Health Monitoring of Early Age Concrete

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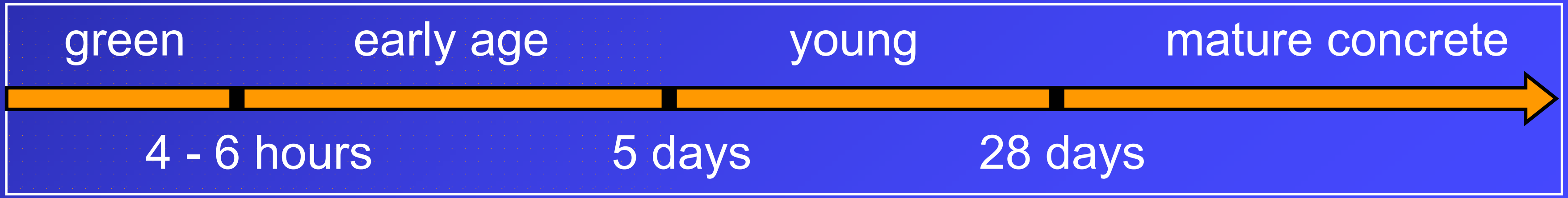
Scope of Research

Test method for *in-situ* testing of *early age* concrete

Requirements

- versatile in application
- nondestructive in nature
- measure physical properties
- access to one side of the structure

Life Cycle of Concrete



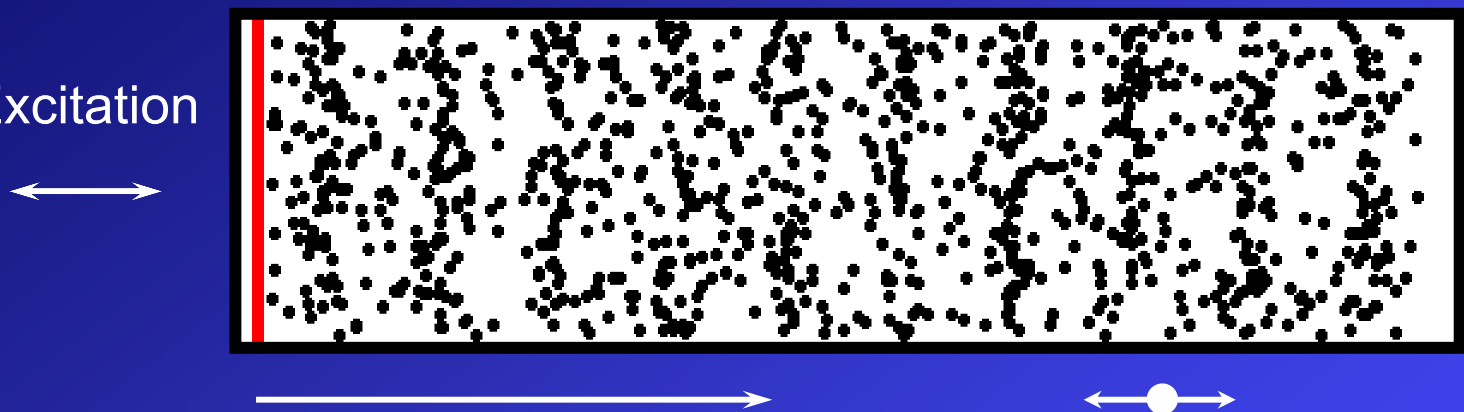
Outline

1. **Basics of Wave Propagation**
2. **Principle of Wave Reflection Method**
3. **General Application**
   - Setting Behavior
   - Compressive Strength
   - Dynamic Shear Modulus
   - Measures of Cement Hydration
   - Microstructural Parameters
4. **Field Application**
5. **Conclusions**

Wave Propagation

Longitudinal Waves (L-Waves)

also: Primary (P-) Waves, Compression Waves



Wave Velocity:

$$v_L = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}}$$

Governing Parameters

Young's Modulus E

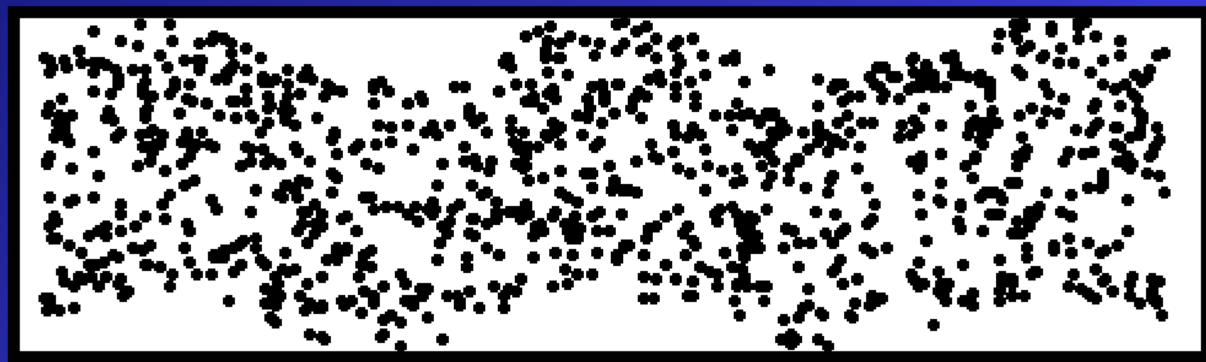
Poisson's Ratio v

Density ρ

Transverse Waves (T-Waves)

also: Secondary (S-) Waves, Shear Waves

Excitation



Direction of Travel

Direction of Particle Motion

Wave Velocity:

$$v_T = \sqrt{\frac{G}{\rho}}$$

Governing Parameters

Shear Modulus G

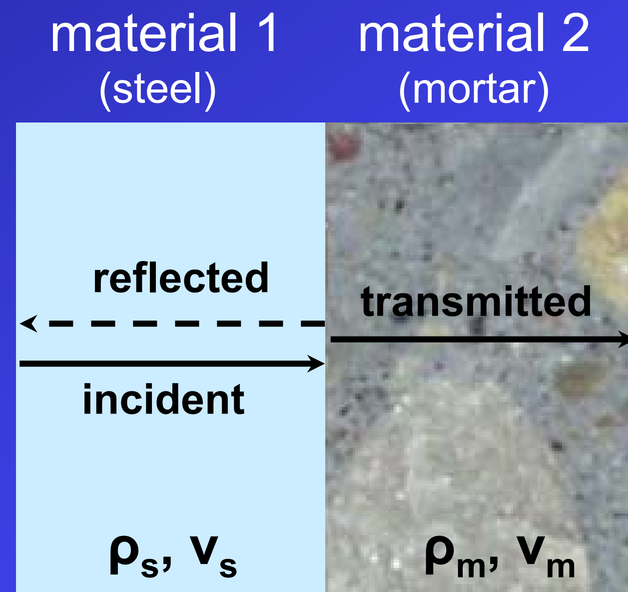
Density ρ

no propagation in liquids or gases !

