Special Topic in Structural Engineering: CE 783

Evaluation, Repair and Rehabilitation of Concrete Structures

Contents

INTRODUCTION

Structural System

MAJOR SYSTEMS

WALL-BEARING SYSTEM: WALLS CARRY CEILINGS THROUGH CUSHION BEAMS.

SKELETON SYSTEM: SLABS, BEAMS COLUMNS

Structural System

	Spans appropriate for resident units	Spans appropriate for large spaces	Flexibility	First cost	Impact on other system costs	Appearance	Material delivery and construction timing	Impact on interior space and building height	Responds to current and future codes	Familiar to local construction industry	Impacted by soil conditions
Wood Frame	○	⊘	○	○	○	○	○	○	⊘	○	○
Structural stud	○	⊘	○	○	○	○	○	○	○	⊘	○
Bearing wall and concrete plank	○	X	X	○	⊘	⊘	⊘	○	○	○	⊘
Steel and concrete plank	○	○	○	⊘	⊘	⊘	⊘	X	○	○	○
Steel and poured concrete deck	○	○	○	⊘	⊘	○	⊘	X	○	○	○
Precast concrete	○	○	⊘	⊘	⊘	○	⊘	⊘	○	⊘	○
"Beam & Slab" poured in place concrete	○	○	○	⊘	○	⊘	○	○	○	○	○
"Flat plate" poured in place concrete	○	⊘	⊘	⊘	○	○	○	○	○	○	○
Prestressed/post-tensioned concrete	○	○	⊘	X	○	○	○	○	○	X	○

○ Not often a significant issue

⊘ May be a problem or issue

X Often a significant problem or issue

Source: Perkins Eastman Architects PC.

Post-tensioned Girders

Post-tensioned Girders

Typical Building Components

- » Slabs
- »Beams
- »Columns
- » Shear Walls
- » Bearing Walls
- » Foundations

CONSTRUCTION STAGES

- **PRE-CONSTRUCTION STAGE**
  - Studying The Engineering Properties of Soil Layers in order to determine:
    - Appropriate Foundation depth.
    - Soil bearing capacity.
    - Whether Piles are needed or not.
    - Appropriate type of foundation.
    - Water level.
    - Chemical composition of soil and water.
    - Secure neighboring structures.

CONSTRUCTION STAGES

- **ARCTICTURAL DESIGN**
  - Dictated by land topography and esthetic view.

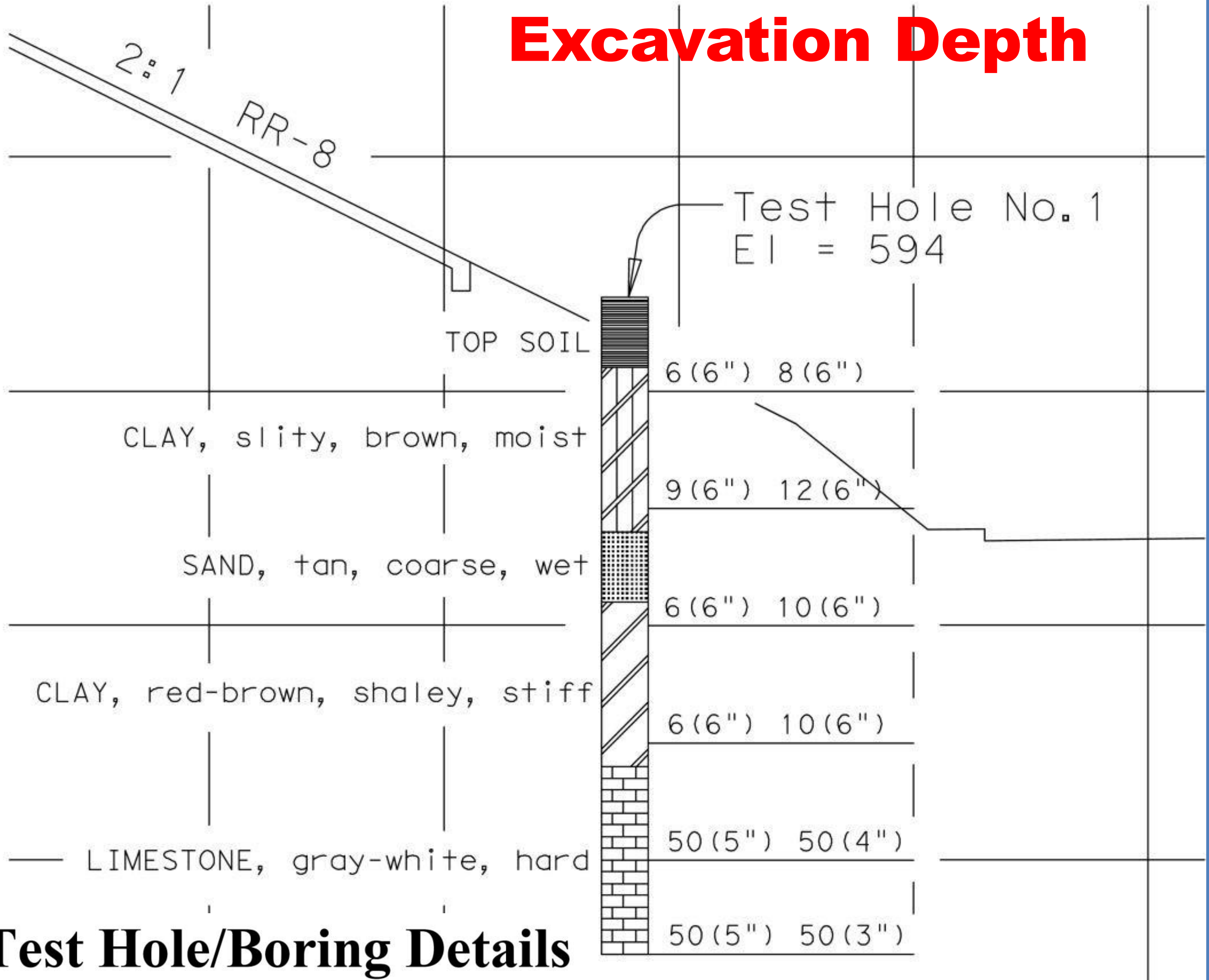
- **STRUCTURAL DESIGN**
  - Foundation Depth.
  - Bearing Capacity of Soil.
  - Live and Dead Loads Imposed.
  - Earth Quake Activity of The Region.
  - Construction Materials Properties.

CONSTRUCTION STAGES

Construction materials

- Selection of appropriate aggregates and cement type.
- Design of concrete mixture such that Fresh and Hardened Concrete Properties satisfy strength and durability requirements.

Excavation Depth



Test Hole/Boring Details

CONSTRUCTION STAGES

CONSTRUCTION PROCEDURES

- Carrying out Pore Hole Test To Ensure Establishing the Foundation on Solid Soil Layers.
- Ensuring the Safety of Neighboring Buildings and Infrastructures.
- Storing Construction Materials in Dry Places.
- Testing of Materials.

CONSTRUCTION STAGES

- **CONSTRUCTION PROCEDURES**
  - » Matching Column and Foundation Axes with Engineering Plans.
  - » Ensuring Columns and Abutments are Straight and Vertical.
  - » Checking Quantities and Distribution of Reinforcing Steel.
  - » Ensuring Appropriate Casting of Concrete.
  - » Ensuring Safety of Sanitary System.

concrete

Concrete Materials

- Cement Paste ▷
- Aggregate ▷
- Concrete Structure ▷
- Concrete Mix Design
- Reinforcing Steel ▷

