundary of the concrete. An illustration of placement of a Strength Meter in concrete is shown in Figure 1(a). An example of the Strength Meter is shown in Figure 1(b).



a) Schematic Figure

b) Photo

Figure 1 Strength Meter and Data Logger *(Courtesy Dr. Luna Lu, Purdue University)*

5.3 Impedance Analyzer. An electrical impedance device suitable for measuring and recording the impedance of the piezoelectric disk, in the frequency range up to the first radial resonant frequency of the piezoelectric disk in a free condition. The device may be an electronic system with on-chip data acquisition and processing capability that can wirelessly transmit data from the project site to present data in both digital and graphic format as desired or may include a server remote from the job site that collects and logs the data for additional processing. An image of an Impedance Analyzer (Data Logger) connected to a Strength Meter are shown in Figure 1(b).

5.4 Data Display Equipment. A smartphone, tablet, laptop, PC, or other computational device used to display the estimated dynamic and static Young's moduli and strength of concrete determined by the Strength Meter and Impedance Analyzer.

6.0 General:

6.1 This test procedure is a six-step process as follows.

6.1.1 The number of Strength Meters shall be determined in accordance with section 7.0

6.1.2 The data acquisition system and Strength Meter shall be calibrated and standardized in accordance with section 8.0

6.1.3 The Strength Meter shall be installed within the testing site of interest before concrete is cast in accordance with section 9.0

6.1.4 The cable of the Strength Meter shall be secured and connected to the Impedance Analyzer

6.1.5 The real-time, in-place dynamic and static Young's moduli and compressive strength of concrete shall be estimated using the EMS data following the equations outlined in section 10.0

6.1.6 The results shall be reported in accordance with section 11.0

7.0 FIELD SAMPLING

7.1 The number of Strength Meters to be installed shall be determined in accordance with the Frequency Manual or as directed by the Engineer.

8.0 SENSOR CALIBRATION AND STANDARDIZATION

8.1 The data acquisition system, including the Impedance Analyzer and the related software, shall be calibrated periodically. The calibration can be done by comparing the measured impedance value of a resister with its known impedance value provided by the vendor (e.g., 100 Ohm).

8.2 The Strength Meters shall be calibrated periodically. The calibration shall be done by one of the following procedures.

8.2.1 Immerse the strength meter in a water tank for 5 minutes. Then connect the Impedance Analyzer with the Strength Meter and measure the EMS data. Assuming the first order radial mode resonant frequency of the piezoelectric disk is f_{pzt}, whose specific value will be specified by the sensor vendor, the testing frequency range should be from $0.5f_{pzt}$ to $1.5\,f_{pzt}$. **Figure 2** shows an example of the conductance spectrum that is acceptable to use. The spectrum should show at least one dominant peak, otherwise, if the spectrum is too flat or fluctuating to show a dominant peak, the Strength Meter shall not be used. After this inspection procedure, dry the Strength Meter with tissue. This (or a similar) calibration procedure should have been completed by the instrument supplier but the same can be repeated by the end user if desired.

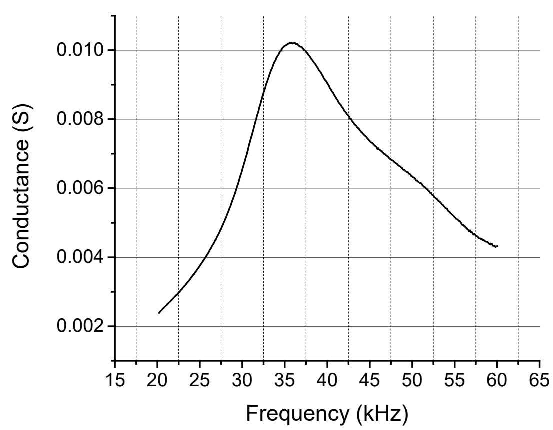


Figure 2 Example of EMS of an acceptable Strength Meter
(Courtesy Dr. Luna Lu, Purdue University)

8.2.2 Alternatively, without processing the data and plotting the spectrum, the operator can check the Strength Meter by connecting it to the Impedance Analyzer, sweeping the frequency from 2 kHz to 20 kHz, and listening for the Strength Meter to emit an audible sound. A non-functional Strength Meter will not emit audible acoustic waves.

9.0 PROCEDURE.

9.1 Strength Meters and Impedance Analyzers shall be procured in sufficient numbers as required for the particular job in accordance with section 7.1.

