Assessing the Differential Fluid-Penetration Resistance in the Concrete Cover Through Formation Factor Mapping

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CPCI

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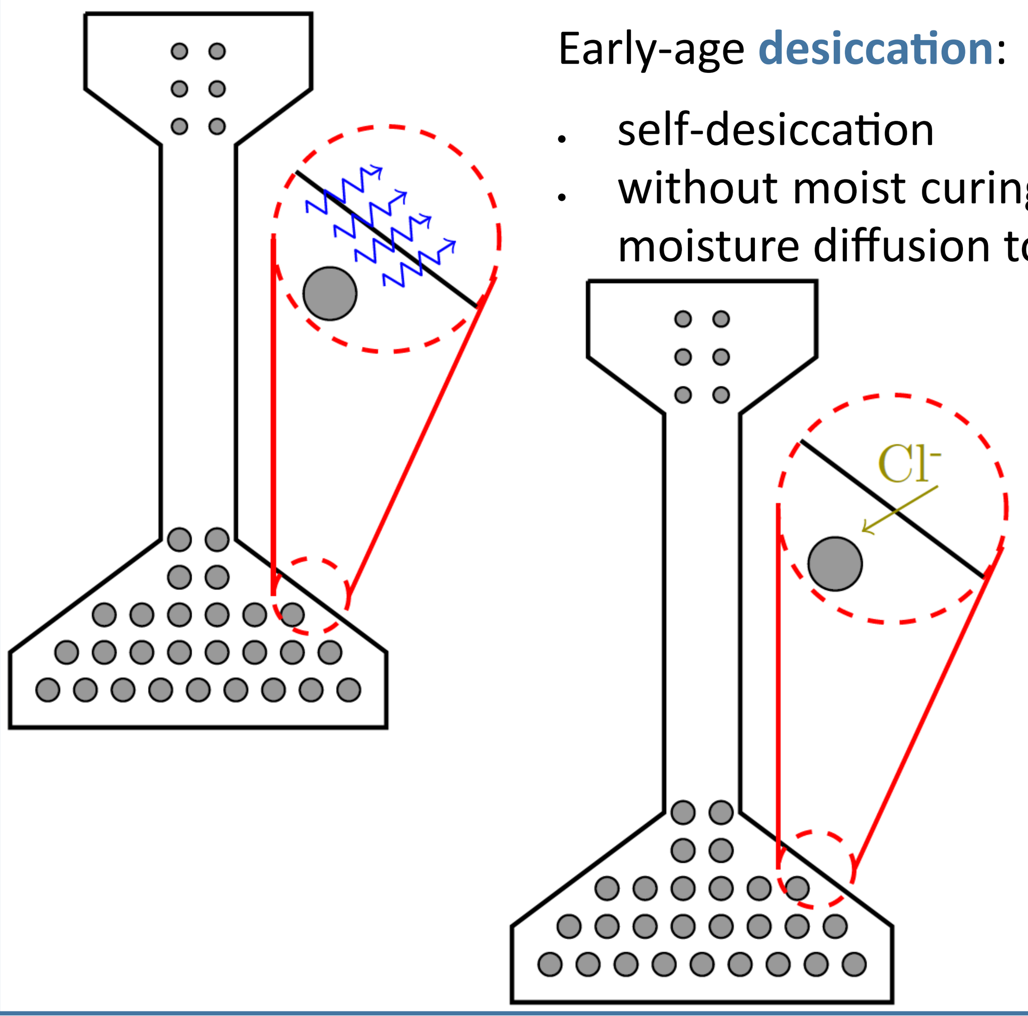
Concrete Curing and the Need for Performance Framework



Early-age **desiccation**:

- self-desiccation
- without moist curing, drying causes moisture diffusion to exterior

Curing needed to minimize porosity, particularly in the near surface → Hydration

Strength ≡ Maturity → **Performance Specifications**

Porosity & tortuosity ≠ Maturity → **Prescriptive Specifications**[1] ✖

Chloride Ingress in concrete cover:

- spatial non-uniformities (**differential** hydration)
- **multi-mechanistic** (sorption and diffusion)

⇒ Limits the advantages of more efficient curing methods, such as **accelerated moist curing**

⇒ Does not **guarantee** appropriate performance levels

Objective

Develop a comprehensive multi-mechanistic curing assessment framework for quality control, quality assurance, curing optimization, and service life modeling

Impedance Spectroscopy of Concrete Cover

Discretize the concrete cover into finite volumes of **representative size** using electrodes embedded in the fresh concrete, enabling a spatial mapping of the electrical resistivity (ρ_{bulk}).

