Motivation

Many industrialized nations currently dedicate a considerable portion of the construction budget for restoration, repair, and maintenance of old structures as opposed to new construction.
In 1991 the U.S. Department of Transportation reported that $90.9 billion dollars were required for the rehabilitation and repair of the highway infrastructure system.

By 1997, the estimated cost had risen to $212 billion.
Essentially, the surface hardness method consists of impacting a concrete surface in a standard manner with a given energy of impact and then measuring the size of indentation or rebound.
The most commonly used method employs the *Schmidt rebound hammer* which consists of a spring-controlled hammer that imparts on a plunger.
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The equipment used to determine the penetration resistance of concrete consists of a powder-activated device.
The *Windsor probe* uses a powder-activated driver to fire a hardened-alloy probe into the concrete. The exposed length of the probe is a measure of the penetration resistance of concrete. The standard test procedure is described in ASTM C-803.
The type and amount of aggregate play an important role in the penetration resistance.

The variation in the Windsor probe-test results is higher when compared with the variation in standard compressive strength tests on companion specimens.

This method is excellent for measuring the relative rate of strength development of concrete at early ages, especially for determining stripping time for formwork.
Non-Destructive Methods

Windsor probe

Compressive strength as a function of exposed probe

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A pullout test consists of casting a specially-shaped steel insert with an enlarged end into fresh concrete.

This steel insert is then pulled-out from the concrete and the force required for pullout is measured using a dynamometer.

A bearing ring is used to confine failure to a well-defined shape.
PULLOUT TESTS

As the steel insert is pulled out, a cone of concrete is also removed, thereby damaging the concrete surface (which must be repaired after the test).
Schematic diagram of the pullout test

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Since the degree of cement hydration depends on both time and temperature, the strength of concrete may be evaluated from the concept of maturity, which is expressed as a function of the time and the temperature of curing.
It is assumed that batches of the same concrete mixtures of same maturity will attain the same strength regardless of the time-temperature combinations leading to that maturity.
A simple maturity function $M(t)$ can be defined as the product between time and temperature:

$$M(t) = \sum (T_a - T_o) \Delta t$$

or in the limit

$$M(t) = \int_0^t (T_a - T_o) \, dt$$

where $\Delta t$, $T_a$, and $T_o$ are time interval, average concrete temperature during the time interval $\Delta t$, and the datum temperature, respectively. Traditionally, $-10^\circ C$ or $14^\circ F$ is assumed to be the datum temperature below which there is no additional gain in strength. ASTM C 1074 recommends a datum temperature of $0^\circ C$ or $32^\circ F$. 

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Influence of curing temperature at early ages on the strength-maturity relationship when equation (1) is used with $T_0 = -10$ °C. This early-age difference can be reduced when better maturity functions are used.
Absorption and Permeability Tests

The rate of water absorption by capillary suction is a good measure of the quality of a concrete and its potential durability when exposed to aggressive environments. Low values of absorption indicate that aggressive ions will have difficulty penetrating the concrete.
Absorption and Permeability Tests

The rate of water absorption by capillary suction is a good measure of the quality of a concrete and its potential durability when exposed to aggressive environments.

Low values of absorption indicate that aggressive ions will have difficulty penetrating the concrete.
Experimental research indicates that the water absorption values are reduced which decrease in the water-to-cement ratio; increase in the curing time; decrease in curing temperature; and increase in the degree of consolidation.
The term permeation is used to describe the mass transport of liquids or gases induced by pressure and concentration gradients or by capillary forces.

Permeation is influenced by the volume and connectivity of the capillary pores in the cement paste matrix.
Absorption and Permeability

The air permeability of concrete increases when the moisture is eliminated, which in turn increases the connectivity of the pores.

The water absorption also increases when the capillary pores are empty.
Methods to measure the water absorption under field conditions

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Configuration of the Figg test

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STRESS WAVE PROPAGATION METHODS.

The maximum displacement is the amplitude $A$, the time between two successive wave crests is the period $T$ and the distance between two successive wave crests is the wavelength $\lambda$. 
Reflection and refraction

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{V_1}{V_2}
\]

\[
\theta_{ic} = \sin^{-1}
\left(\frac{V_1}{V_2}\right)
\]
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Ultrasonic Pulse Velocity Methods

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Many receivers

\[ \text{Distance from transmitter} \]

\[ \text{Transient time} \]

slope: \(1/V\)

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Detect the presence of layers

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Method to determine the thickness of the layer
Impact Methods

A simple method of assessing the condition of concrete is to tap the surface with a hammer and listen to the resulting tone.

