Advanced Cement-Based Sustainable Material Technology

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Characterization and measurement

- Introduction
- Destructive methods
- Non-destructive methods

  -Elastic wave method

  -Infrared thermal method

  -Non-contact resistivity method

  -Dynamic modulus method

  -Ellipse ring for crack sensitivity

Introduction

- Destructive test – *obtain the material properties by seriously destroying sample*
- Nondestructive test – *obtain the information without damaging samples*

Introduction-destructive methods

- Compression test
- Tension test
- Bending test
- Impact test

Introduction-nondestructive

Quality control

- Finished products
- Injection of grout
- Position of reinforcing steel
- Welding of reinforcing steel
- Hydration rate of fresh concrete
- Selection of watermelon and eggs

Introduction-nondestructive

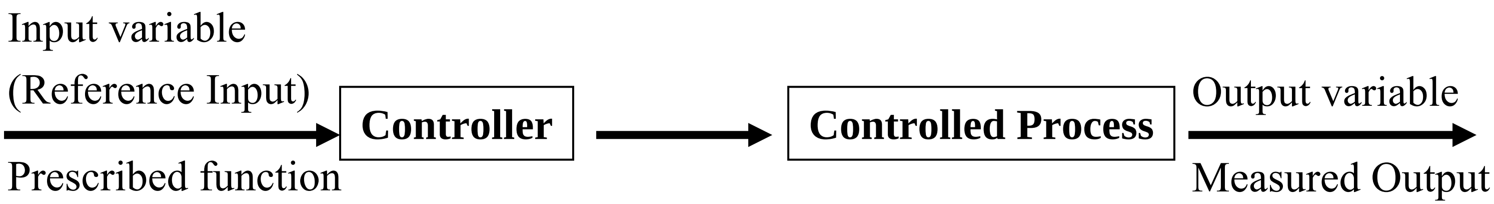
b. In-service inspection

- Boiler and vesile safety monitoring
- Bridge safety monitoring
- Building finish monitoring
- Airplane

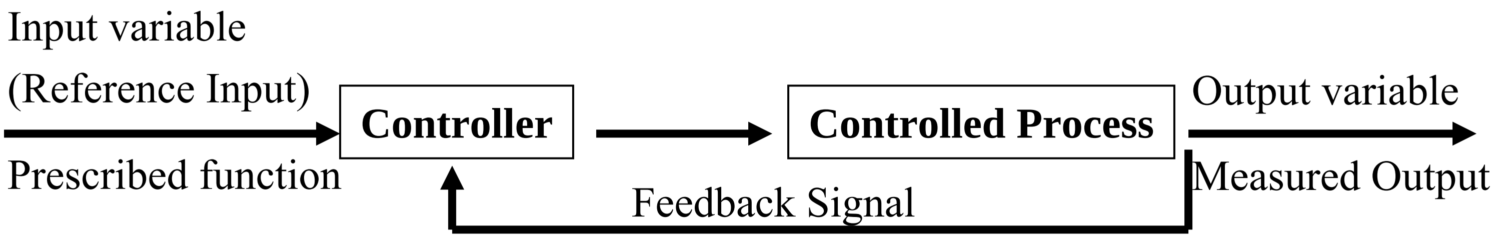
Destructive tests

- Control methods for strength test

- Open Loop Control (OLC)
- Close Loop Control (CLC)



Open Loop Control (OLC)



Closed Loop Control (CLC)

Destructive tests

- Calibration of transducers (1)

a. **Mechanical parameters:**
   Displacement, Strain, Crack opening, Force

b. **Electric parameters:**
   Voltage, Capacity, Impedance, Current

c. **Calibration:**
   - Find relationship between electrical variables and mechanical variables
   - General procedures
     - Connect the transducer to be calibrated
     - Provide a known mechanical parameter output
     - Adjust the reading of transducer to a desired value

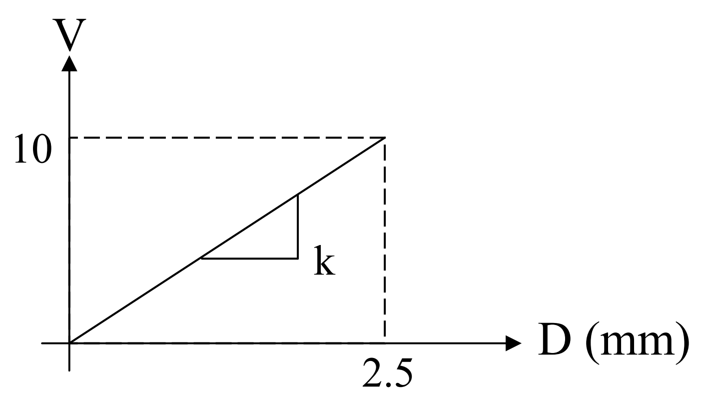
Destructive tests

- Calibration of transducers (2)

c. **Calibration**

- e.g. A displacement transducer of 2.5mm full range

Displacement:	0.25	. . . .	0.5	. . . .	1.25	. . . .	2.5mm
Voltage:	1	. . . .	2	. . . .	5	. . . .	10V



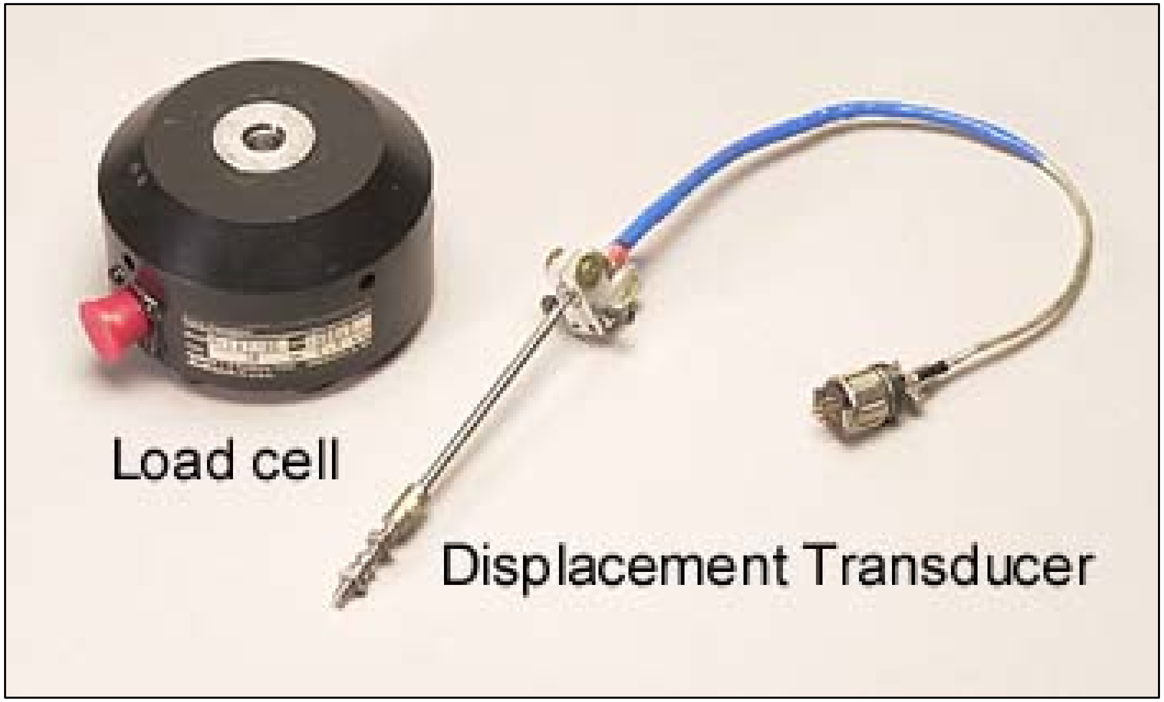
For measurement:

Displacement = $\frac{1}{k}V$ **= C V**

Destructive tests

- Calibration of transducers (3)

Transducer



Destructive tests- **Compressive test (1)**

A set-up for compression test

Destructive tests- **Compressive test (2)**

Typical load versus axial displacement and load versus circumferential Displacement curves for three classes for concrete

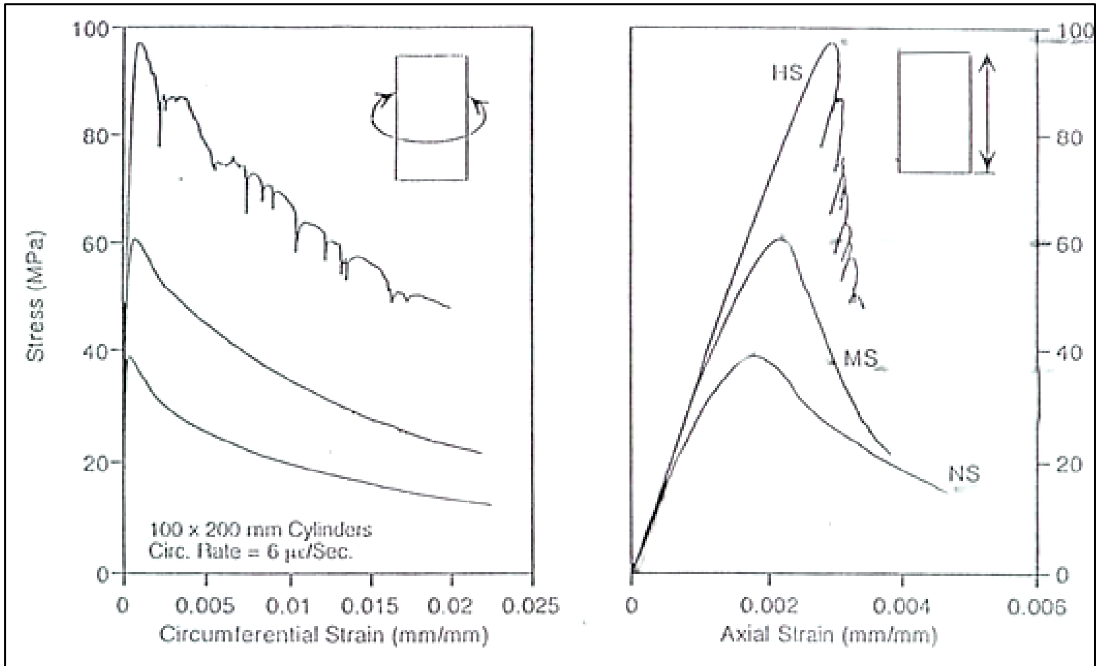
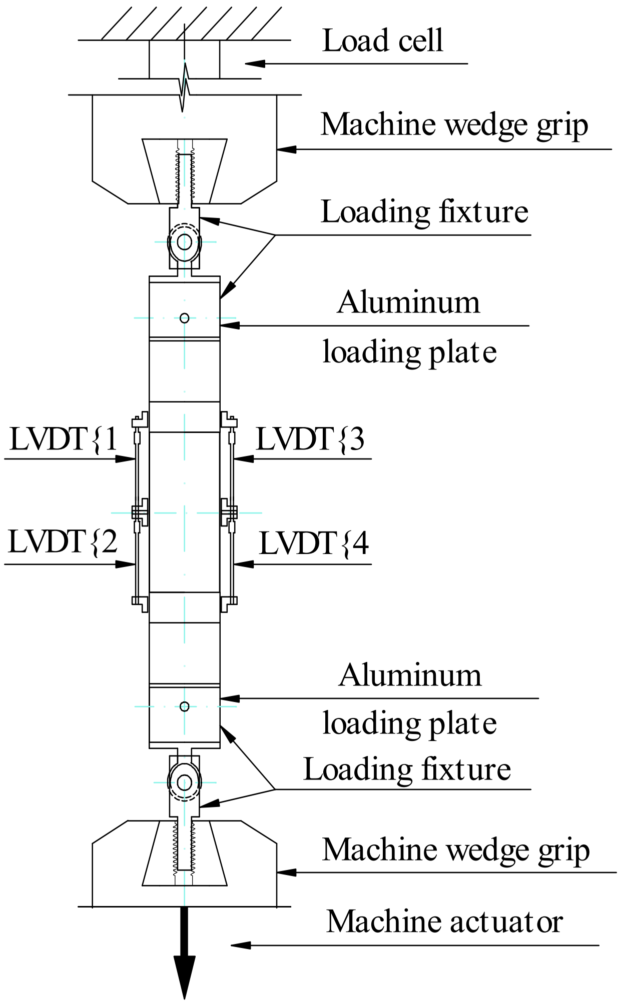
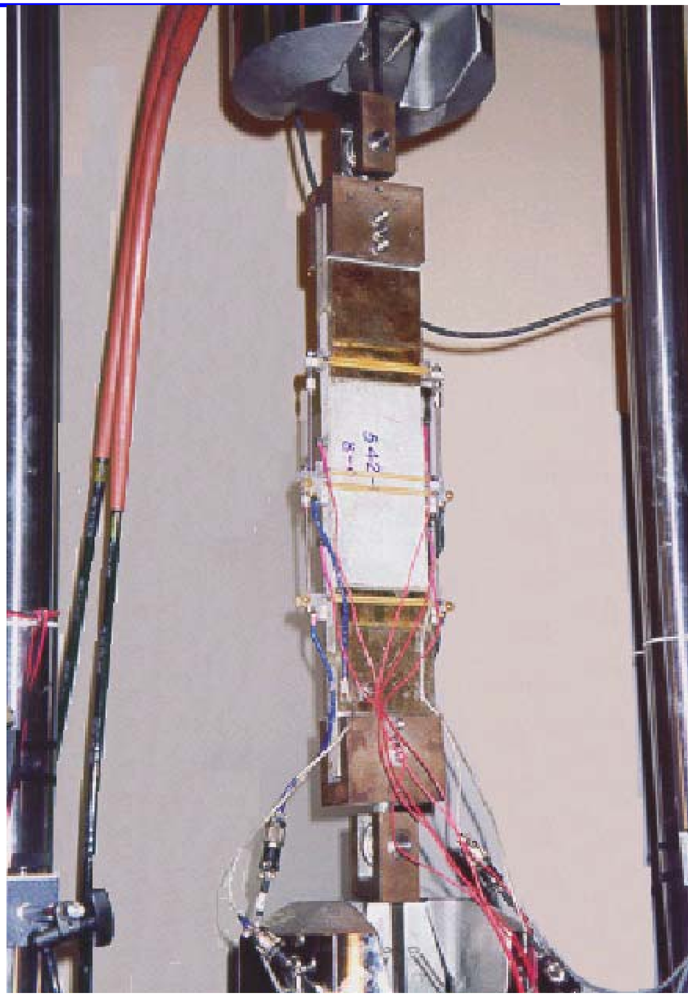


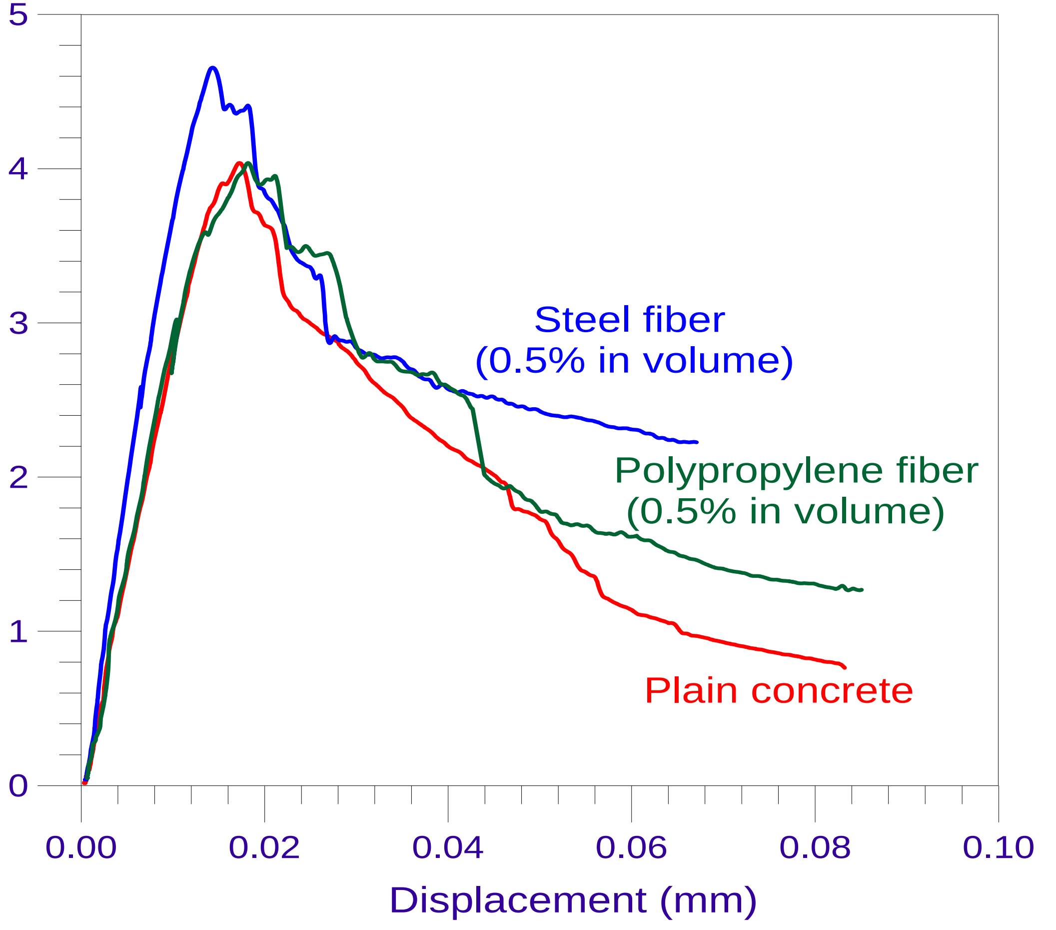
FIGURE 12. Typical load versus axial displacement and load versus circumferential displacem curves for three classes of concrete [31].

Destructive tests –Tension test

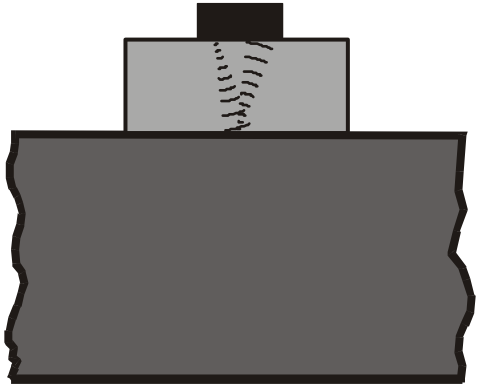




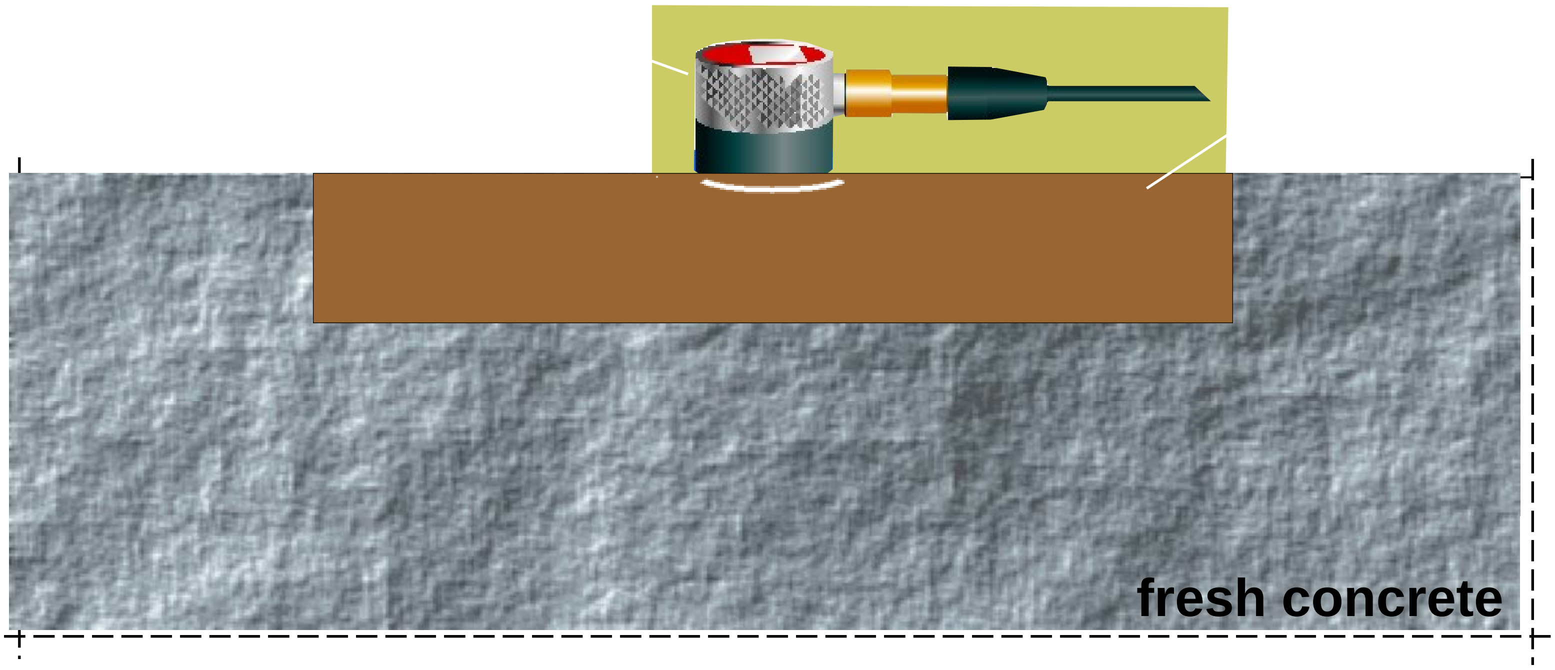
Destructive tests –Tension test



Nondestructive test
-Shear wave reflection method



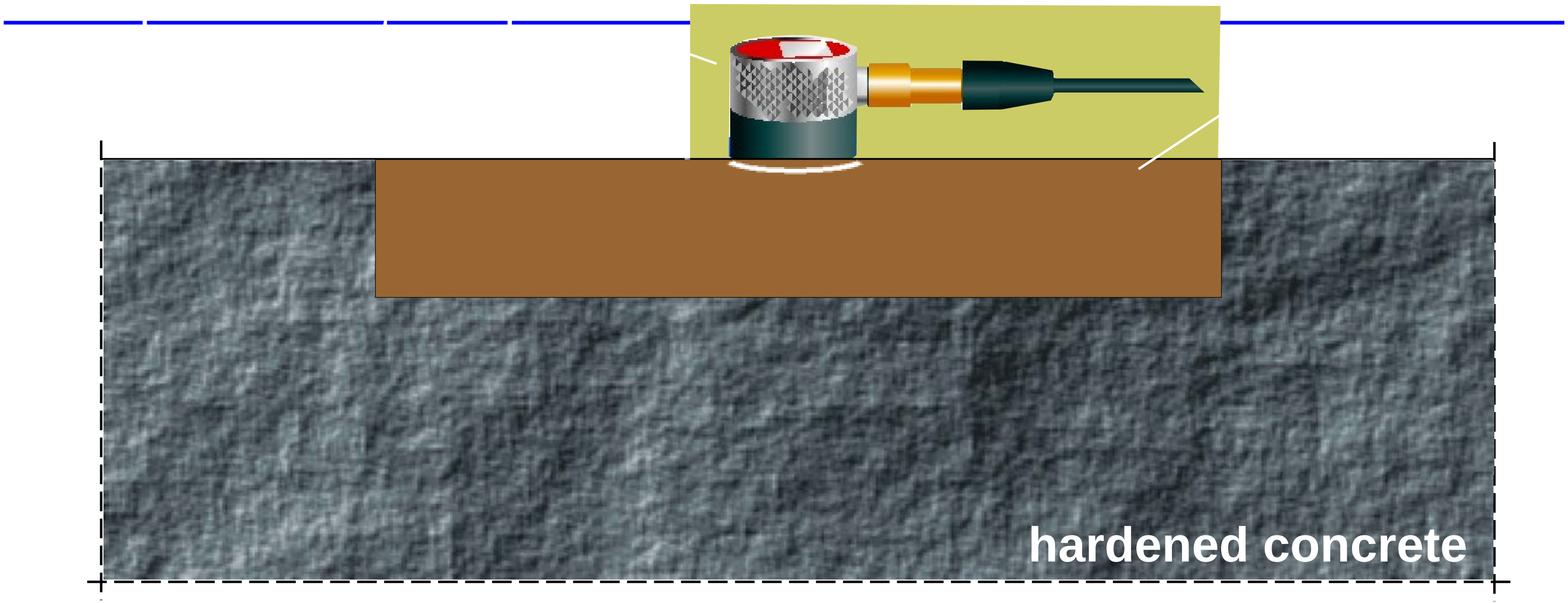
Principle of Shear Wave Reflection Method



Case 1: concrete is liquid

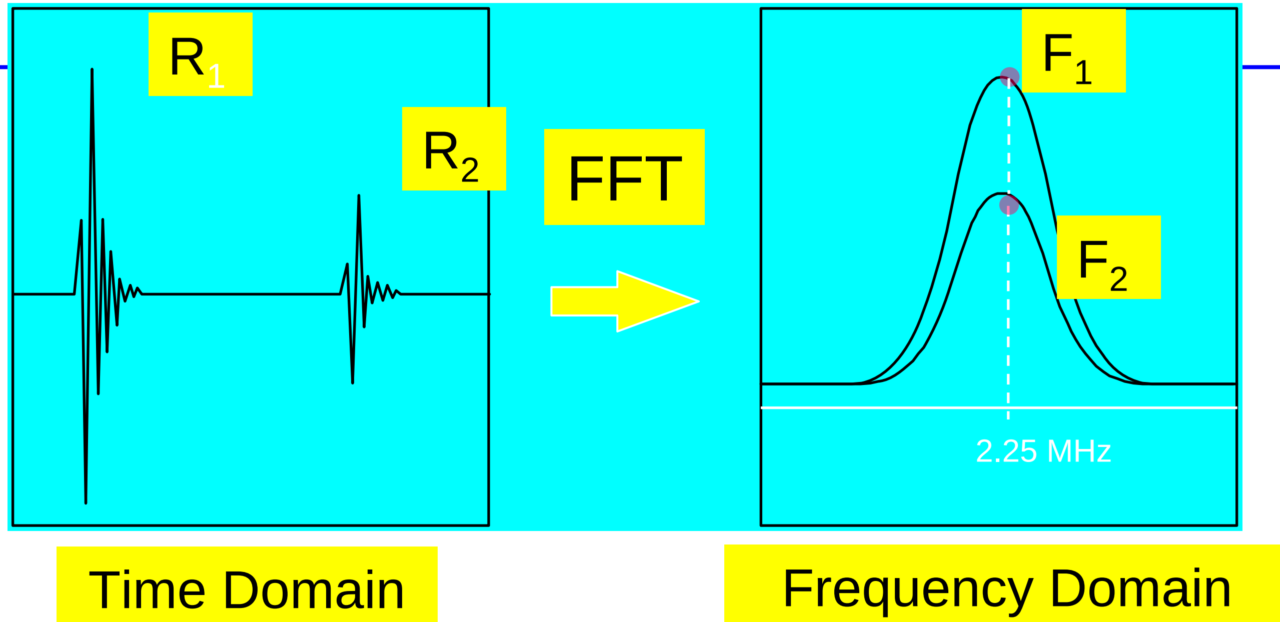
no wave transmission at interface

Principle of Wave Reflection



Case 2: concrete is hardening

transmission losses at interface



Reflection Factor r

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

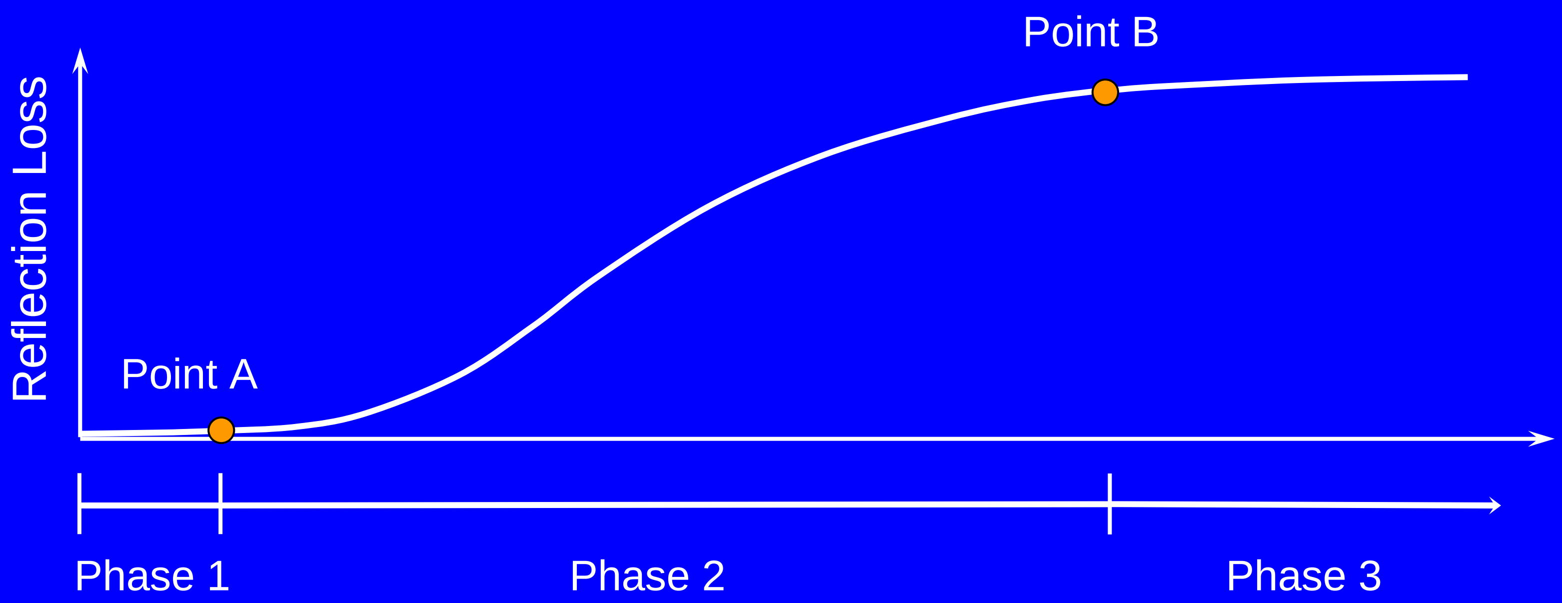
F_1, F_2 …. FFT of reflections at 2.25 MHz