Wave Reflection at Boundaries

if P- or S-wave encounters an interface between two materials the wave is

- partially reflected
- partially transmitted



reflection coefficient

$$r = \frac{Z_{mortar} - Z_{steel}}{Z_{mortar} + Z_{steel}}$$

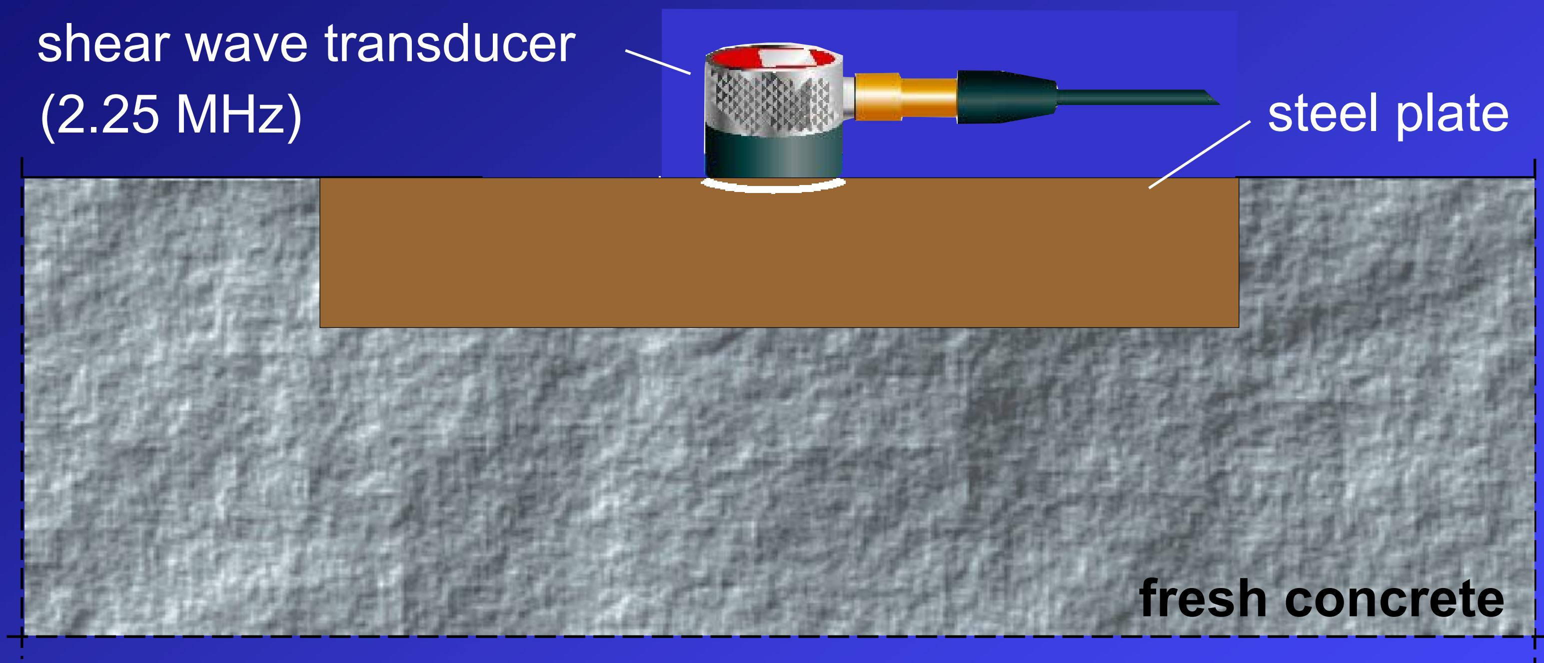
acoustic impedance

$$Z = \rho \cdot v$$

→ governs the reflection process

Principle of WR-Method

Principle of Wave Reflection Method

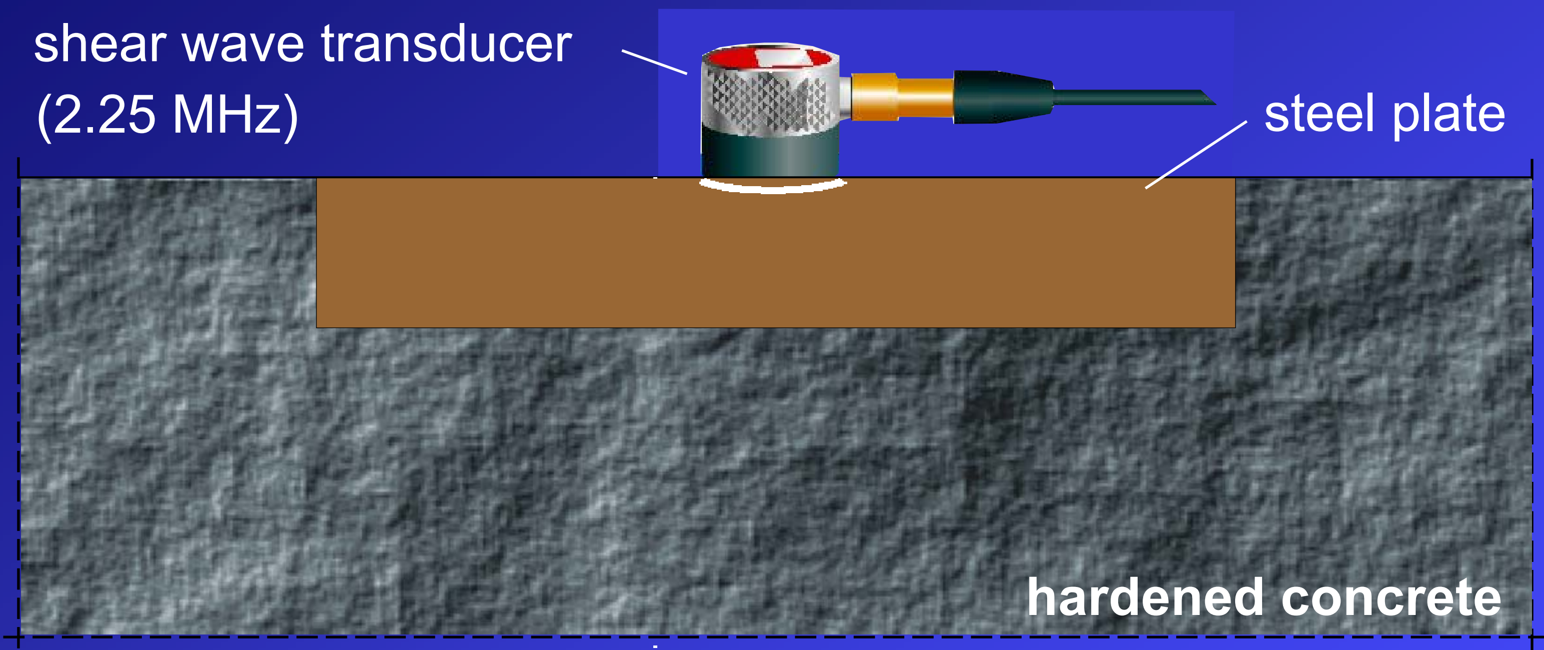


Case 1: concrete is liquid

no wave transmission at interface

shear waves: do not propagate in liquids

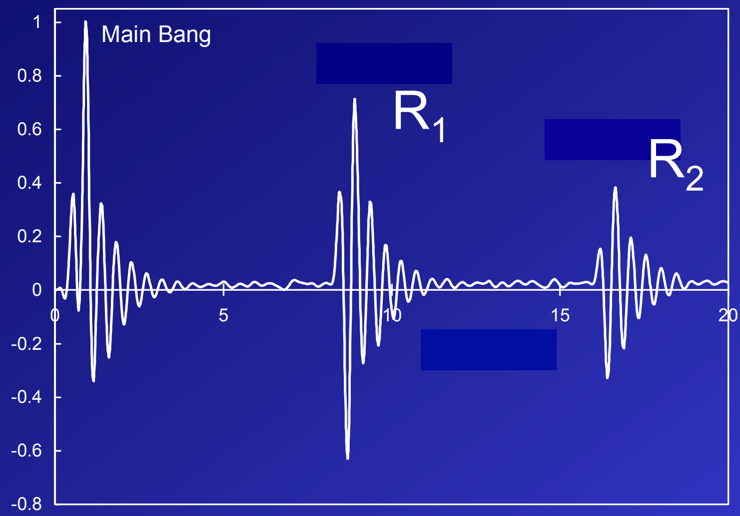
Principle of Wave Reflection Method



Case 2: concrete is hardening

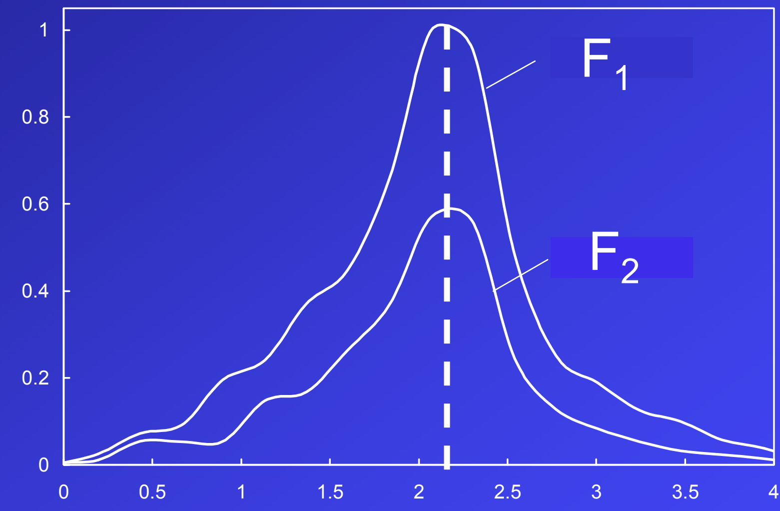
transmission losses at interface

Signal Analysis



Time Domain

FFT



Frequency Domain

Reflection Coefficient r

$$\frac{F_2(f)}{F_1(f)} = L \cdot r$$

F_1, F_2 …. FFT of reflections at 2.25 MHz

L …. Losses (material, coupling, geometry)