A high-frequency pitch indicates a sound concrete and a low-frequency pitch indicates the presence of flaws.
A trained operator can delineate zones of high and low pitch using this method.

The disadvantage of the method is that it is dependent on the skill level of the operator and does not provide quantitative information on the amount of damage in the interior of the concrete.
To overcome these limitations, different methods were developed to control the duration of the impact force so as to assure the reproducibility of the test and (b) to characterize the surface displacement generated by the impact on concrete.
Impact-echo

*Impact forces generated by steel spheres*

*Use of sensitive broadband transducer at the surface.*

*Analysis of the waveforms in frequency domain*
Non-Destructive Methods

Impact-echo

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Surface waves are not confined to the surface but, rather, are capable of penetrating a finite depth inside the material, sensing its properties.

Waves with short wavelength may not be able to sense a discontinuity deep in the interior of a structure, however waves with long wavelengths will be affected by its presence and their velocity will change.

This change of velocity with wavelength can be used to establish layers of high and low velocities.
Set up for the SASW method
Acoustic Emission (AE) is a noninvasive, nondestructive method that analyzes the noises created when materials deform or fracture. Each acoustic emission event is a signature of an actual mechanism, a discrete event that reflects a given material response.
Acoustic emission waves propagate through the material and can be detected on the surface by a sensor, which turns the vibrations into electrical signals. The sound of fracture propagation was originally called acoustic emission since it is acoustic and audible, however the frequency of these emissions can range from the audible range to many megahertz.
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Generation, propagation, and detection of Acoustic Emission

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There is a critical difference between acoustic emission and ultrasonic methods. In the former, a known signal is imparted into a material and the material’s response to on the signal is studied while in the latter the signal is generated by the material itself.
**Non-Destructive Methods**

Typical Result

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**Fig. AE waveform parameters**

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The relationship between current, $i$, and potential, $V$, is given by Ohm’s law:

$$ i = \frac{V}{R} $$

where $R$ is the resistance of the system. Resistance is not a material property as it depends on the dimensions of the system. The resistance is normalized to establish resistivity, $\rho$, as a material property

$$ R = \rho \frac{L}{A} $$

where $L$ is the length and $A$ is the cross-section.
Non-Destructive Methods

Wenner array \( (a=c=b/2) \)

\[
\rho = \frac{2 \pi a \Delta V}{i}
\]

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CEB (Comite Euro-International du Beton) recommendations

<table>
<thead>
<tr>
<th>Concrete Resistivity (Ω.m)</th>
<th>Likely Corrosion rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 200</td>
<td>Negligible</td>
</tr>
<tr>
<td>100 to 200</td>
<td>Low</td>
</tr>
<tr>
<td>50 to 100</td>
<td>High</td>
</tr>
<tr>
<td>&lt;50</td>
<td>Very high</td>
</tr>
</tbody>
</table>
Corrosion Potential

Can be measured as the voltage difference between the steel and a reference electrode in contact with the surface of the concrete.

Half-cell measurements may be made using only a high impedance voltmeter and a standard reference electrode, such as a copper-copper sulfate electrode.
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Corrosion Potential

High impedance voltmeter

Connection to reinforcing bar

Reference electrode

Sponge

Concrete

Reinforcing bar

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Polarization Resistance

(a) Potentiostatic measurement

(b) Galvanostatic measurement

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## Typical polarization resistance for steel in concrete

<table>
<thead>
<tr>
<th>Rate of corrosion</th>
<th>Polarization resistance, $R_p$ (kΩ.cm²)</th>
<th>Corrosion penetration, $p$ (µm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>$0.25 &lt; R_p &lt; 2.5$</td>
<td>$100 &lt; p &lt; 1000$</td>
</tr>
<tr>
<td>High</td>
<td>$2.5 &lt; R_p &lt; 25$</td>
<td>$10 &lt; p &lt; 100$</td>
</tr>
<tr>
<td>Low/moderate</td>
<td>$25 &lt; R_p &lt; 250$</td>
<td>$1 &lt; p &lt; 10$</td>
</tr>
<tr>
<td>Passive</td>
<td>$250 &lt; R_p$</td>
<td>$p &lt; 1$</td>
</tr>
</tbody>
</table>
Advantages in using linear polarization technique

The determination of the corrosion rate is an important parameter in the assessment of the life cycle of the structure.