L …. Losses (material, coupling, geometry)

Attenuation of Wave Reflections

Attenuation (dB) = - 20 · log (r)

Typical Reflection Loss Development

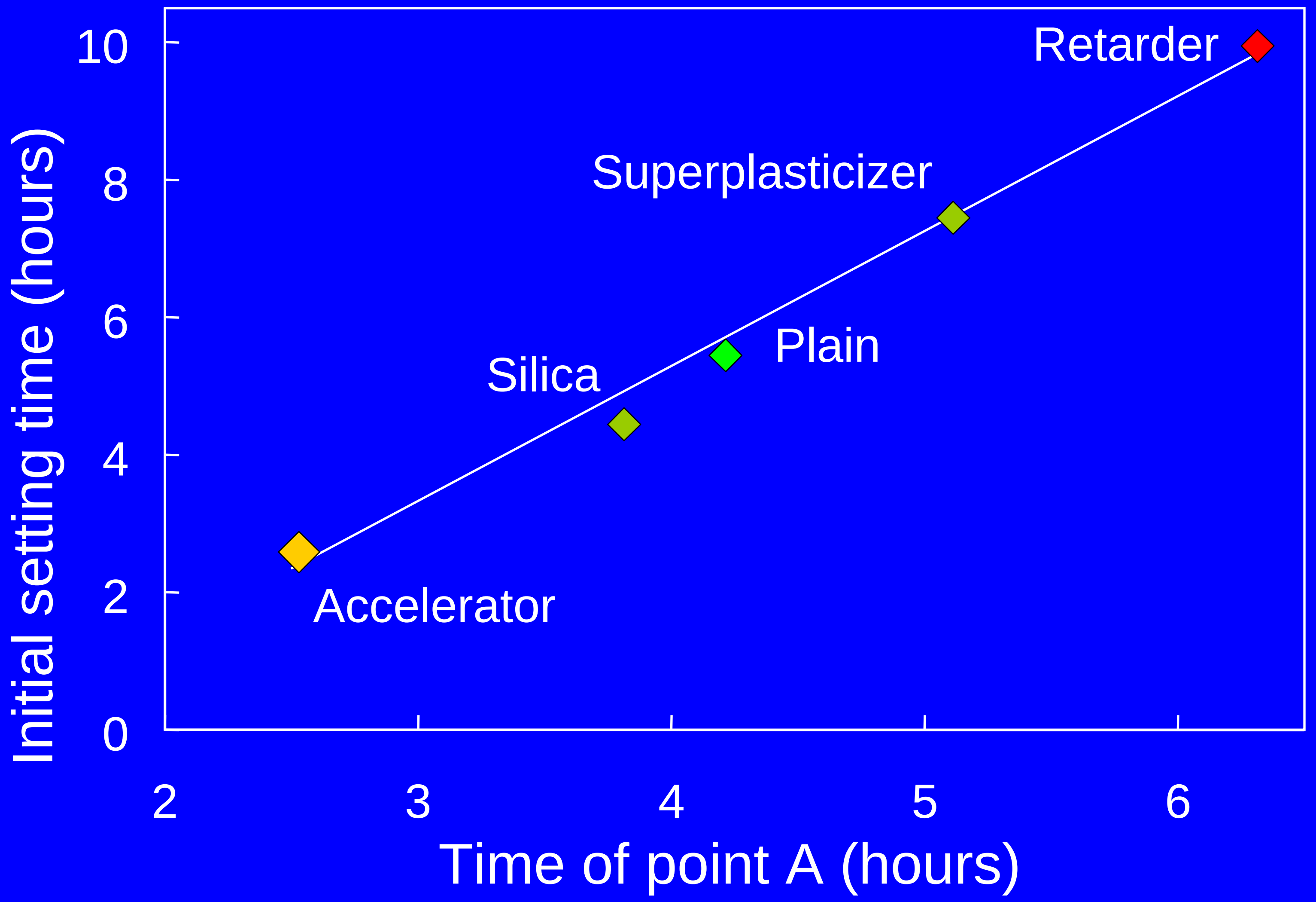


Phase 1: liquid concrete ➔ no reflection loss

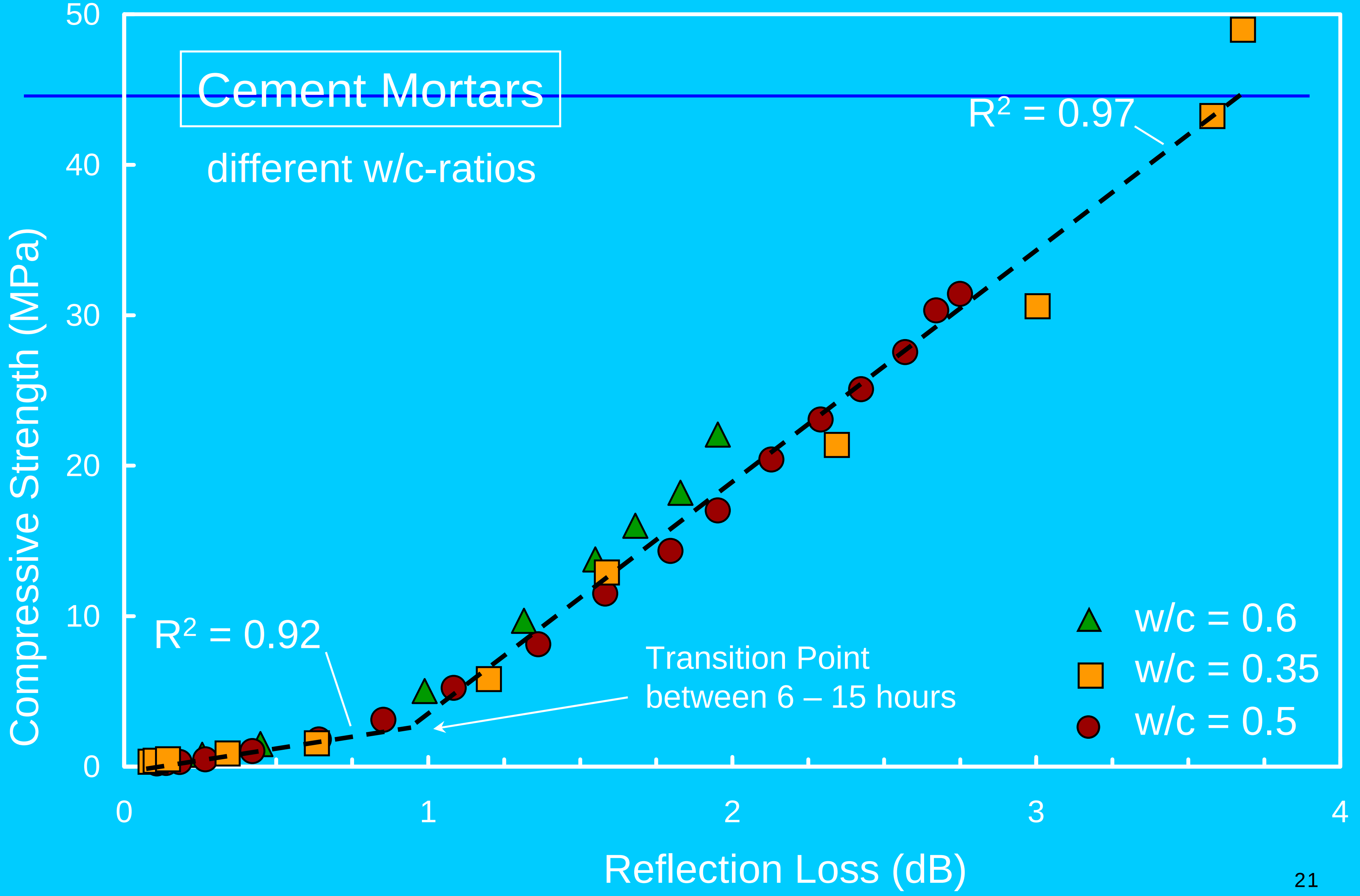
Phase 2: concrete hardens ➔ attenuation increases

Phase 3: hardening continues ➔ attenuation approaches final value

Point A – Initial Setting

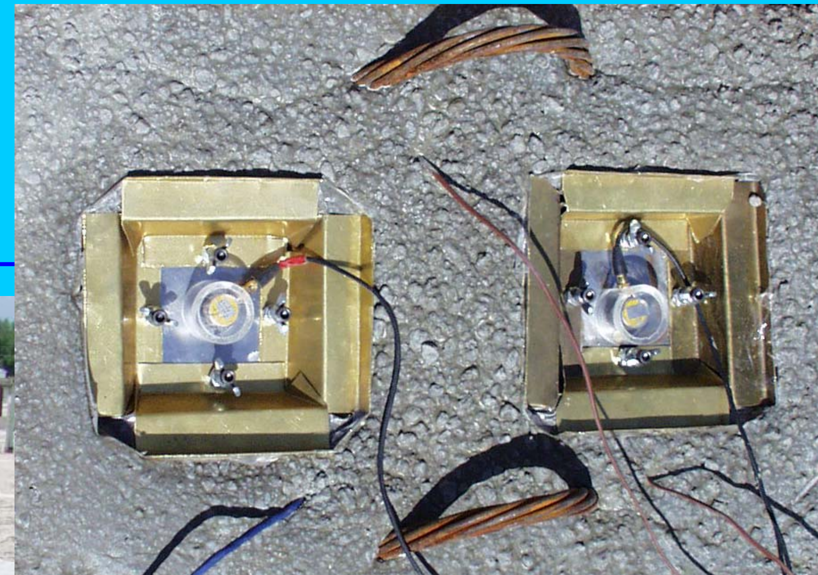


R_L vs. Strength

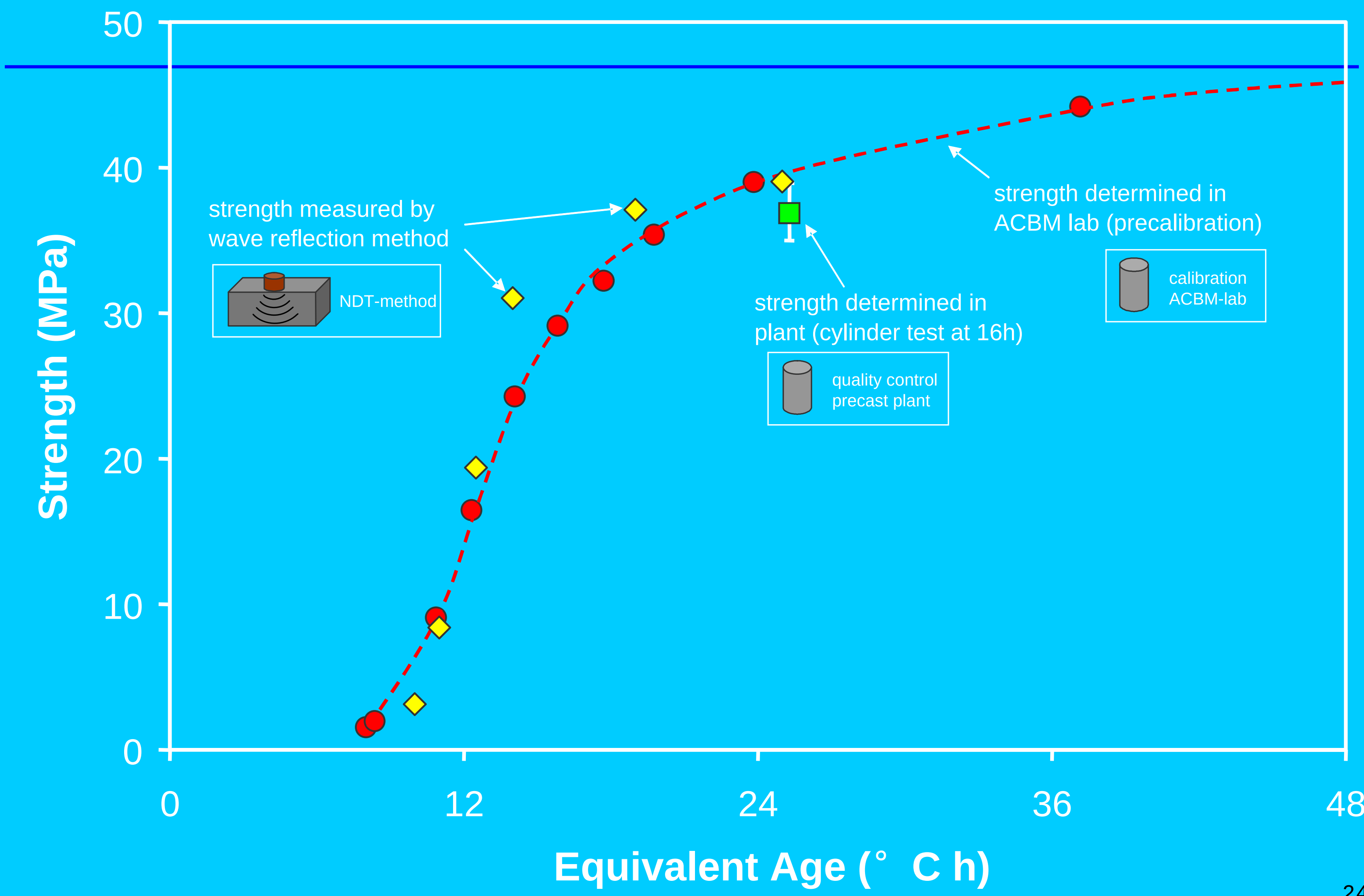



Pulser/
Receiver
Laptop
Computer
Temperature
Logger
Main Power
Switch
Transducer
Central Power Supply

On-Site Measurements

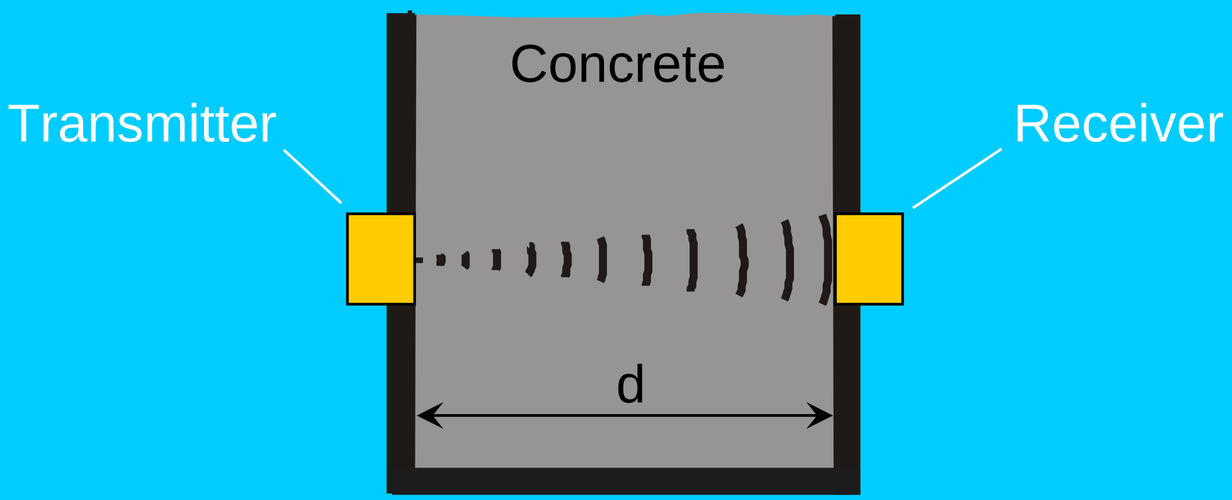


Result of Field Test



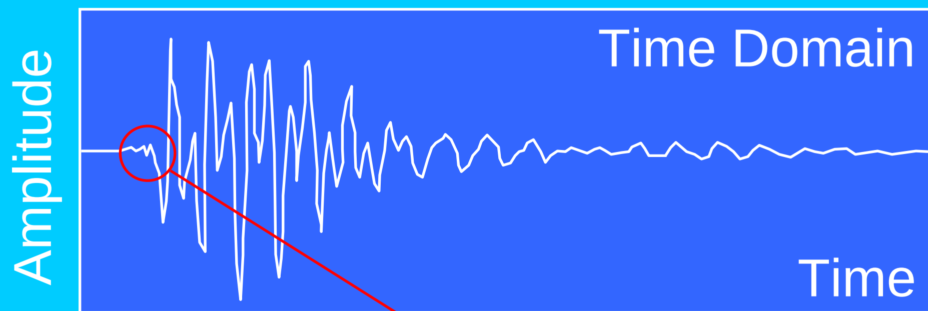
弹性波法-

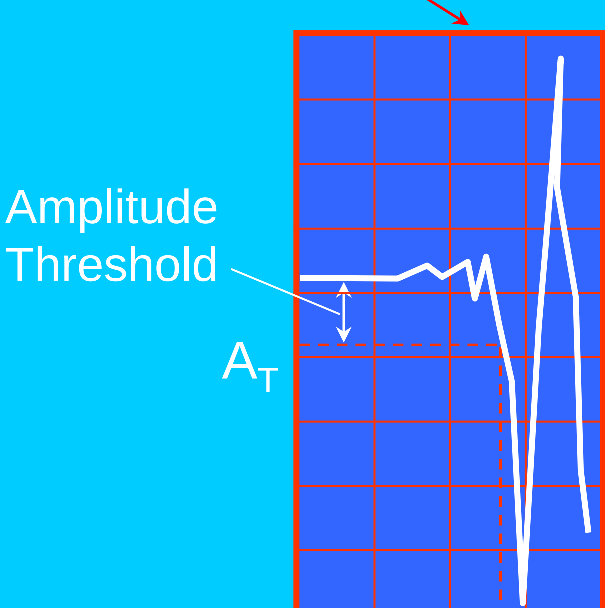
透射超声波法

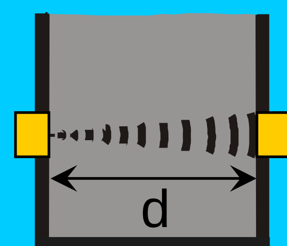


Pulse Velocity

Determination







$$v = \frac{d}{\Delta t}$$

t_o – Onset time of signal

Relationships

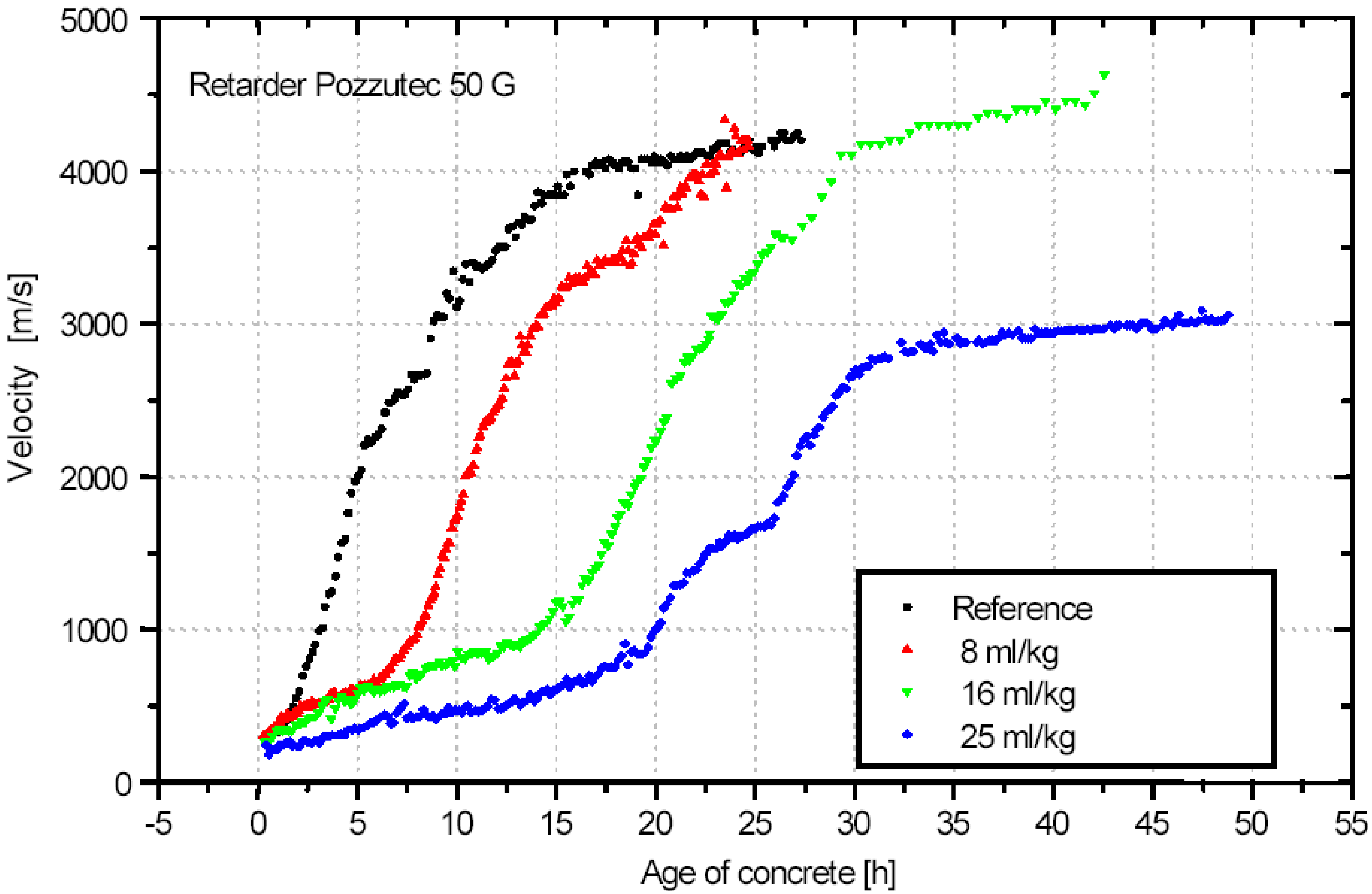
Velocity ~ Density, ρ
E-Modul, E
Poisson's Ratio, ν

P-waves

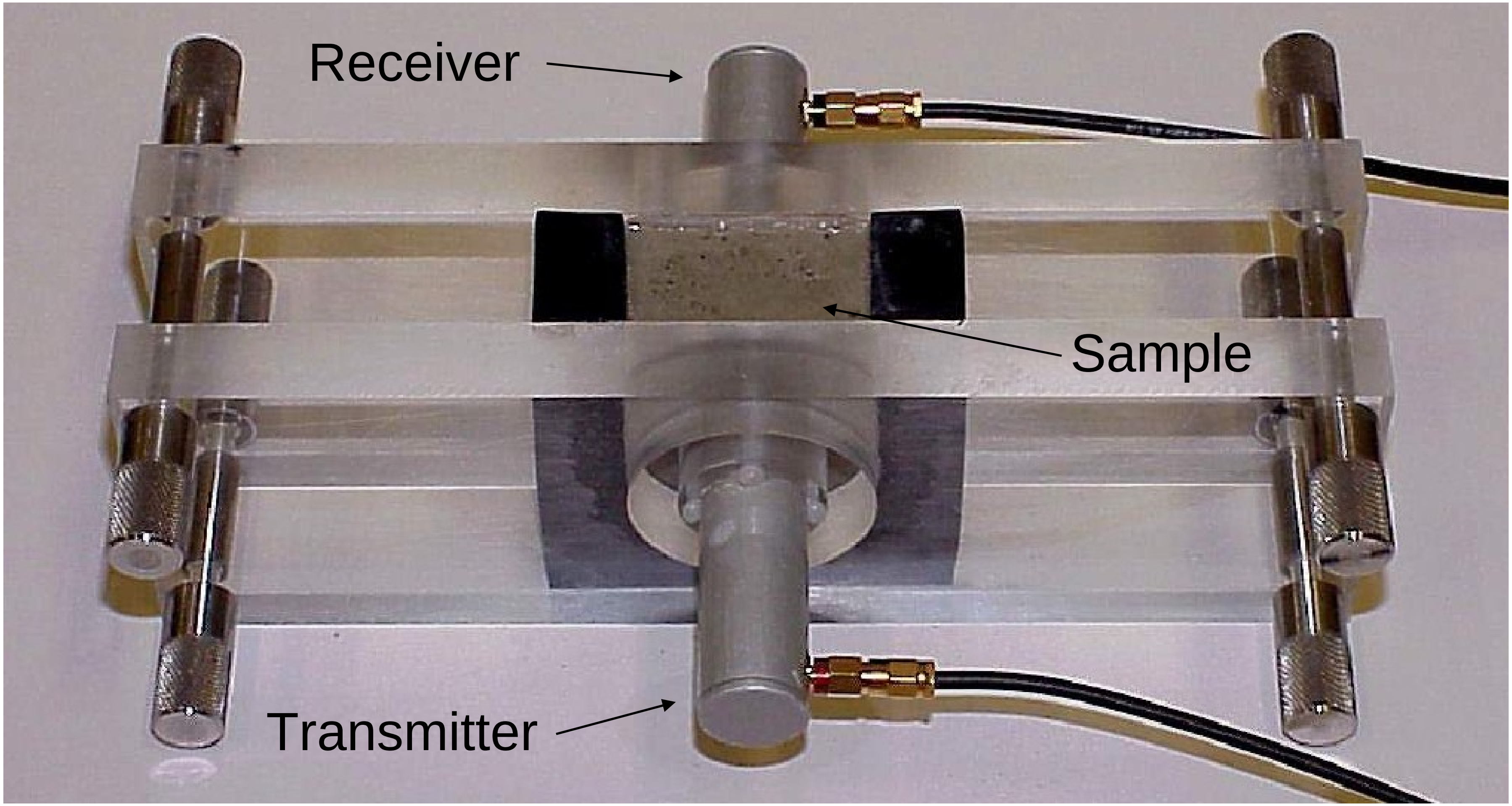
$$v_P = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