Reflection Loss

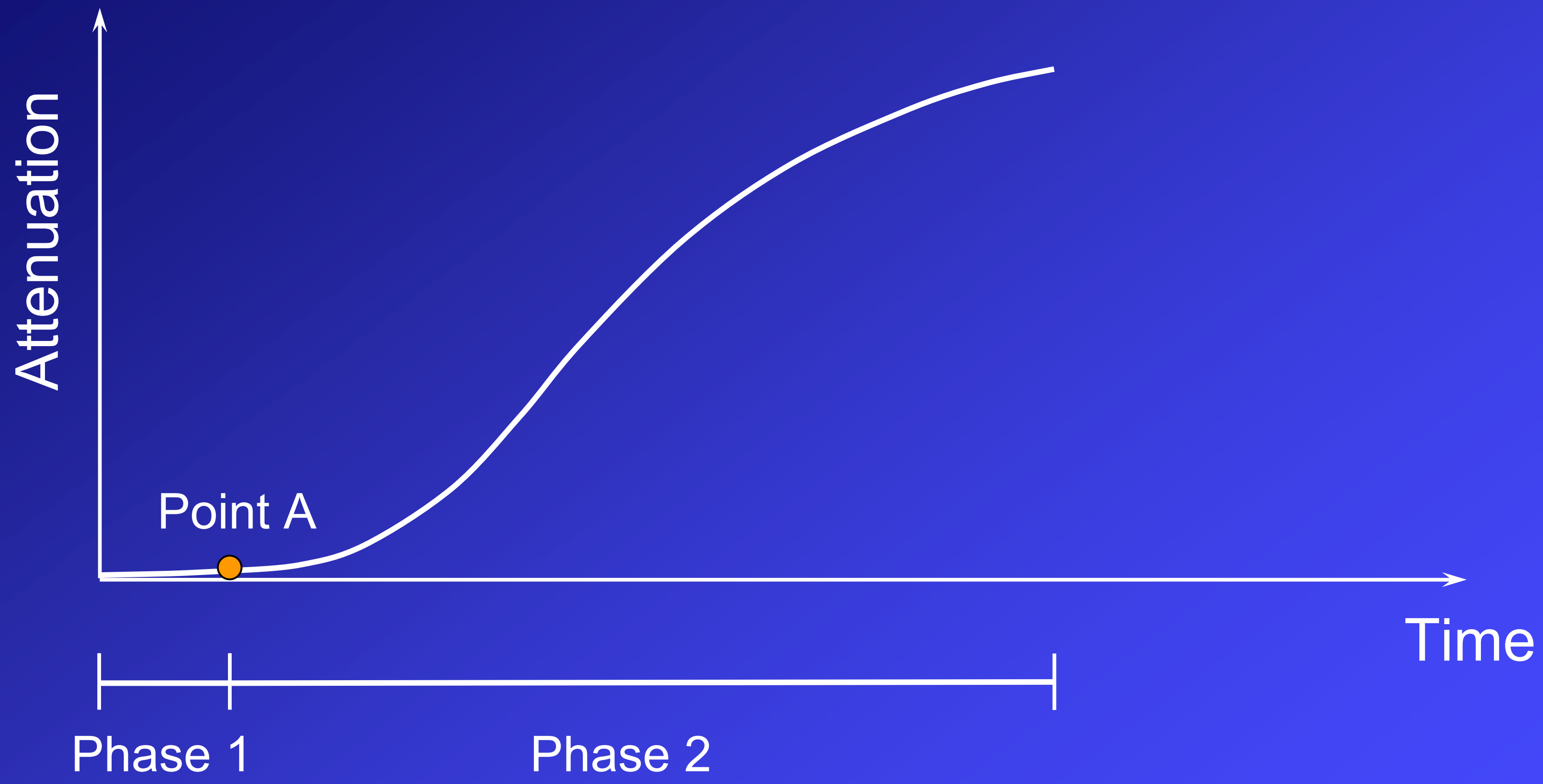
$$R_L\ (dB) = -\ 20 \cdot \log (r)$$

Attenuation Development

Phase 1: immediately after casting

Concrete is liquid → no transmission → attenuation is zero

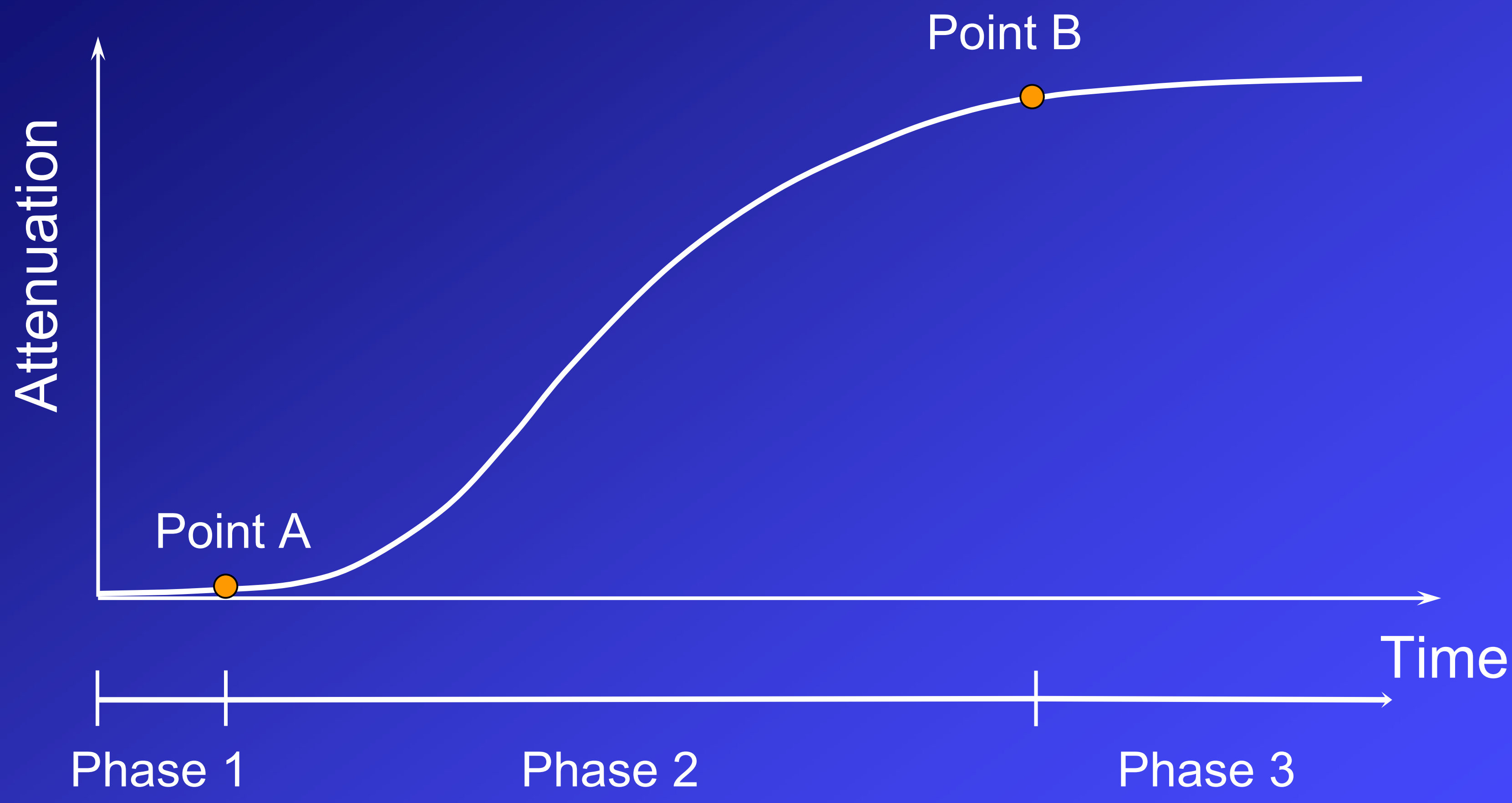
Attenuation Development



Phase 2: accelerating hydration

Concrete hardens rapidly → transmission → attenuation increases

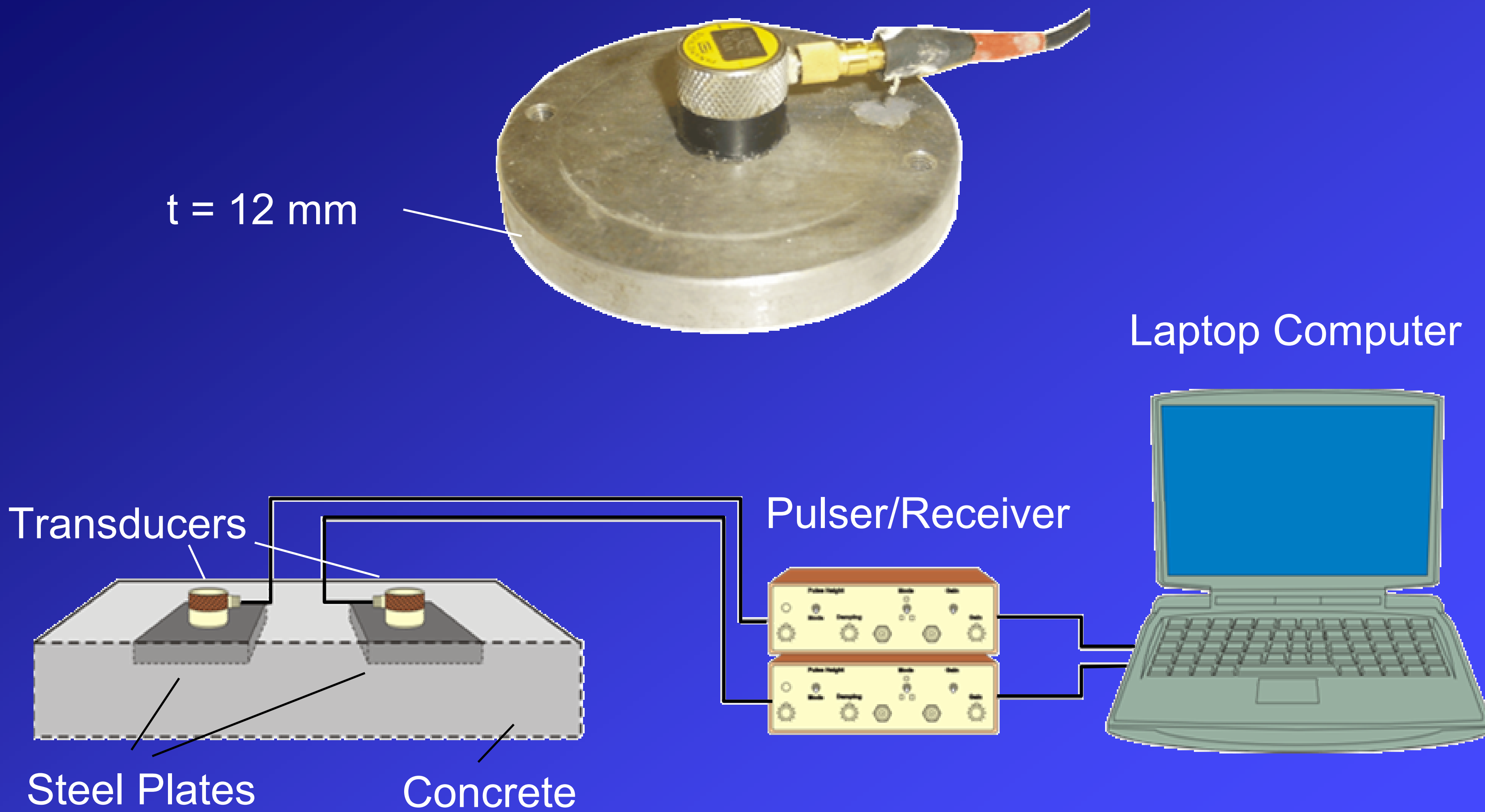
Attenuation Development



Phase 3: decelerating hydration

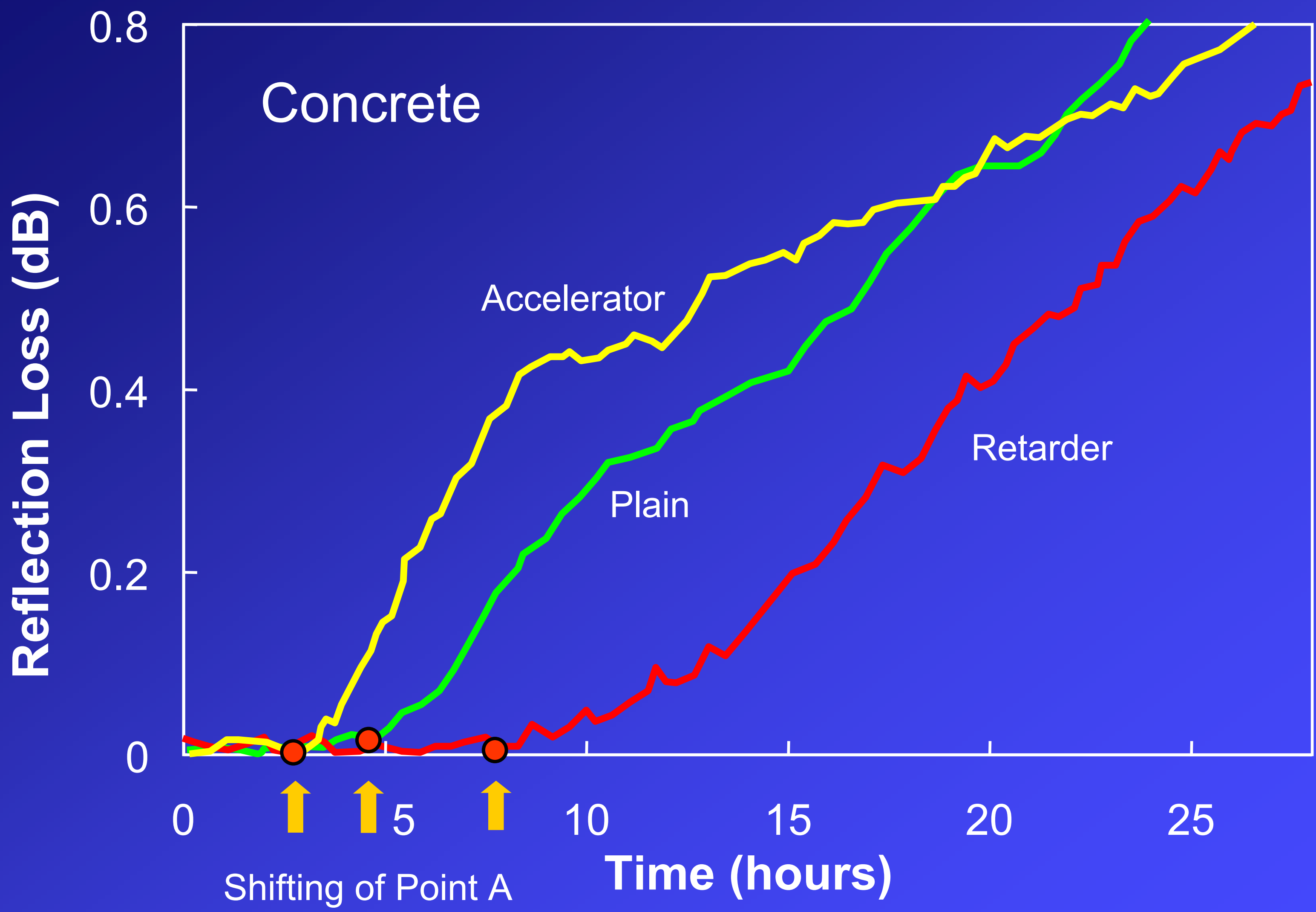
Concrete hardens → constant transmission → attenuation levels off

Test Equipment

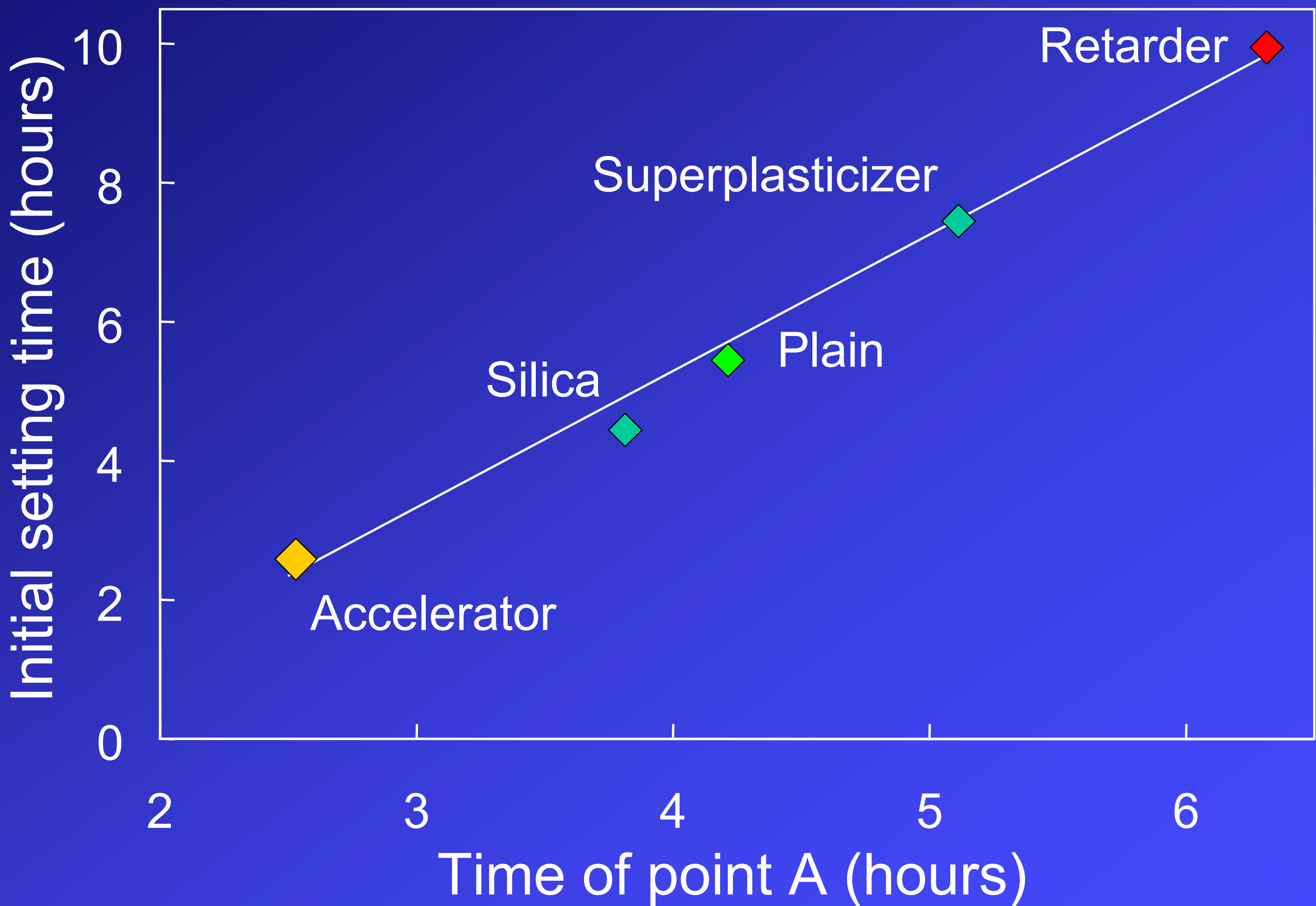


Reflection Loss
vs.
Setting

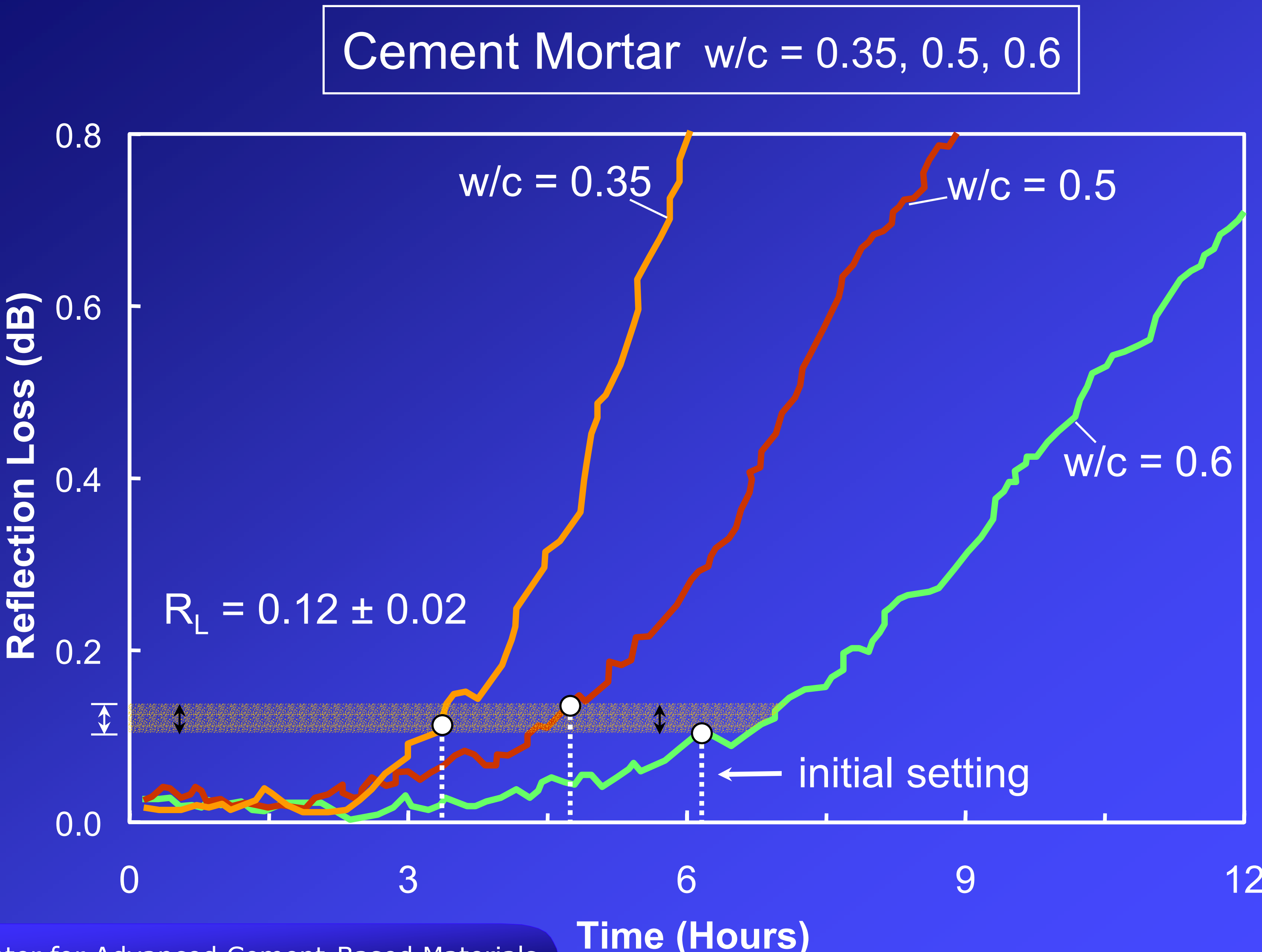
Influence of Admixtures



Influence of Admixtures



Influence of w/c-ratio



Summary – Setting

WR-Method can measure influence of

- admixtures
- w/c-ratio
- temperature (not shown)

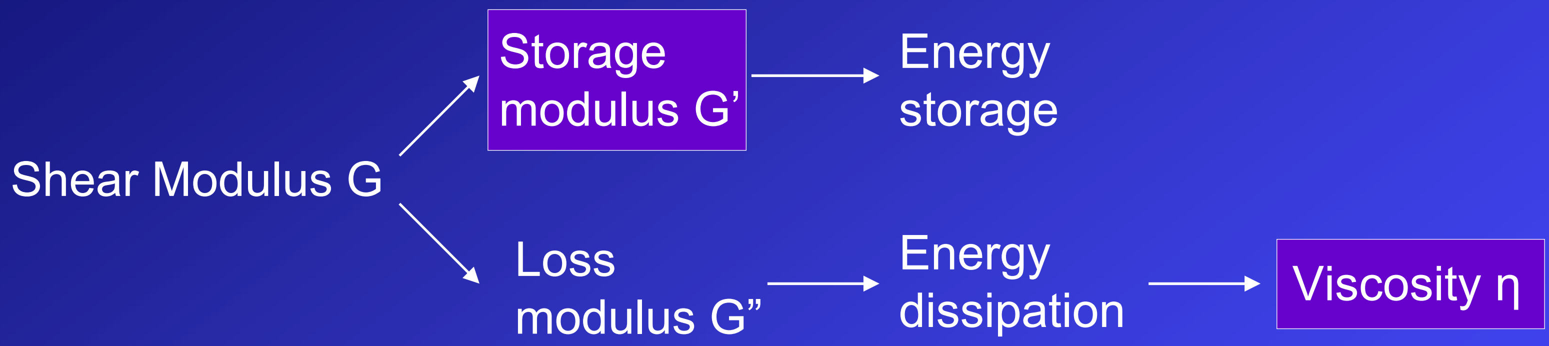
on the setting behavior of cement-based materials