CAUSE OF DETERIORATION & DURABILITY ASPECTS

Faults in Concrete Structures

Non-structural Faults ((Materials

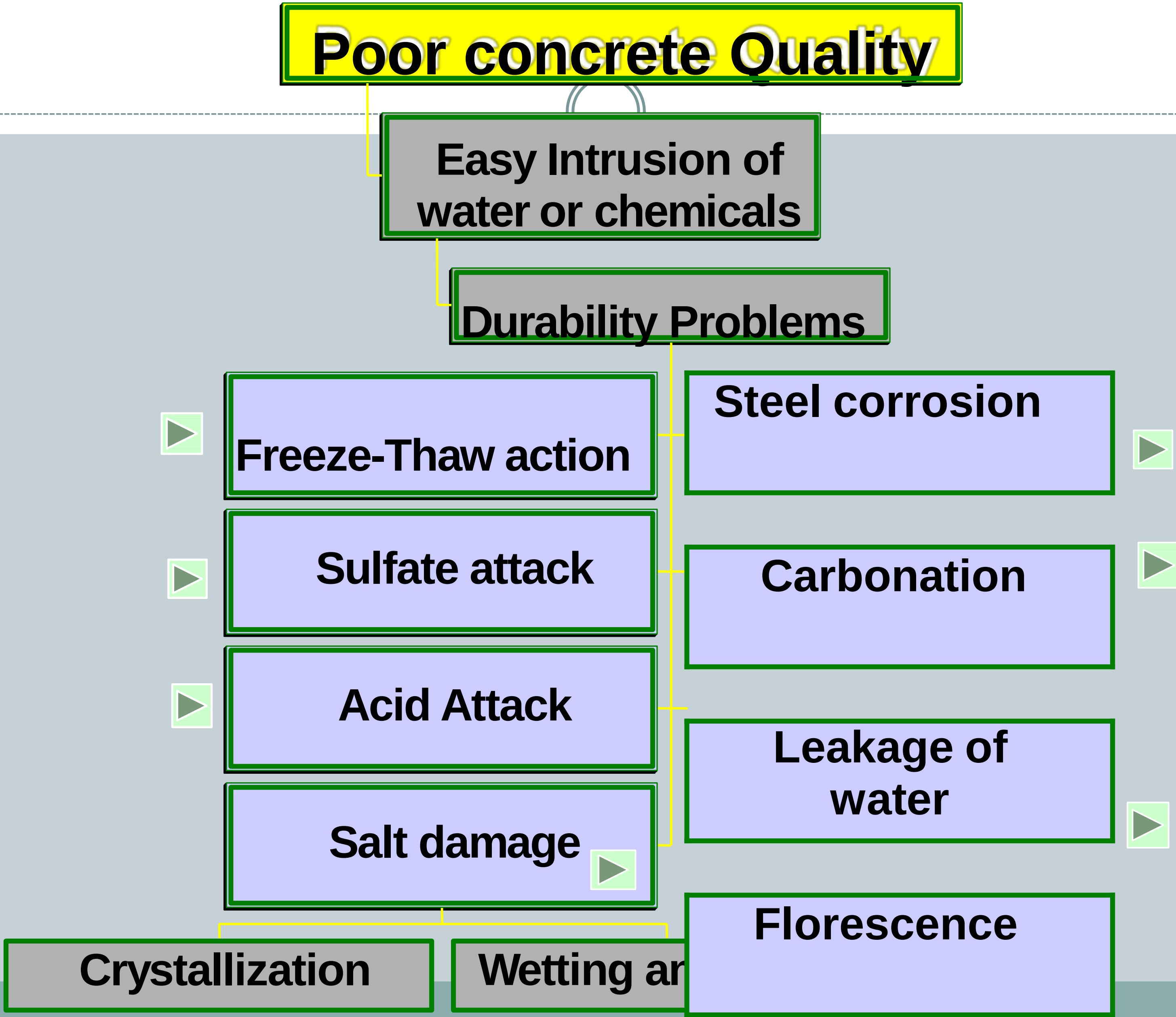
Sources

- Poor Concrete Quality
- Improper selection of materials
- Improper Constructio n Practices
- Exposure to sever Conditions

Structural Faults
Structural Faults

Sources

- Faults in Structural Design
- Foundations Problems
- Improper Structural Related Construction Practices
- Over-Loading & Excessive Deflection
- Lack of Expansion Joints


Poor concrete Quality
Easy Intrusion of water or chemicals
Durability Problems
Freeze-Thaw action
Sulfate attack
Acid Attack
Salt damage
Steel corrosion
Carbonation
Leakage of water
Florescence
Crystallization
Wetting ar

Improper Selection of Materials

- ***Impure water***
  - ***Steel corrosion***
  - ***Weak concrete***
  - ***Delay cement reactions***
- ***Reactive Aggregate***
  - ***Thermal stresses***
  - ***Sulfate attack***
  - ***Alkali silica reaction(ASR)***
- ***Cements***
  - ***Plastic Shrinkage***
  - ***Tempreture Gradient***
  - ***Expansion***
  - ***Harmful reaction***
  - ***Low strength***

Construction Faults

- Segregation
- Frame-work settlement
- Honeycombing
- Insufficient concrete cover
- Over compaction of concrete
  - Bleeding
  - Segregation
- Insufficient compaction
  - High void ratio (%)
  - Concrete settlement cracks
- Improper wetting, curing or covering of concrete
  - Plastic shrinkage
  - Low strength concrete
- Poor concrete quality
  - Non-homogenous mixture
  - High water content
- Miss-positioned reinforcing steel (Tendons)
- Low Prestressing Force (Girders)

Permeability and Durability

The durability of concrete is one of its important properties because it is essential that concrete should be capable of withstanding conditions for which it has been designated throughout the life of the structure.

According to Darcy's Equation:

$$\frac{1}{A}\frac{dq}{dt} = k\frac{\Delta h}{L}$$

where $\frac{dq}{dt}$ is the rate of flow of water,

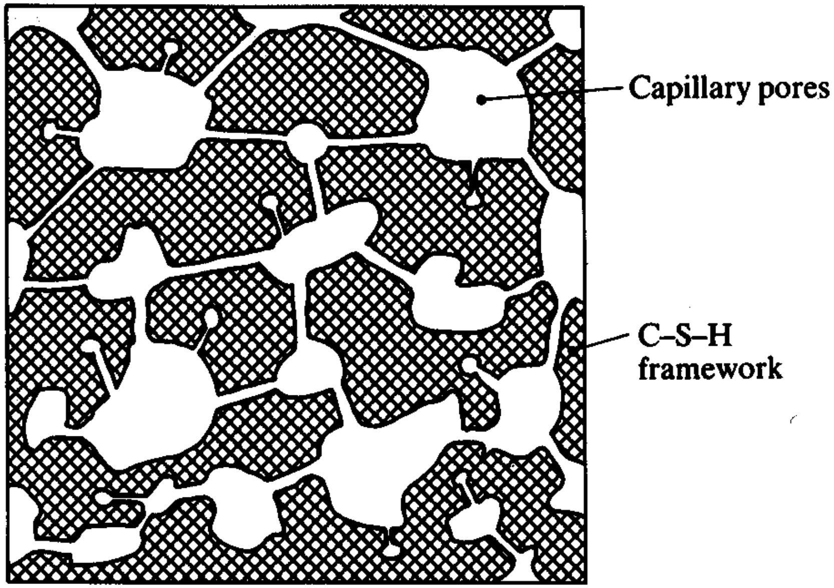
A is the cross-sectional area of the sample,

Δh is the drop in hydraulic head through the sample, and

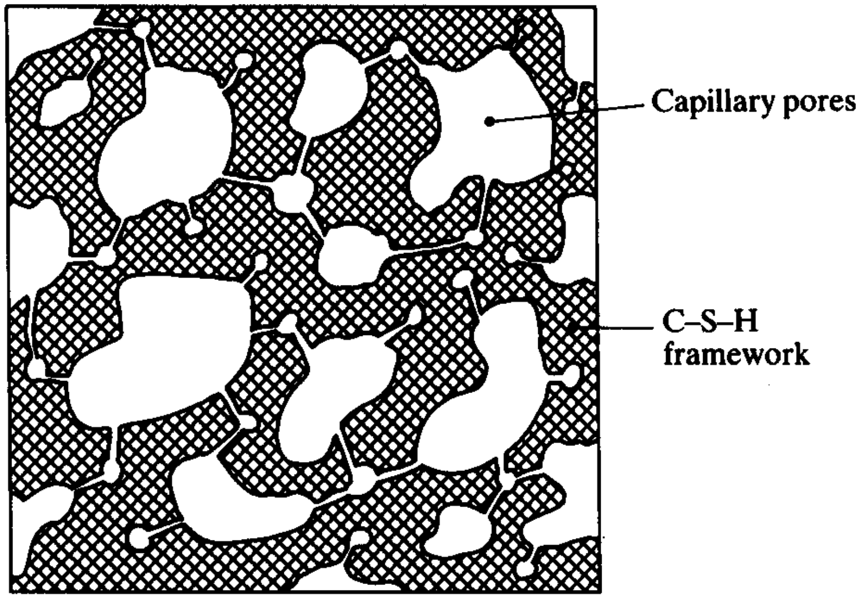
L is the thickness of the sample.

Permeability and Durability

Schematic representation of materials of similar porosity.



(a)



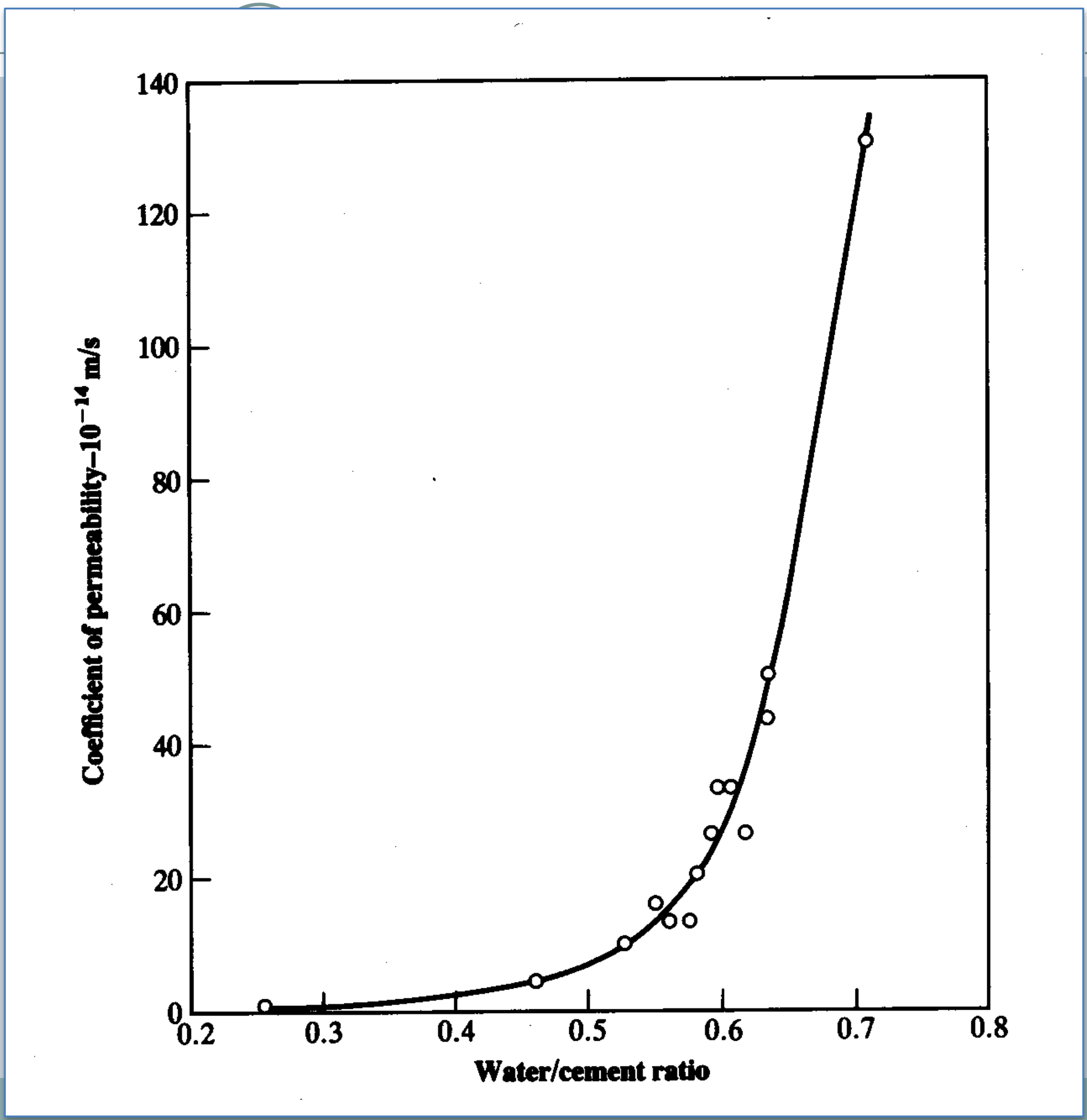
(b)