S-waves

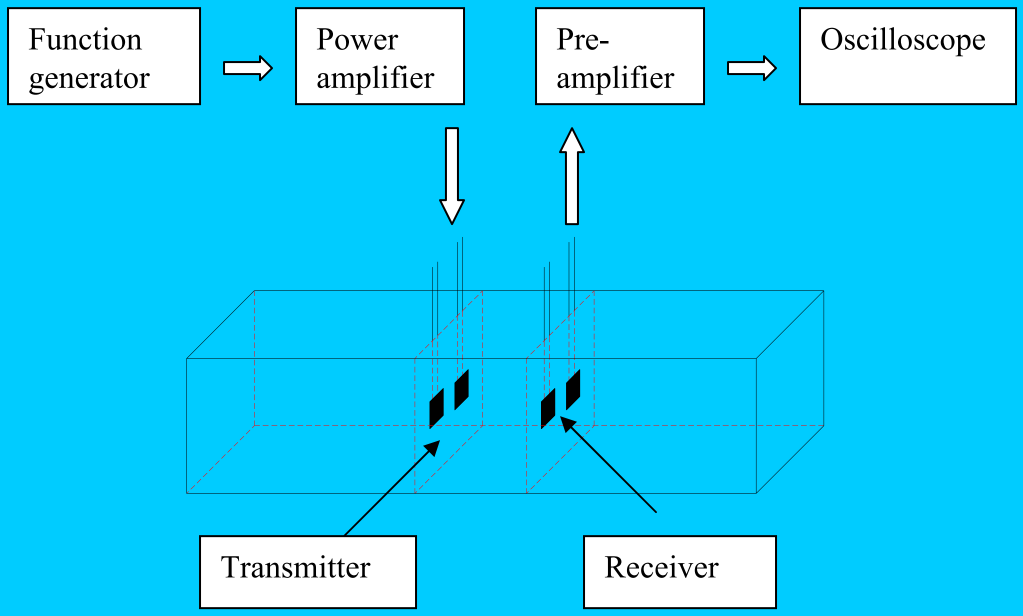
$$v_S = \sqrt{\frac{E}{2\rho(1+\nu)}}$$

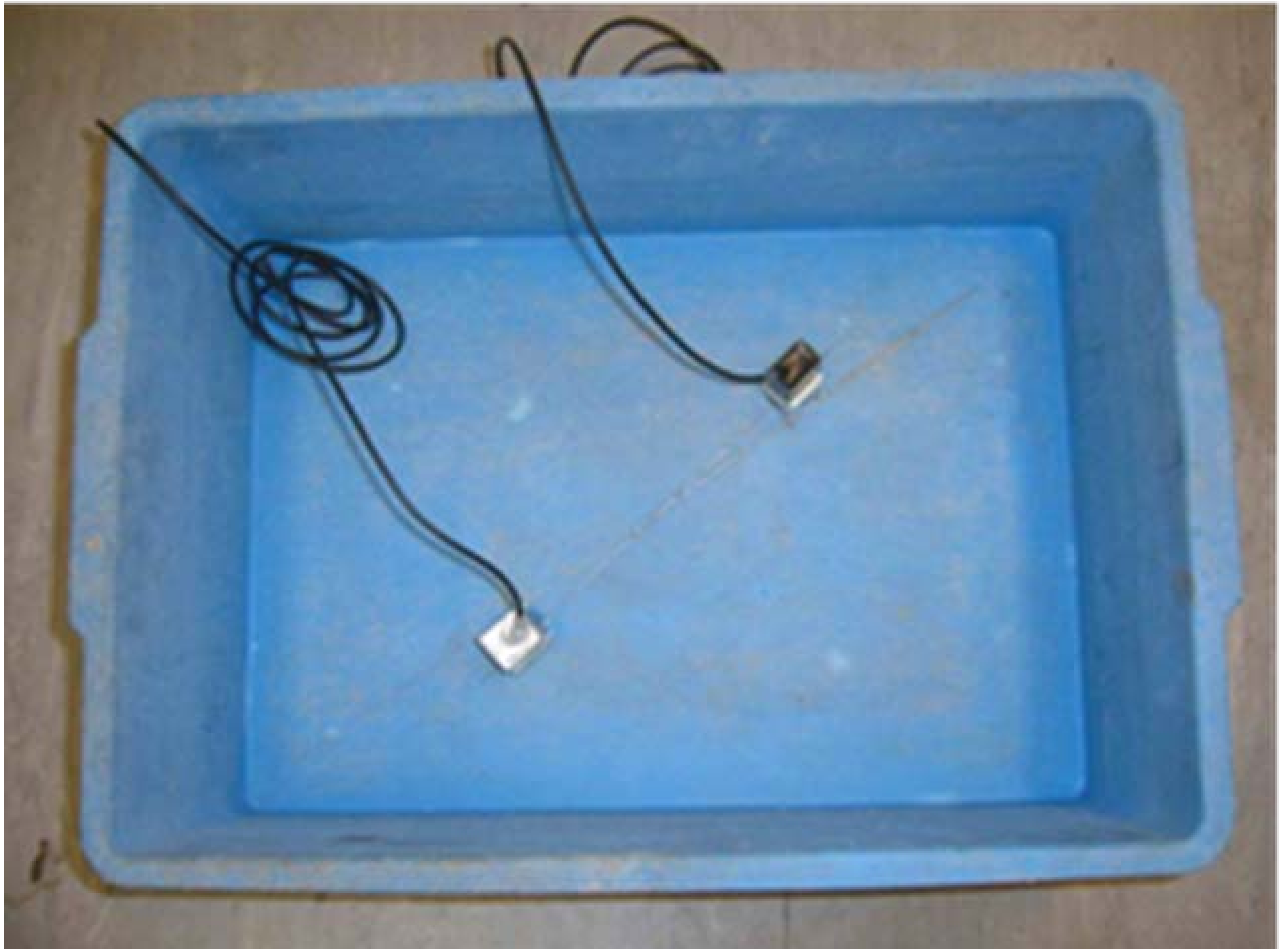

Retarder Pozzutec 50 G
Velocity [m/s]
Age of concrete [h]
Reference
8 ml/kg
16 ml/kg
25 ml/kg
5000
4000
3000
2000
1000
0
-5
0
5
10
15
20
25
30
35
40
45
50
55

Experimental Setup



Embedded sensor





Dynamic modulus and Poison's ratio

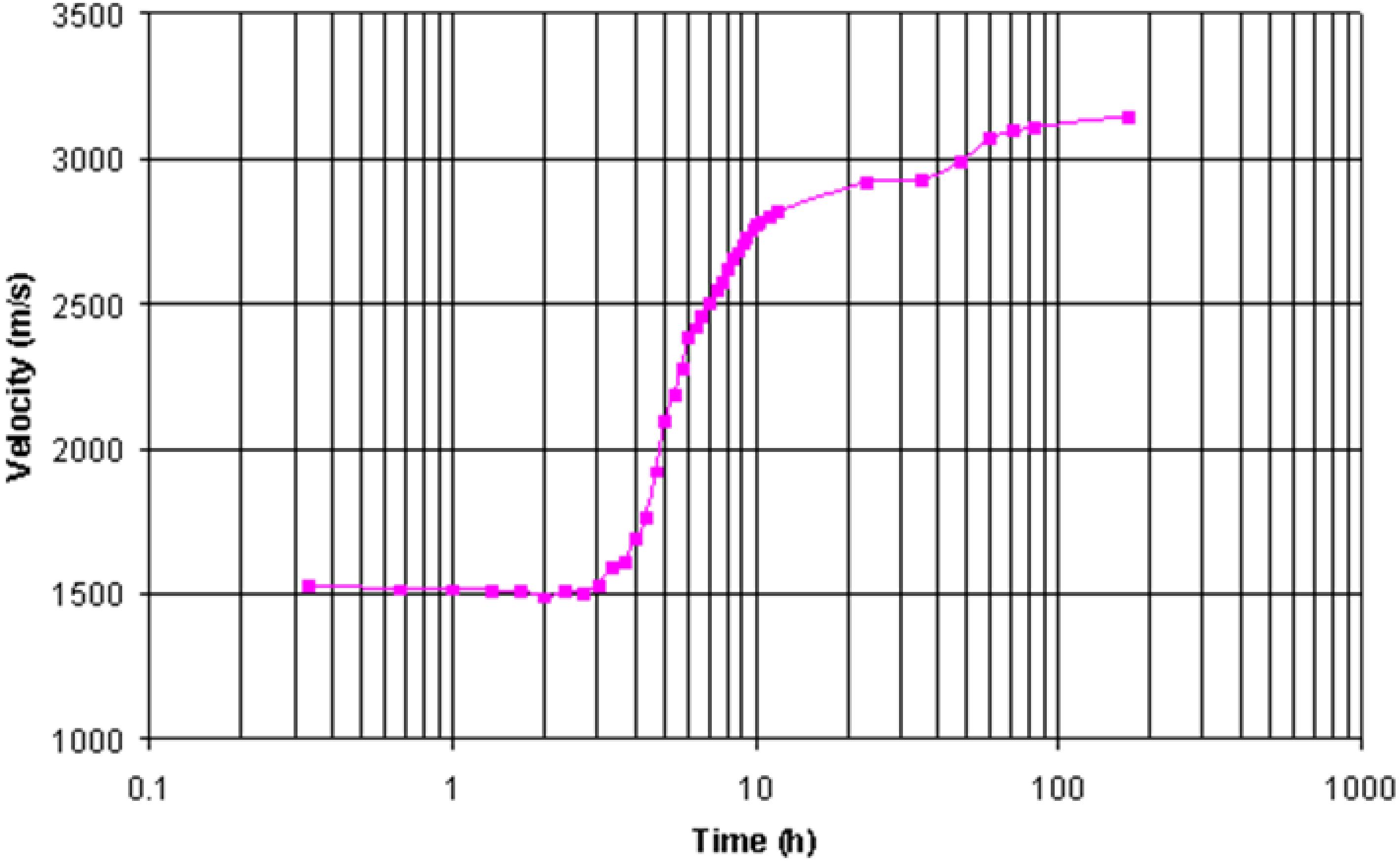
$$E = \rho C_L{}^2 \qquad \upsilon = \frac{C_L{}^2}{2C_T{}^2} - 1$$

Where,

C_L and C_T are longitudinal and transverse velocities, respectively. ρ is the density of the concrete specimen.

The calculated result fit well with the dynamic Young' modular measured by standard method.

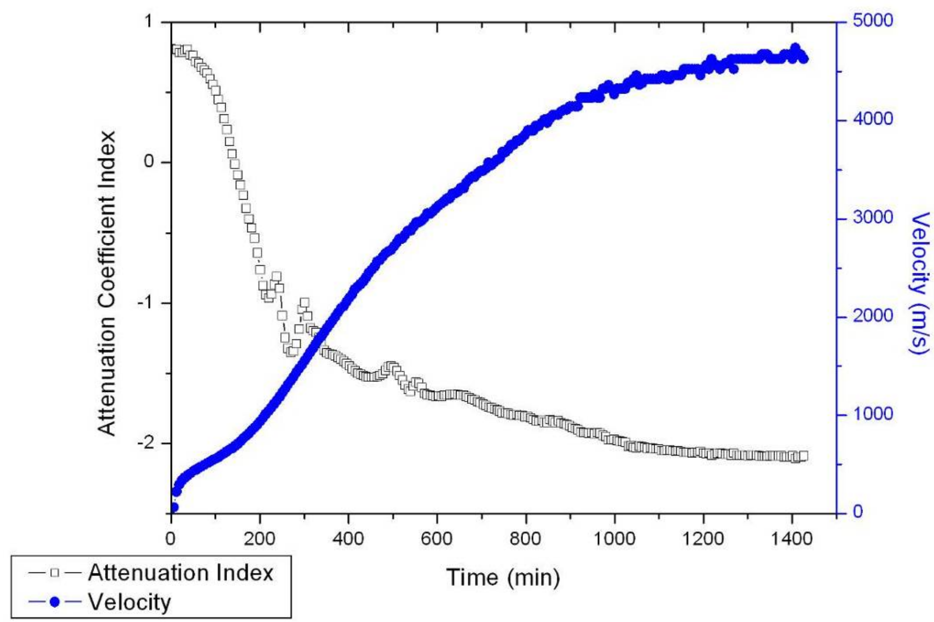
Hydration monitoring using embedded sensor



Hydration monitoring using embedded sensor

✓In situ and real time monitoring

✓Life time healthy monitoring

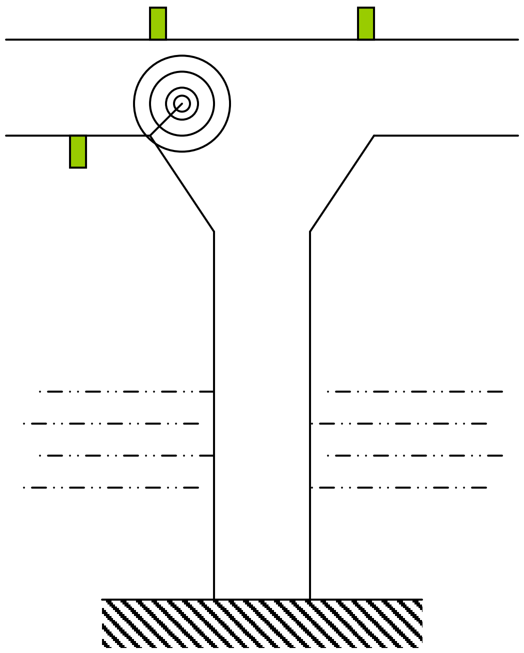


AE technique

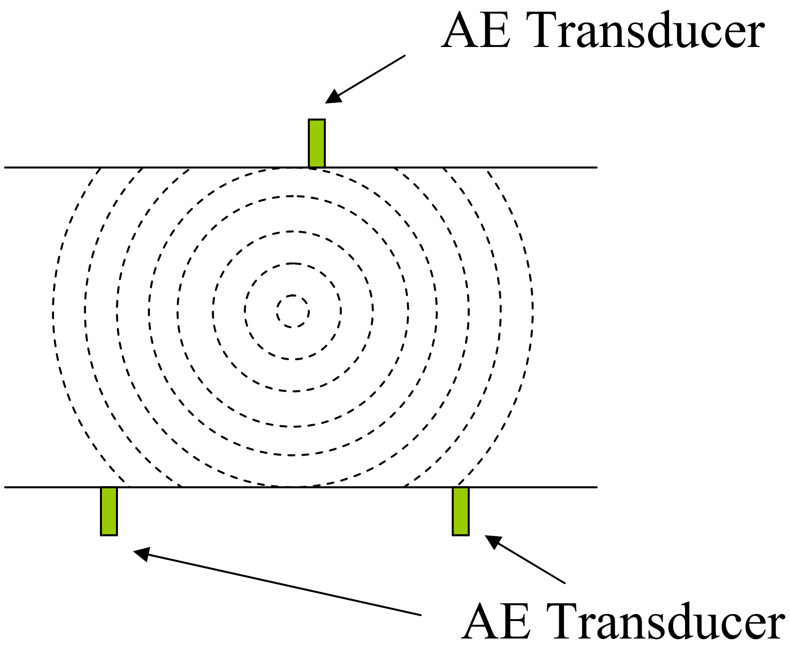
AE technique is a passive NDT method. It relies on the detection of elastic waves generated by sudden release or change of energy or deformation in materials.

AE technique

- Active movement of defects
- whole structure
- highly sensitive
- on-line monitoring

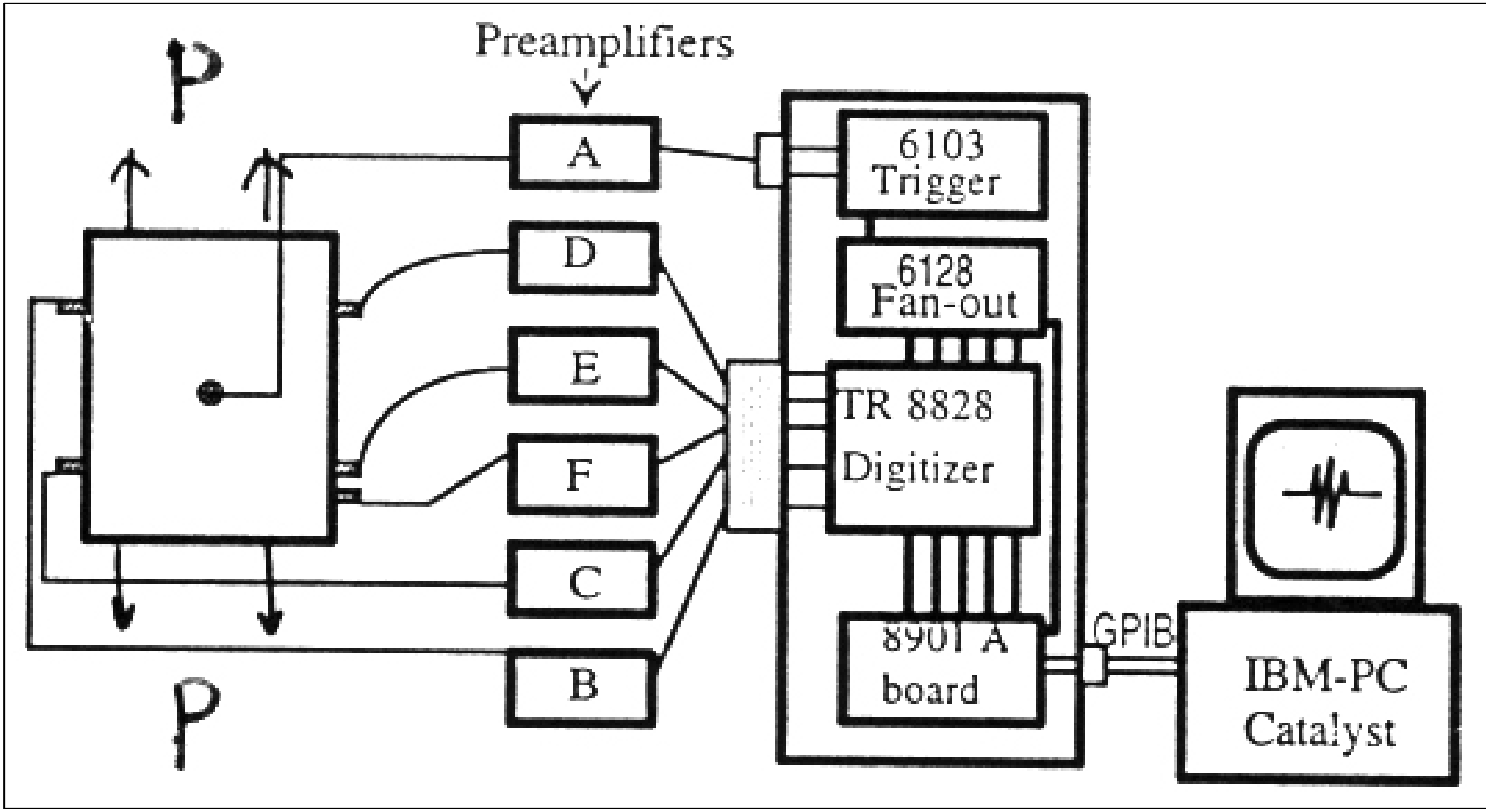


聲發射測試技術

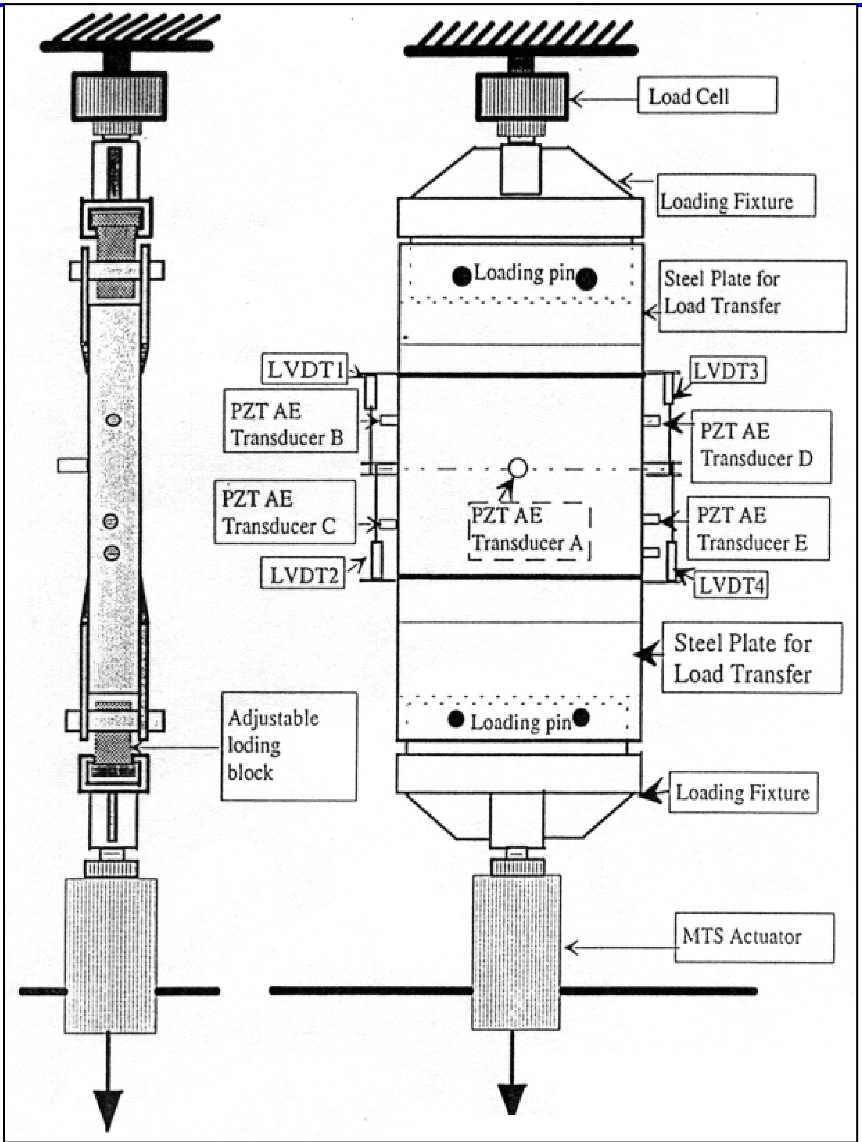


A acoustic wave propagation

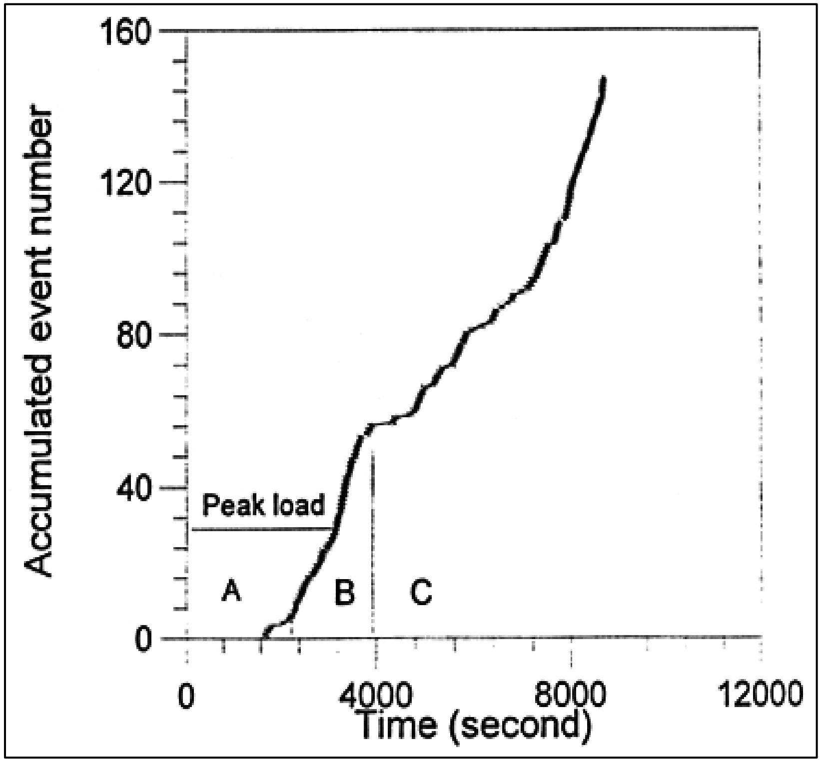
Basic AE measurement system



AE technique

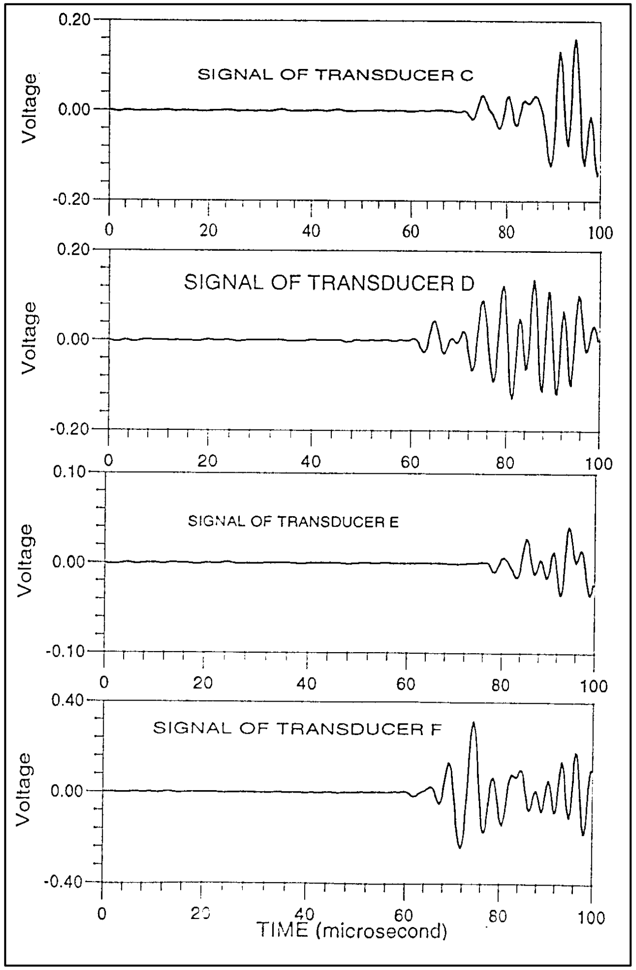


AE Technique



Occurrence of AE rate during the tension test

AE technique



AE source location

For 3-D case

$$e_{1i} = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} - \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} - \Delta t_{1i} C$$

Sum of the square of the errors

$$e = \sum_{i=2}^{n} (e_{1i})^2$$

$$= \sum_{i=2}^{n} (d_1 - d_i - \Delta t_{1i} C)^2$$

AE source location

- Differential with respect to x, y, z and C are in forms of;

$$f_x(x,y,z,C) = \frac{\partial e}{\partial x}$$
$$= 2\sum_{i=2}^{n}\left(\frac{x-x_1}{d_1} - \frac{x-x_i}{d_i}\right)(d_1 - d_i - \Delta t_1 iC)$$

$$f_y(x,y,z,C) = \frac{\partial e}{\partial y}$$
$$= 2\sum_{i=2}^{n}\left(\frac{y-y_1}{d_1} - \frac{y-y_i}{d_i}\right)(d_1 - d_i - \Delta t_1 iC)$$