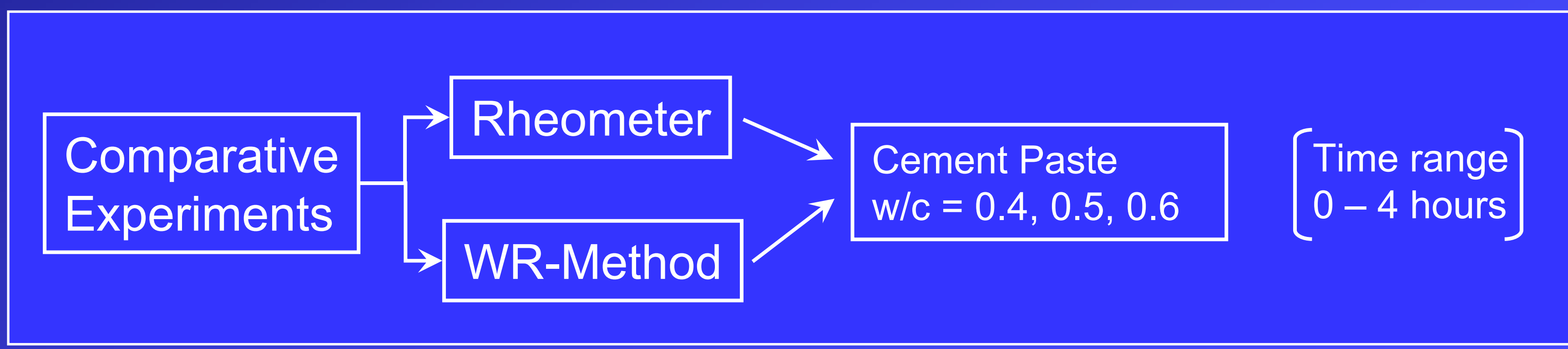
Reflection Loss
vs.
Viscoelastic Properties

Background

- WR-method can be used to measure rheological parameters of fresh cement paste

Parameters of interest

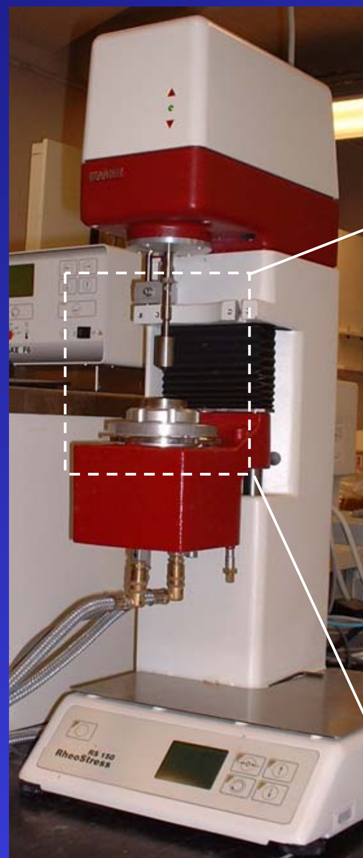


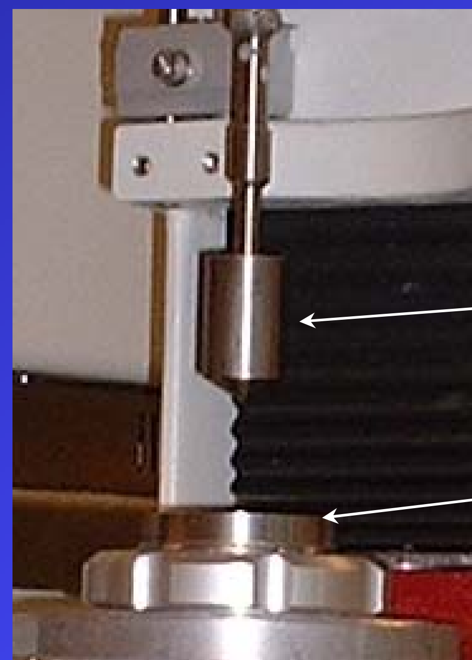


Rheometric Measurements

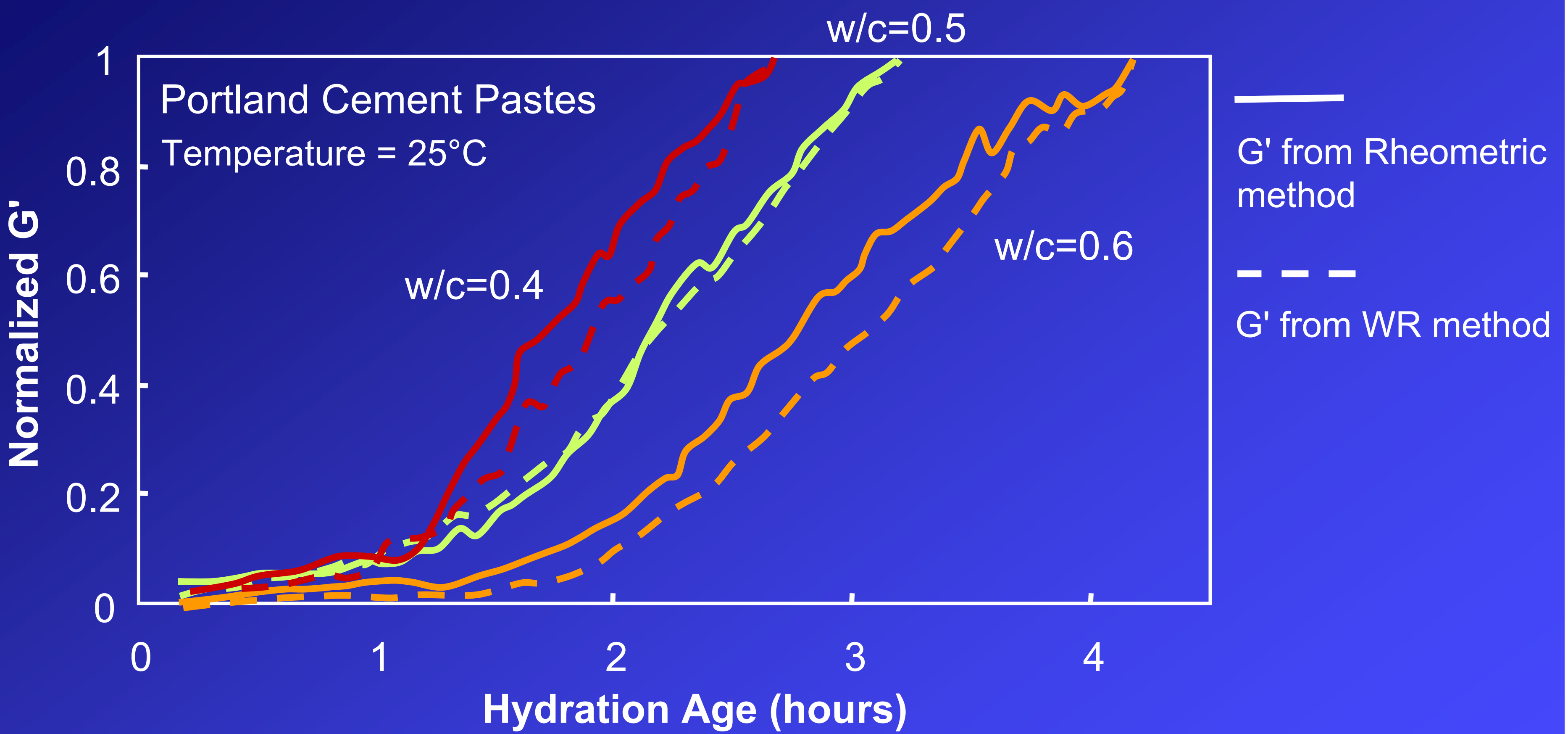
for comparison

Rheometer



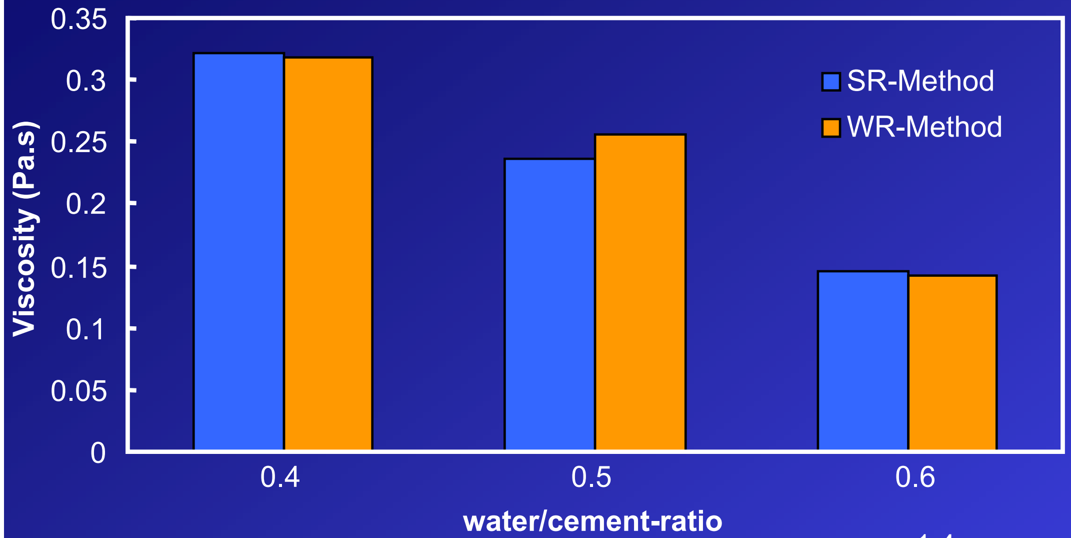


Storage Shear Modulus



normalized values show similar trends

Viscosity

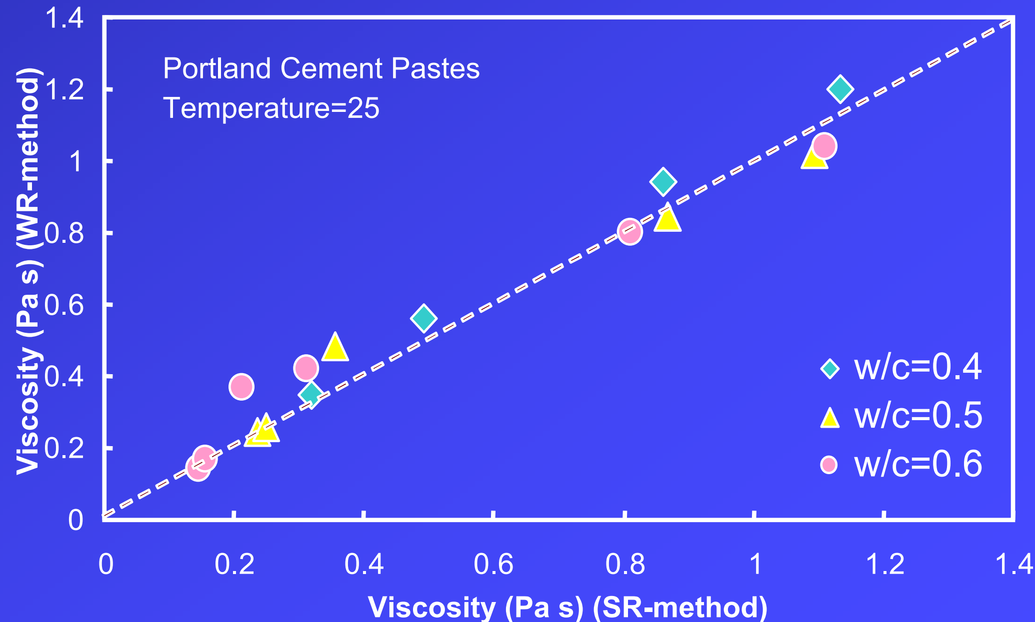


Portland Cement Paste

Temperature=25°C

Hydration Age=15mins

Good correlations of the viscosity



Summary – Visco-elastic Parameters

WR-Method can reproduce

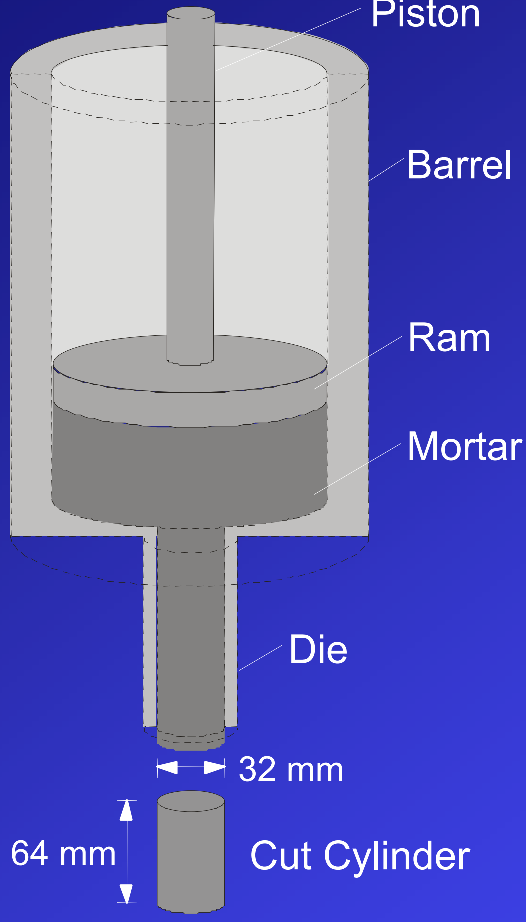
- storage modulus (measure of elasticity)
- viscosity