⇒ Detect **curing differential** effect on porosity and pore structure connectivity:

$$\frac{\delta curing}{\delta x} \propto \frac{\delta \rho_{bulk}}{\delta x}$$

⇒ **Quantify** resistance to mass and ionic ingress through the formation factor (F); **ionic diffusion** (D)[2] and **Darcian permeability** (k)[3,4]:

$$\frac{\delta curing}{\delta x} \propto \frac{\delta F}{\delta x} = -\frac{\delta D^{-2}}{\delta x} = -2\frac{\delta d_c}{\delta x}\frac{\delta k^{-2}}{\delta x}$$

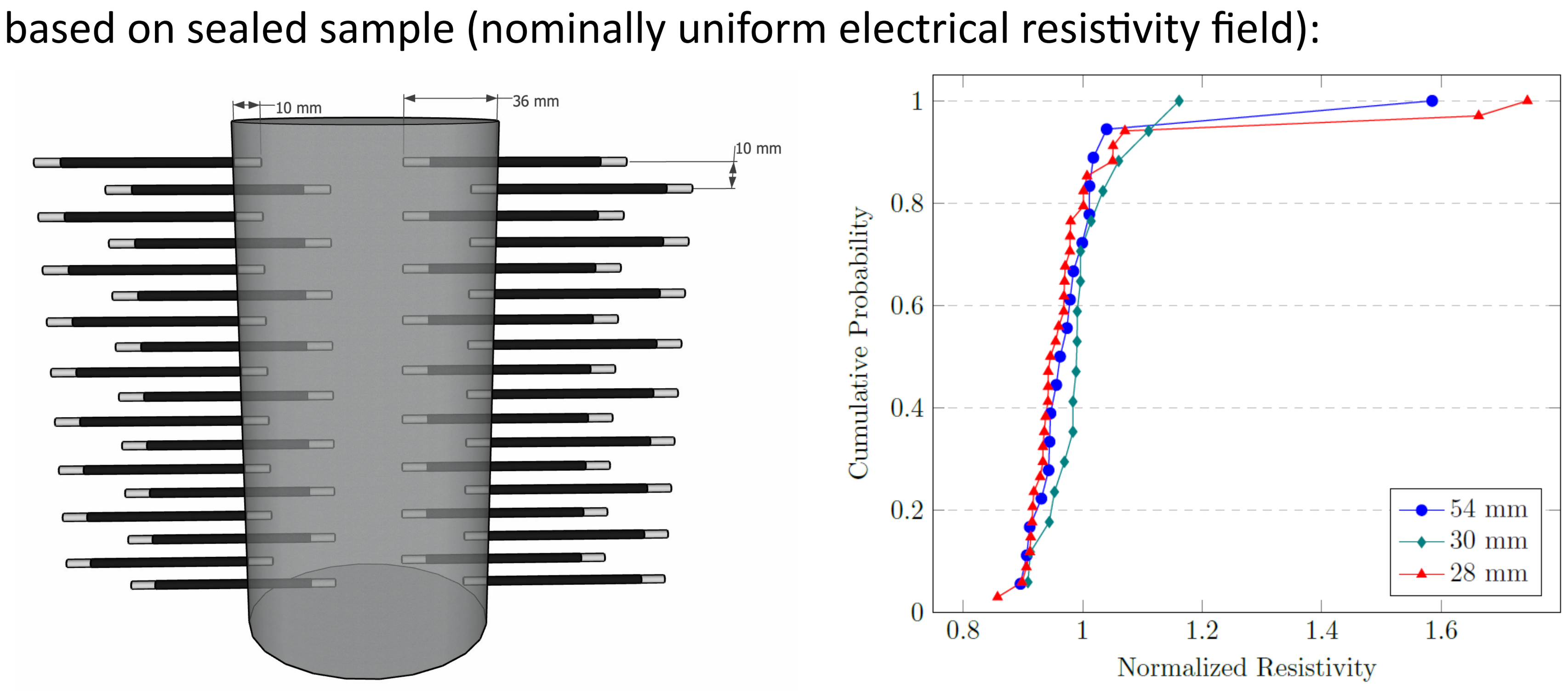
Considerations

⇒ **Electrode layout** should define a representative volume element

⇒ Non-uniform **degree of saturation** and **pore fluid** composition to be homogenized

Electrode Layout

Accounting for the **intrinsic variability** caused by the composite nature of concrete with phases of variable electrical conductivity. Defining the layout is a trade between **precision** and **accuracy**—opt for an alternate electrode depth (maximize tip distance with minimum vertical spacing). Empirical sensitivity analysis of layout based on sealed sample (nominally uniform electrical resistivity field):



Variability Caused by Different Layouts (25 mm max aggregate size)