AE source location

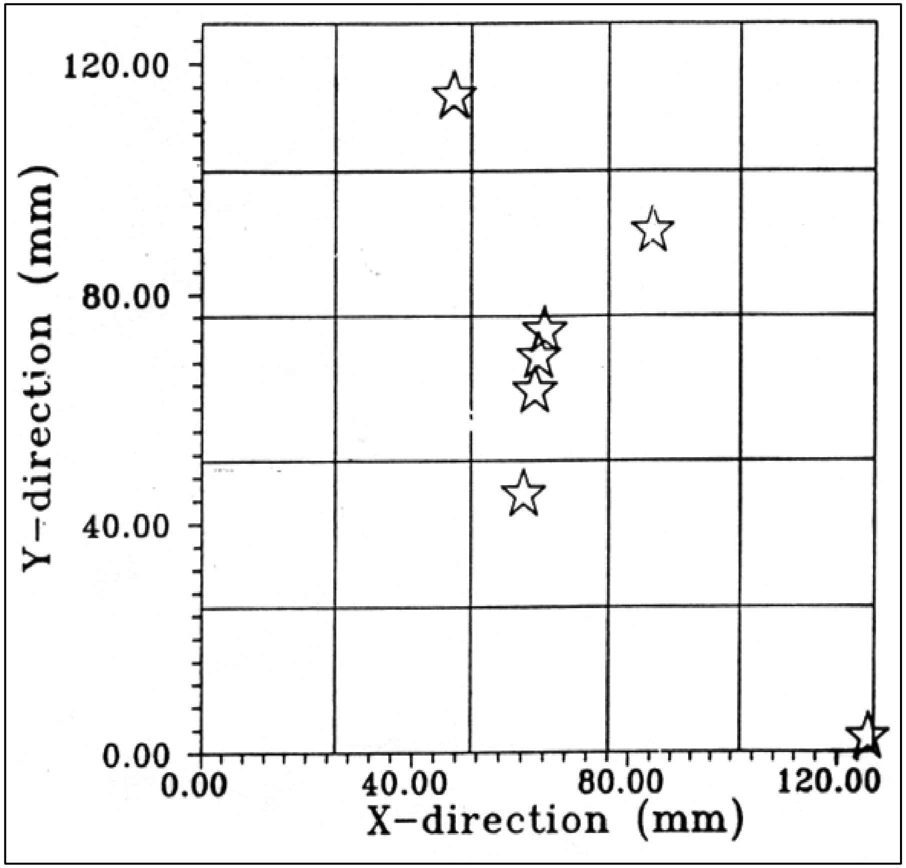
$$f_z(x,y,z,C) = \frac{\partial e}{\partial z}$$

$$= 2\sum_{i=2}^{n}\left(\frac{z-z_1}{d_1} - \frac{z-z_i}{d_i}\right)\left(d_1 - d_i - \Delta t_1 iC\right)$$

$$f_C(x,y,z,C) = \frac{\partial e}{\partial C}$$

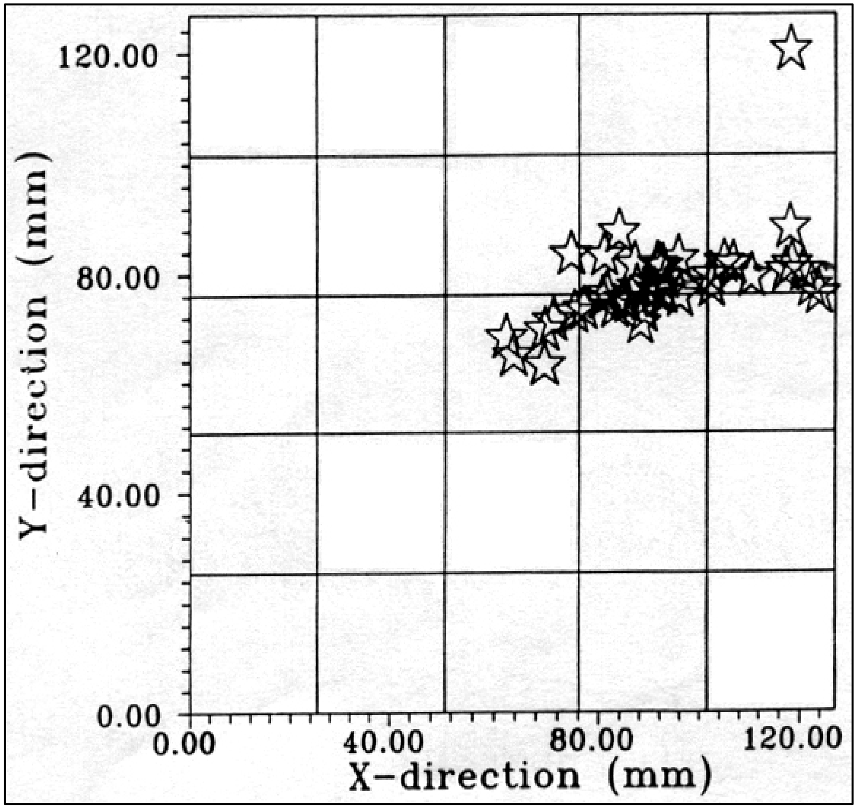
$$= 2\sum_{i=2}^{n} \Delta t_{1i}\left(\Delta t_{1i} C + d_i - d_1\right)$$

AE source location



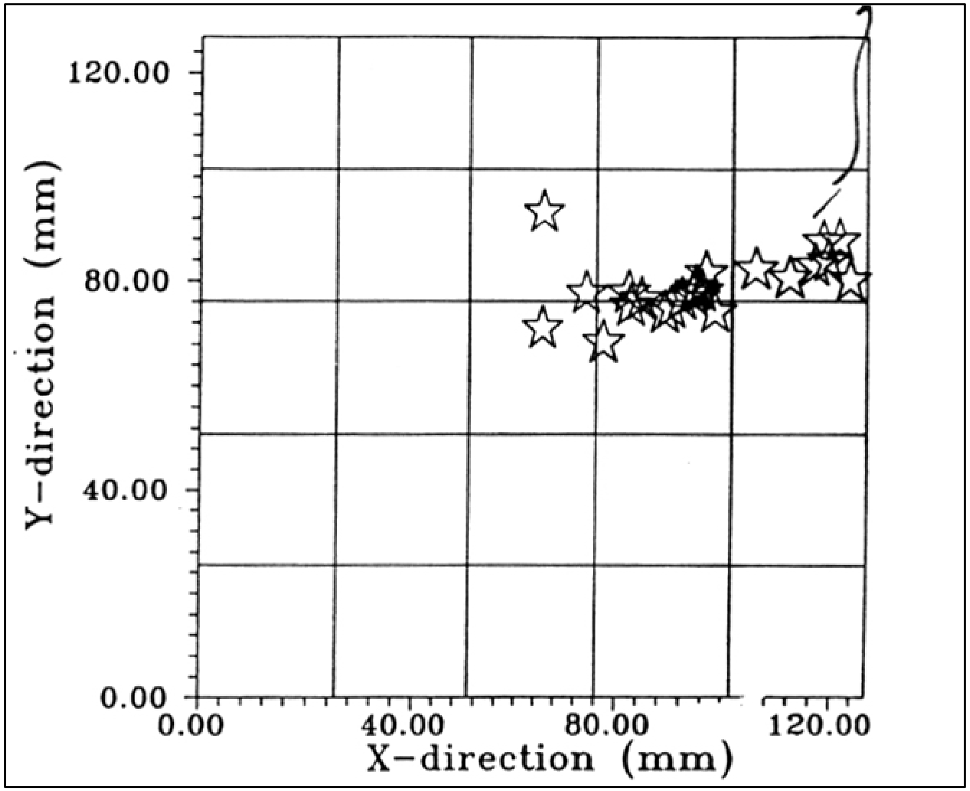
AE events during period between pre 0.0 to 0.8 peak load

AE source location



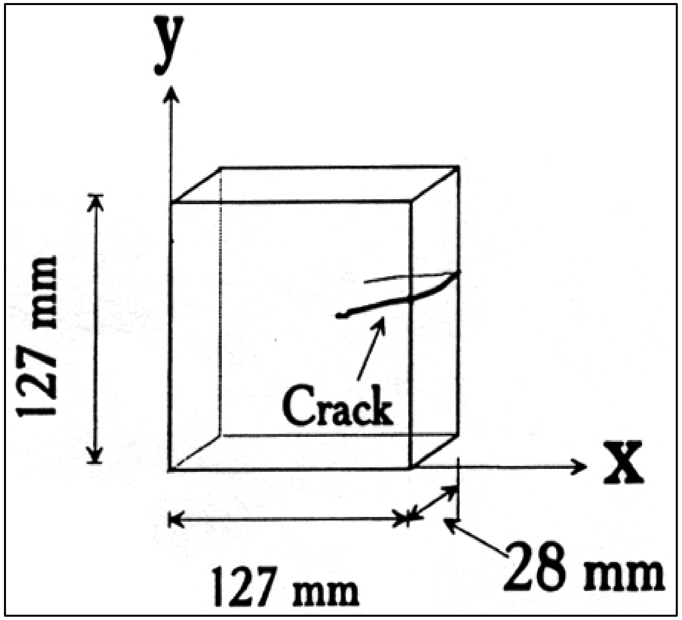
AE events during period after post 0.8 peak load

AE source location



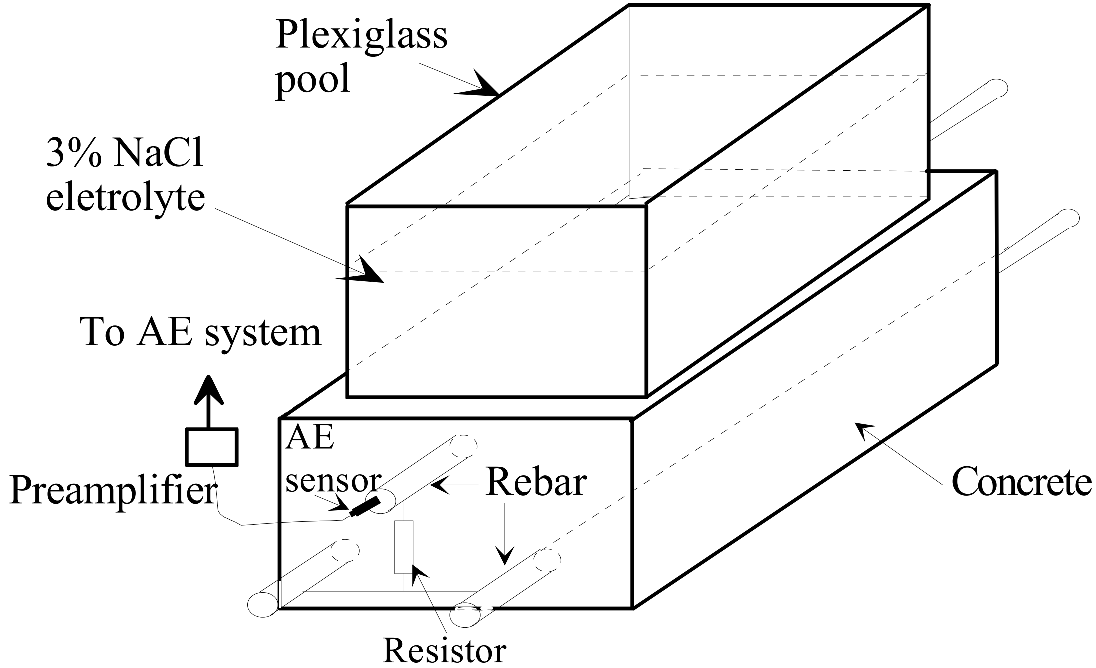
AE events during period between pre 0.0 to post 0.8 peak load

AE source location

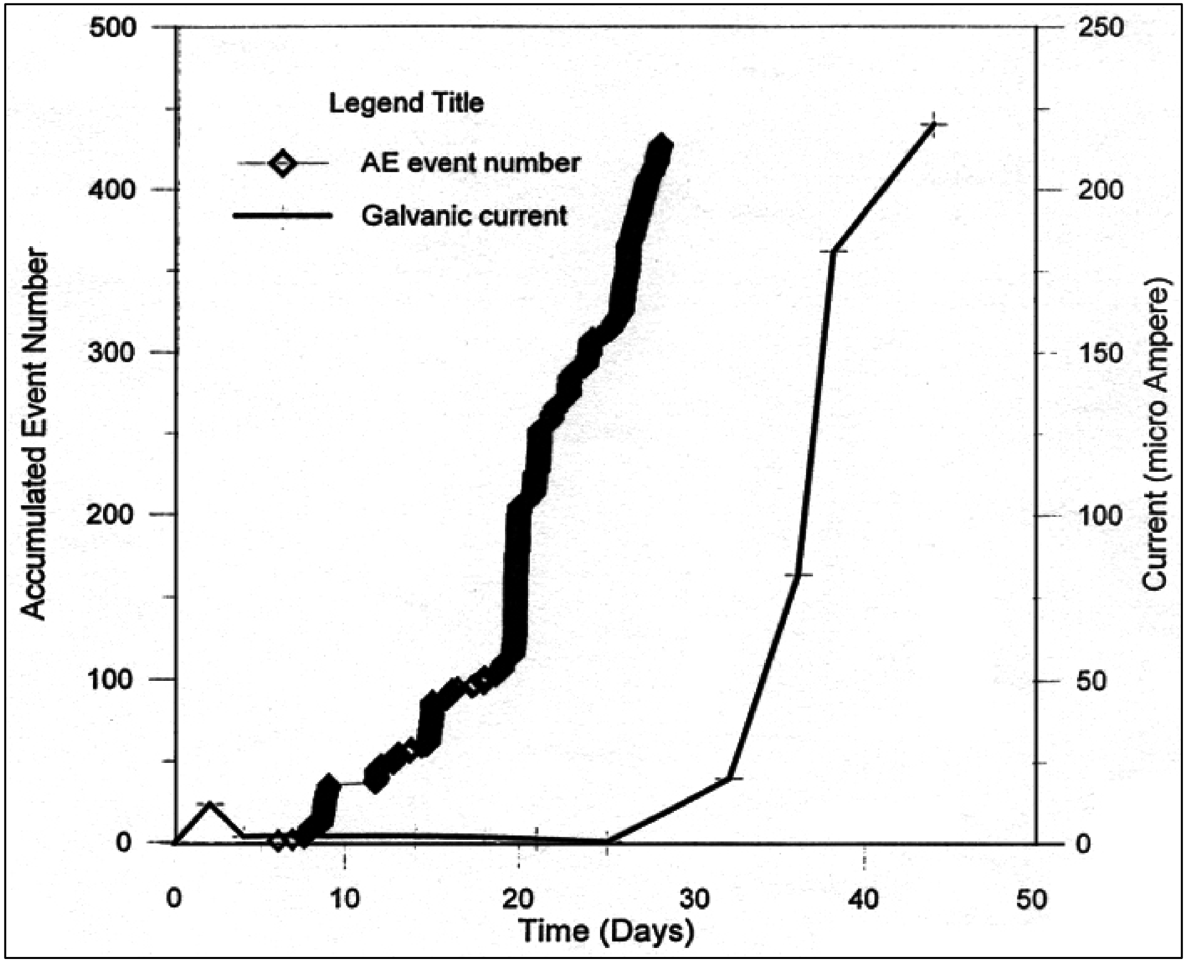


Major crack position for concrete specimen C-M13

Accelerated corrosion test



Comparison of AE and Galvanic measurement results



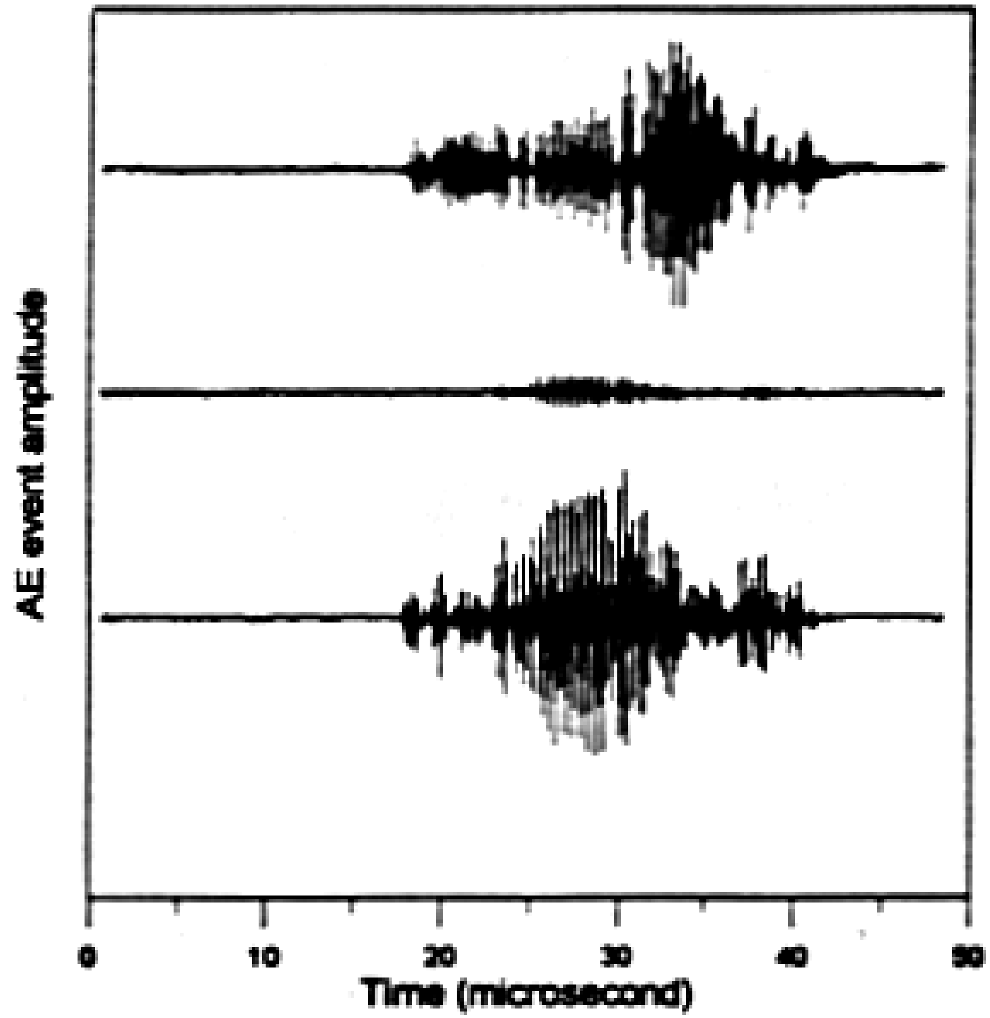
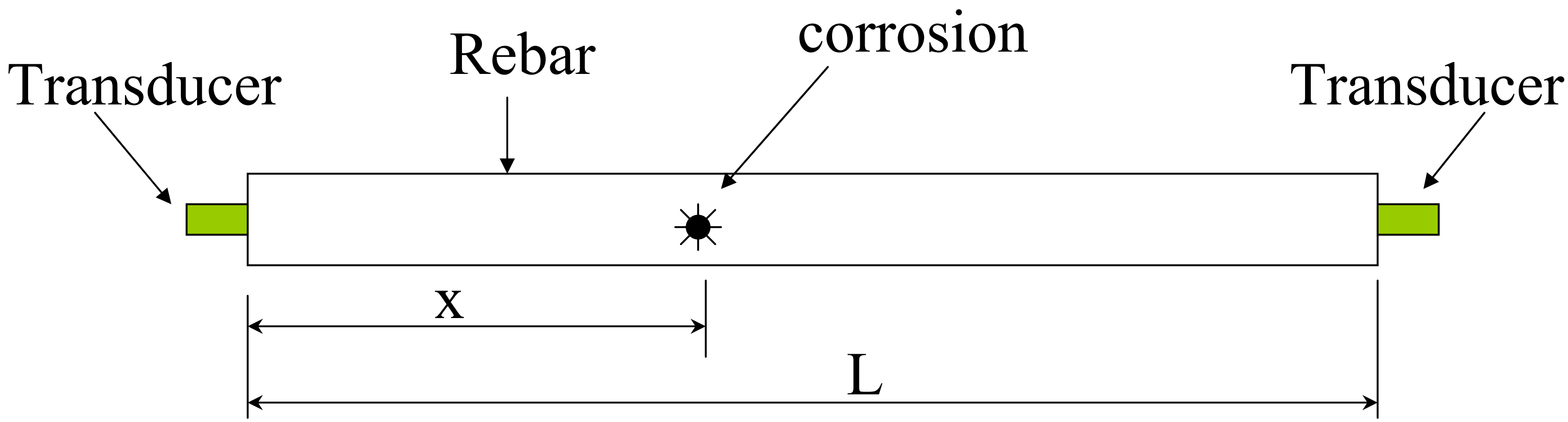
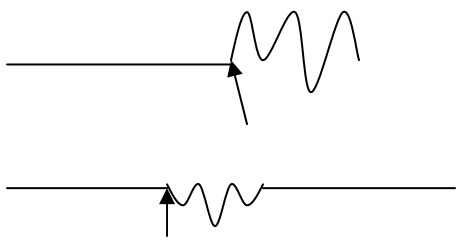


FIGURE 3b - AE Signal at the Three Transducers for a Single AE Event

AE source location





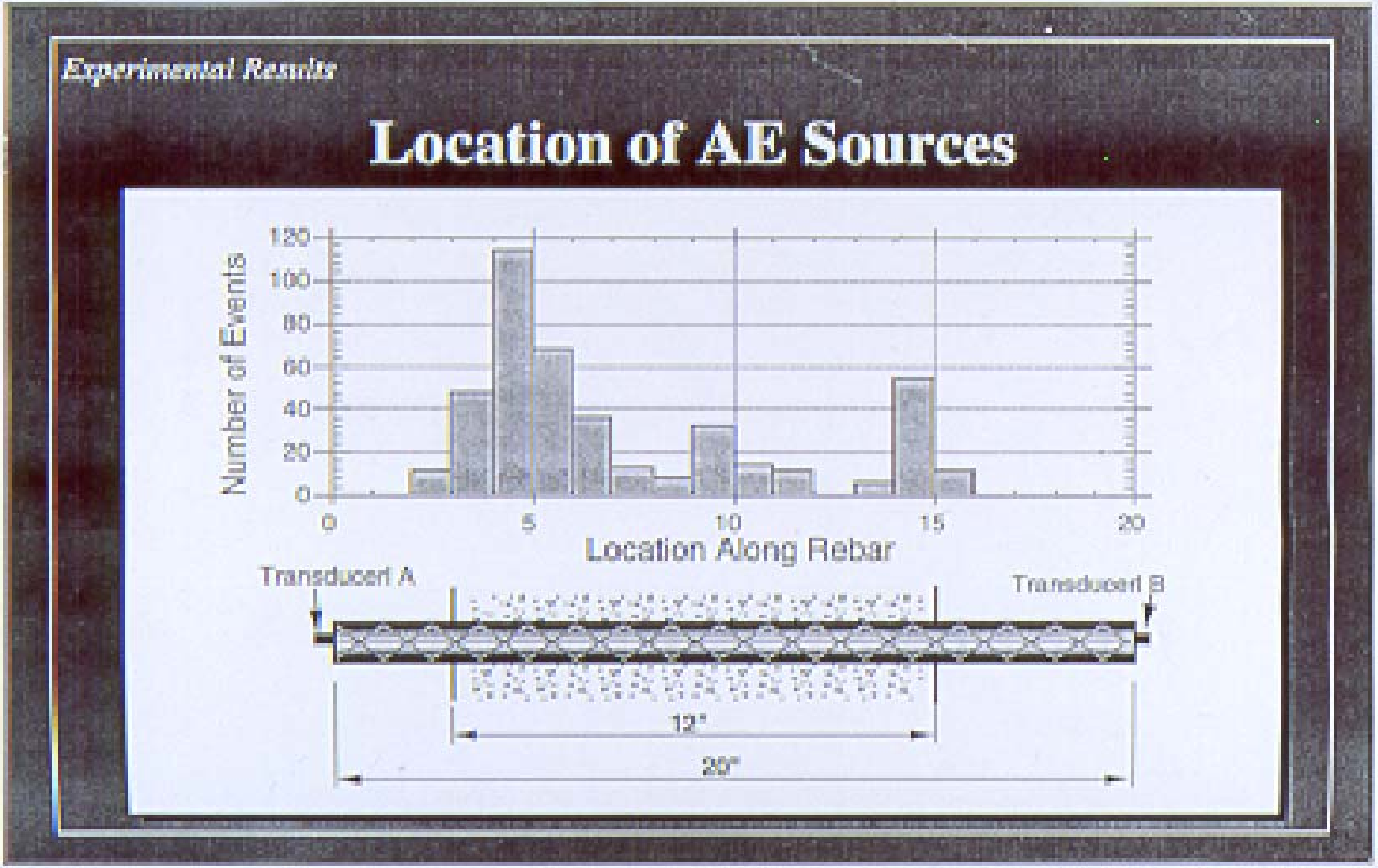
Computation of corrosion position

$$(L-x)-x=\Delta t\cdot C$$

$$L-2x=\Delta+C$$

$$x=\frac{L-\Delta tC}{2}$$

AE source location



AE source location

Infrared thermograph --Introduction (1)

a) Light

An electromagnetic wave and travels at $3\text{x}10^8$ m/s

EM waves can be either visible or invisible according to their wavelength

Infrared thermograph --Introduction (2)

b) Visible light frequency range

Wave length (nm)	*Color*
400-450	violet
450-480	blue
480-510	blue-green
510-550	green
550-570	yellow-green
570-590	yellow
590-630	orange
630-700	red

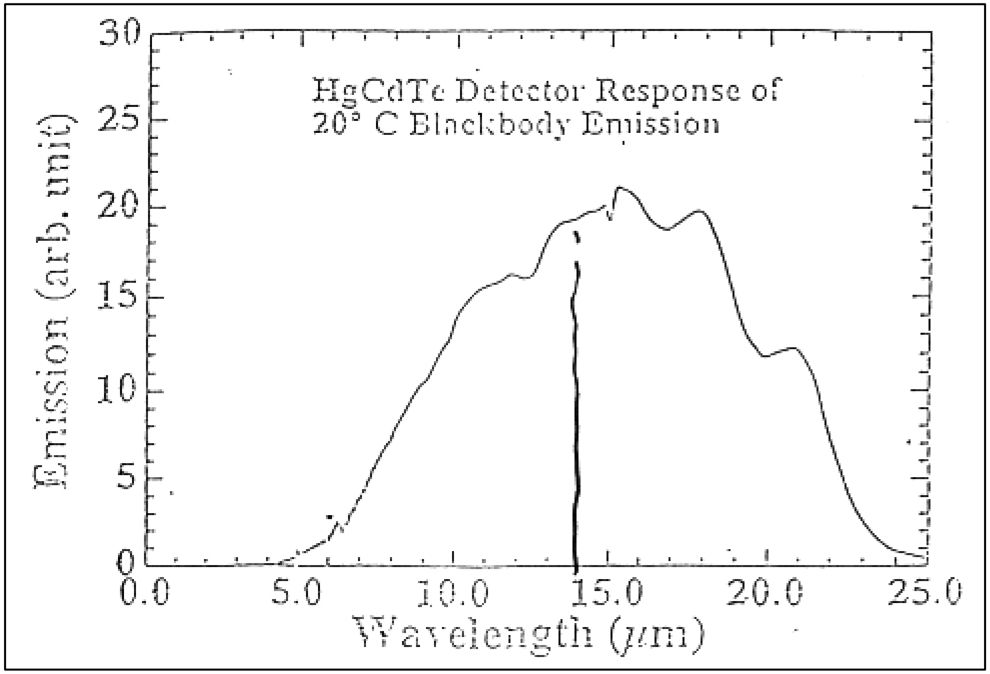
Infrared thermograph --Introduction (3)

c) Invisible EM Waves

- Wavelength $\lambda < 0.4\ \mu m$ == ultraviolet
- $0.7\ \mu m < \lambda < 1.5\ \mu m$ == near-infrared
- $1.5\ \mu m < \lambda < 20\ \mu m$ == mid-infrared
- $20\ \mu m < \lambda$ == far infrared

Infrared thermograph --Introduction (4)

d) Infrared frequency range



Infrared thermograph --Mechanism (1)

Emission of EM waves by objects

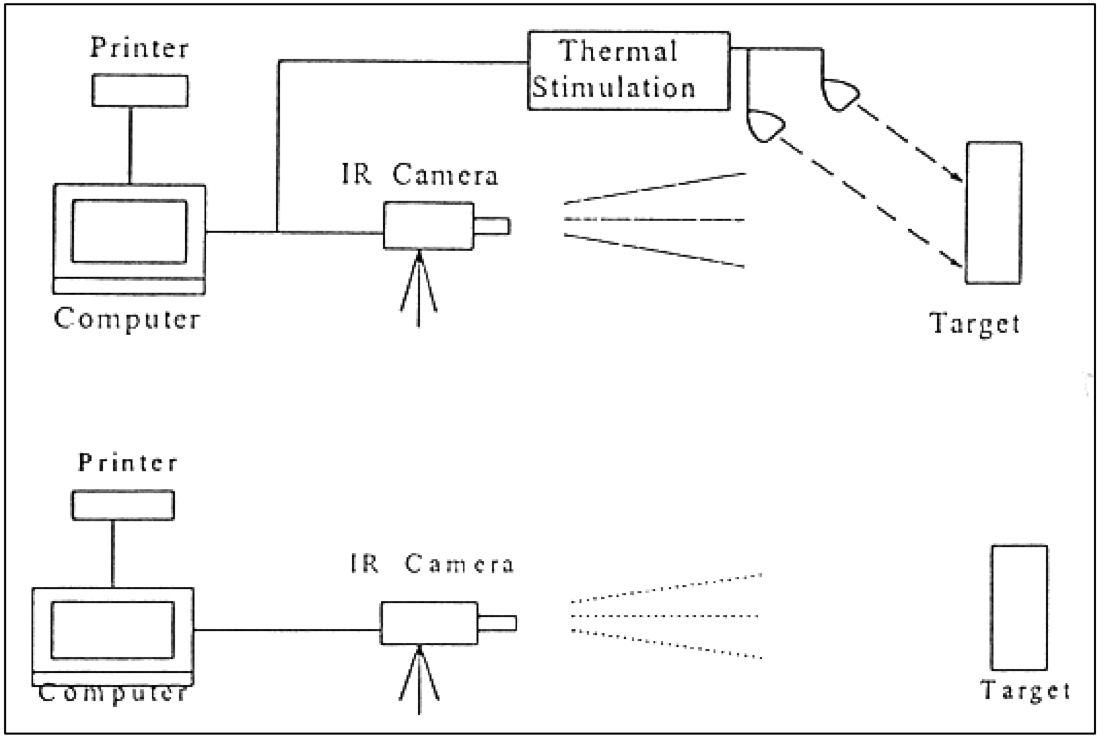
(The principle of blackbody radiation)

Any object at non-zero temperature emits EM waves

Infrared thermograph --Mechanism (2)

- Infrared radiation and temperature related
- The wavelength of ITC is within the emission wavelength range of any object in the normal temperature range of -30^{o}C to 100^{o}C.
- Defects underneath can be detected by measuring the slight temperature fluctuation over the surface of an object.