during the setting of cement-based materials

Reflection Loss vs. Strength

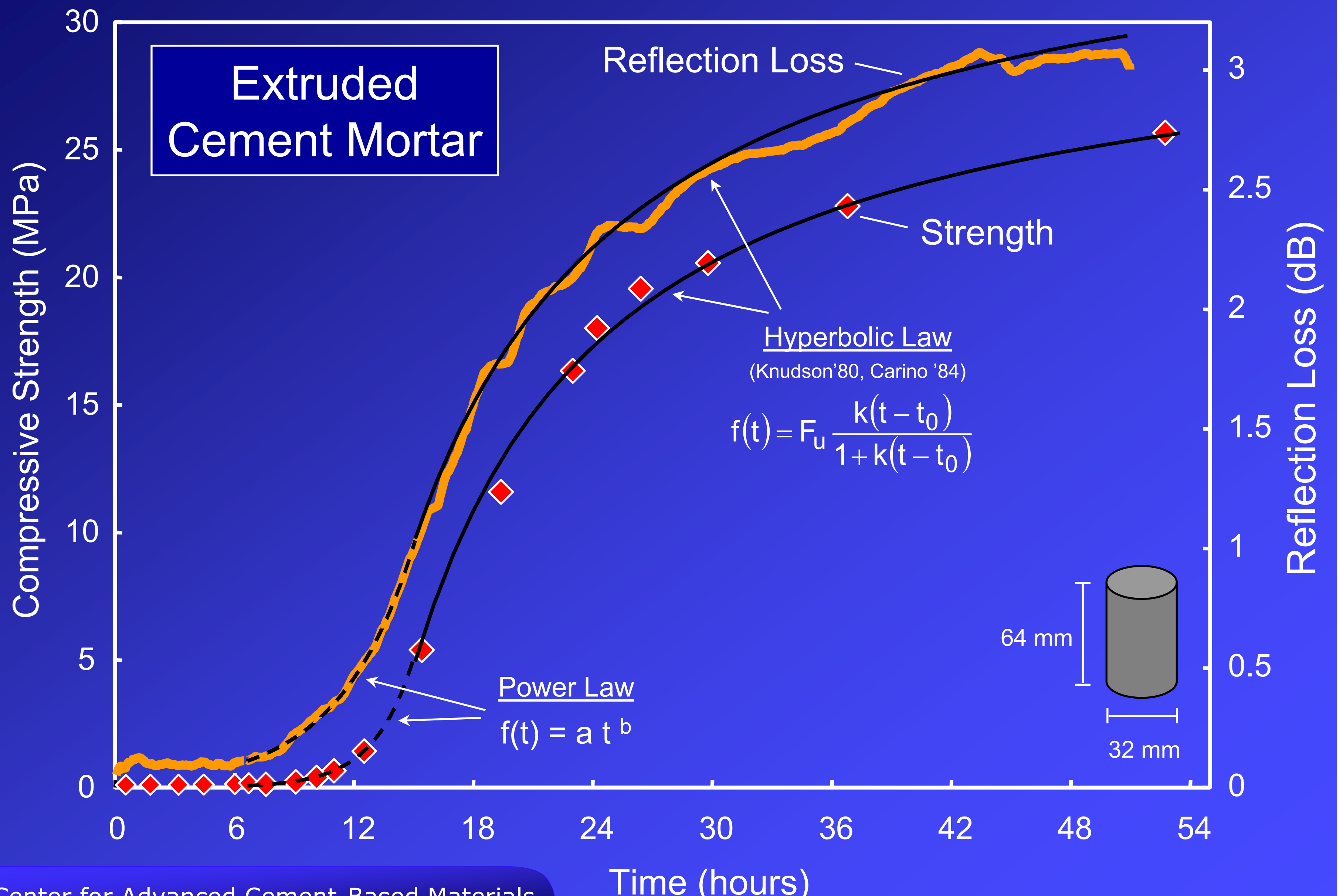
Strength Test on Extruded Cylinders

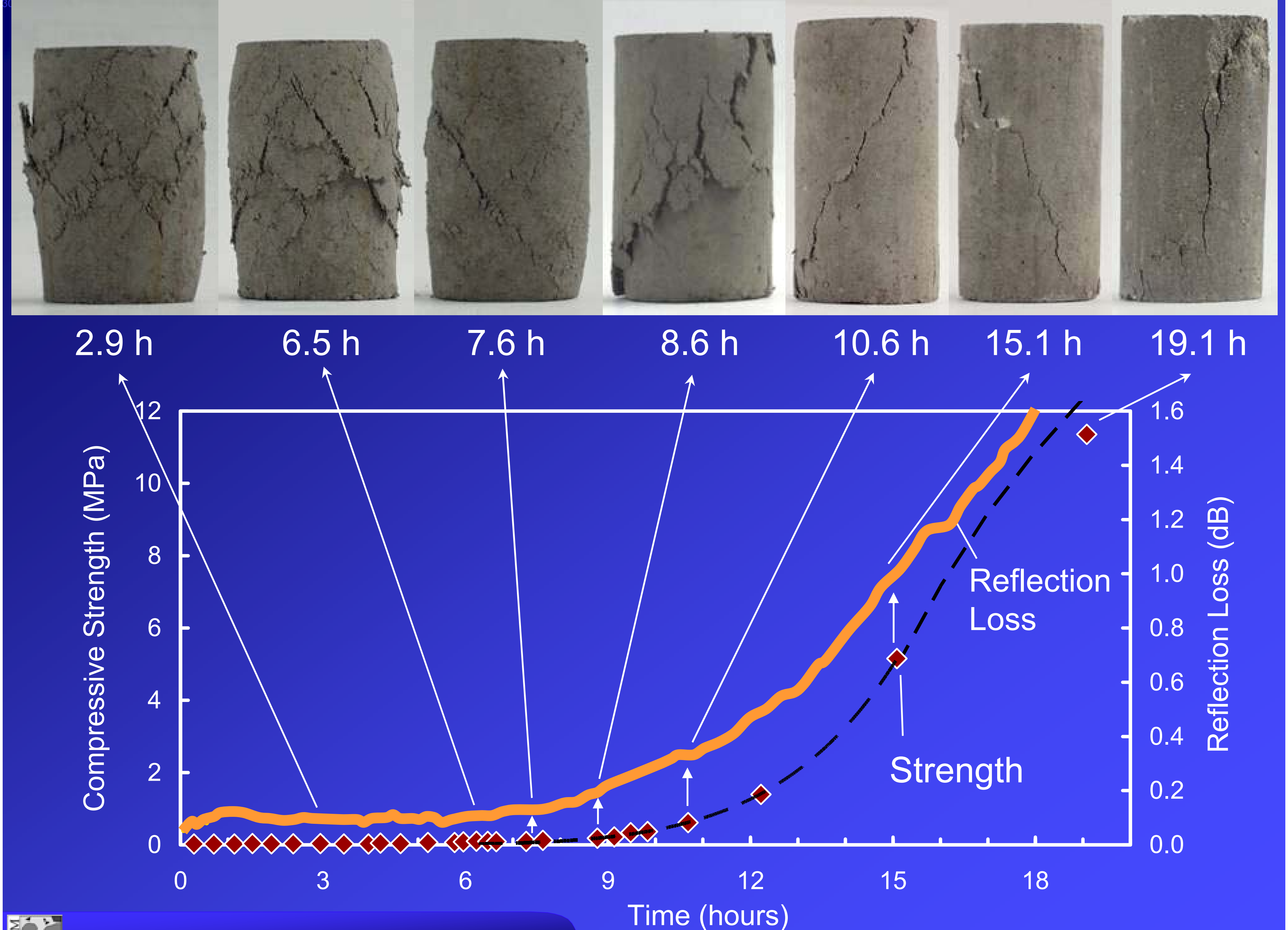
Ram-Extruder



Strength Test

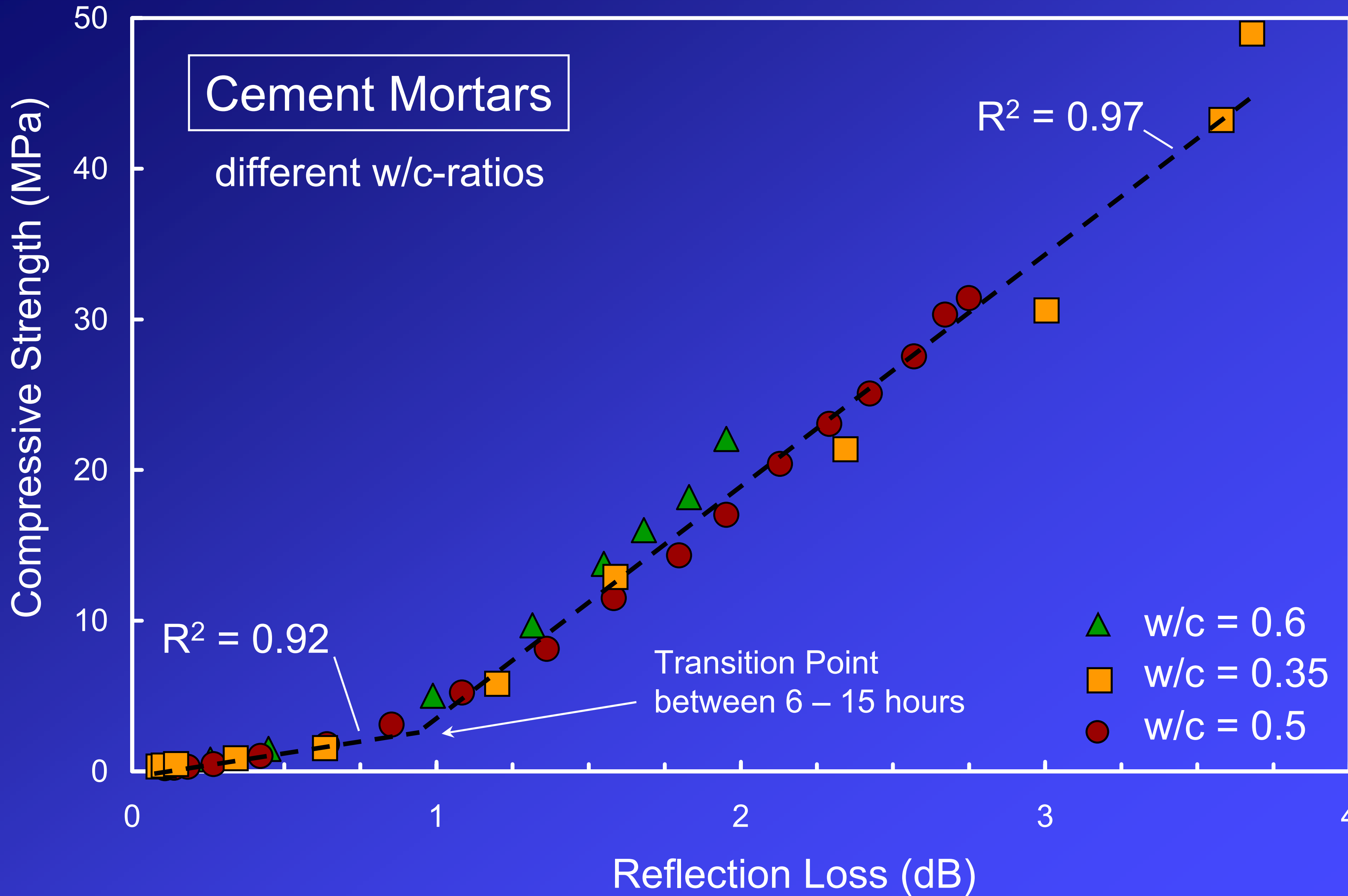
Reflection Loss vs. Strength





2.9 h
6.5 h
7.6 h
8.6 h
10.6 h
15.1 h
19.1 h
Compressive Strength (MPa)
Reflection Loss (dB)
Reflection Loss
Strength
Time (hours)
0
3
6
9
12
15
18
0
2
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

R_L vs. Strength



Summary – Compressive Strength

Strength and reflection loss follow similar trends

Reflection loss is (bi-) linearly related to compressive strength at early ages.

Relationship is independent

– of w/c-ratio (for mortar)

– of temperature (results not shown)