High permeability-capillary pores connected by large passages;

Low permeability-capillary pores segmented and only partly connected

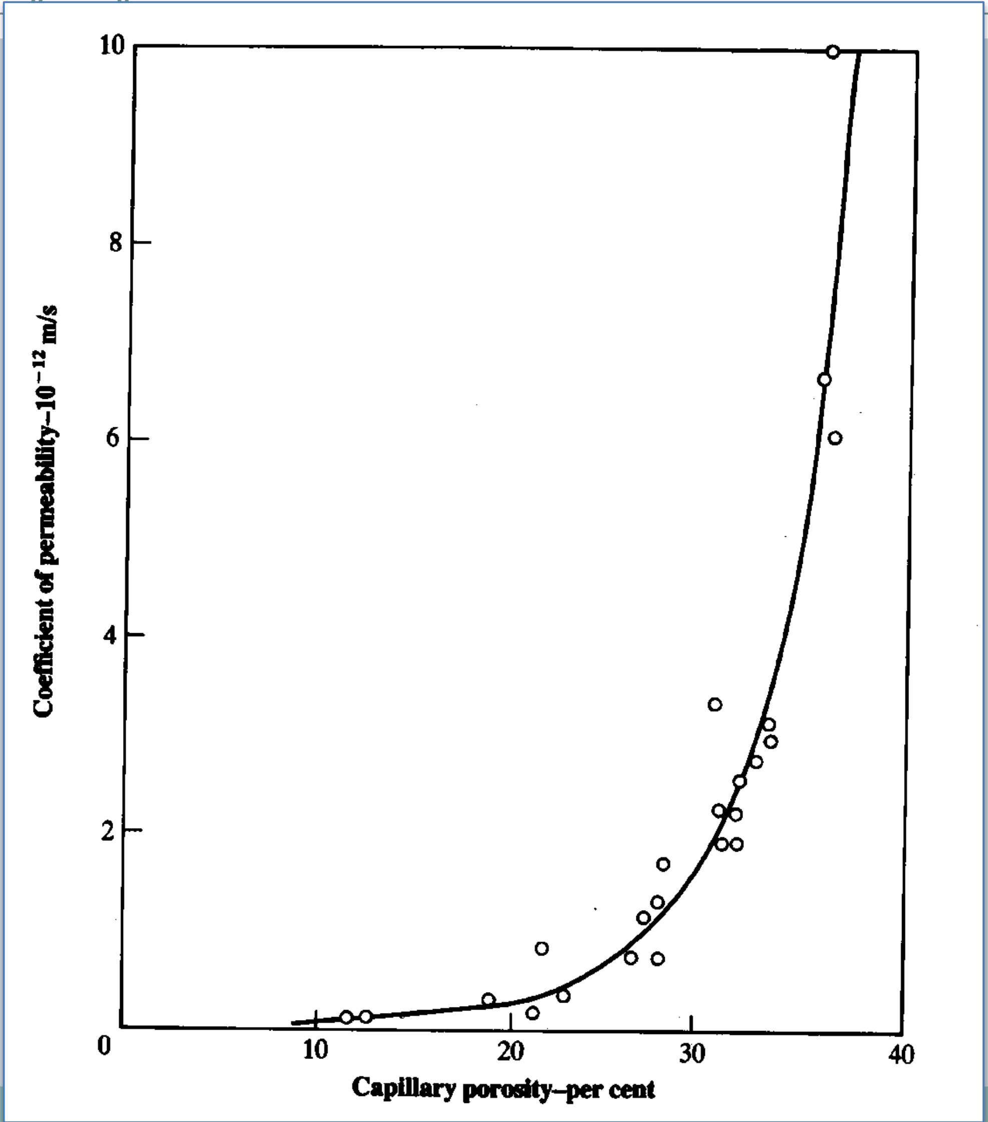
Permeability and Durability

Relation between permeability and capillary porosity of cement paste.



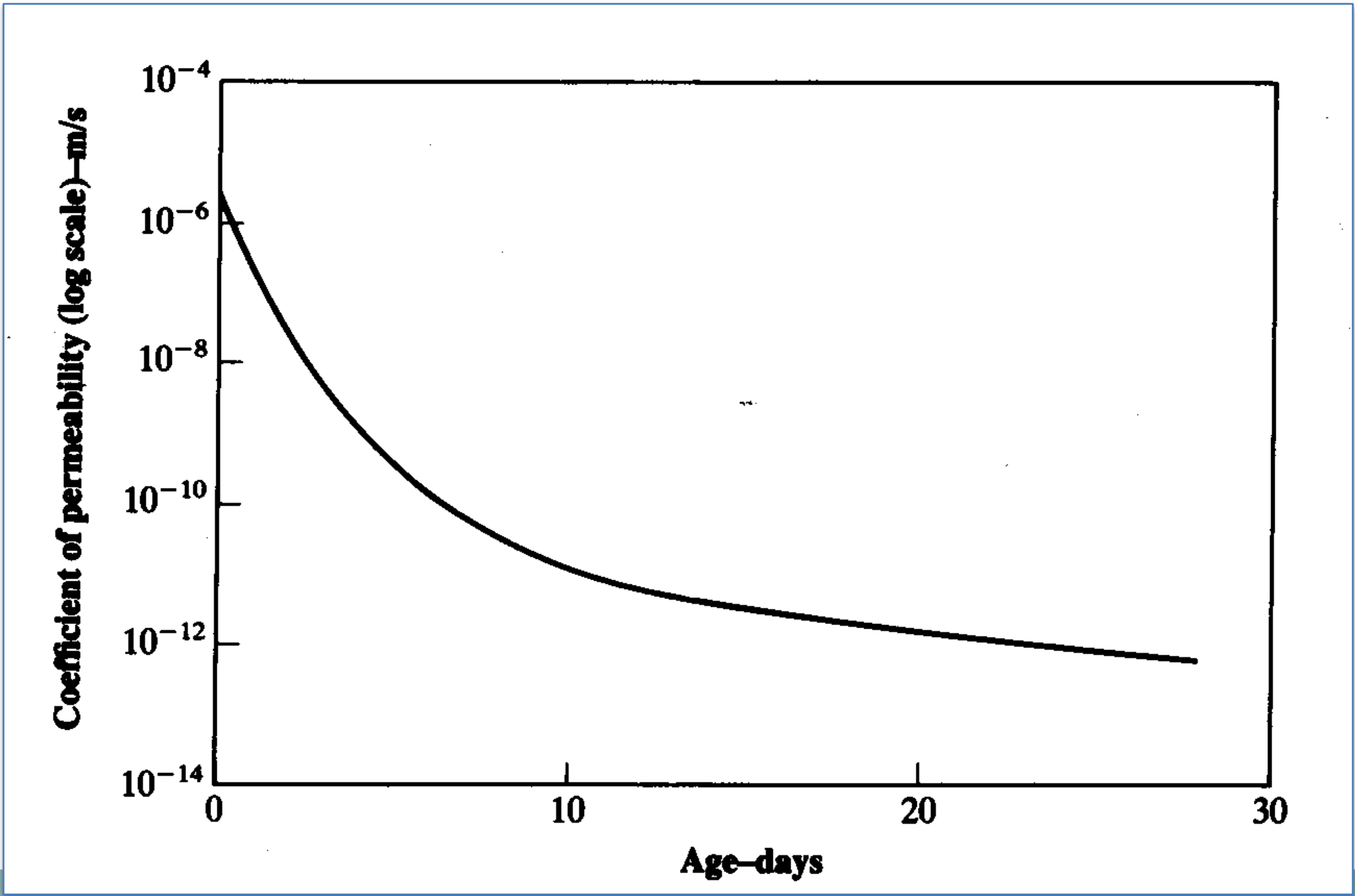
Permeability and Durability

Relation between permeability and W/C ratio for mature cement paste.



Permeability and Durability

Reduction in permeability of cement paste with the progress of hydration (W/C ratio = 0.7).