Infrared thermograph -Active and passive measurements



Active measurement

Passive measurement

Theoretical background for debonded tile detection (1)

$$B\frac{dT}{dt} = H - K(T - T_0)$$

B - Heat capacitance

H - Heat flow rate

K - Thermal conductivity

Initial condition:

$t=0, \; T=T_0$

Theoretical background for debonded tile detection (2)

- For heating process (H>0)

$$T = T_0 + \frac{H}{K}\left(1 - e^{-\frac{K}{B}t}\right)$$

- For cooling process (H<0)

$$T = T_0 - \frac{|H|}{K}\left(1 - e^{-\frac{K}{B}t}\right)$$

Two Cases (1)

Two cases for voids between tile and substrate

- Case 1 = = voids are filled with water
- Case 2 = = Voids are empty (filled with air)

Two Cases (2)

Thermal Properties		
Material	Heat Capacity ($J\ cm^{-3}C^{-1}$)	Conductivity ($W\ m^{-1}C^{-1}$)
Air	0.0008	0.024
Concrete	1.9	1
Water	4.2	0.6

Two Cases (3)

Case 1: Gap filled with water

- *During Heating proces*

$$T = T_0 + \frac{H}{K}\left(1 - e^{-\frac{K}{B}t}\right)$$

	H/K	K/B
Concrete	H	~1/1.9≈0.5
Water	1.6H	~1/7 ≈0.14

∴T is lower than concrete

- *During Cooling process*

T is higher than concrete

Two Cases (4)

Case 2: Gap filled with air

- *During Heating proces*

$$T = T_0 + \frac{H}{K}\left(1 - e^{-\frac{K}{B}t}\right)$$

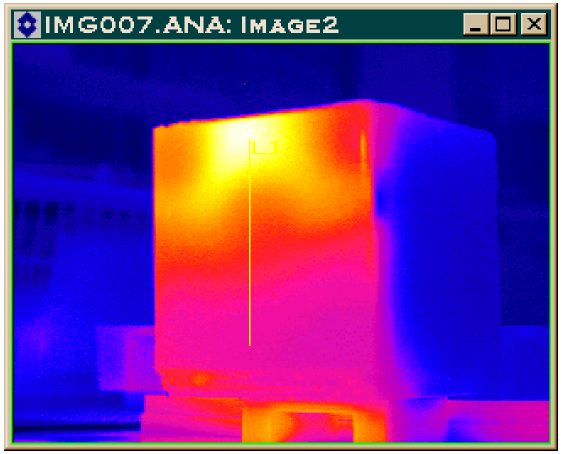
	H/K	K/B
Concrete	H	~0.5
Water	42H	~30

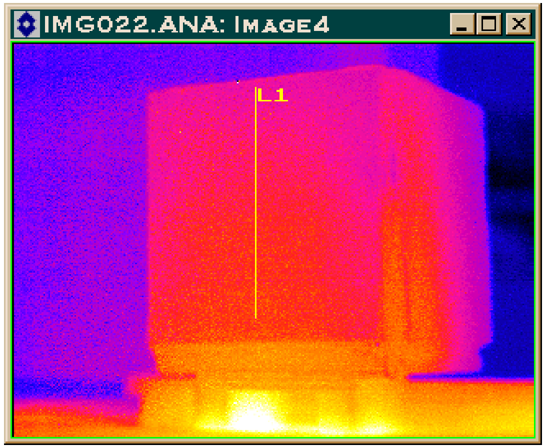
$\therefore$T is higher than concrete

- *During Cooling process*

T is lower than concrete

Two Cases (5)





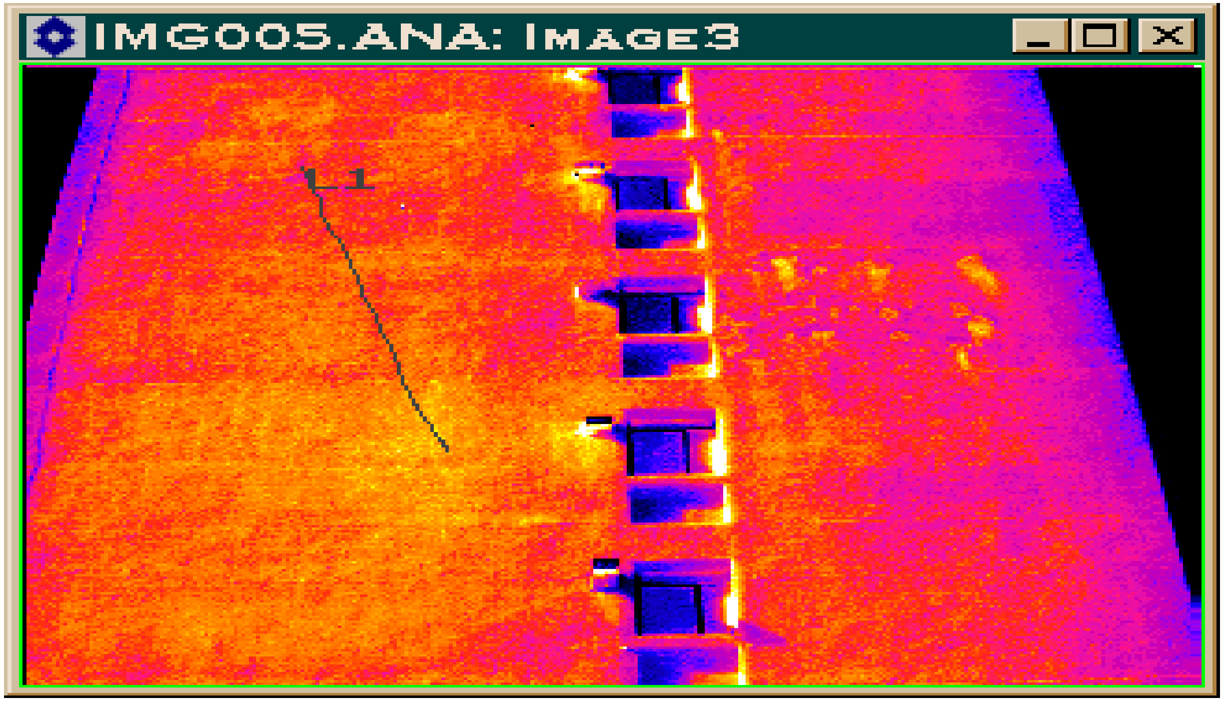
A debonded tile sample with half air and half water

- uniform heating of the inspected face
- after cooling for half an hour.

Examples (1)

Thermal image of HKUST library indicating defected area filled with water on the external tiled wall

Examples (2)



Thermograph of the government staff quarter under sunshine - indicating heavy damage on external wall

Reflection correction

$$N_{CAM} = \varepsilon N_{obj} + \rho N_{env}$$

where

ε = object emissivity (the object is considered opaque)

ρ = object reflectivity

N_{obj} = radiance from the surface of the object

N_{env} = radiance of the surrounding environment

Reflection correction

High emissivity case (ε > 0.9. ε = (1-ρ))

$$N_{obj} \approx N_{CAM}$$

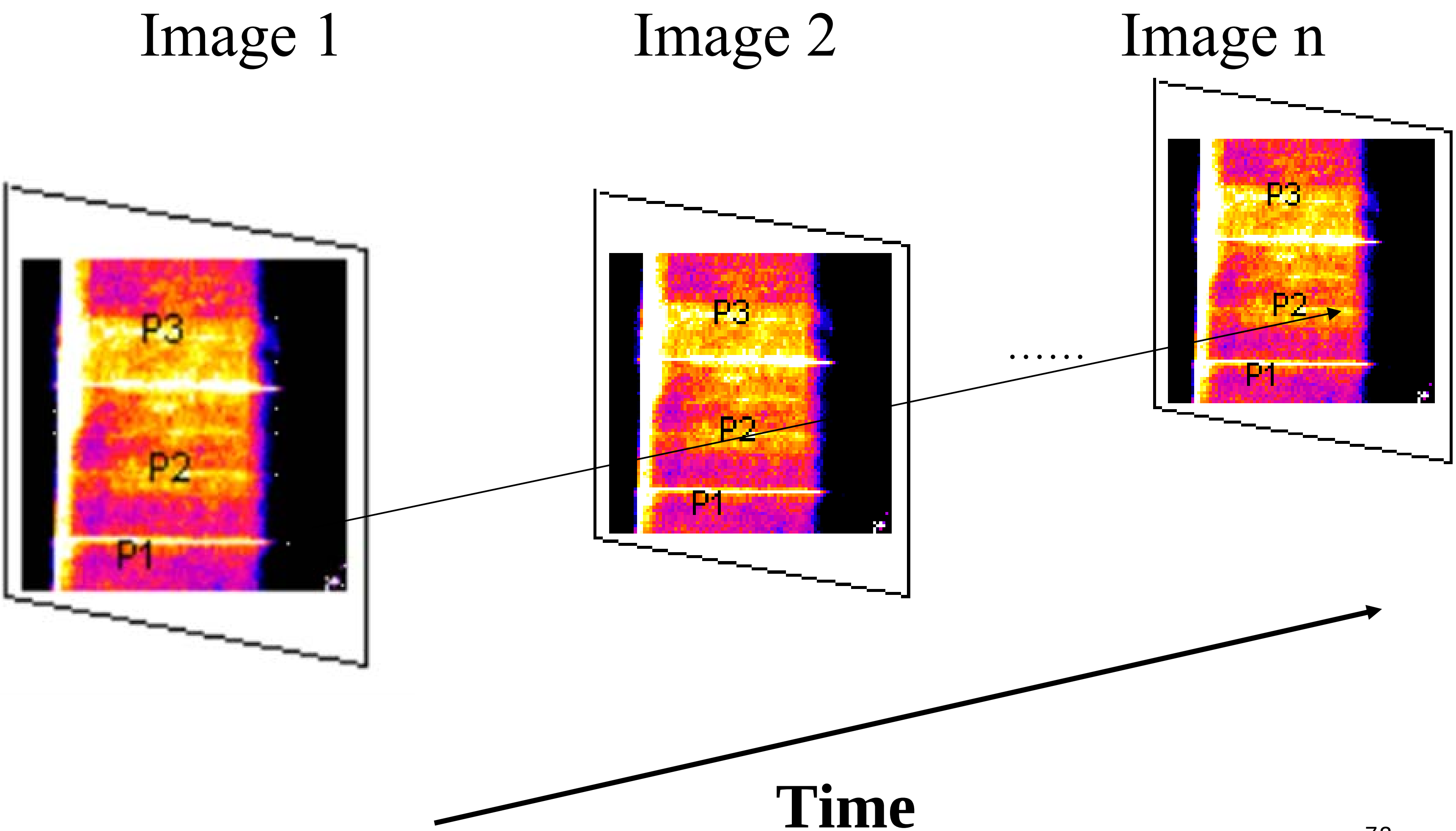
Low emissivity case (ε < 0.9)

Reflection should be considered

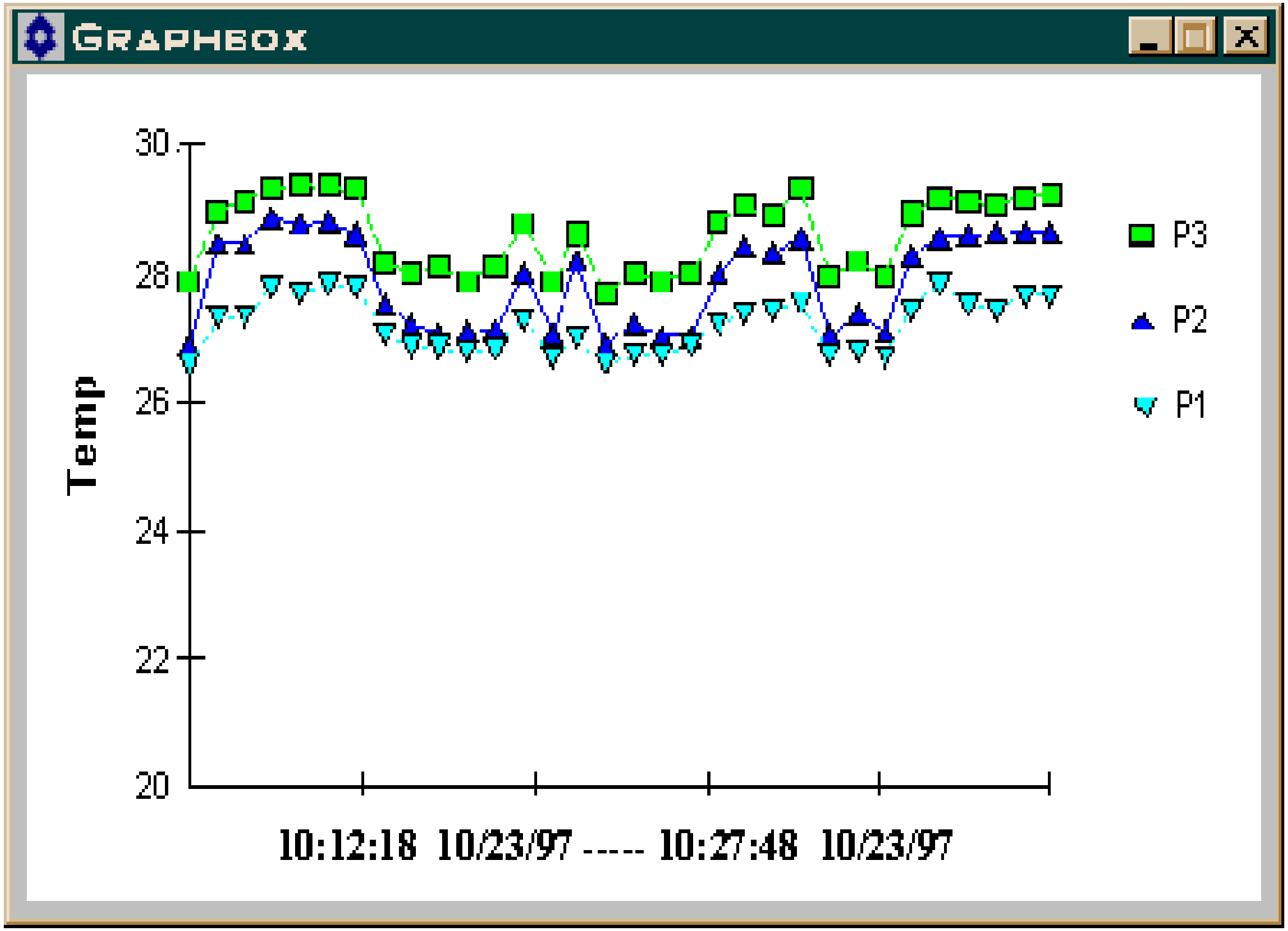
Ceramic tile case (ε = *0.6* - 0.8)

Reflection can not be neglected

Reflection correction



Reflection correction



Distance and angle
--Space resolution

- Field view of an ITC depends on the lens of the system
- A camera may consist of 320 x 240 detectors in an array
- The area covered by each detector is the smallest size of an object
- Instantaneous field of view (IFOV)

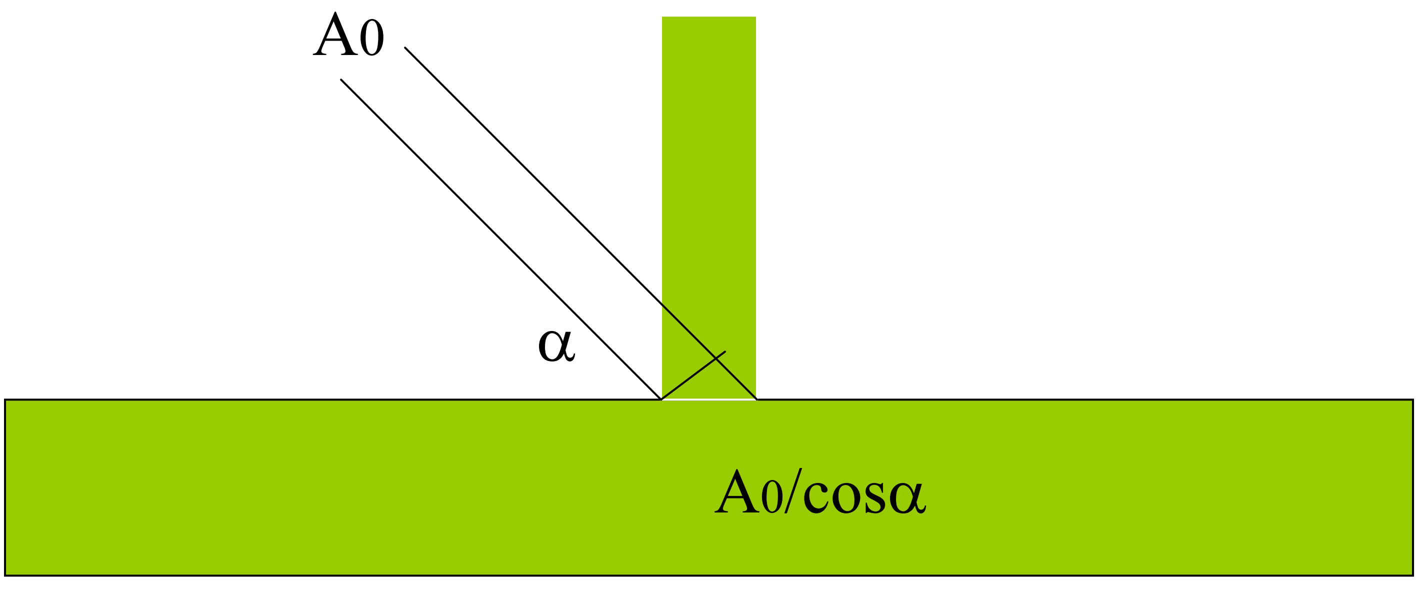
Distance and angle
- Space resolution

- Example (20 degree by 15 degree lens)

Distance to object	Field of view	IFOV
1m	0.35 x 0.26 m	1.1 x 1.1mm
5m	1.76 x 1.32 m	5.5 x 5.5mm
10m	3.52 x 2.63 m	11 x 11mm
50m	17.6 x 13.2 m	55 x 55mm

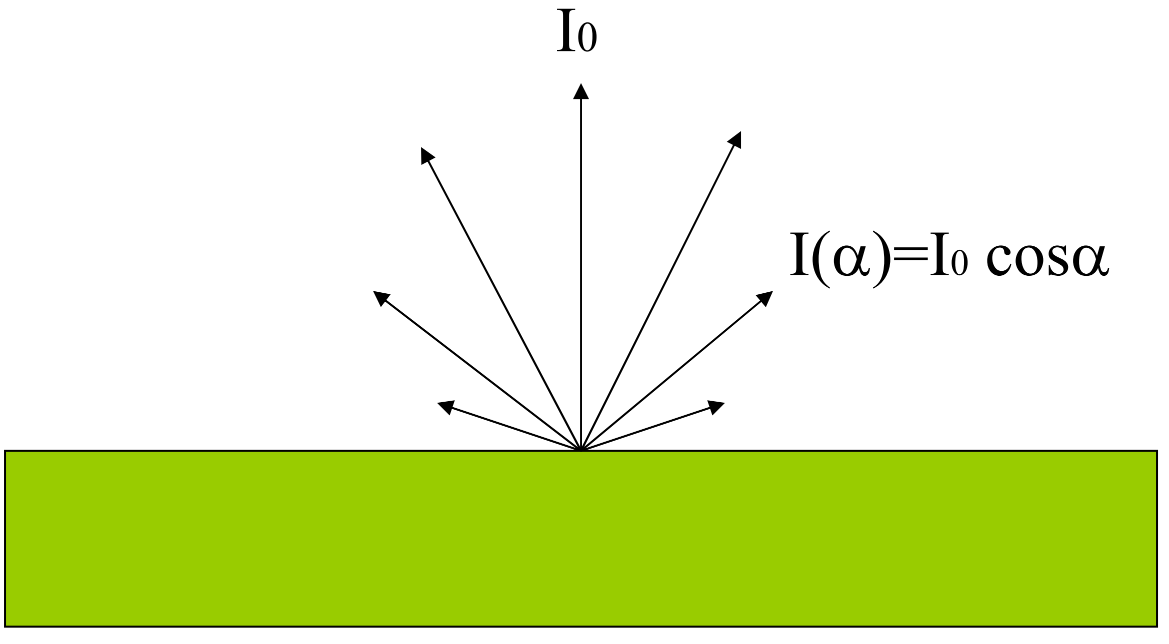
Distance and angle
- Influence of angle

- Influence on the area



Distance and angle
- Influence of angle

- Influence on radiation



Distance and angle
- Influence of angle

- Total received radiation

$$A_0/\cos\alpha \; I_0 \cos\alpha = A_0 \; I_0$$

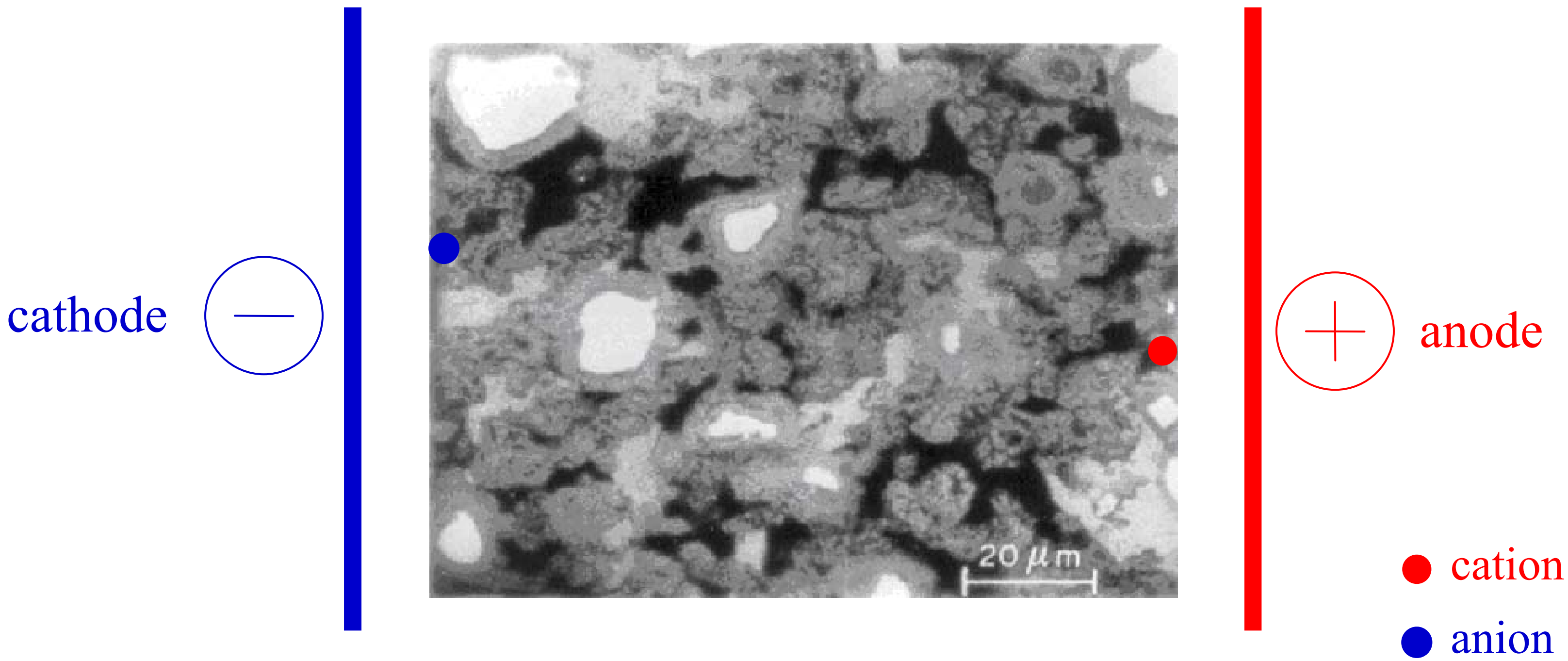
Distance and angle
- Influence of angle

- Thumb rule for reality

  - No [erfectly diffuse bodies exist

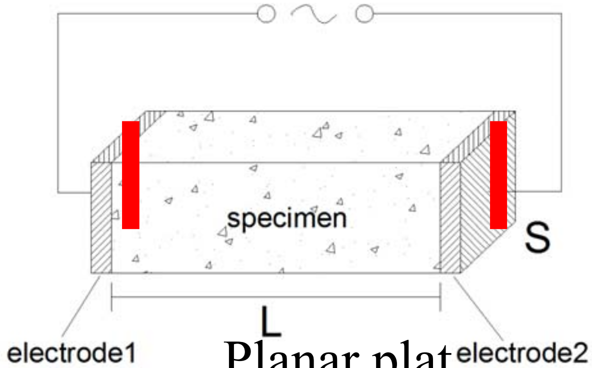
  - For most bodies, the emissivity uually goes down from 50 degree from normal

Cement conduction mechanism

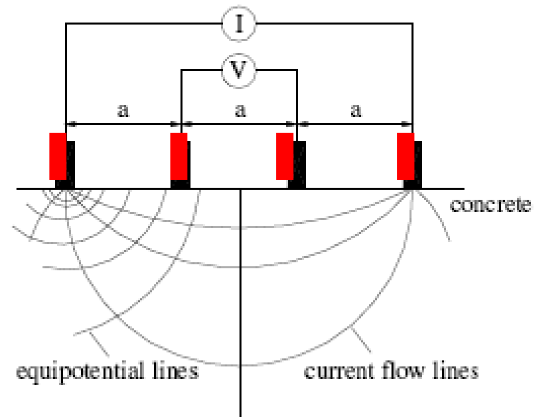


Conduction in cement is essentially electrolytic via ion transport through the interconnected pore network.