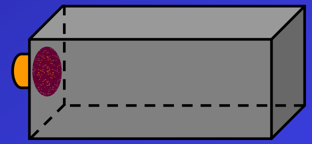
Reflection Loss vs. Shear Modulus

Determination of Shear Modulus

Reflection Loss

R_L = f (Shear Modulus) → G_r

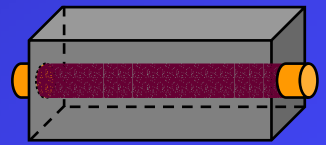
local measurement



Shear Wave Velocity

v_s = f (Shear Modulus) → G_{vs}

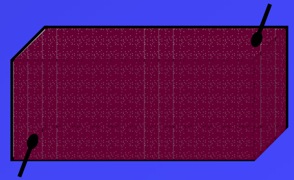
measurement along wave path



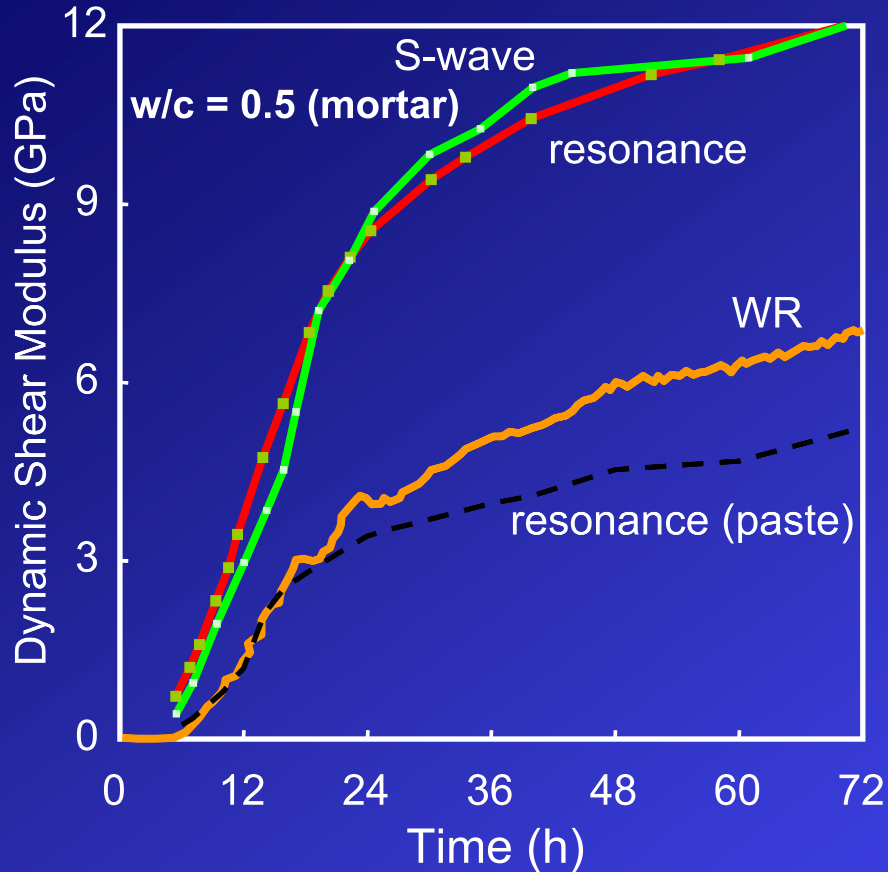
Torsional Resonant Frequency

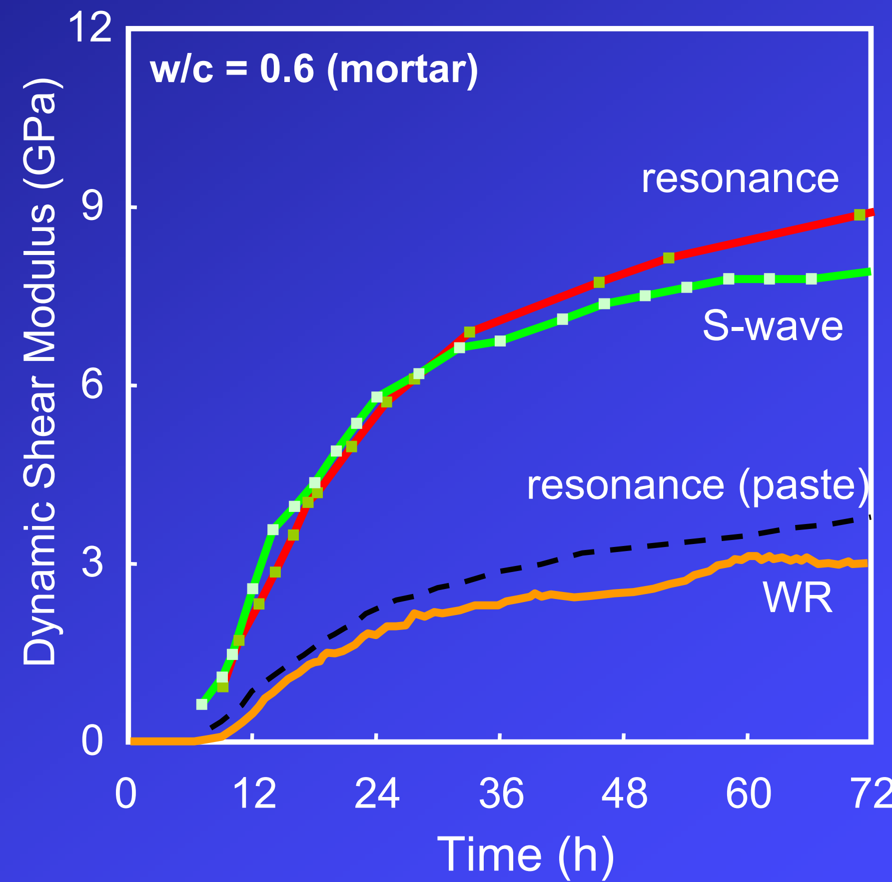
f_{tor} = f (Shear Modulus) → G_{tor}

bulk measurement



Dynamic Shear Modulus





Reflection Loss is governed by cement paste properties

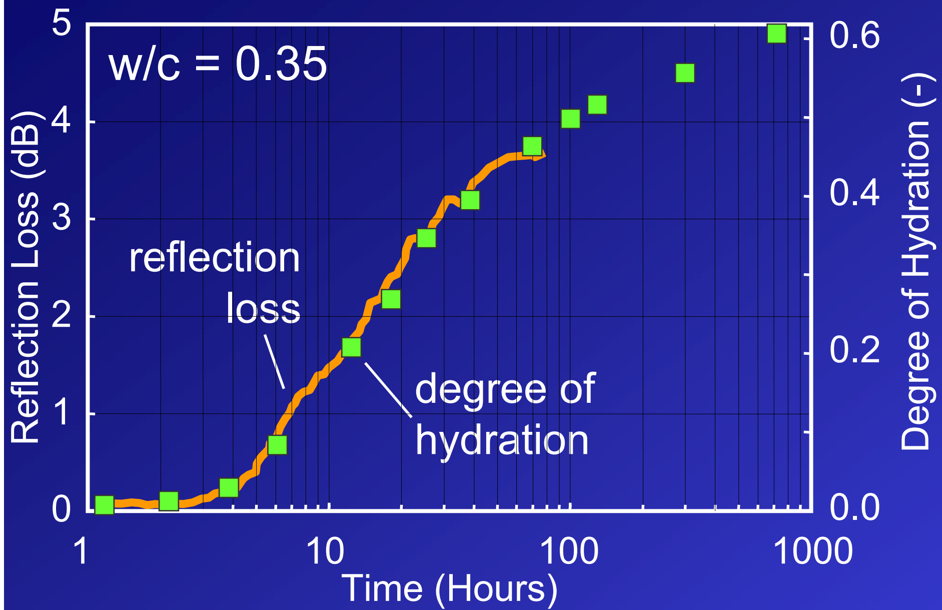
Summary – Shear Modulus

Reflection loss

- is governed by dynamic shear modulus,
- measures shear modulus of cement paste portion of mortar