Commercial equipment is available to measure the polarization resistance in existing structures.
Advantages in using linear polarization technique

It has been verified experimentally that the magnitude of the corrosion rate measured by polarization resistance is similar to that measured by gravimetry.

The measurement times are small.

The method applies small perturbations that do not interfere with the existing electrochemical processes.
Non-Destructive Methods

Limitations

The whole reinforcing bar or the steel mat along which uniform corrosion is rare, must be polarized. Therefore, the measured Rp is essentially an average result for all of the steel in the structures whereas the actual corrosion is non-uniform.
Limitations

This method assumes that the concrete resistivity is low, when in reality the concrete resistivity is usually high. Linear polarization is a DC method. Because of the electrical capacitance across the steel/concrete interface, it takes time to obtain a full response. As a result, the scanning rate plays an important role in obtaining accurate measurements.
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Equipment

- ECE
- Central Counter Electrode
- External Counter Electrode (ECE)
- Reinforcing bar
- Concrete

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Electrochemical impedance spectroscopy, or AC impedance, is an informative method because not $R_p$ only is measured, but also the physical processes in concrete and steel/concrete interface are assessed.

Impedance measurement employs small-amplitude alternating (AC) signals in a wide range of frequency as a perturbation.
Voltage response, $V$, to sinusoidal current signal $i$
Non-Destructive Methods

Model of equivalent circuit.

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Limitations

The equipment used is quite bulky and complex.

The entire reinforcing bar or network must be polarized.

Similar to the linear polarization, this method also requires a physical connection to the steel embedded in concrete. AC impedance measurements can have lengthy data acquisition times, especially for low frequency measurements.
Covermeter is the generic term for equipment used to locate steel reinforcing bar in concrete and to estimate the thickness of the concrete cover over the reinforcement. Unlike concrete, steel bars interact strongly with low-frequency electromagnetic waves applied at the surface of the concrete, making it easy to identify their location.
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Equipment I

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Equipment II

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Ground Penetrating Radar (GPR) methods use electromagnetic energy, typically at frequencies of 50-1500 MHz, to probe the subsurface.

This method has been used in concrete structures to detect voids and delaminations, locate the reinforcing bars, measure the pavement thickness, and monitor structural changes.
Recently, field research has been performed on the material characterization of concrete, such as water content, degree of cement hydration, and presence of chlorides.
Non-Destructive Methods

Method

\[ S \]

\[ T_x \rightarrow A \rightarrow R_x \rightarrow \text{air} \]

\[ d \]

Material with dielectric constant \( \varepsilon_1 \)

Material with dielectric constant \( \varepsilon_2 \)

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Example

Air/Ground Wave Arrival  Distance along the concrete surface

Hyperbolic reflections caused by the reinforcing bars

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To Find Delamination
Imperfections and localized zones of high porosity have different thermal properties than the rest of the concrete, so under heat flux they will produce zones with different temperatures than the surrounding concrete.
Effect of a flaw or imperfection on the temperature distribution of a concrete slab
Tomography comes from the Greek word *tomos* (slice) and it has the goal of imaging an object by taking measurements from “slices” of its cross-section.
In computed tomography, the image of an object is reconstructed from projections of the object.

Most commonly the projections are obtained by using penetrating x-rays, although other modalities for measuring projection data are also available.
X-ray Computed tomography

A radiation source (x-rays or γ-rays) is rotated a full 360° around the structure under inspection, and at each source position, the attenuation of the radiation penetrating through the material is measured with a linear array, or a 2D array of detectors at the opposite side.
Non-Destructive Methods

Configuration

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Examples

Radiographic (left) and CT image (right) images of the unloaded fiber-reinforced concrete cylinder

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Radiographic (left) and CT image (right) images of the loaded fiber-reinforced concrete cylinder

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Examples

Radiographic (left) and CT (right) image.

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Microtomography (courtesy from Prof. Landis)
Non-Destructive Methods

Examples

reinforced concrete column

radiography

3-D tomography

images courtesy of Dr. Harry Martz from LLNL

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Backscattering Microwave Tomography

To obtain higher resolution, it is necessary to employ electromagnetic radiation with shorter wave-length, leading to the use of microwave frequencies in the range of 300 MHz to 300 GHz.

This frequency range corresponds to wavelengths in the air of 1 m to 1 mm, respectively.
Non-Destructive Methods

Microwave camera