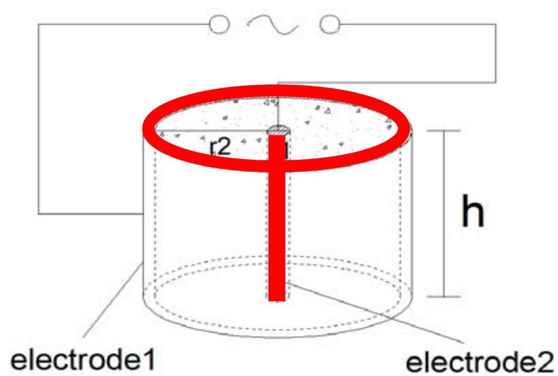
Traditional resistivity measurements



Planar plat



Four-probe



Concentric circle

Non-contact resistivity measurement

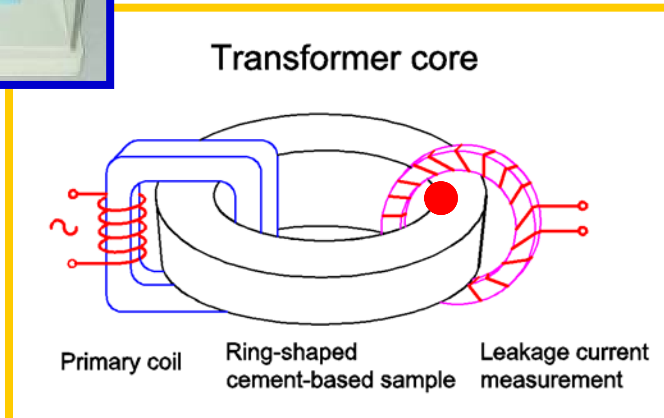
Non-contact resistivity measurement

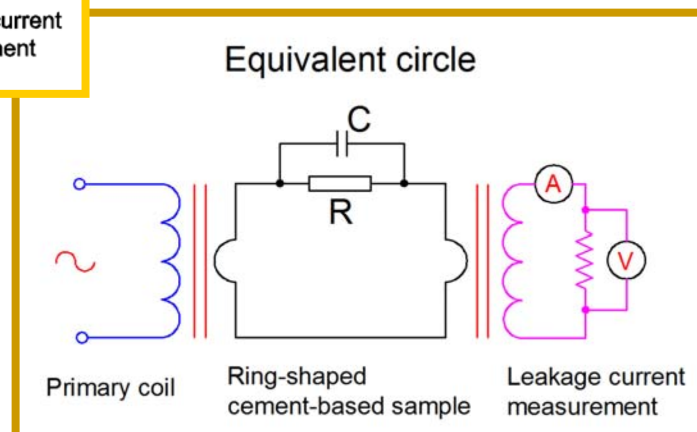
Works as a transformer

No electrode

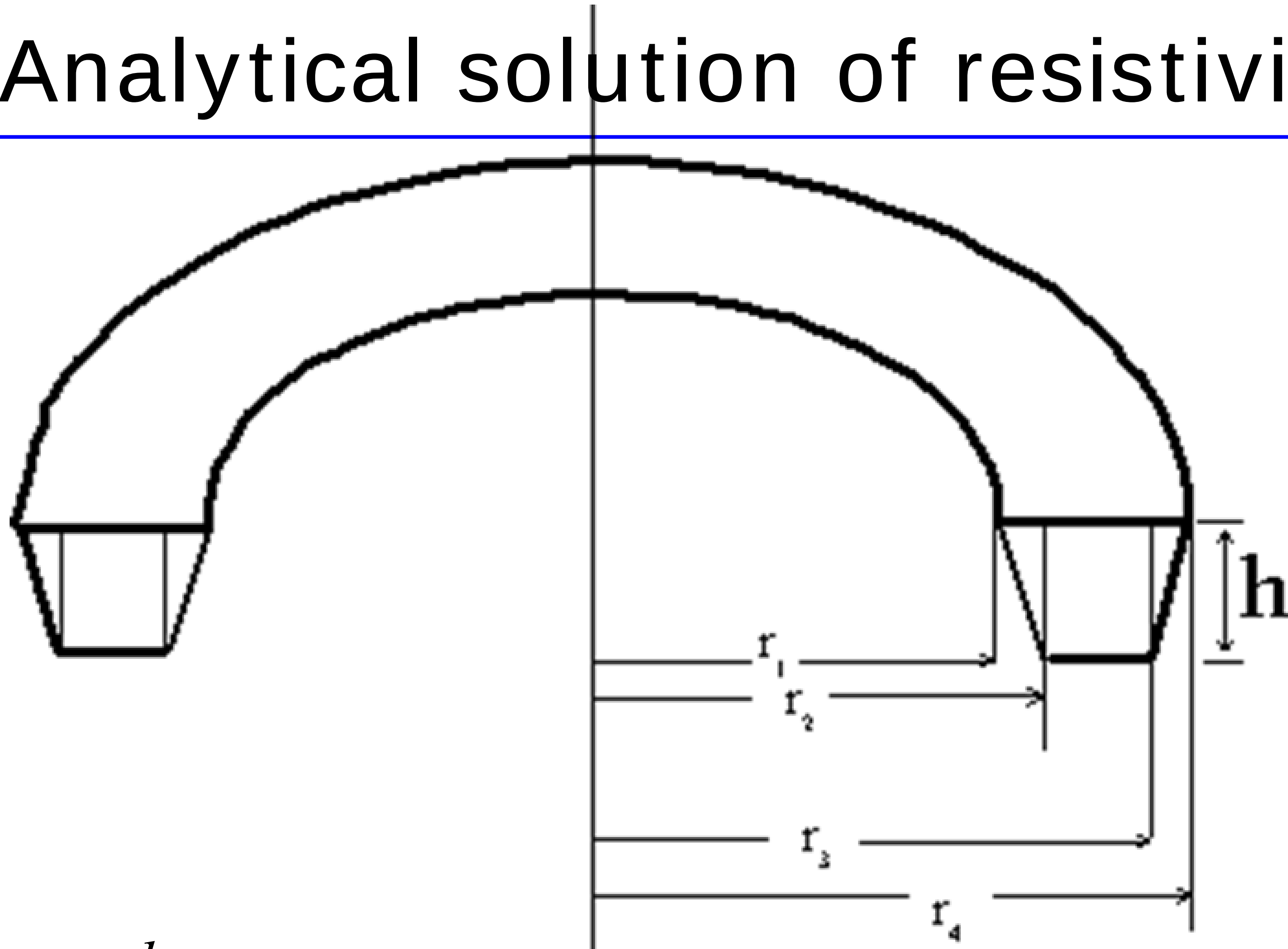
AC signal

1 KHz





Analytical solution of resistivity

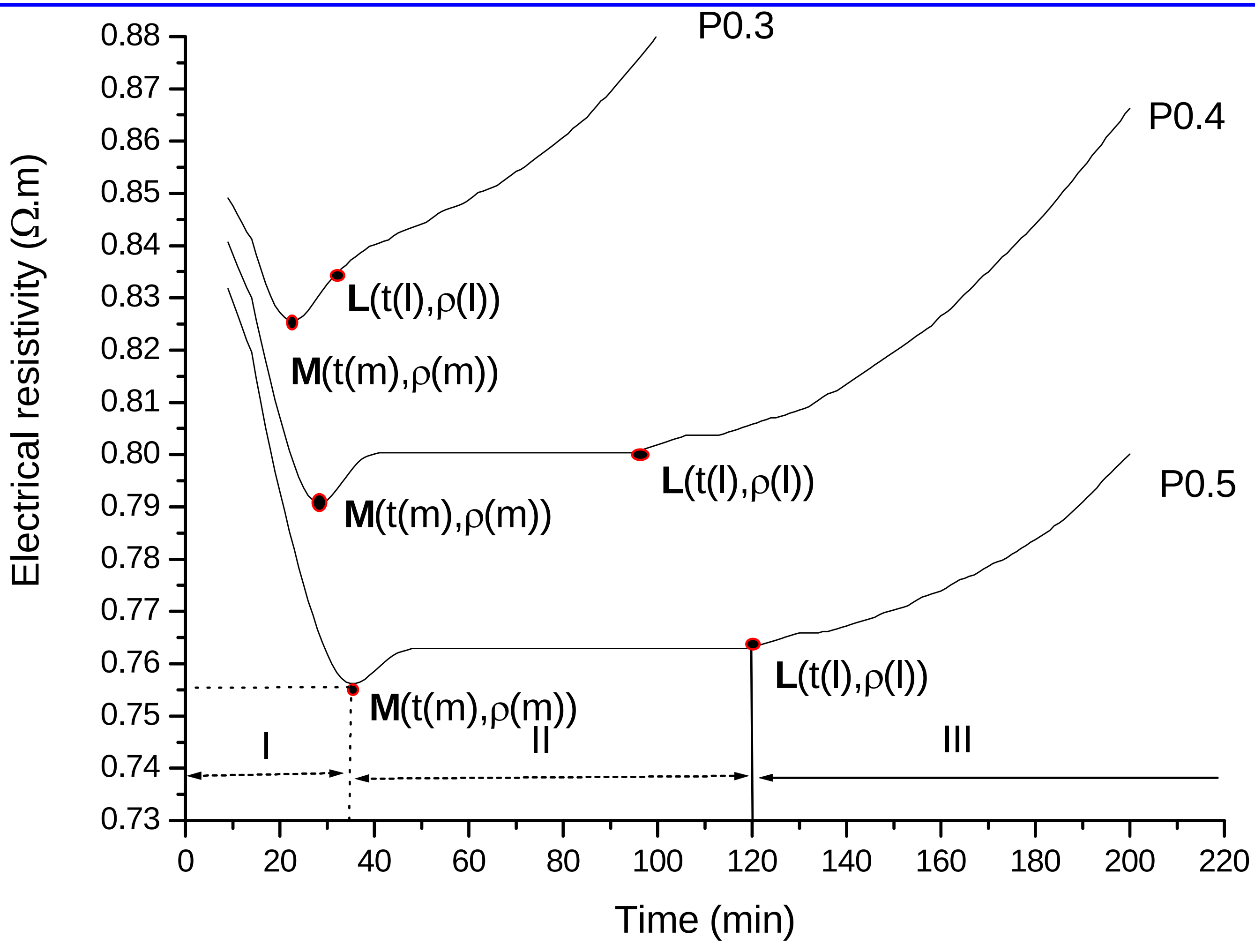


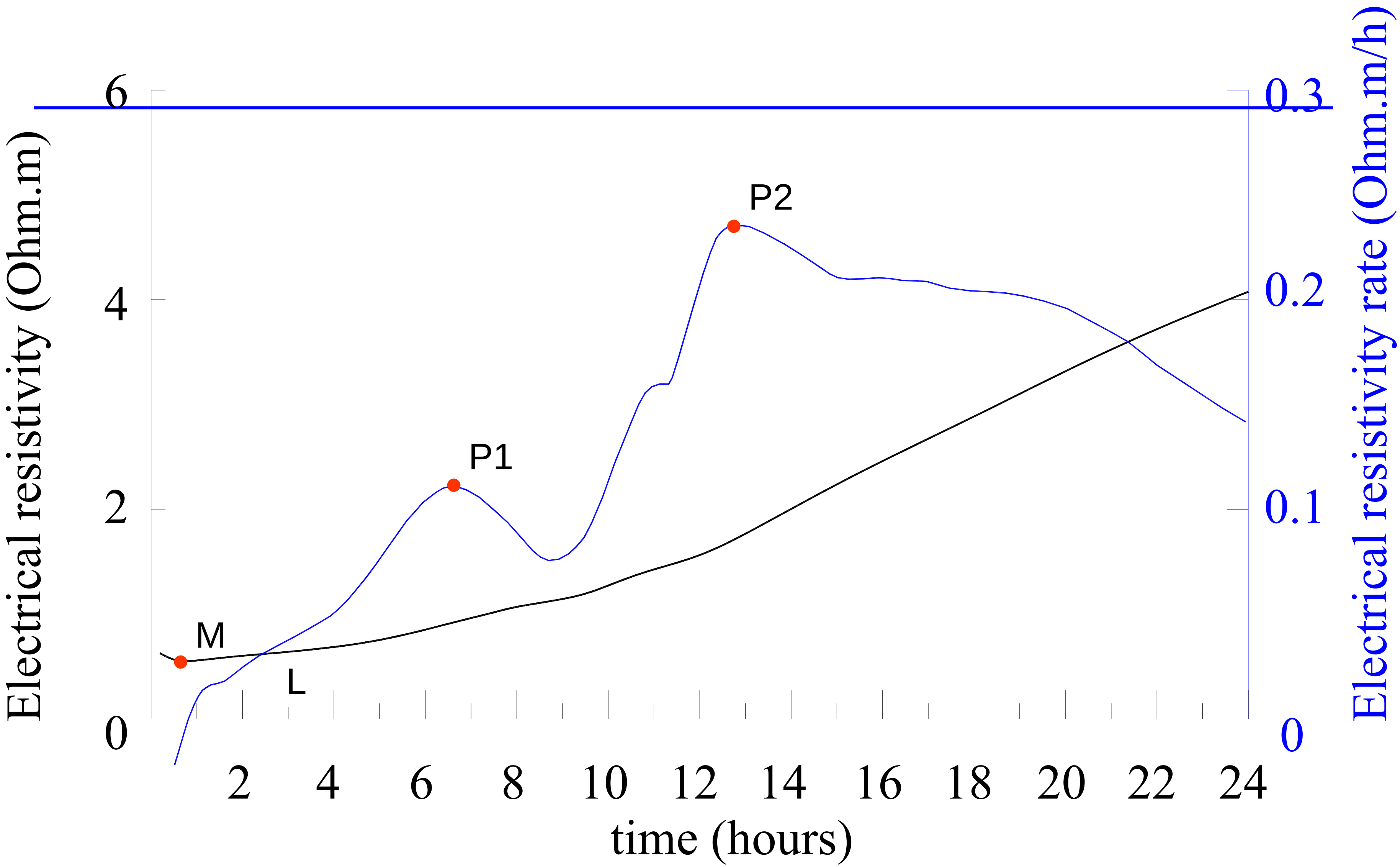
$$\rho = R_{total}\ \frac{h}{2\pi}\left[\ \ln(r_3/r_2)\ + \frac{r_4}{r_4 - r_3}\ln(r_4/r_3)\ - \frac{r_1}{r_2 - r_1}\ln(r_2/r_1)\right]$$

Procedures

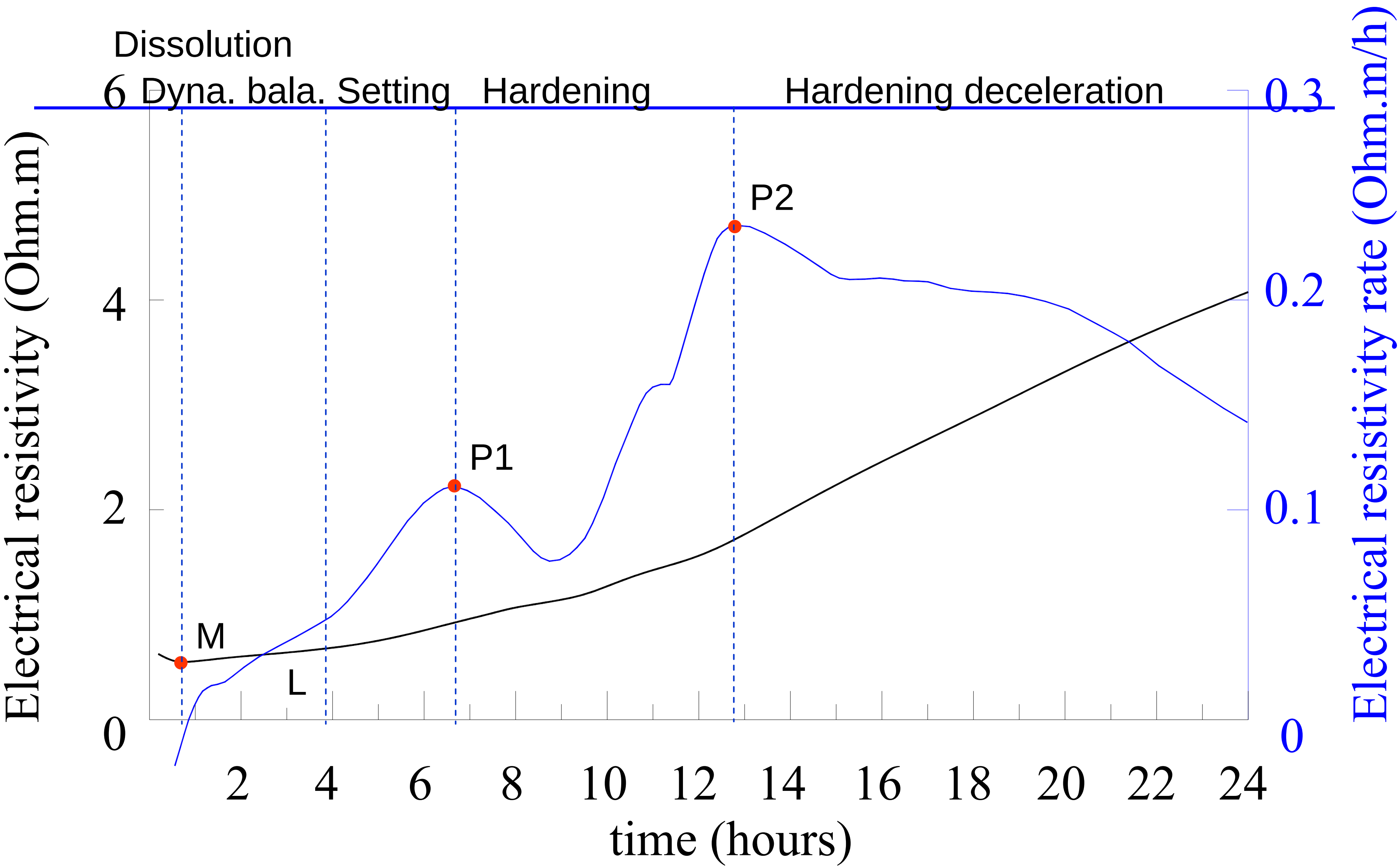


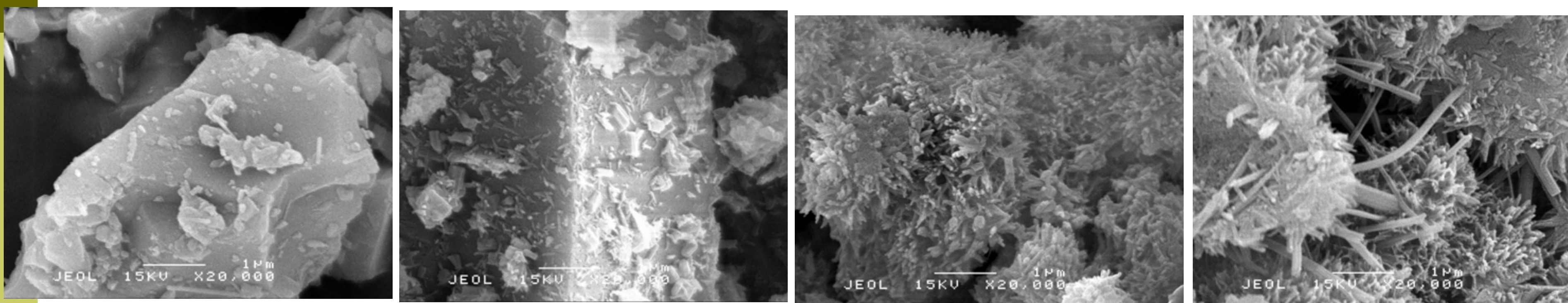

Typical resistivity curve





Electrical resistivity (Ohm.m)
Electrical resistivity rate (Ohm.m/h)
6
4
2
0
0.3
0.2
0.1
0
P2
P1
M
L
2
4
6
8
10
12
14
16
18
20
22
24
time (hours)


Dissolution
Dyna. bala.
Setting
Hardening
Hardening deceleration
P2
P1
M
L
6
4
2
0
0.3
0.2
0.1
0
2
4
6
8
10
12
14
16
18
20
22
24
time (hours)
Electrical resistivity (Ohm.m)
Electrical resistivity rate (Ohm.m/h)



microstructure formation process

Penetration method for setting time

Initial setting:

Penetration resistance: 3.5 MPa

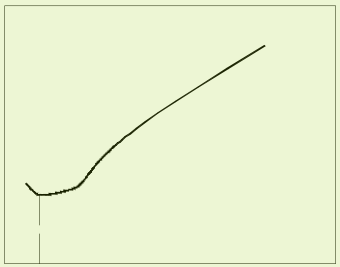
Final setting:

Penetration resistance: 28 MPa

(ASTM 403)

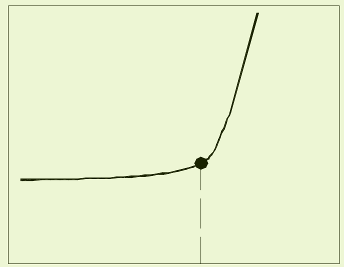
t_m and t_t from electrical resistivity response

ρ~t



t_m

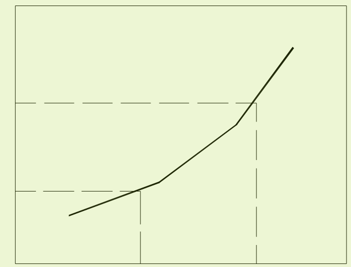
ρ~t (log scale)



t_t

t_{ini} and t_{fin} from penetration resistance

PR~t

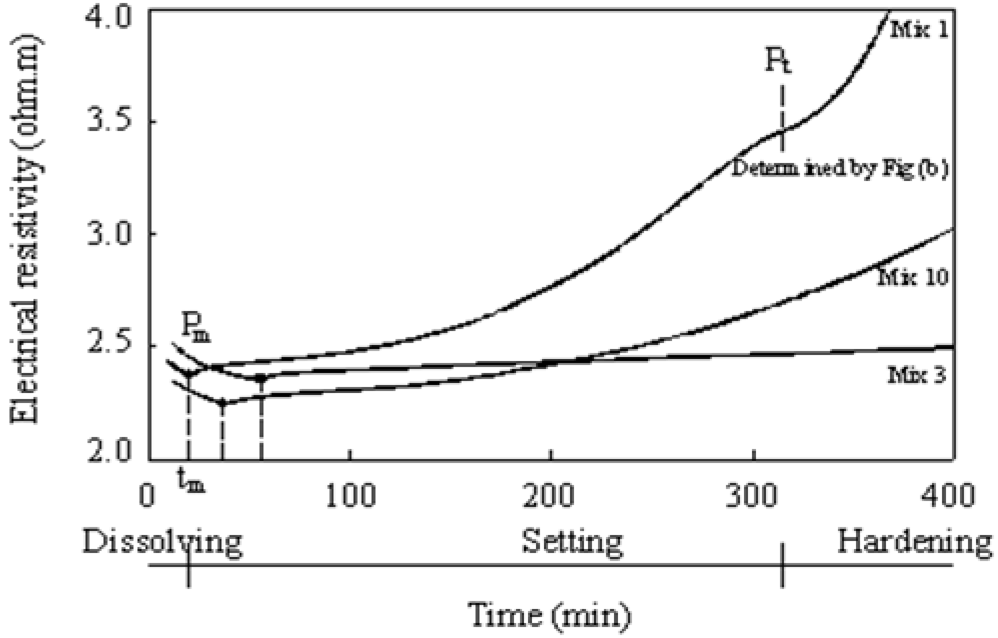


t_{ini} t_{fin}

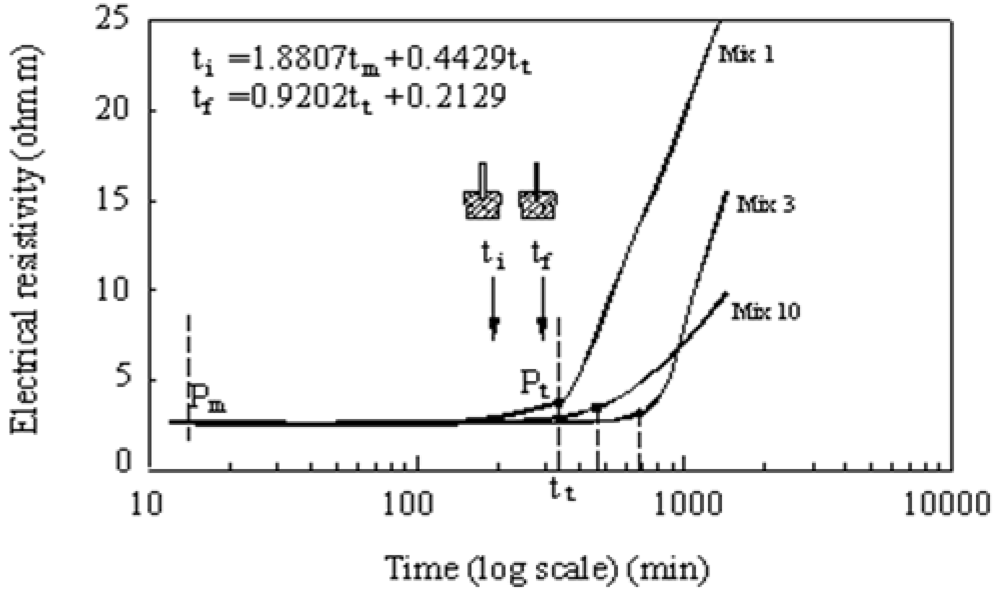
The relationship for the resistivity response and setting time

$$t_{ini} = f\,(t_m\,,\,t_t) \qquad (1)$$

$$t_{fin} = g\,(t_m\,,\,t_t) \qquad (2)$$

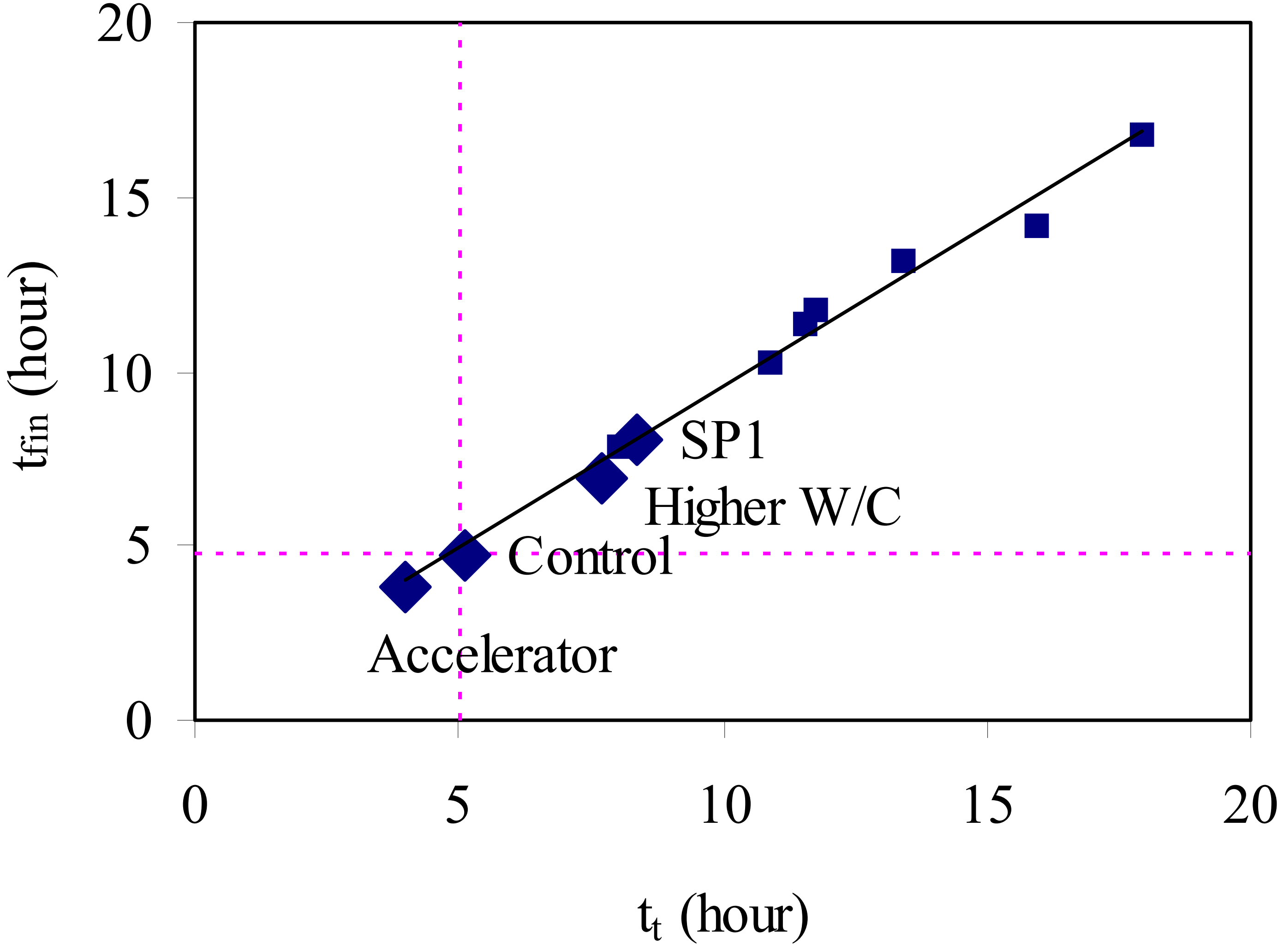

4.0
3.5
3.0
2.5
2.0
Electrical resistivity (ohm.m)
Mix 1
Pt
Determined by Fig (b)
Mix 10
Pm
Mix 3
tm
0
100
200
300
400
Dissolving
Setting
Hardening
Time (min)