Reinforcing Steel Corrosion

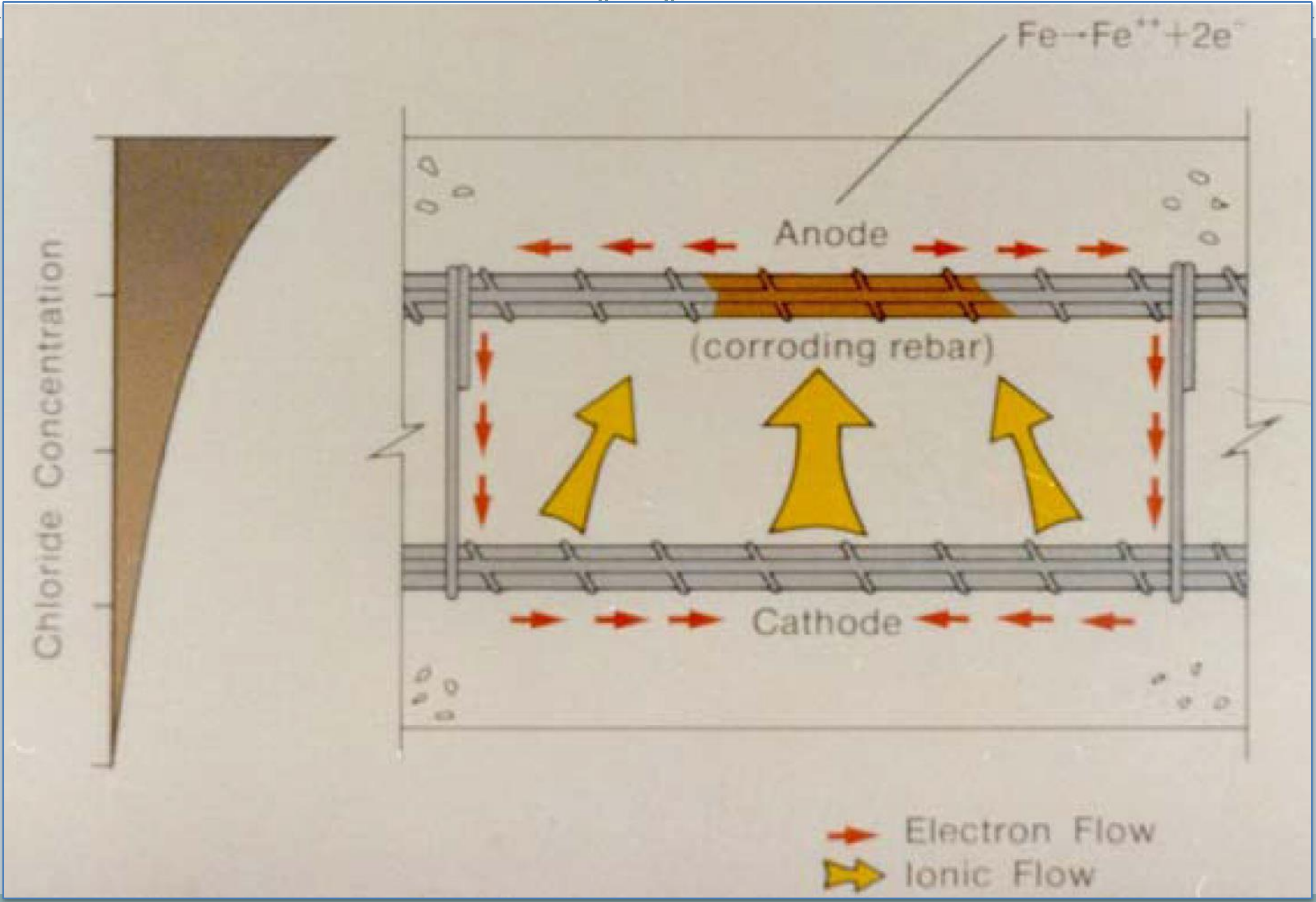
The strongly alkaline nature of Ca(OH)2 (pH=13) prevents the corrosion of the steel reinforcement by the formation of thin protective film of iron oxide on the metal surface: this protection is known as passivity.

To break passivity:

- Carbonation of concrete with contact of steel
- Penetration of soluble chlorides to reinforcement.

- Corrosion of steel occurs because of electro-chemical action which is usually encountered when two dissimilar metals are in electrical contact in the presence of moisture and oxygen. The same process takes place in steel alone because of the difference in the electro-chemical potential on the surface which forms anodic and cathodic regions; connected by the electrolyte in the form of the salt solution in the hydrated cement.

Steel Corrosion: Chloride Induced



Steel Corrosion

anodic reactions:

$$Fe \rightarrow Fe^{++} + 2e^-$$
$$Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2 \quad \text{(ferrous hydroxide)}$$
$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \quad \text{(ferric hydroxide)}$$

cathodic reaction:

$$4e^- + O_2 + 2H_2O \rightarrow 4(OH)^-.$$

For corrosion to be initiated, the passivity layer must be penetrated. Chloride ions activate the surface of the steel to form an anode, the passivated surface being the cathode. The reactions involved are as follows:

$$Fe^{++} + 2Cl^- \rightarrow FeCl_2$$
$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl.$$