Reflection Loss
vs.
Direct Measures of Hydration

Reflection Loss vs. Degree of Hydration

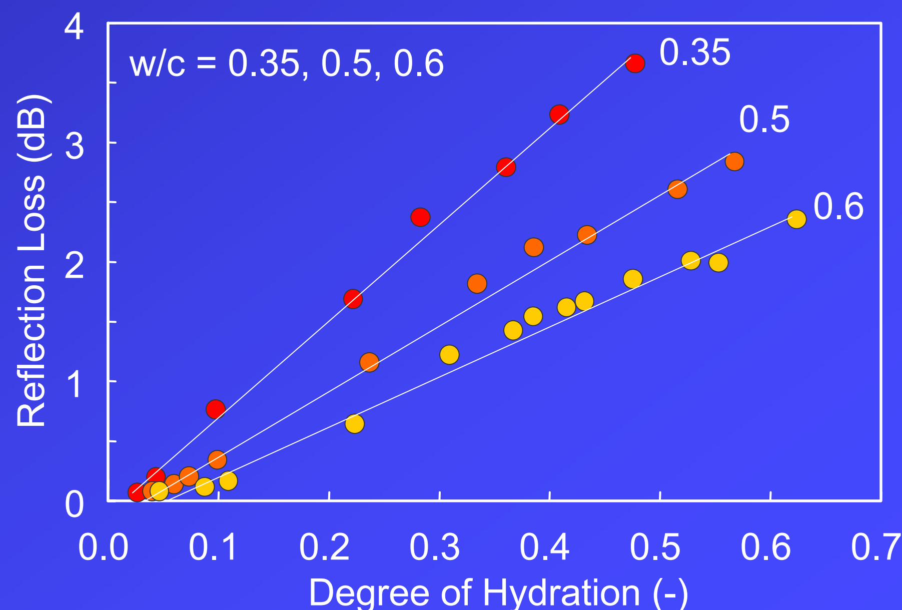


Degree of hydration measured by TGA

Comparison in time

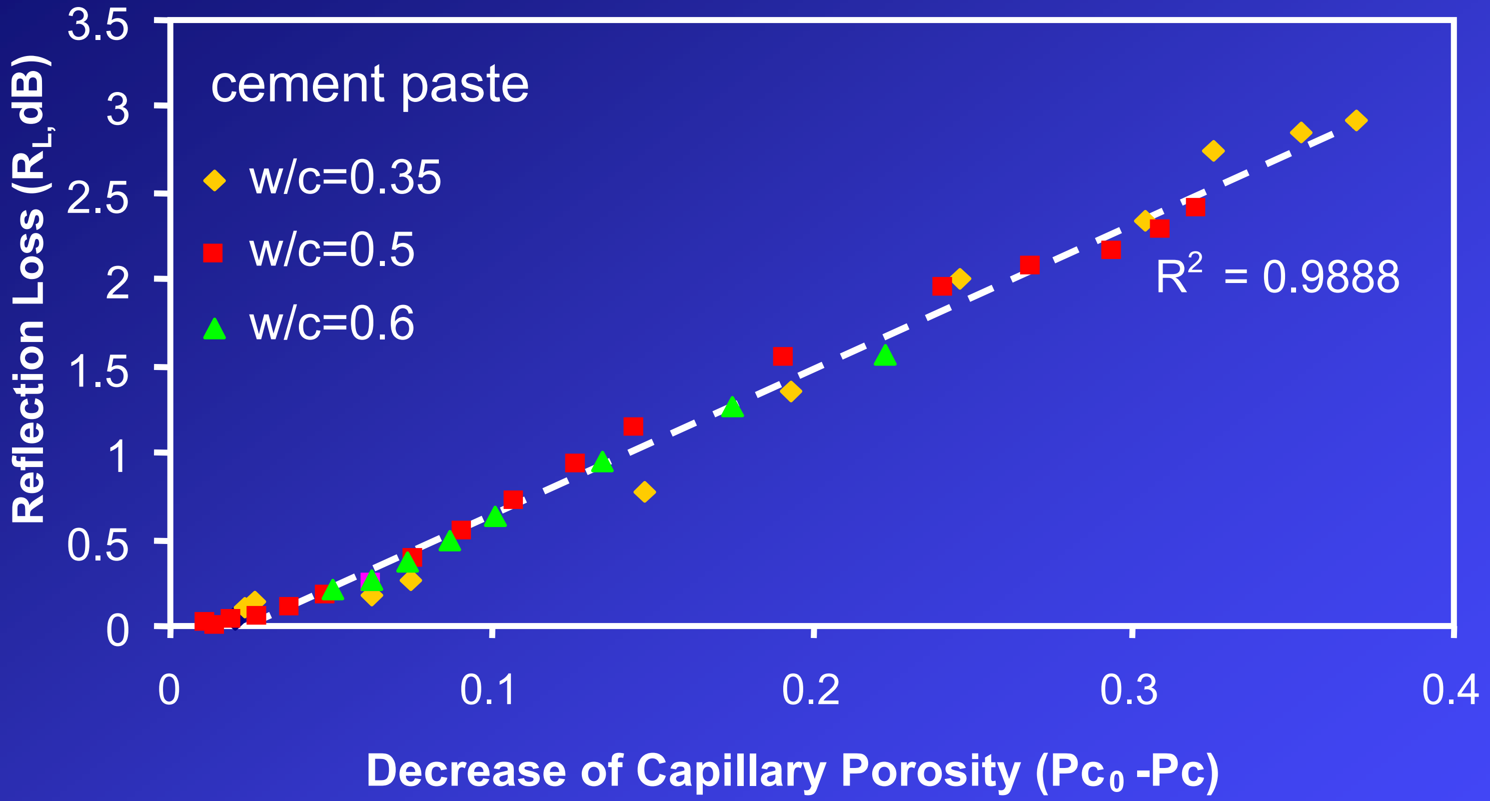
Direct comparison

linear relationship



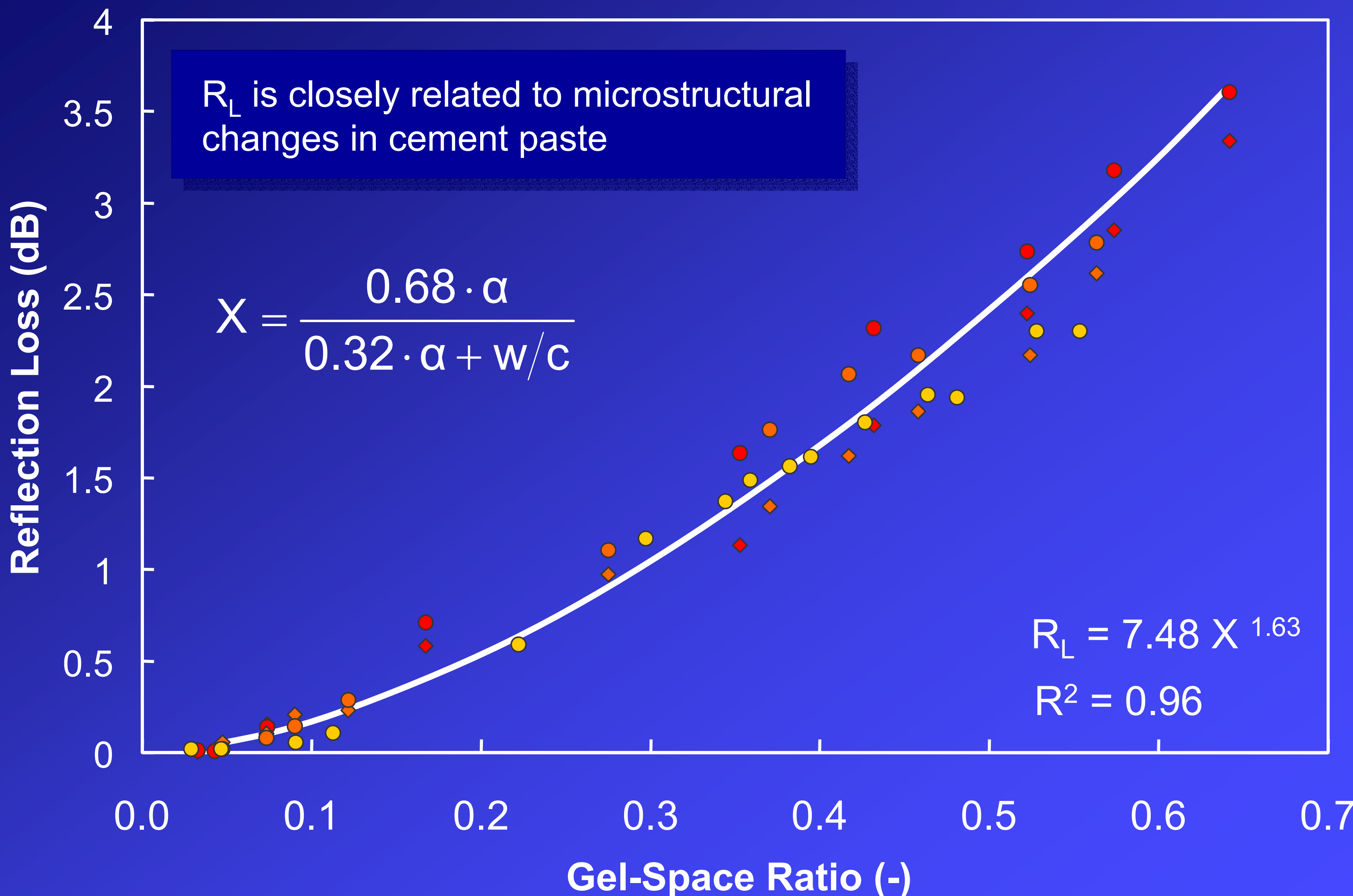
Reflection Loss vs. Microstructure

Reflection Loss vs. Capillary Porosity



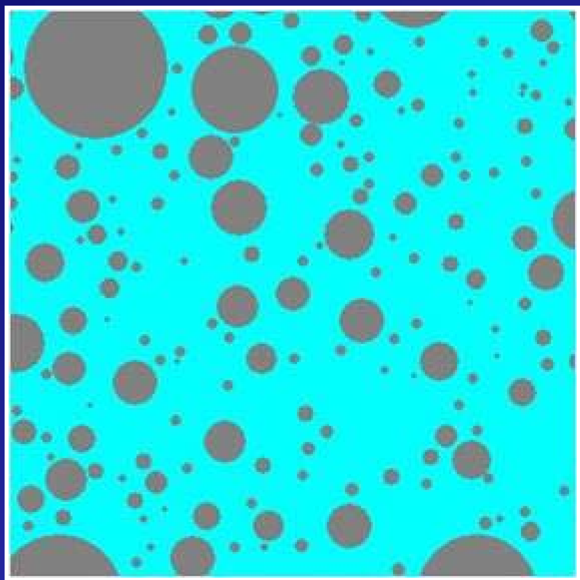
Reflection loss uniquely related to decrease in porosity

Gel-Space Ratio vs. Reflection Loss

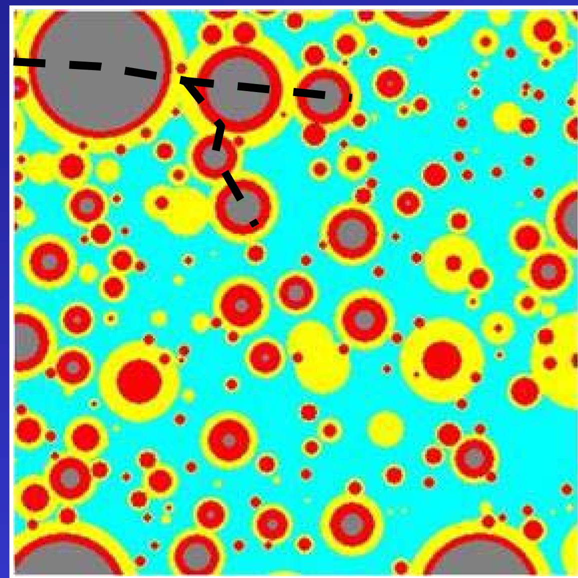


Numerical Simulation – HYMOSTRUC3D

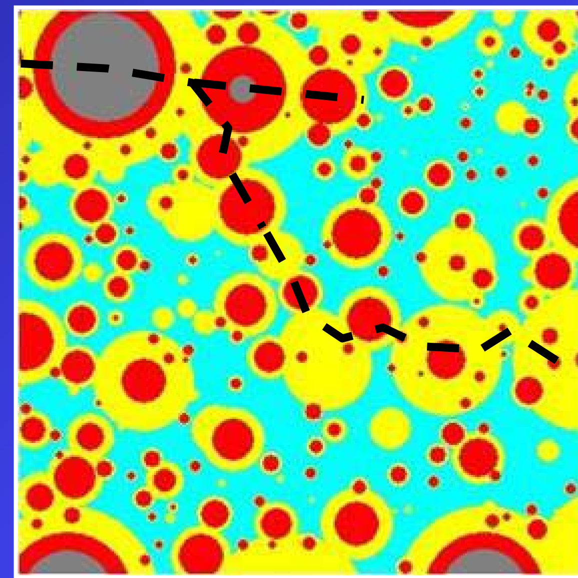
Connectivity of Solid Phase



initial stage
no contacts



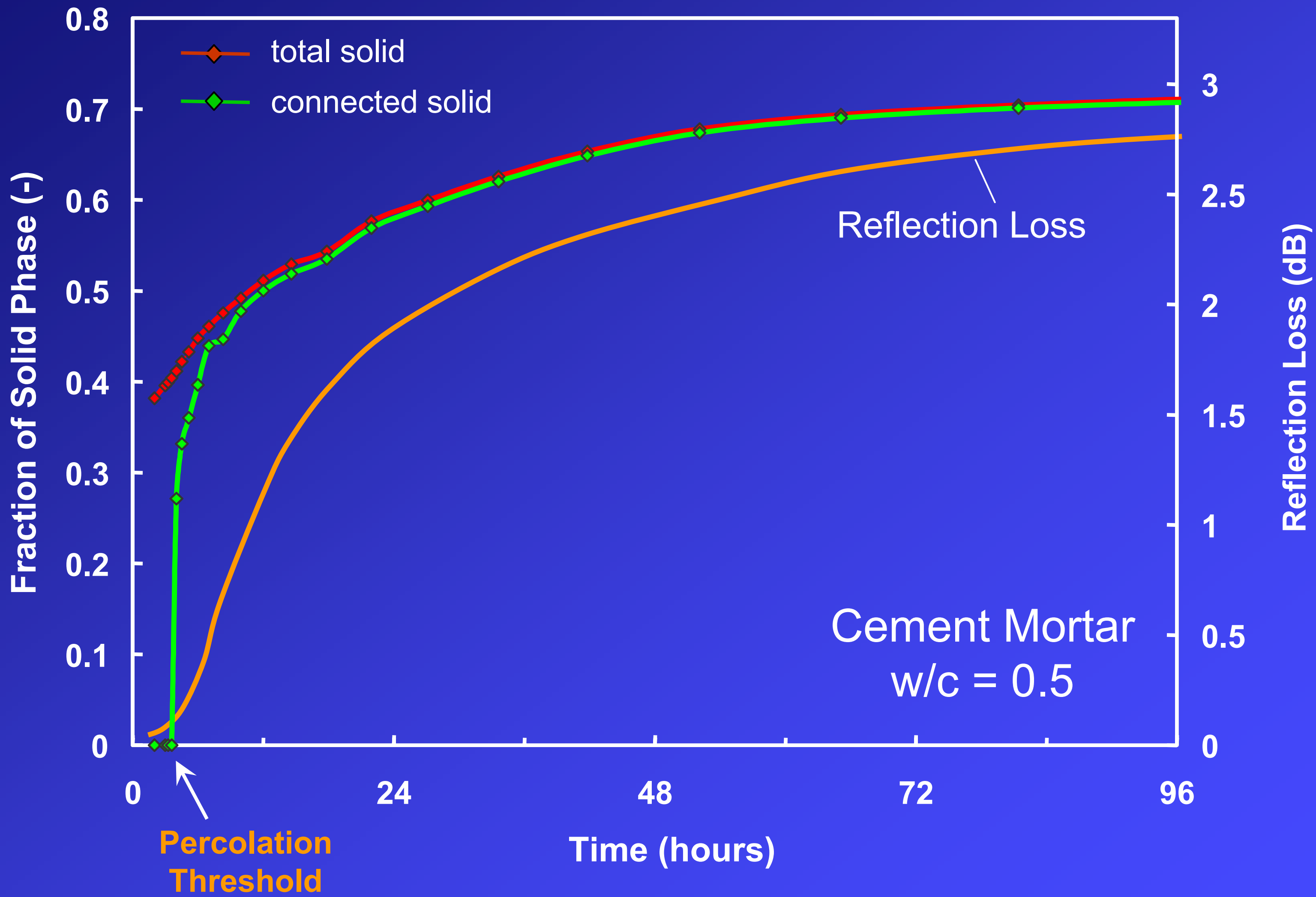
hydration step x
clusters



hydration step y
closed path

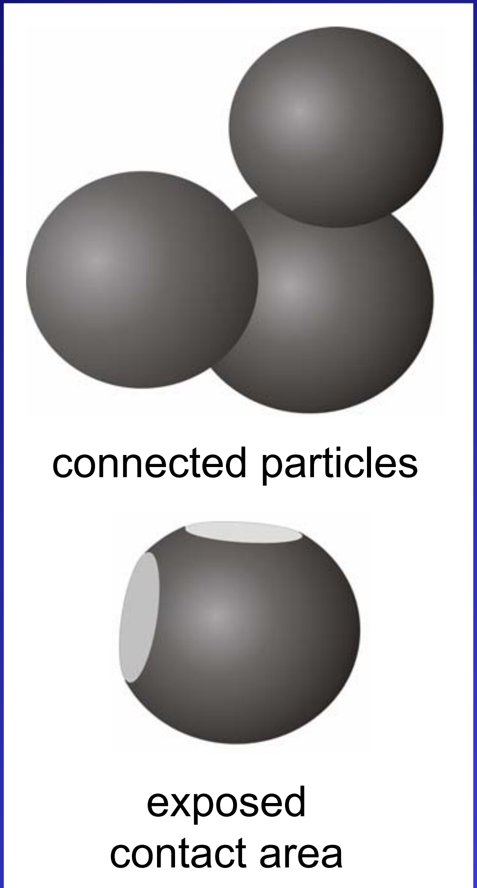
Results: **percolation threshold**
total amount of solids
connected solid

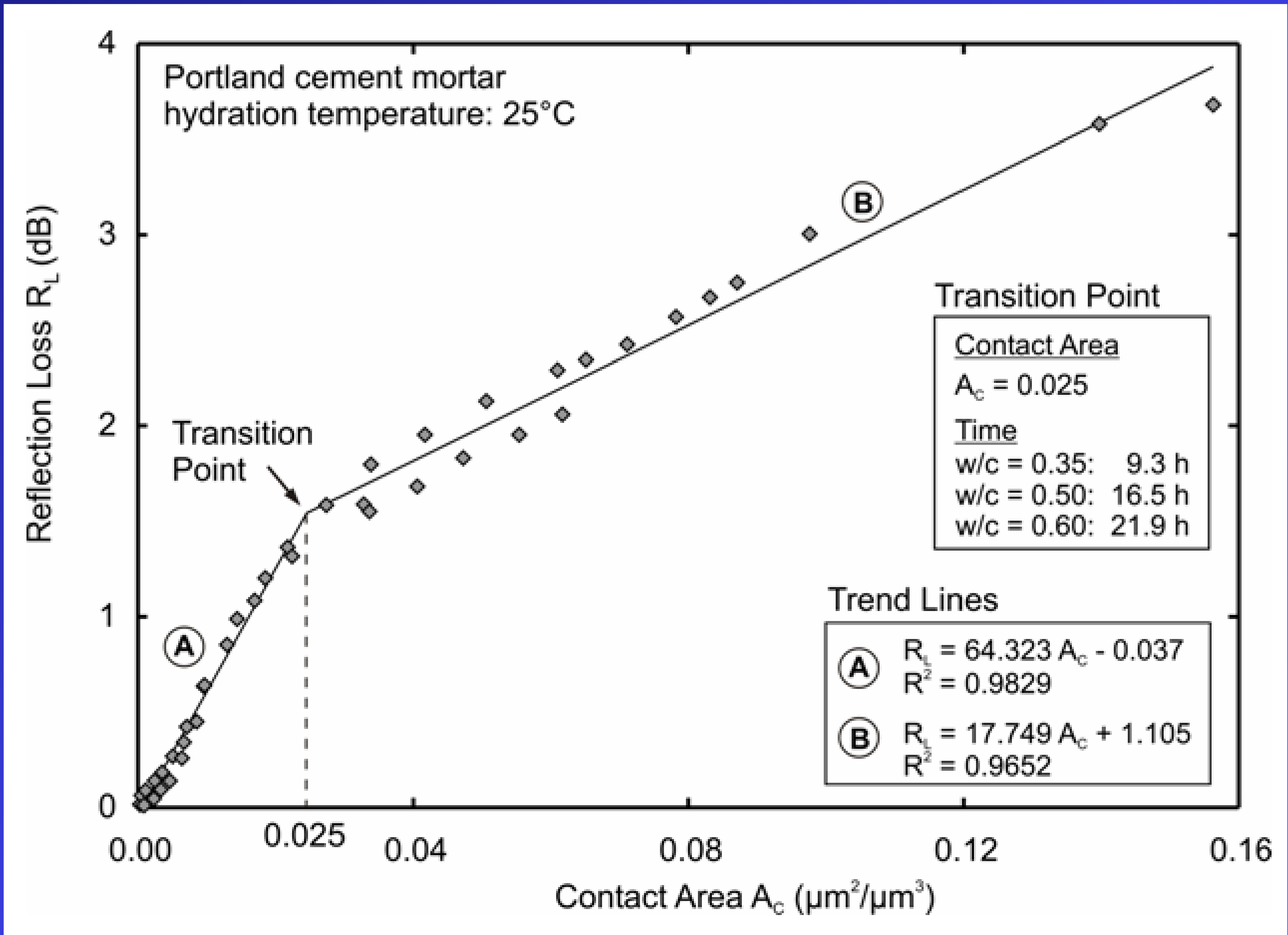
Solid Phase vs. Reflection Loss



Contact Area

Reflection loss uniquely related to contact area





Summary – Microstructure

Reflection loss is closely related to microstructural changes.