(a)


25
20
15
10
5
0
Electrical resistivity (ohm.m)
ti =1.8807tm +0.4429tt
tf =0.9202tt +0.2129
Mix 1
Mix 3
Mix 10
ti
tf
Pt
Pm
tt
10
100
1000
10000
Time (log scale) (min)

(b)

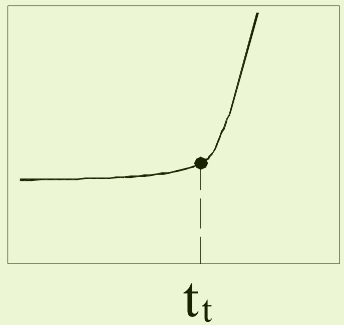
$$t_{fin} = 0.9202 t_t + 0.2129$$



t_m and t_t from electrical resistivity response

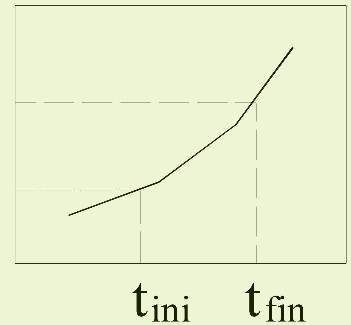
$\rho \sim t$

$\rho \sim t$ (log scale)



t_{ini} and t_{fin} from penetration resistance

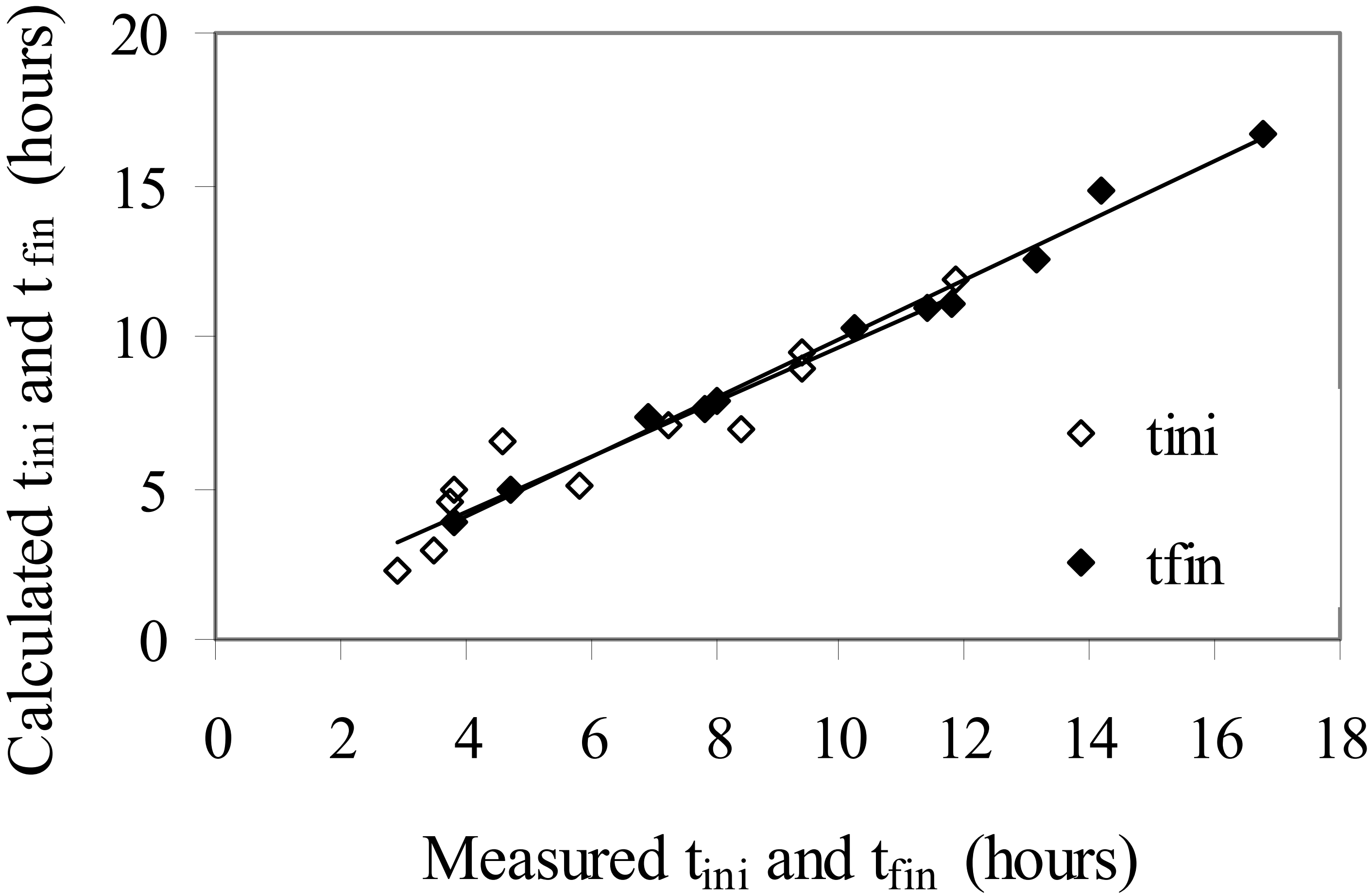
PR~t



The relationship for the resistivity response and setting time

$$t_{ini} = f\,(t_m\,,\,t_t) \qquad (1)$$

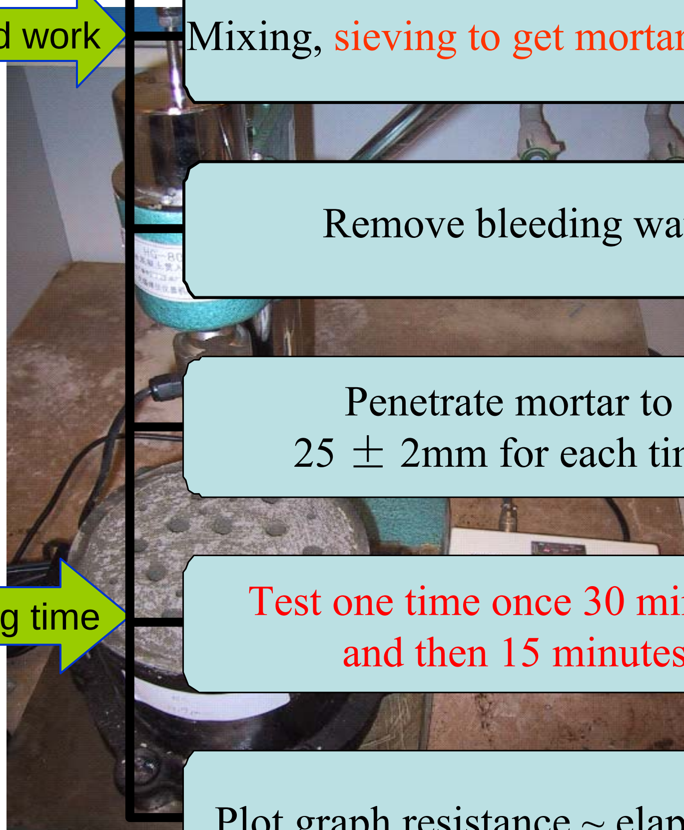
$$t_{fin} = g\,(t_m\,,\,t_t) \qquad (2)$$



Calculated t_{ini} and t_{fin} (hours)
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
tini
tfin
Measured t_{ini} and t_{fin} (hours)

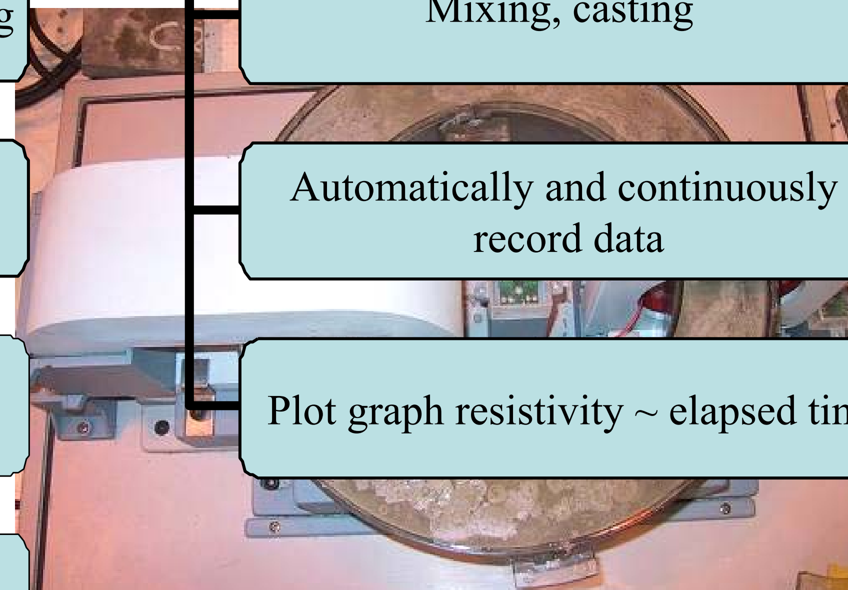
Penetration resistance

- Hard work → Mixing, sieving to get mortar, casting
- Remove bleeding water
- Penetrate mortar to 25 ± 2mm for each time
- Quite long time → Test one time once 30 minutes, and then 15 minutes
- Plot graph resistance ~ elapsed time

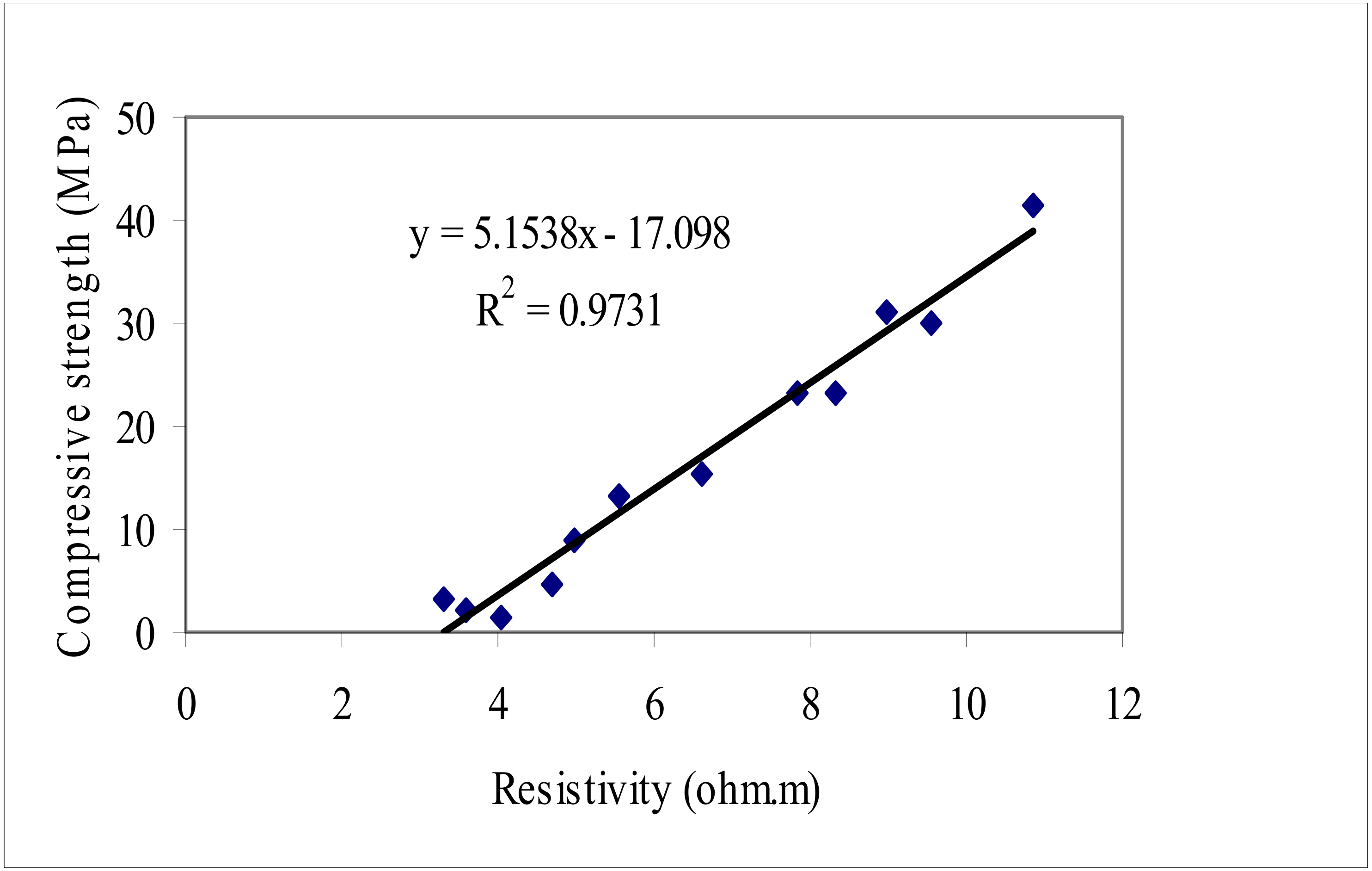


Electrical resistivity

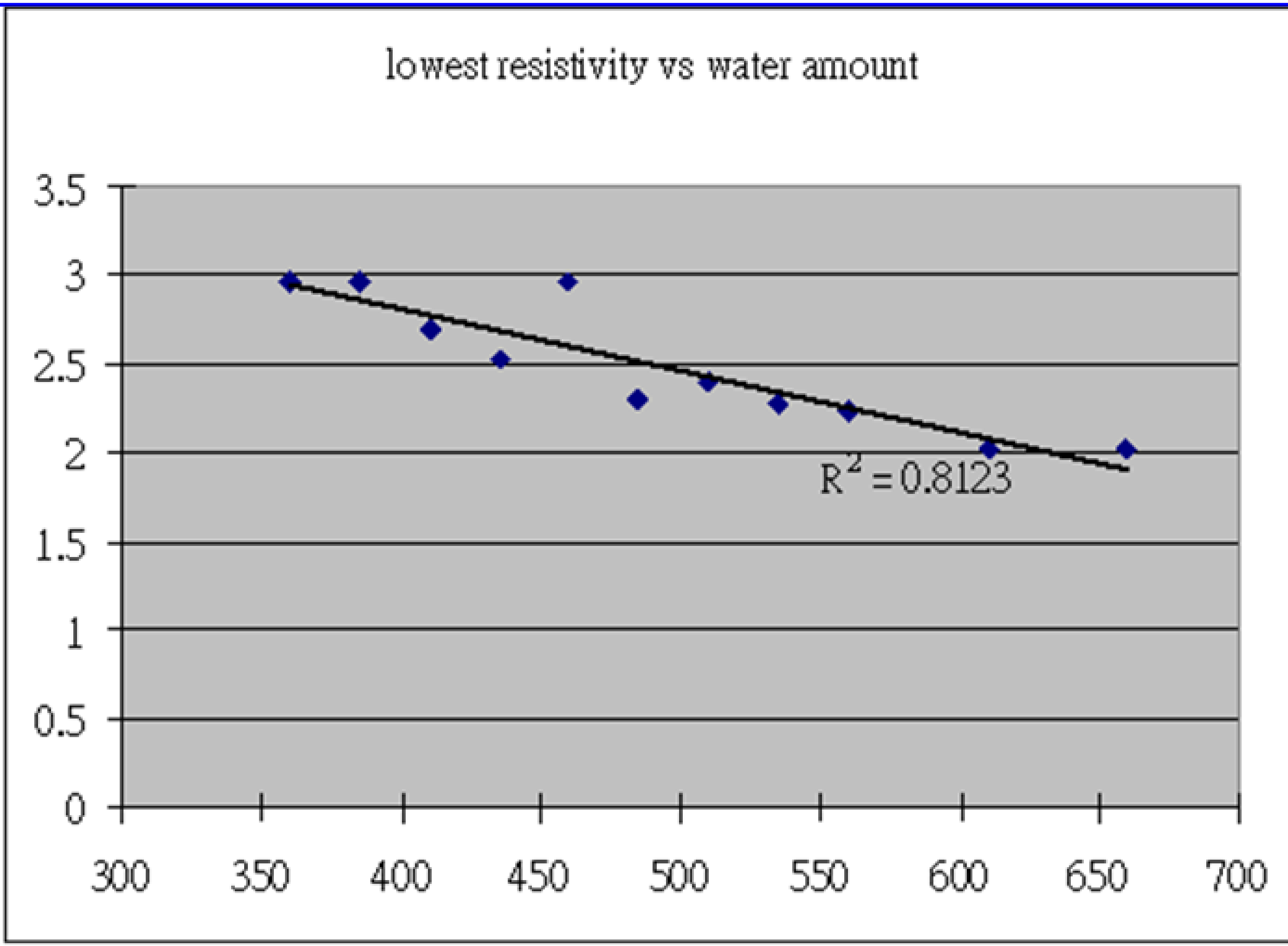
- Mixing, casting
- Automatically and continuously record data
- Plot graph resistivity ~ elapsed time



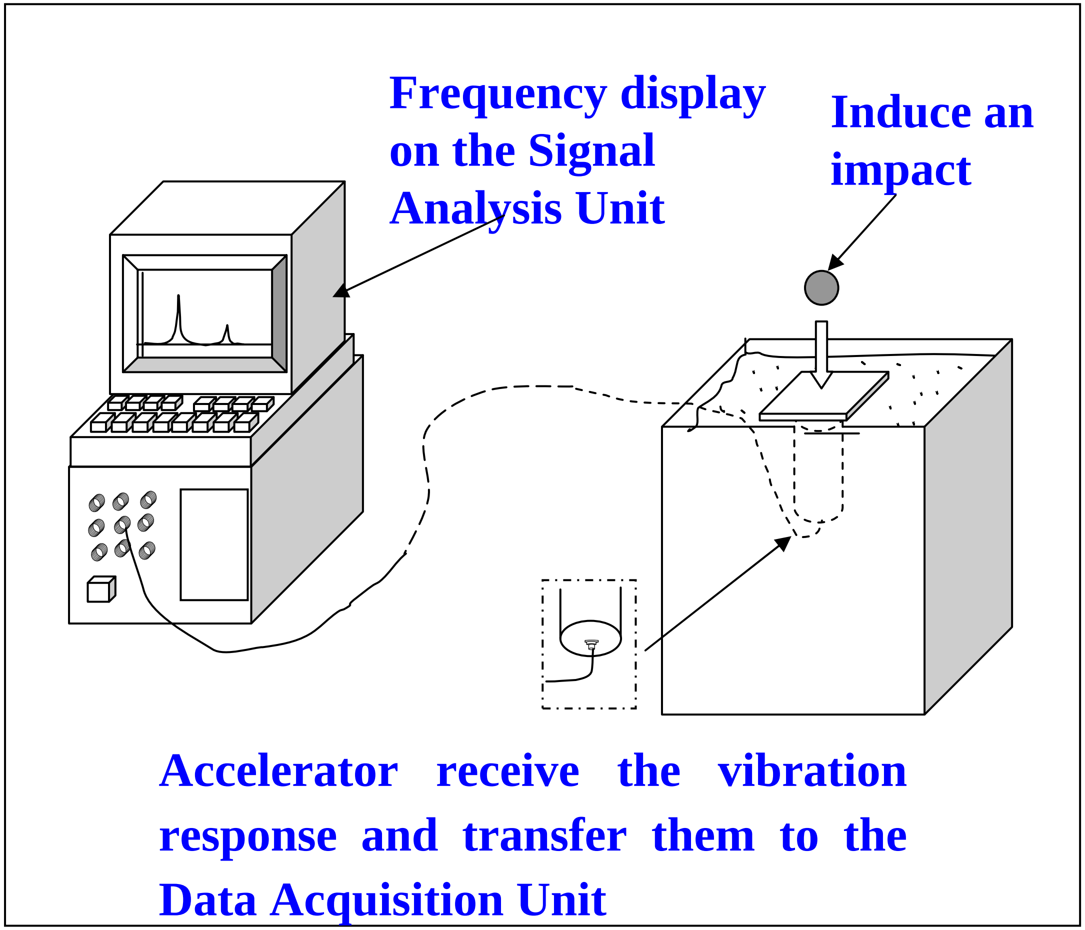
Relationship between resistivity and strength



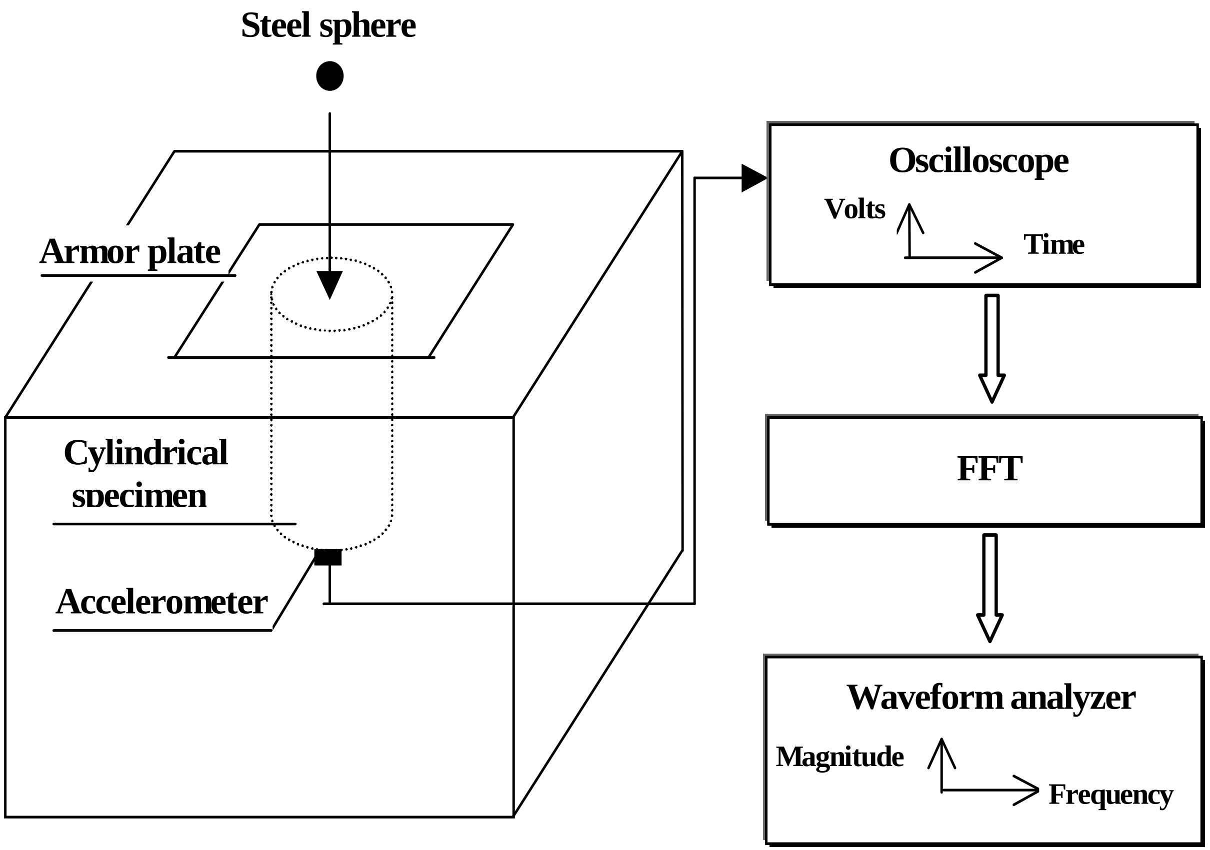
Relationship between water amount and lowest resistivity value