Steel Corrosion: Chloride Induced

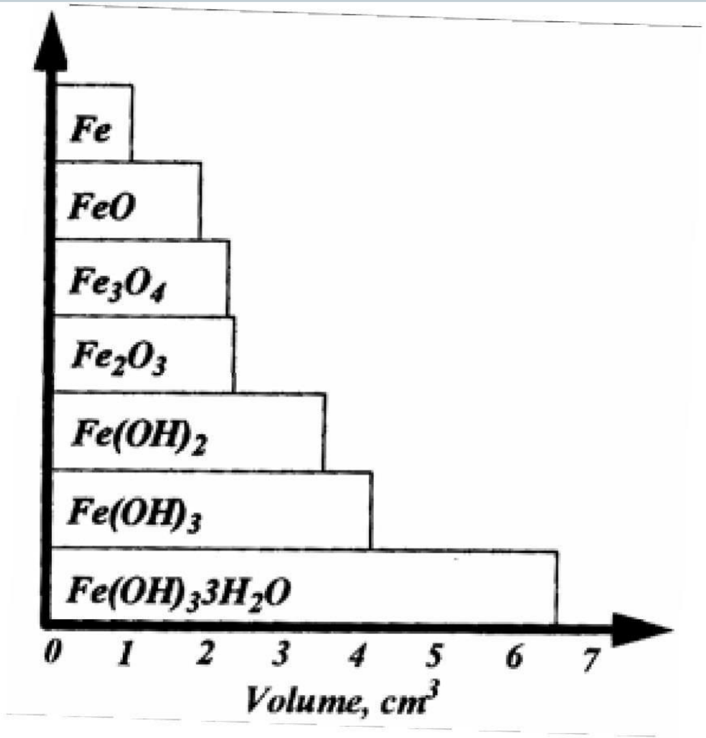
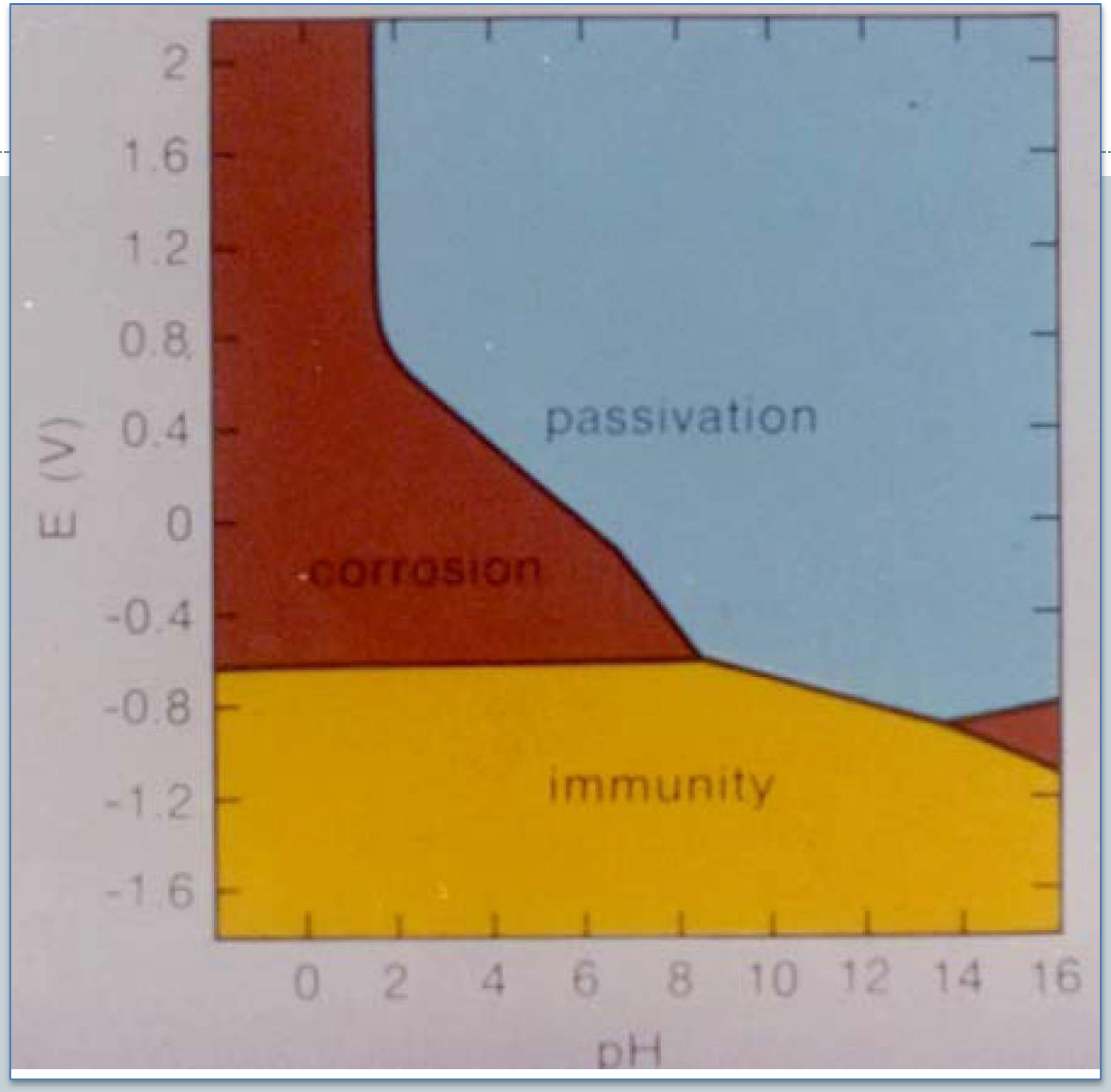
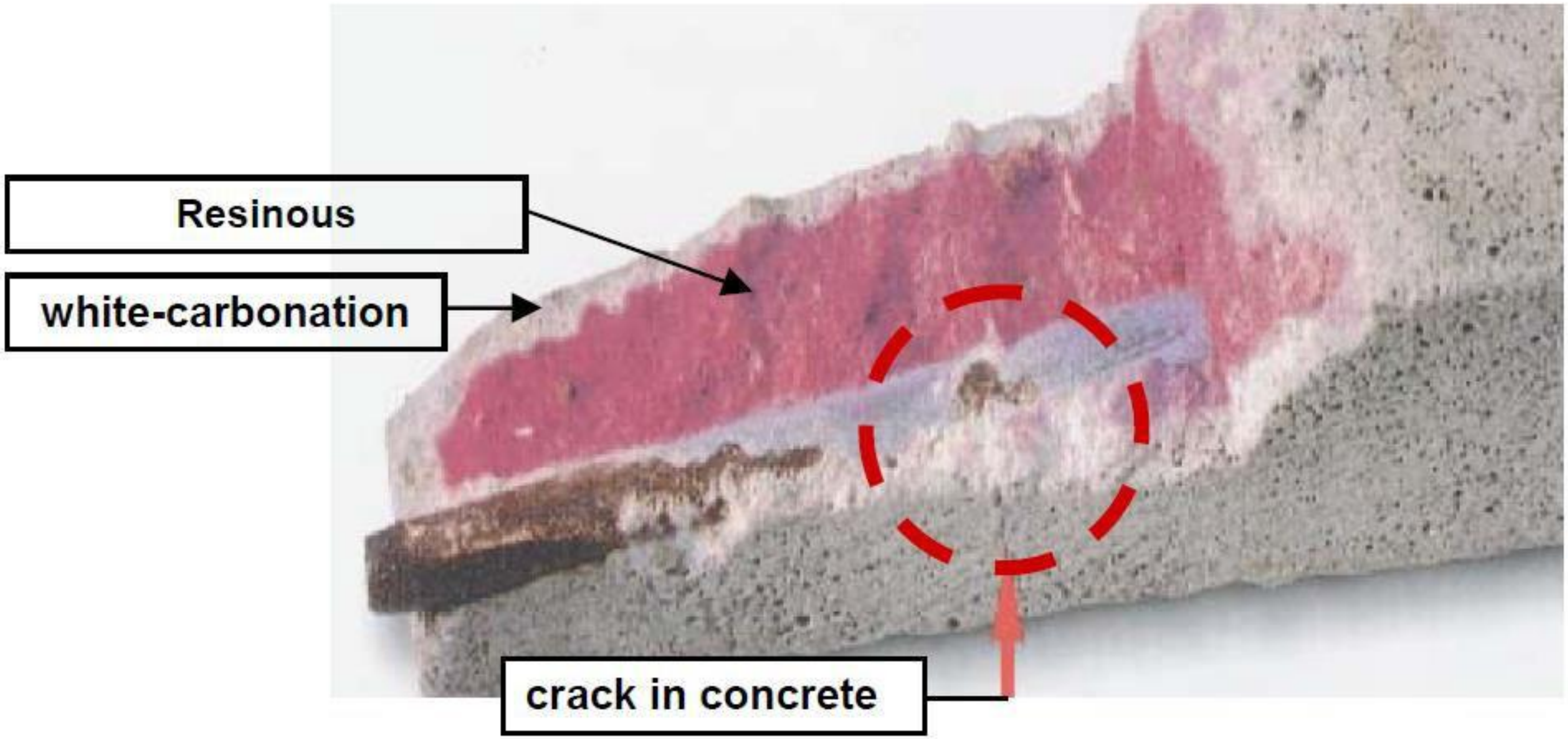


Diagram of the progression of rust over time during corrosion.

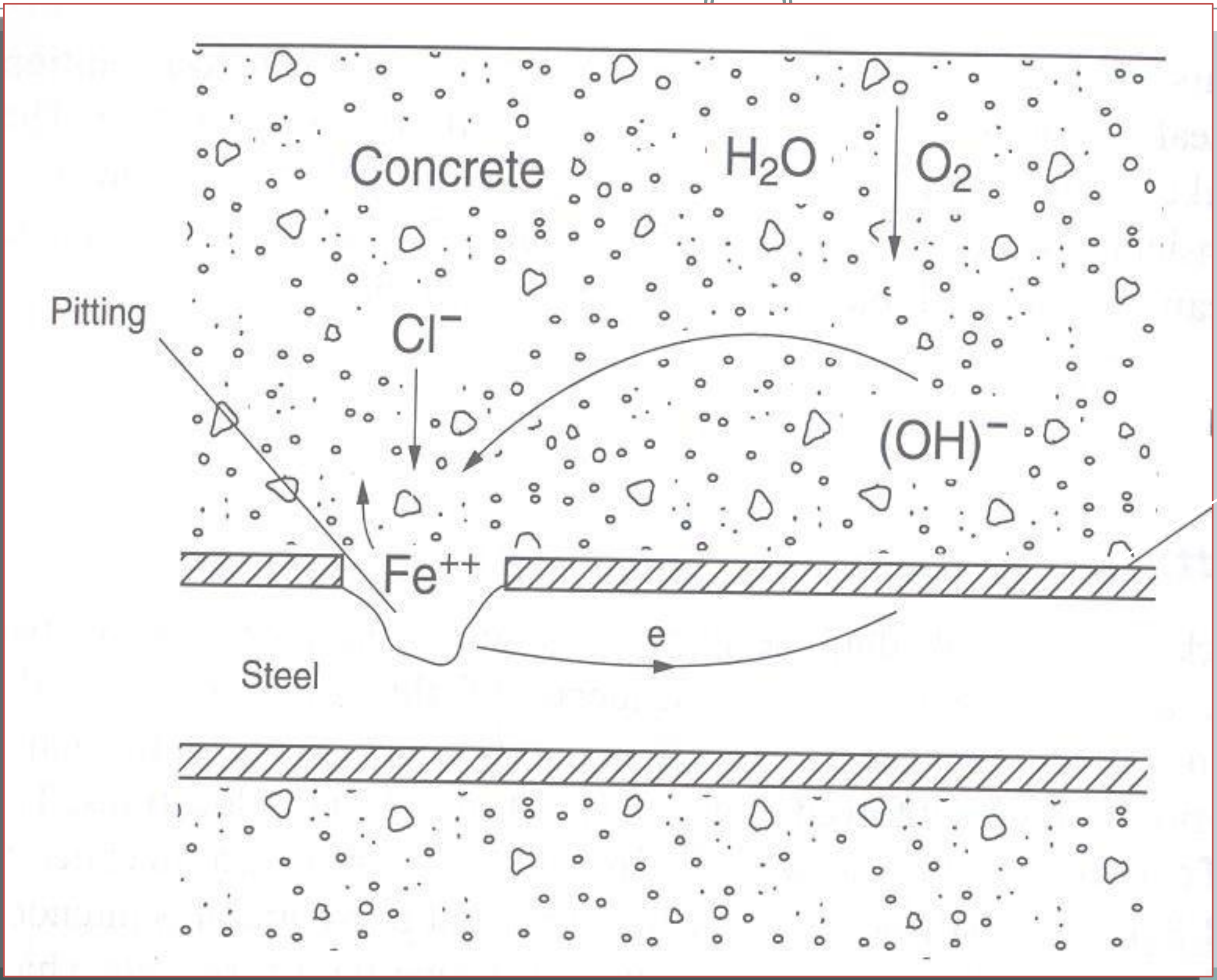


Steel-Water Pourbaix Diagram.