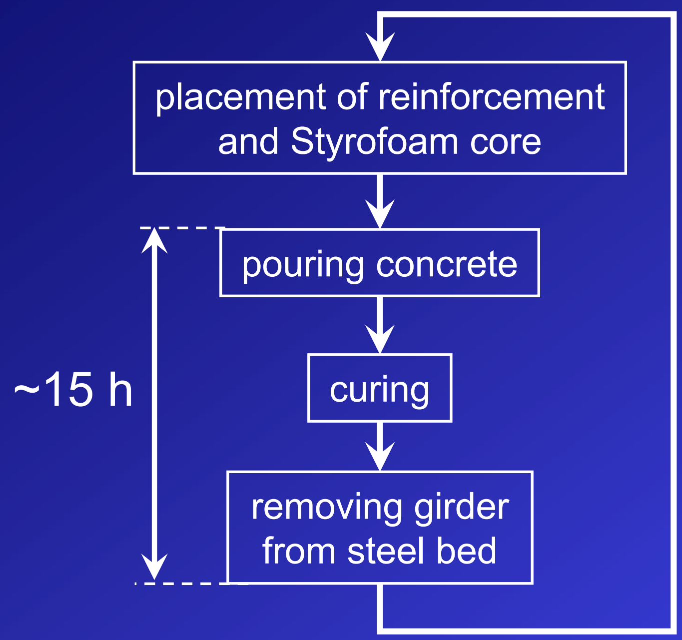
Unique relationships to:

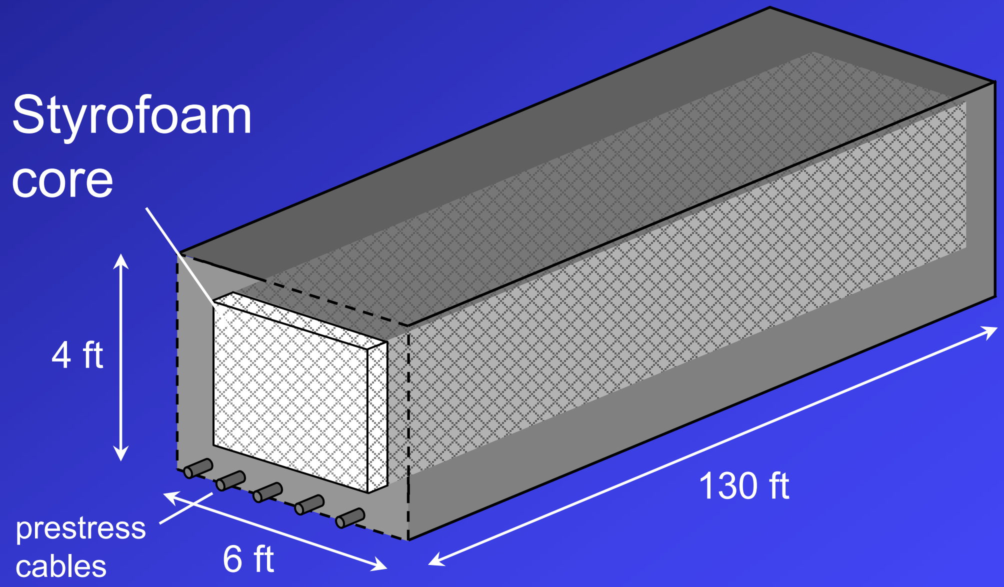
- decrease of capillary porosity
- gel-space ratio
- contact area

Field Application

Test Object – Prestressed Box Girder

Production Process



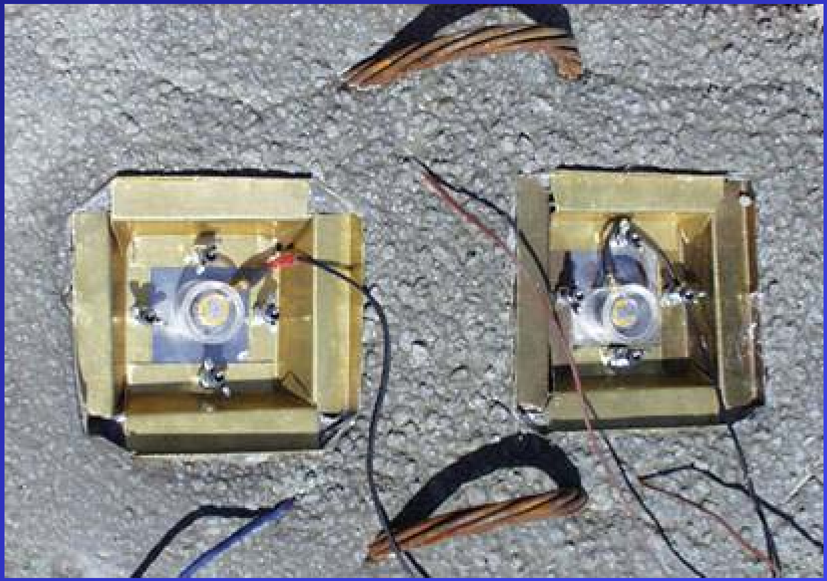


Need for Quality Control

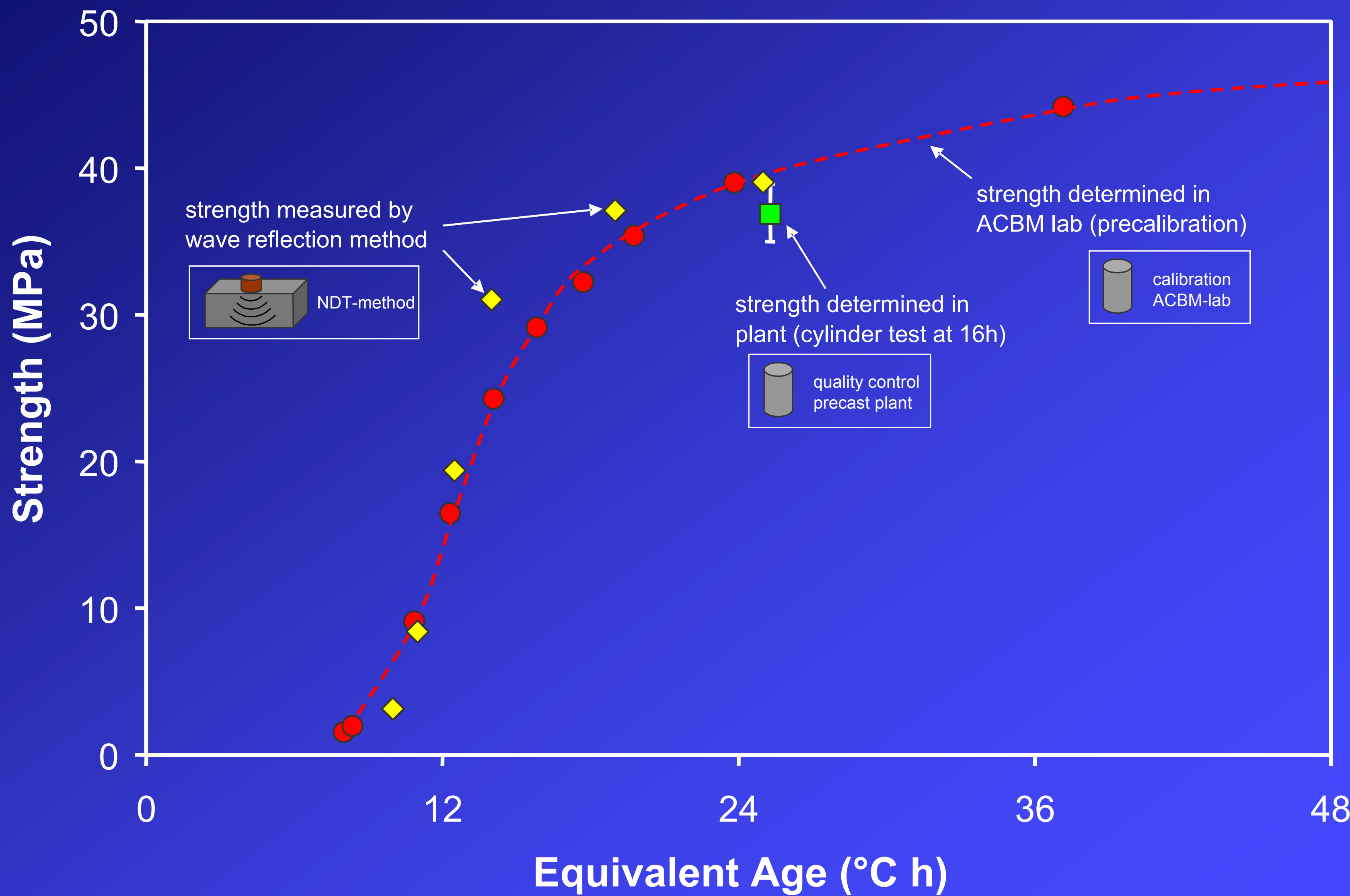
When has concrete reached the critical strength for removing girder?


Pulser/
Receiver
Temperature
Logger
Main Power
Switch
Transducer
Laptop
Computer
Central Power Supply

On-Site Measurements

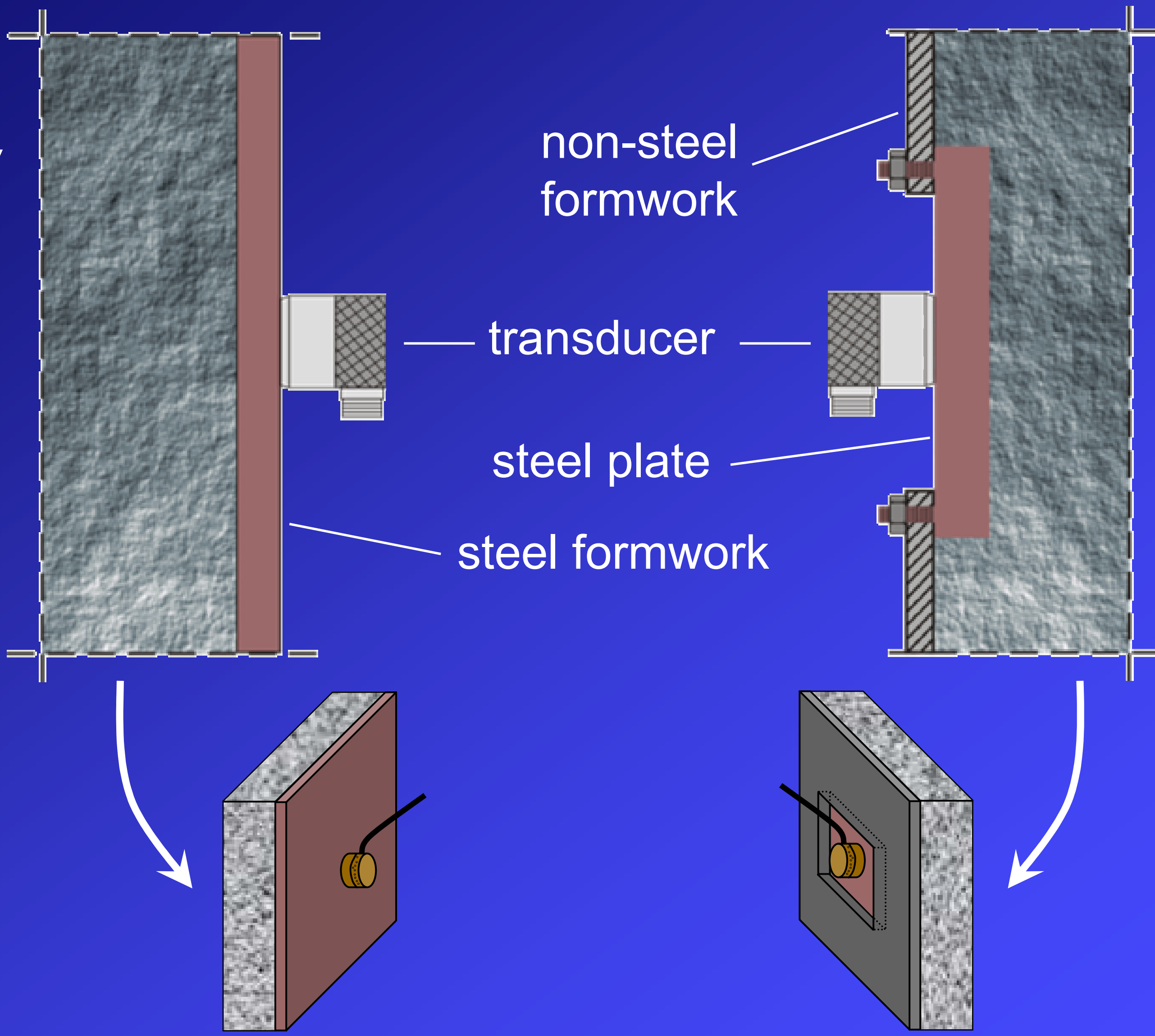


Result of Field Test



Options for Vertical Structures

e.g. walls, columns



Summary – Field Application

WR-method can be used for field testing during production process.

- in-situ strength can be assessed
- equipment can be made portable
- advance laboratory testing necessary

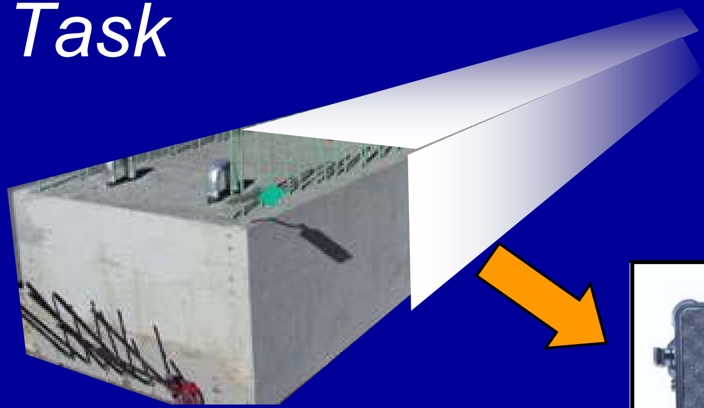
Final Conclusions

Wave Reflection Method can nondestructively monitor:

- setting behavior
- viscoelastic properties
- compressive strength
- dynamic shear modulus
- progress of cement hydration
- microstructural changes
- in-situ strength of concrete structures

Vision

Task



Expert System

Early Age Concrete Properties

decision support on construction site