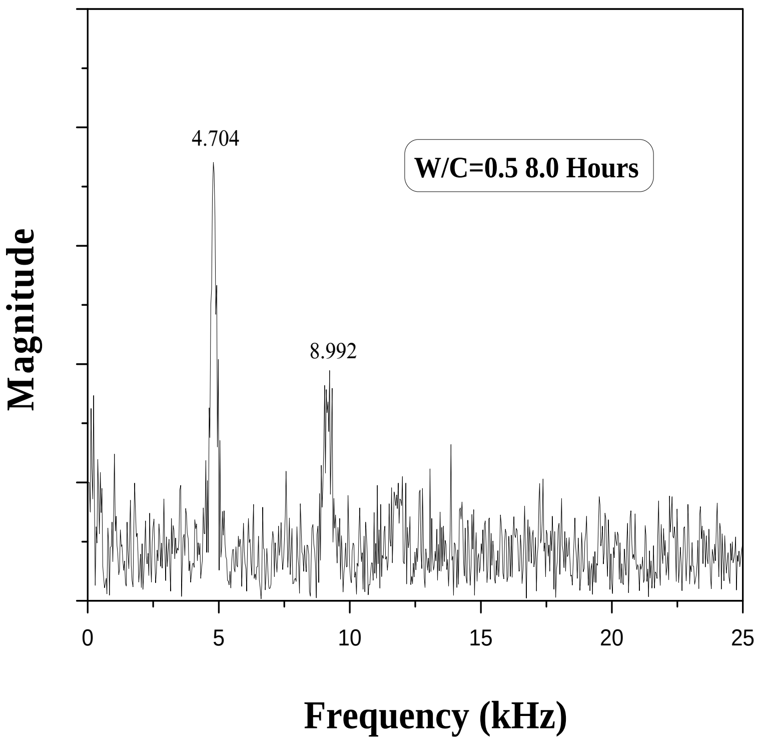
Dynamic modulus



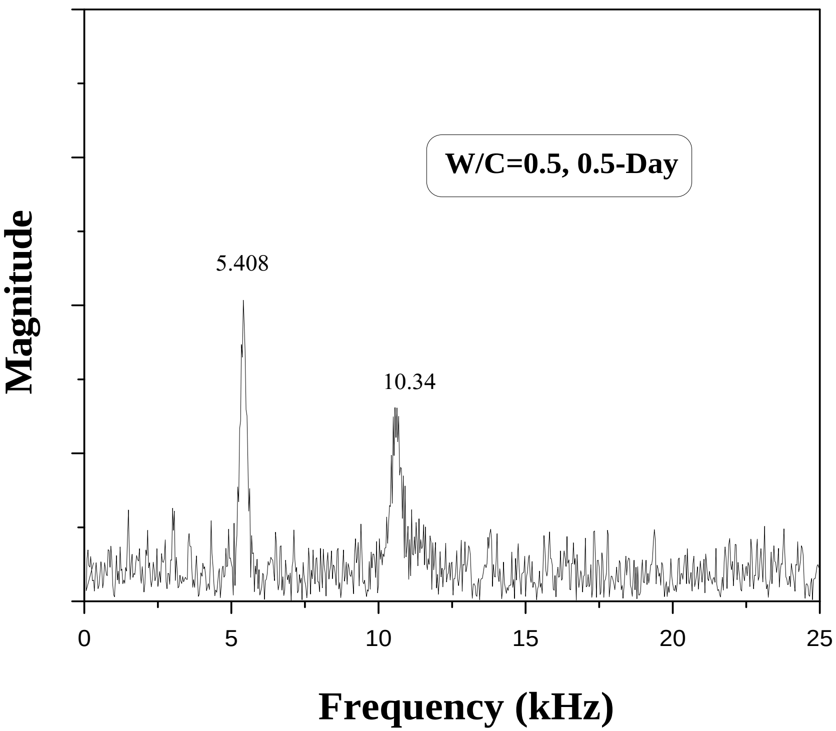
Dynamic modulus



Results

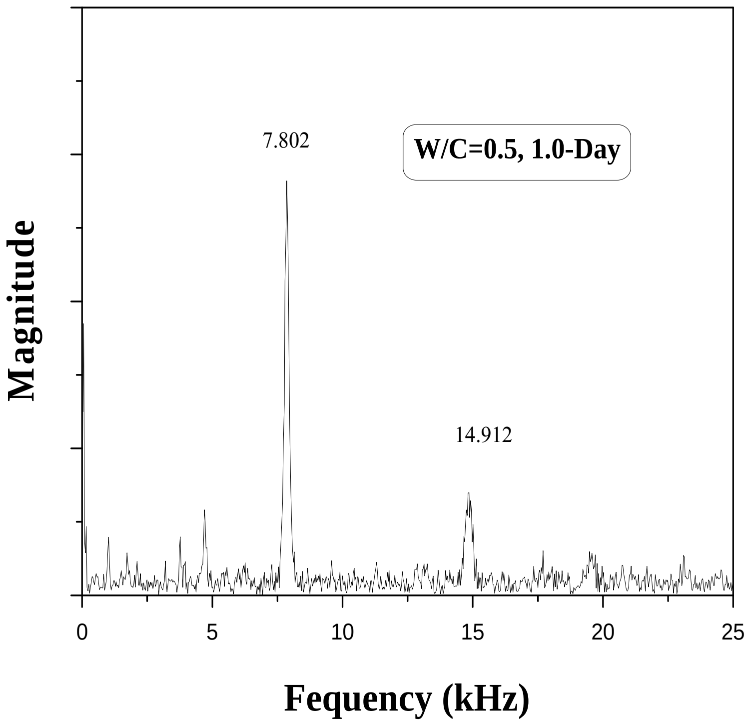


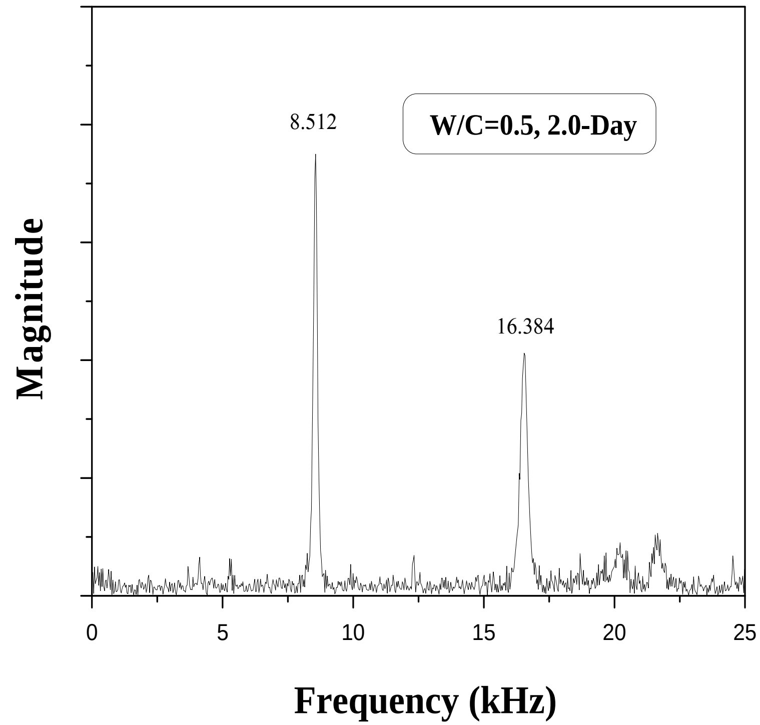
4.704
W/C=0.5 8.0 Hours
8.992
Magnitude
0
5
10
15
20
25
Frequency (kHz)



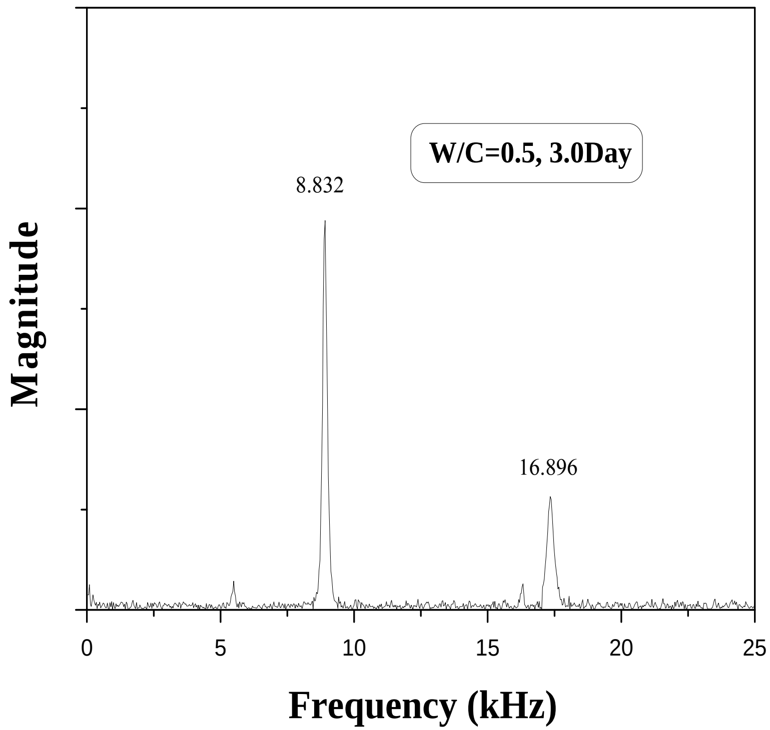
W/C=0.5, 0.5-Day
5.408
10.34
Magnitude
0
5
10
15
20
25
Frequency (kHz)

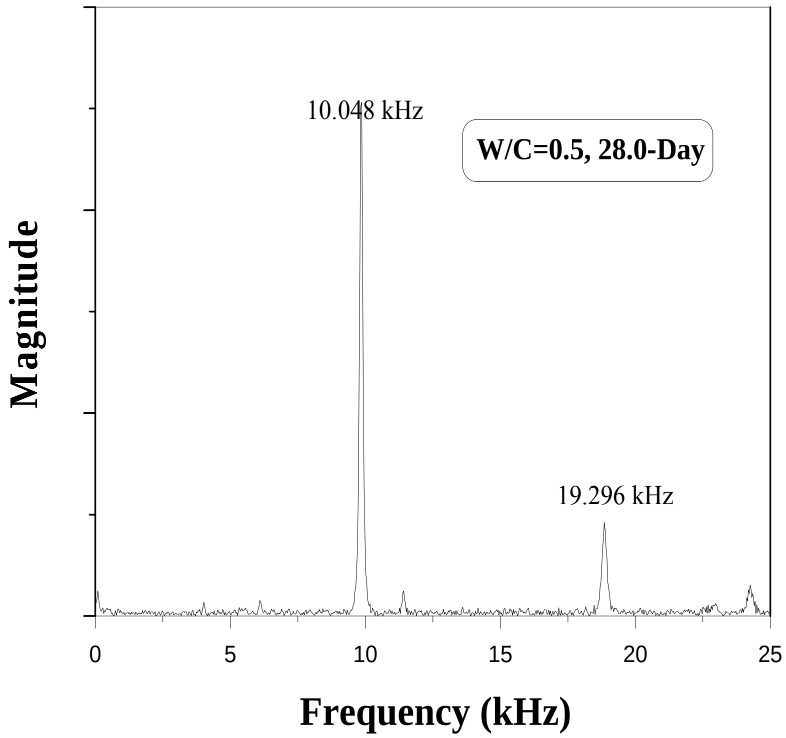
Results


Magnitude
7.802
W/C=0.5, 1.0-Day
14.912
0
5
10
15
20
25
Fequency (kHz)


Magnitude
8.512
W/C=0.5, 2.0-Day
16.384
0
5
10
15
20
25
Frequency (kHz)

Results


W/C=0.5, 3.0Day
8.832
16.896
Magnitude
0
5
10
15
20
25
Frequency (kHz)


10.048 kHz
W/C=0.5, 28.0-Day
19.296 kHz
Magnitude
0
5
10
15
20
25
Frequency (kHz)

Poison’s ratio

$$\nu = A_1\left(\frac{f_2}{f_1}\right)^2 + B_1\left(\frac{f_2}{f_1}\right) + C_1 \quad (1)$$

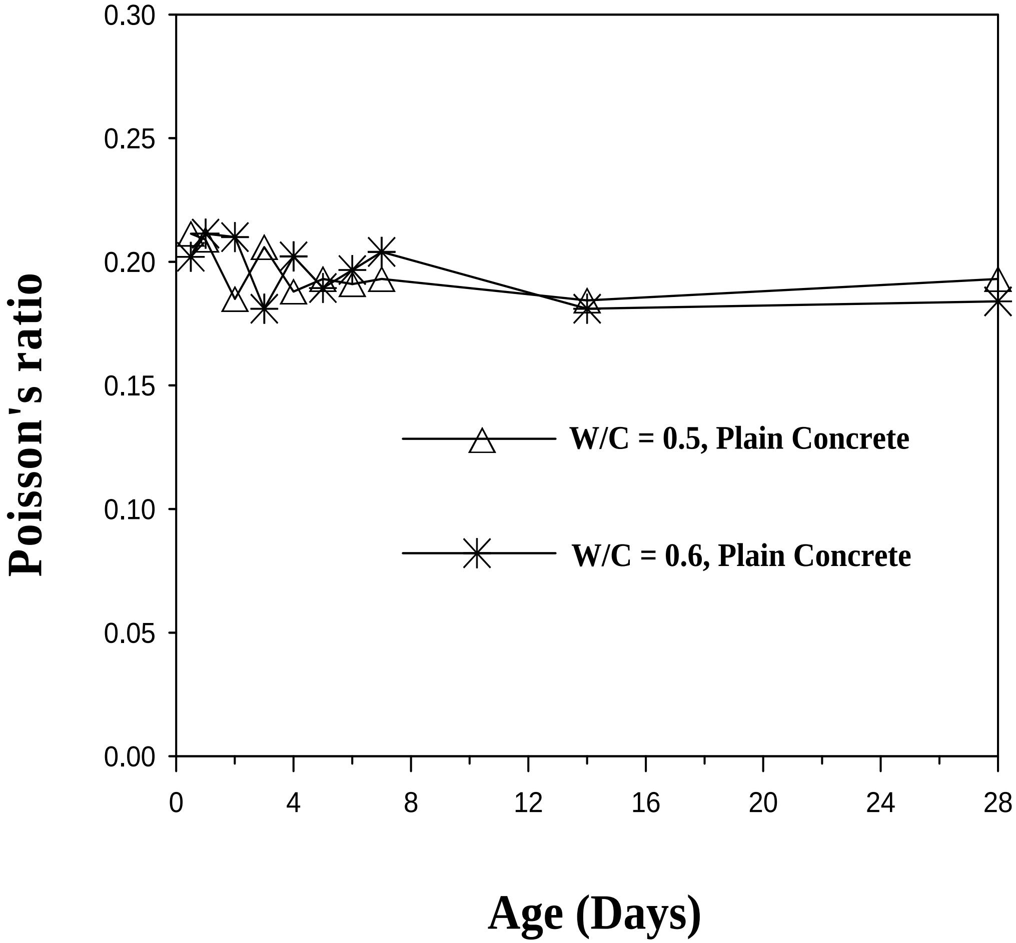
where

$$A_1 = -8.6457\left(\frac{L}{D}\right)^2 + 24.443\left(\frac{L}{D}\right) - 12.478$$

$$B_1 = 34.599\left(\frac{L}{D}\right)^2 - 101.72\left(\frac{L}{D}\right) + 56.172$$

$$C_1 = -34.681\left(\frac{L}{D}\right)^2 + 105.98\left(\frac{L}{D}\right) - 62.731$$

Poison's ratio



Dynamic modulus

$$E_d = 2(1+\nu)\rho\left(\frac{2\pi f_1 R_0}{f_n^{\,1}}\right)^2 \quad (2)$$

where

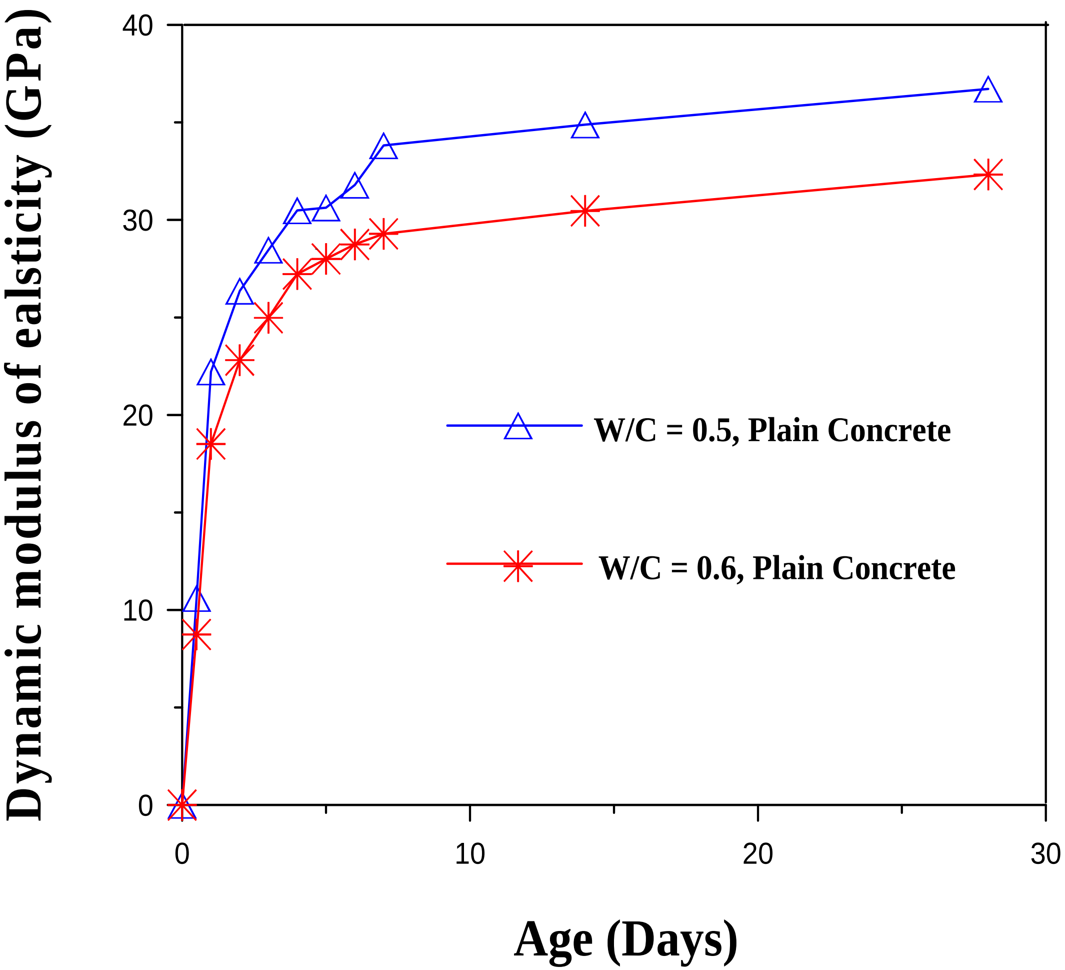
$$f_n^{\,1} = A_2(\nu)^2 + B_2(\nu) + C_2$$

$$A_2 = -0.2792\left(\frac{L}{D}\right)^2 + 1.4585\left(\frac{L}{D}\right) - 2.1093$$

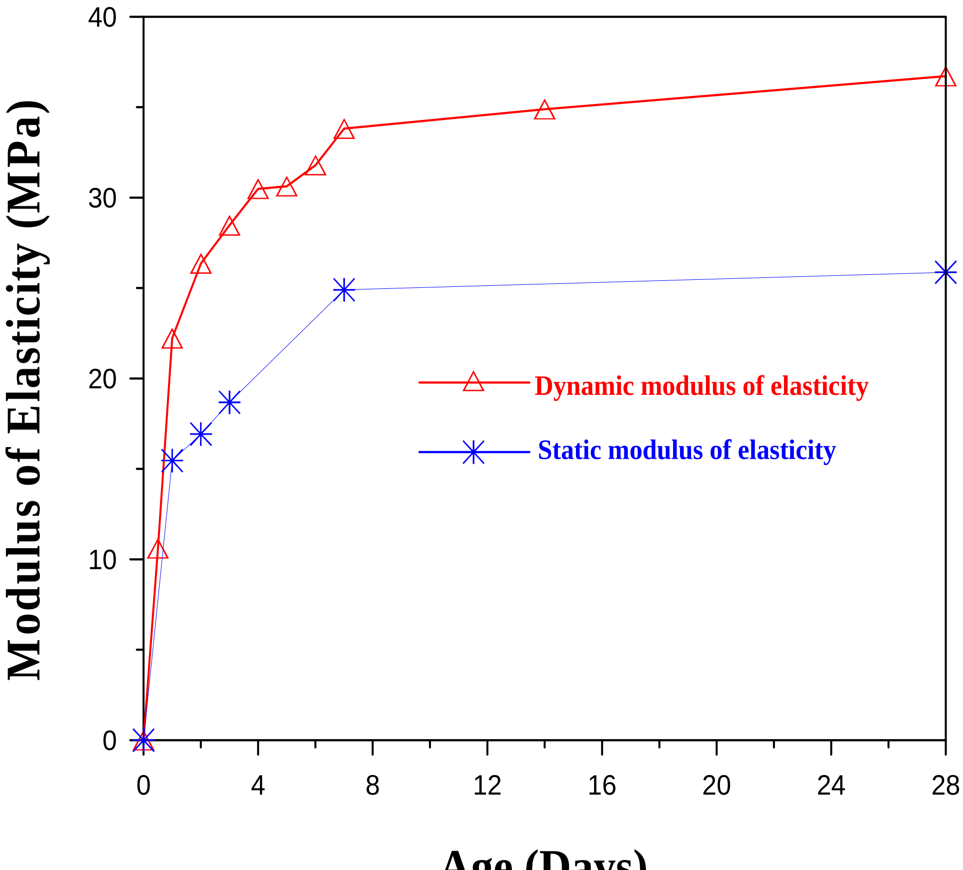
$$B_2 = 0.0846\left(\frac{L}{D}\right)^2 - 0.5868\left(\frac{L}{D}\right) + 1.3791$$

$$C_2 = 0.285\left(\frac{L}{D}\right)^2 - 1.7026\left(\frac{L}{D}\right) + 3.3769$$

Dynamic Modulus

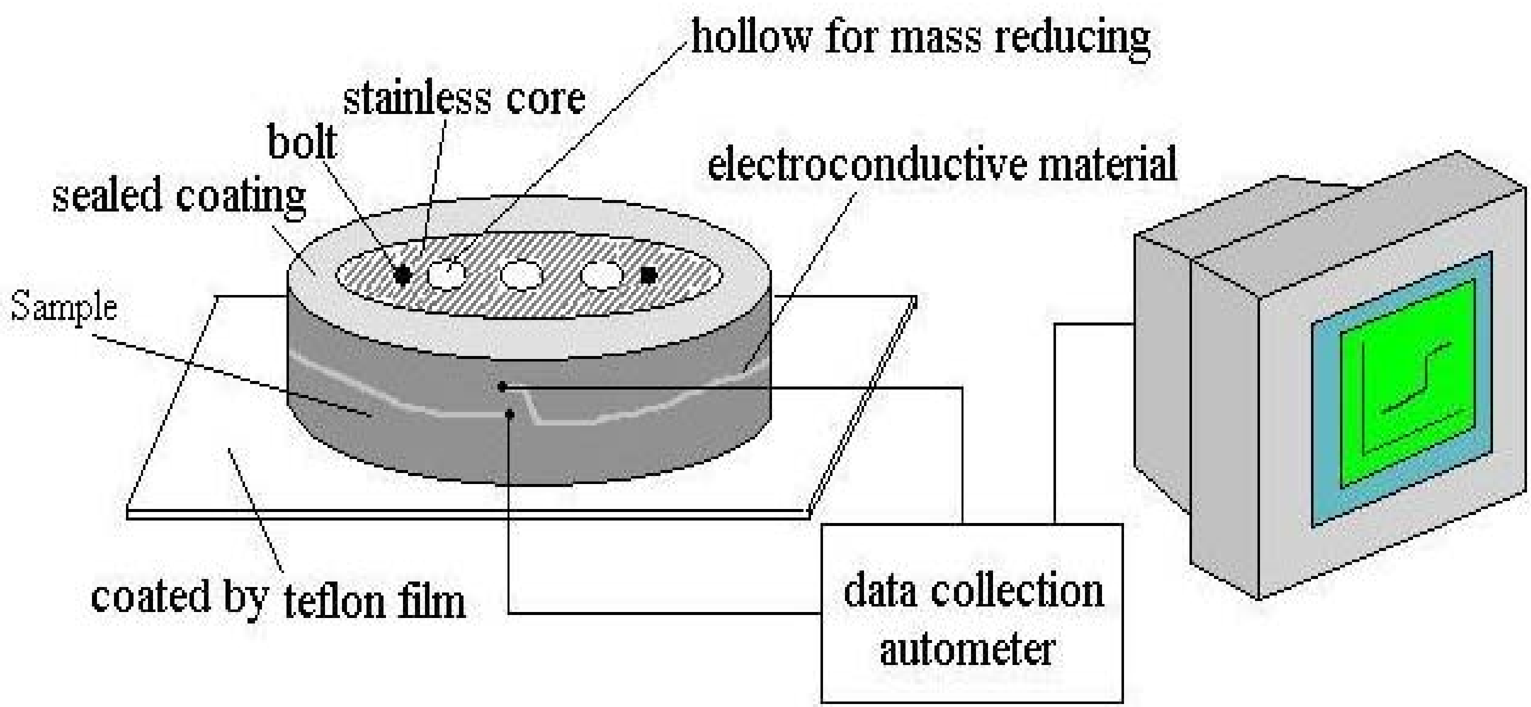


Static and dynamic modulus



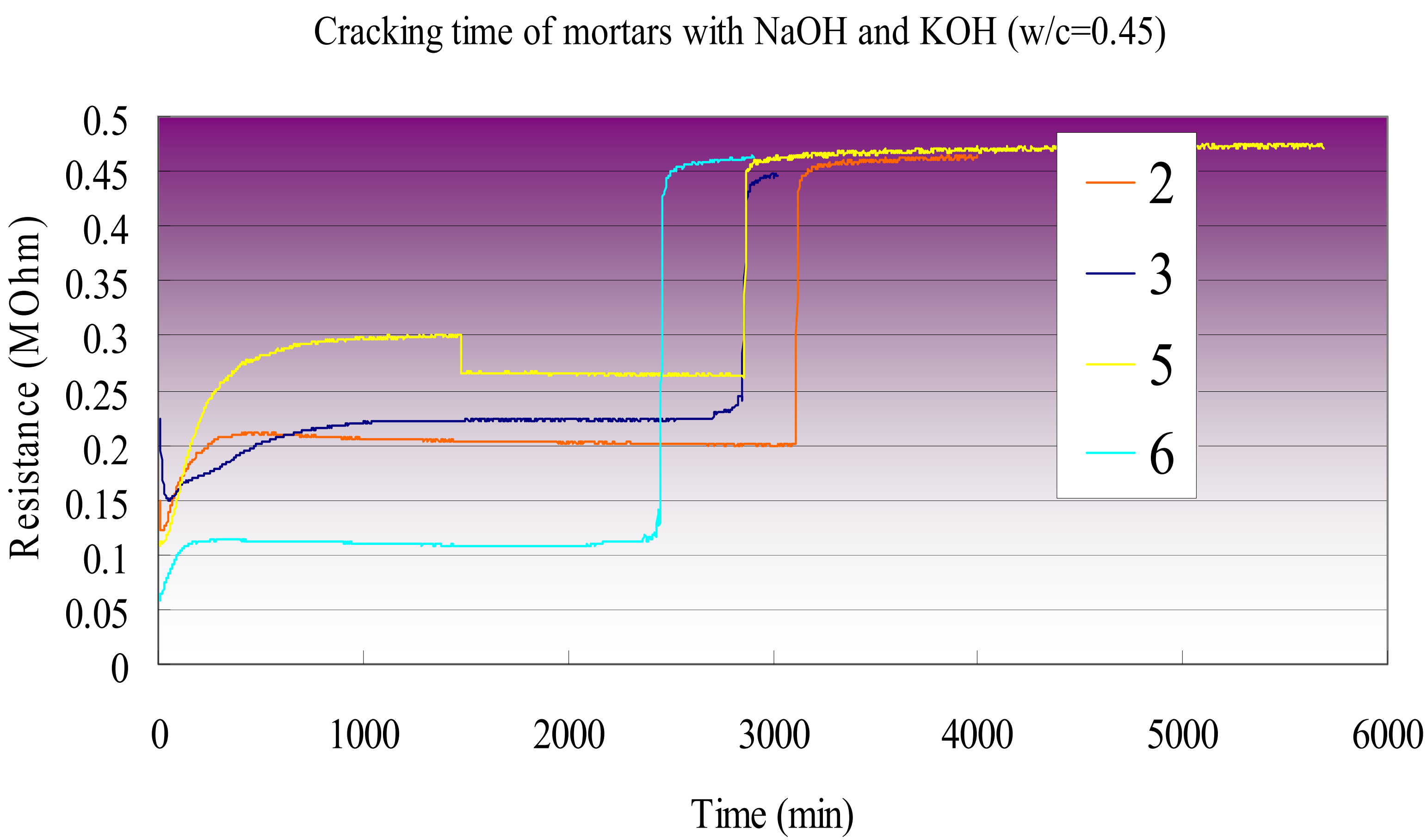
Crack sensitivity test

Crack sensitivity test



Crack sensitivity test

Crack sensitivity test



THE END

THANKS!