Carbonation of concrete



Steel Corrosion: Chloride Induced

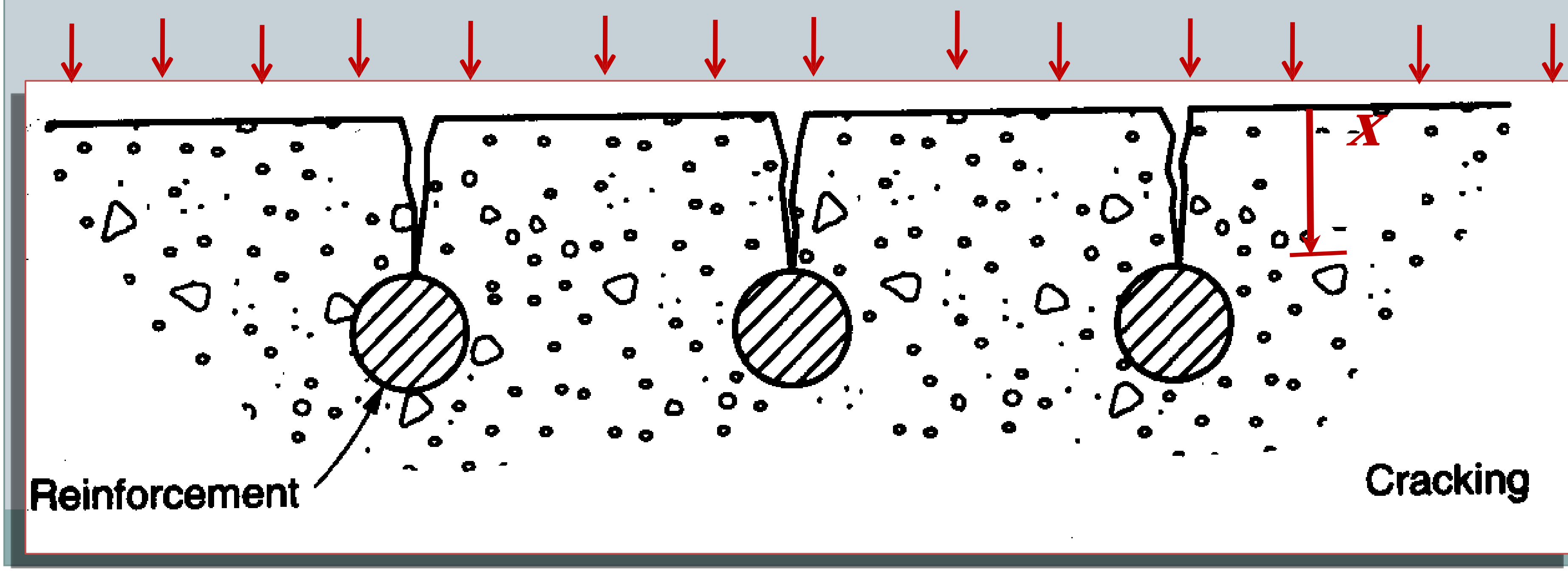


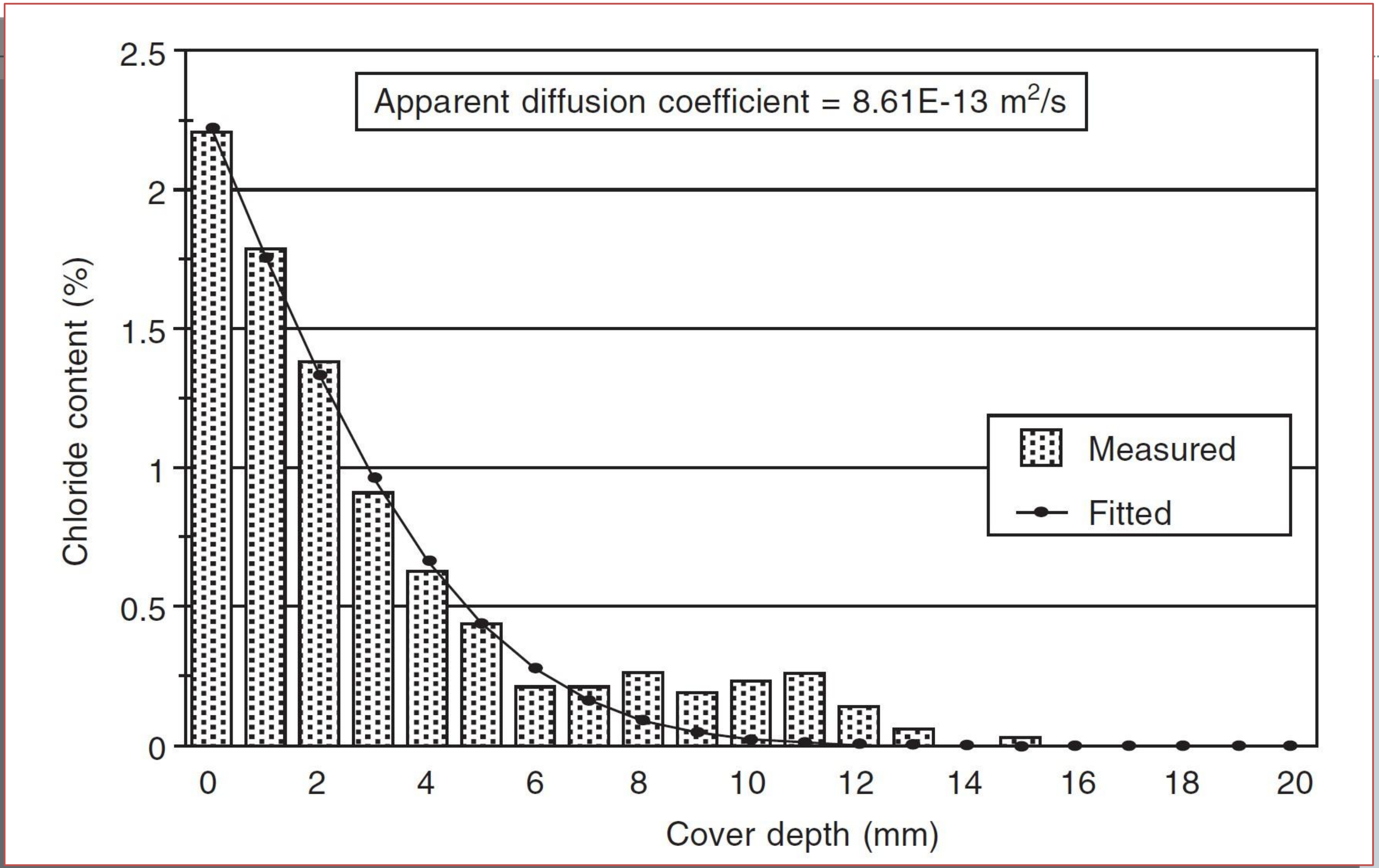
Passivity Layer

following formula:

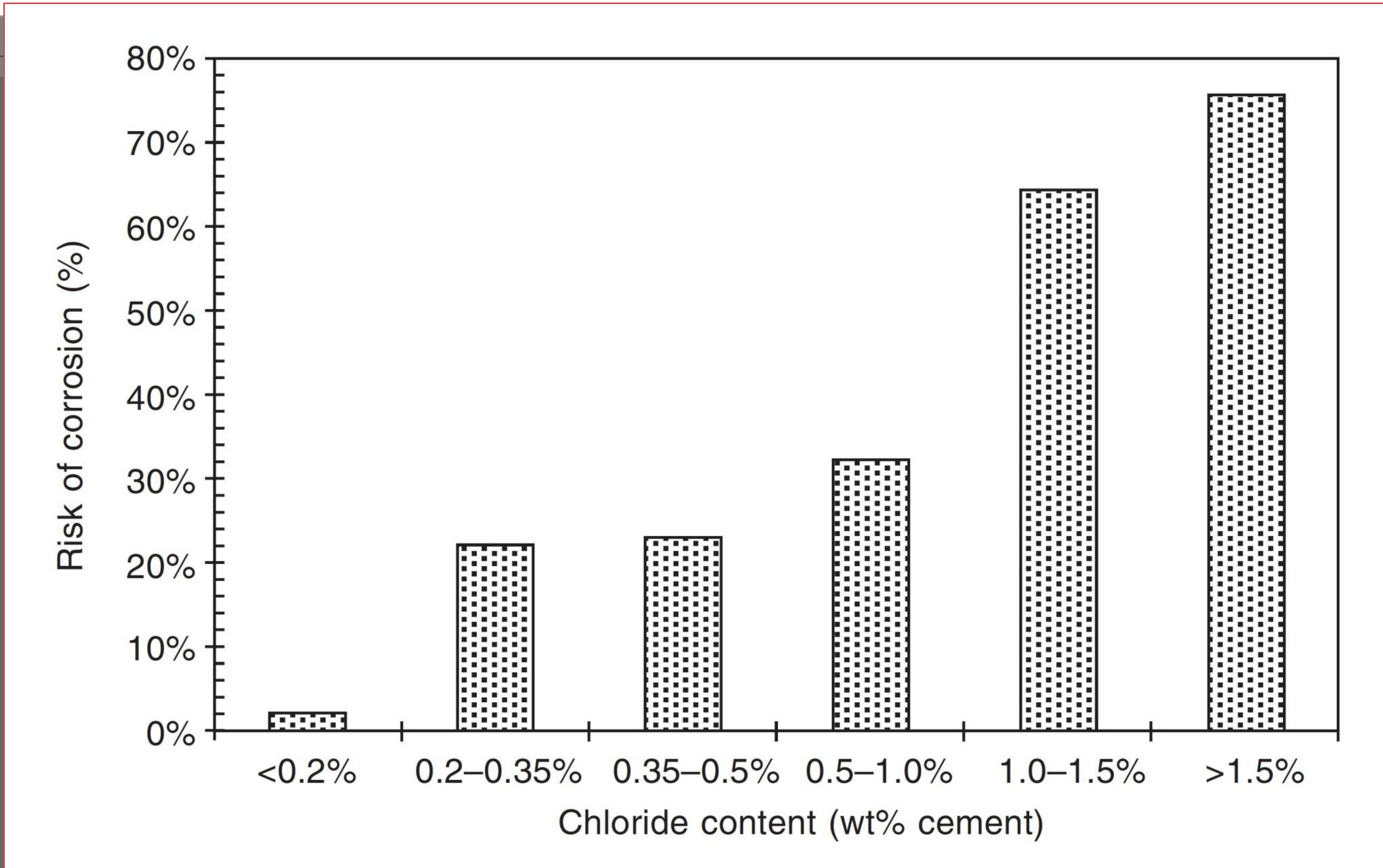
$$C(x,t) = C_0 \operatorname{erfc}\left(\frac{x}{2\sqrt{D_p t}}\right)$$

Where, C(x,t) is the concentration of chloride at depth x from surface after time t; Dp is the diffusion coefficient, and erfc is the error function.