9.2 Place the Strength Meter with the open end facing upward to allow complete filling of the sampling reservoir with concrete. The Strength Meter may be placed on a flat surface of the roadbed or floor of the concrete formwork or rebar reinforcements, depending upon the component of the structure. The operator shall use personal discretion in securing (or not securing) the Strength Meter based upon the particular application, site conditions, and Strength Meter design and instructions for use. The Strength Meter may require no securement, depending on site conditions and application, so long as the sampling reservoir can be maintained upright. **Figure 3** shows the typical installation of a Strength Meter in a pavement project in which the Strength Meter is simply placed on the ground.

Figure 3 Example of typical Strength Meter installation
(Courtesy Dr. Luna Lu, Purdue University)

9.3 Generally, Strength Meters shall be placed to provide a minimum clearance of 2 in. from any concrete boundary, except the floor of the formwork (as demonstrated in **Figure 1** and **Figure 3**).

9.4 Connect the cable of each Strength Meter to an Impedance Analyzer. Protect the cable wires from construction operations and traffic. In locations deemed critical by the engineer or contractor, duplicate Strength Meters and Impedance Analyzers are recommended.

9.5 Activate the Impedance Analyzer in advance of concrete casting to confirm the functionality of the Strength Meter, Impedance Analyzer, and connecting cable. If not automated by the Impedance Analyzer manufacturer, set the frequency range and frequency resolution for EMS measurement. Assuming the first-order radial mode resonant frequency of the piezoelectric disk is f_{pzt}, which will be specified by the sensor vendor, the testing frequency range should be from $0.5f_{pzt}$ to $1.5f_{pzt}$. The automatic feature is often provided by a strength meter manufacturer or impedance analyzer.

9.6 After placement of the concrete in the field, read the EMS data every 15 minutes (or at such other time interval as desired) from the Impedance Analyzer.

9.7 Identify the concrete resonant frequency, f_r, in the EMS spectrum. This process can be done manually, through visual inspection, or automatically through the use of a peak selection program provided by the Impedance Analyzer manufacturer. **Figure 4** shows a typical spectrum pattern, in which the f_r is shifting towards a higher frequency while the concrete is being cured over time.

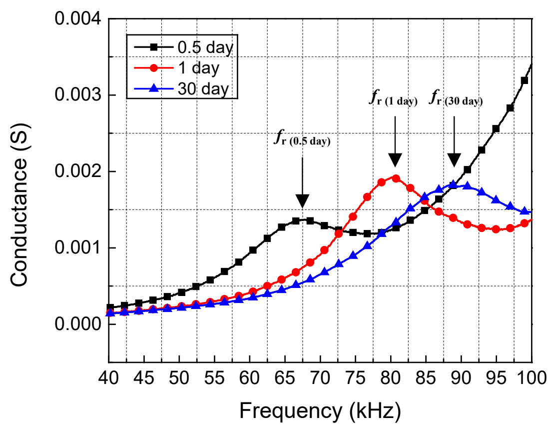


Figure 4 A typical EMS spectrum pattern

(Courtesy Dr. Luna Lu, Purdue University)

9.8 Estimate the real-time, in-place dynamic and static Young's moduli, and strength of the concrete using the resonant peak of EMS through manual calculation or use of an automated program supplied by the Impedance Analyzer manufacturer. The calculations shall be in accordance with section 10.0.

10.0 CALCULATIONS.

10.1 Determine the dynamic Young's modulus of the concrete as follows:

$$E_d = (f_r \cdot g)^2 \cdot \rho \cdot \frac{(1+\mu)(1-2\mu)}{1-\mu} \cdot 10^{-9} \quad (1)$$

Where:

E_d = Dynamic modulus of concrete in GPa (1 GPa = 145 ksi)
f_r = Resonant frequency in Hz
g = Geometry factor provided by manufacturer of Strength Meter, in m
ρ = Density of concrete in kg/m^3
μ = Poisson's ratio of concrete

10.2 Determine the static modulus of the normal weight of concrete as follows:

$$E_s = 0.65 \cdot {E_d}^{1.04} \qquad (2)$$

Where:

E_s = Static modulus of concrete in GPa

10.3 Determine the strength of the concrete in accordance with ACI 318 given:

$$f_c' = (E_s \cdot \frac{10^3}{0.043 \cdot \rho^{1.5}})^2 \qquad (3)$$

Where:

f_c' = Strength of concrete in MPa (1 MPa = 145 psi)

11.0 REPORT.

11.1 Project name, address, and date/time of concrete pour(s)

11.2 Type of concrete, concrete mix design, quantity of concrete

11.3 Quantity and locations of strength meters installed

11.4 Resonant frequency determined for each strength meter location

11.5 Estimated strength of concrete determined for each strength meter location

11.6 Estimated average strength of concrete determined for each lot of concrete (7200 sys)

11.7 Graph of estimated average concrete strength versus time of data acquisition

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