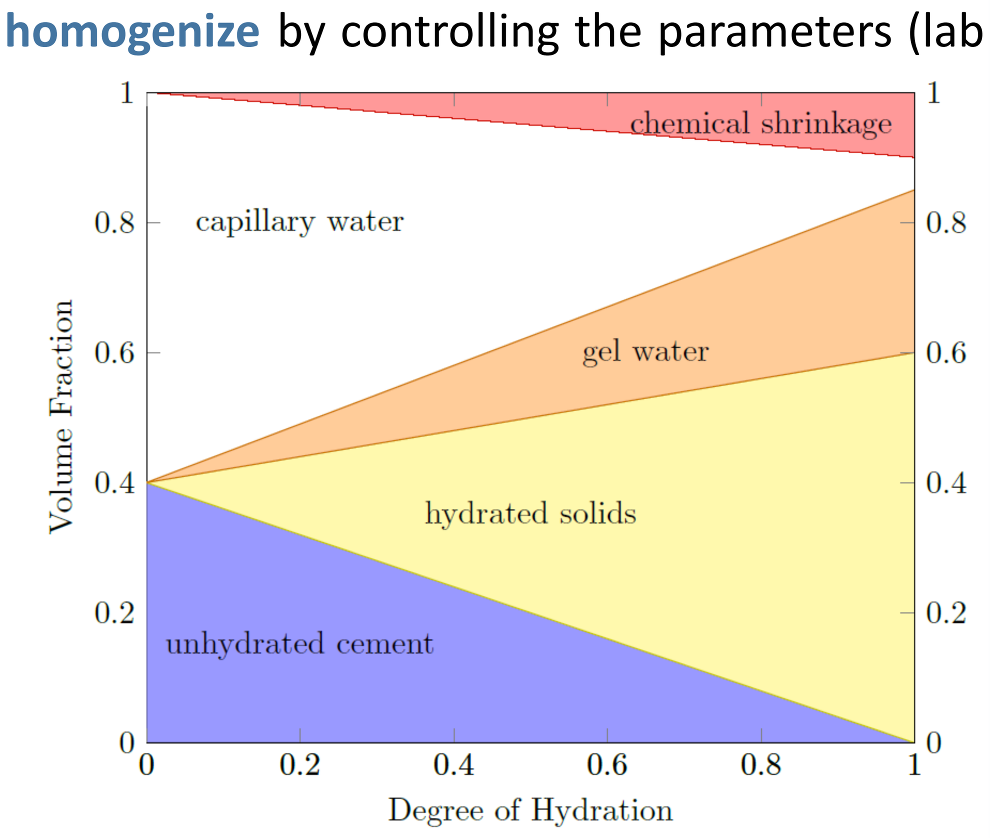
Sample Conditioning

Moisture desiccation causes differential degree of hydration, leading to variability in **volume assemblage** and pore solution **ionic concentration**. In addition, the **degree of saturation** of the pores is variable, strongly affecting the measured electrical resistivity. Options: 1) **estimate** the parameters and adjust the output (for in-situ testing—quality control), or 2) **homogenize** by controlling the parameters (lab specimen—quality assurance).