Chloride profile in concrete.

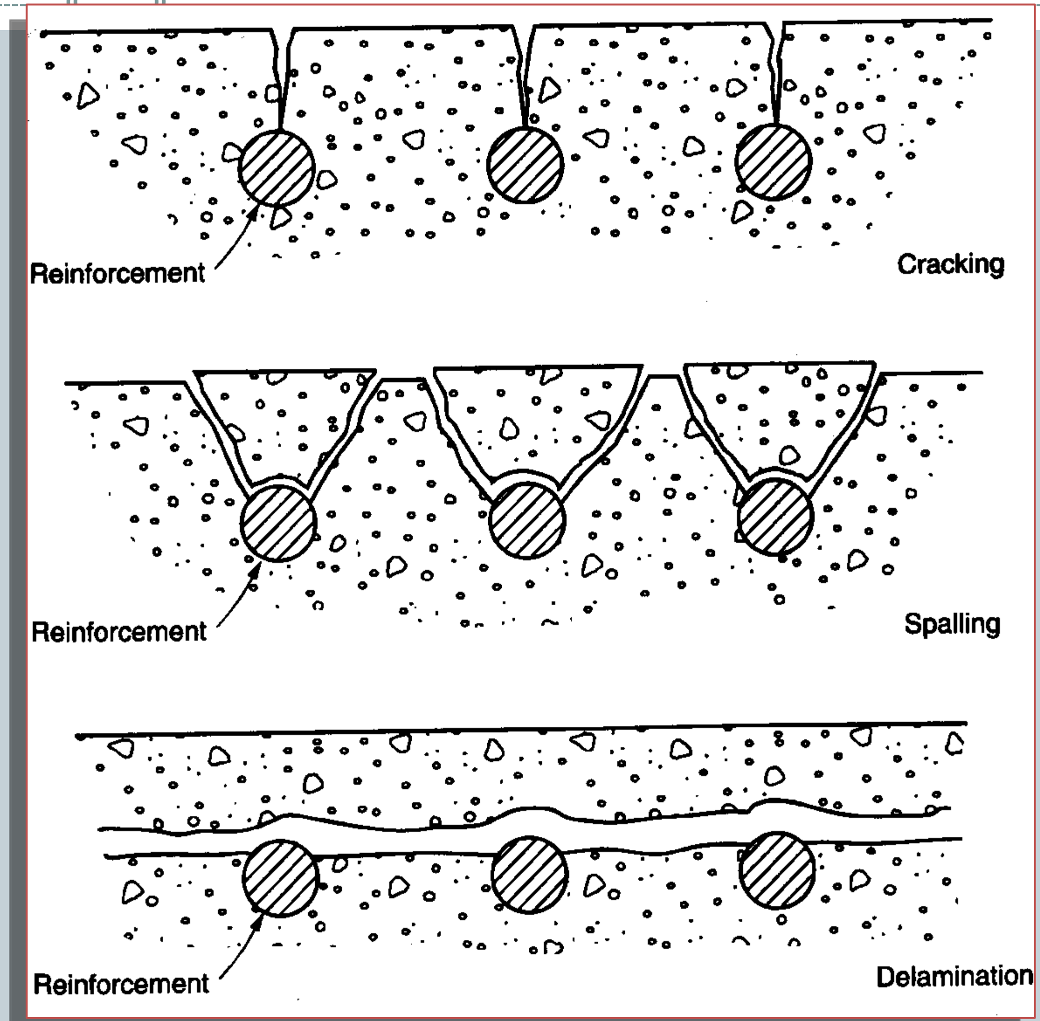


Risk of corrosion initiation as a function of the chloride content (Vassie, 1984)

Steel Corrosion-Damage

Diagrammatic representation of damage induced by corrosion:

- ✓Cracking
- ✓Spalling
- ✓Delamination



✓**Spalling**

✓**Delamination of A Concrete Beam**

✓Delamination of Concrete Slab

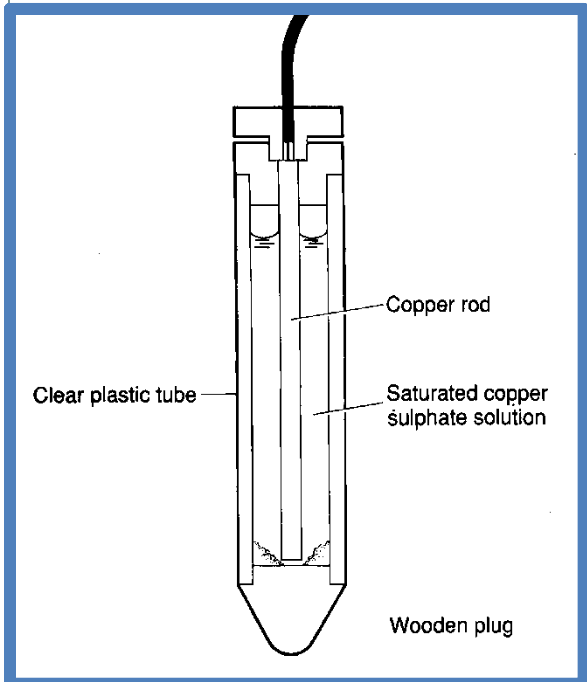
Steel Corrosion: Chloride Induced

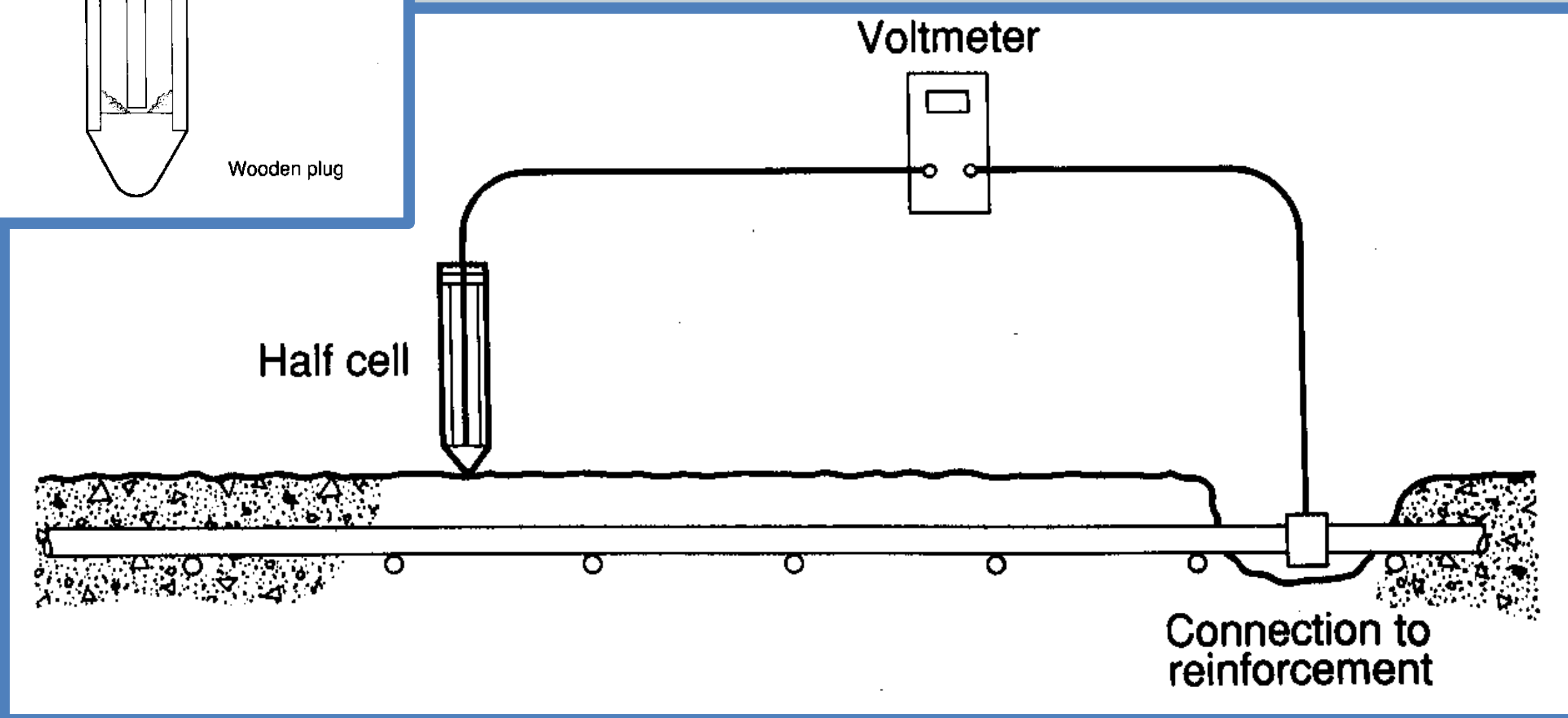
Requirements of ACI 318-89 for W/C ratio and strength for special exposure conditions.