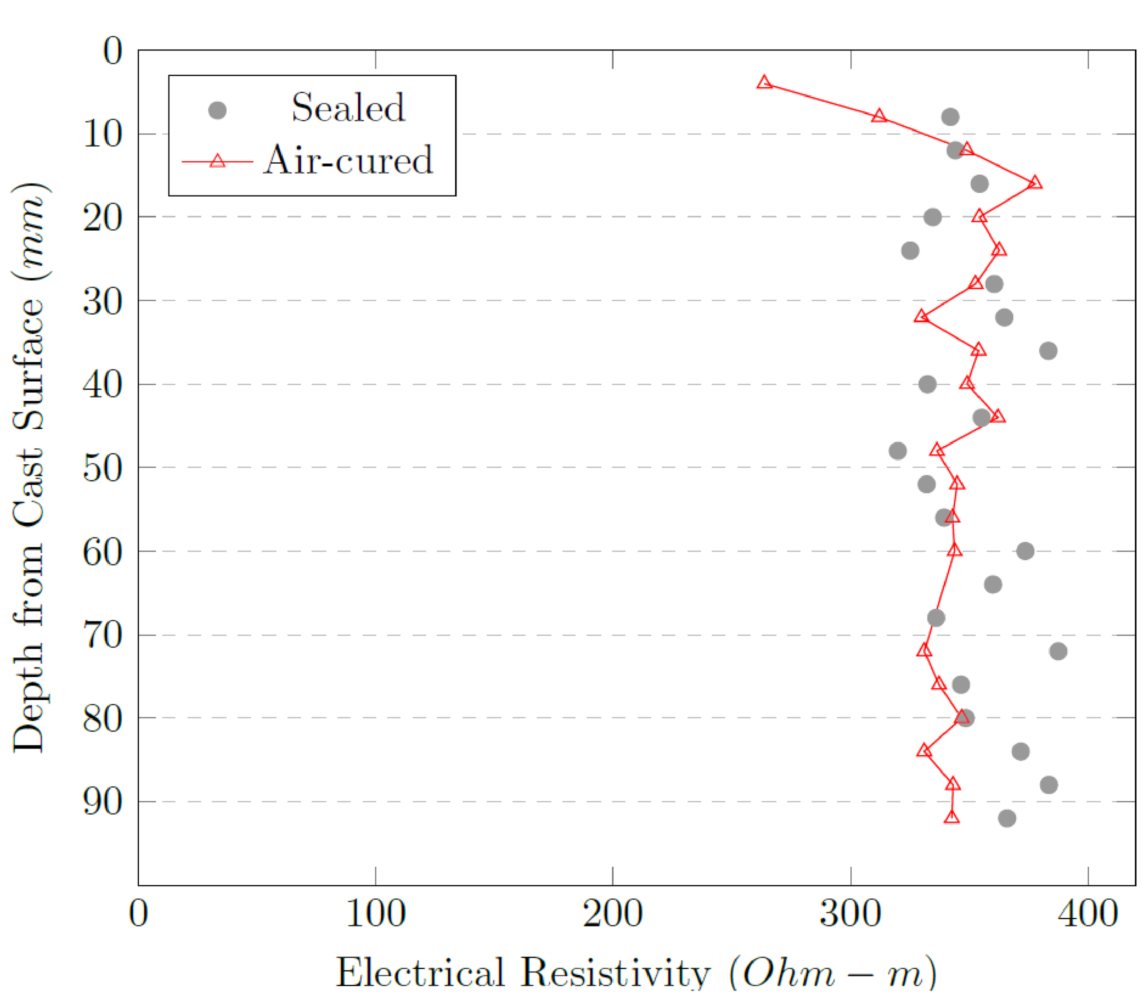
Condition specimen for testing by submerging in **simulated pore solution** for 6 days (Ca^{2+}, Na^{+}, K^{+}, OH^{-})[5]

⇒ Saturate capillary pores

⇒ Homogenize pore solution chemistry



Curing Effect Detection



Electrical Resistivity Profile for Sealed-Cured and Air-Cured Concrete

⇒ Proof of concept test prisms subjected to **sealed** curing or **air** curing (23 °C; 50 % RH) for 7 days

⇒ Specimens submerged in simulated pore solution to saturate capillaries

⇒ Electrical impedance profiled daily; figure showing results at **6 days after submersion**

⇒ Assuming sealed specimen is uniformly hydrated along its depth, the **intrinsic variability** (systematic error) was estimated by the coefficient of variation of **5.5 %**

⇒ Qualitative appreciation of curing detection (gradient at the near-surface)

⇒ Ability to detect **differentials in transport properties** caused by improper curing

⇒ **24 % drop** in electrical resistivity over initial 12 mm, considerable effect on **durability performance** (depending on exposure conditions: surface chloride concentration and degree of liquid saturation)

⇒ More reliable and precise curing characterization will be obtained as **hardware** and **testing setup** improve

⇒ Use of **Archie's power formulation** to account for differential degree of saturation for **in-situ** testing[6]

[1] CSA A23.1 (2019). Concrete materials and methods of concrete construction. Standard, Canadian Standards Association, Mississauga, Ontario, Canada

[2] Snyder, K. A. (2001). The relationship between the formation factor and the diffusion coefficient of porous materials saturated with concentrated electrolytes: theoretical and experimental considerations. Technical report, National Institute of Standards and Technology, Gaithersburg, Maryland, USA

[3] Nokken, M. R. and Hooton, R. D. (2008). Using pore parameters to estimate permeability or conductivity of concrete. Materials and Structures, 41(1):1-16

[4] Moradllo, M. K., Isgor, O. B., Qiao, C., and Weiss, W. J. (2018). Relating formation factor of concrete to water absorption. ACI Materials Journal, 115(6):887 - 898

[5] ASTM C1876 (2019). Standard test method for bulk electrical resistivity or bulk conductivity of concrete. Standard, ASTM International, West Conshohocken, Pennsylvania, USA

[6] Weiss, J., Bullard, K. S. J., & Bentz, D. (2013). Using a saturation function to interpret the electrical properties of partially saturated concrete. Journal of Materials in Civil Engineering, 8 (55), 1097-1106