Exposure condition	Maximum water/cement ratio, normal density aggregate concrete	Minimum design strength* in MPa (psi), low density aggregate concrete
Concrete intended to be watertight:		
(a) exposed to fresh water	0.50	25 (3630)
(b) exposed to brackish or sea water	0.45	30 (4350)
Concrete exposed to freezing and thawing in a moist condition:		
(a) kerbs, gutters, guardrails or thin sections	0.45	30 (4350)
(b) other elements	0.50	25 (3630)
(c) in presence of de-icing chemicals	0.45	30 (4350)
For corrosion protection of reinforced concrete exposed to de-icing salts, brackish water, sea water or spray from these sources	0.40†	33 (4790)†

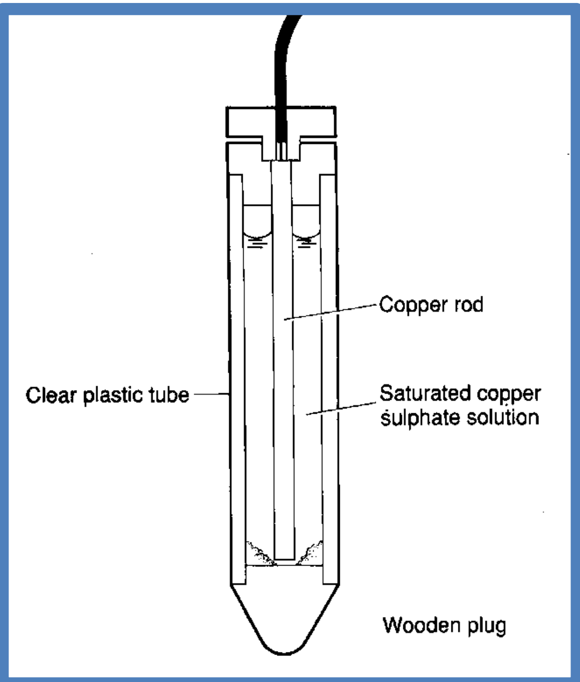
* See page 330.
† If minimum cover required by Table 14.7 is increased by 10 mm ($\frac{1}{2}$ in.), water/cement ratio may be increased to 0.45 for normal density concrete or design strength reduced to 30 MPa (4350 psi) for low density concrete.

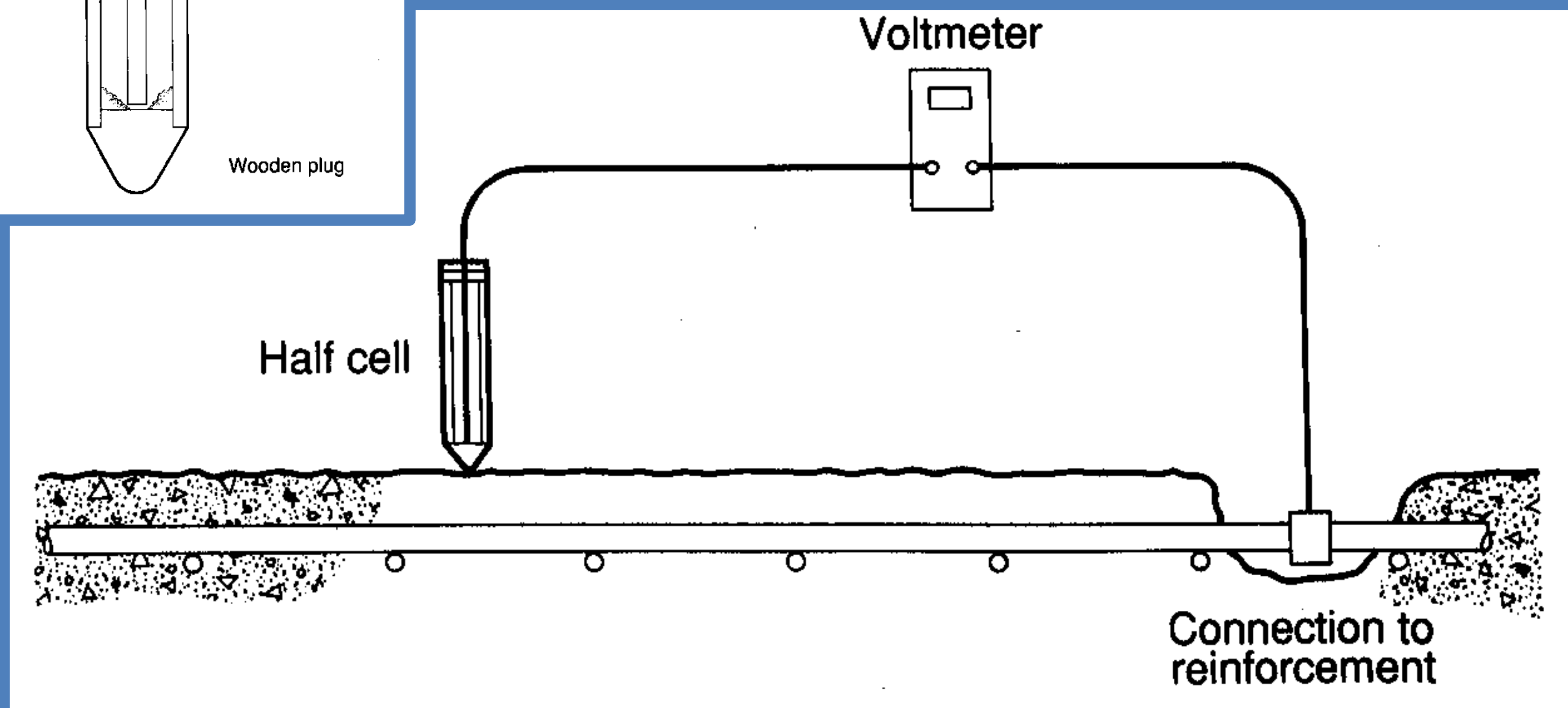
Potential Test Setup





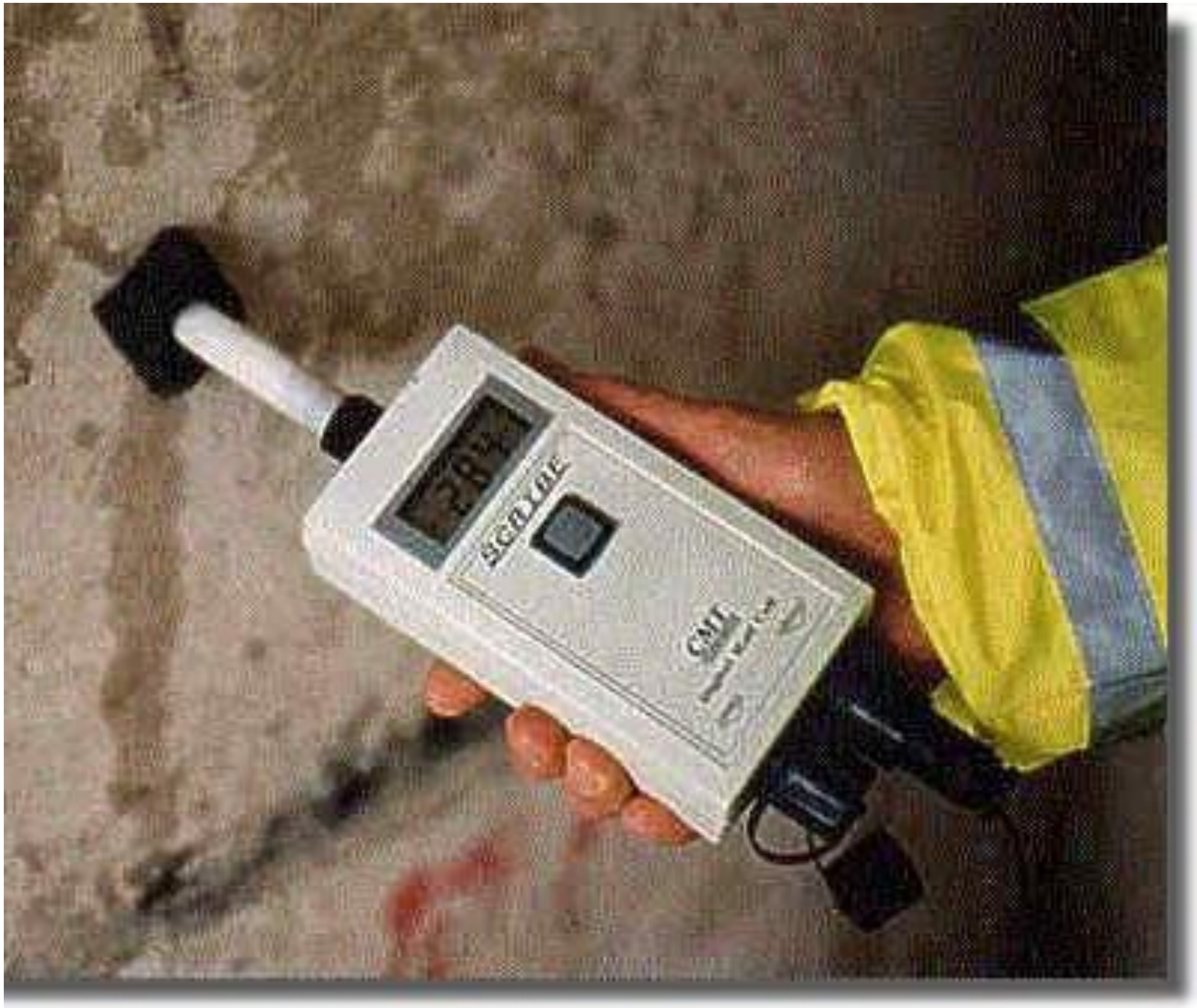
Potential Test Setup





According to ASTM C876, a potential that is more negative than -350 mV (Cu/$CuSO_4$) indicates that there is 90% probability that active corrosion is taking place.

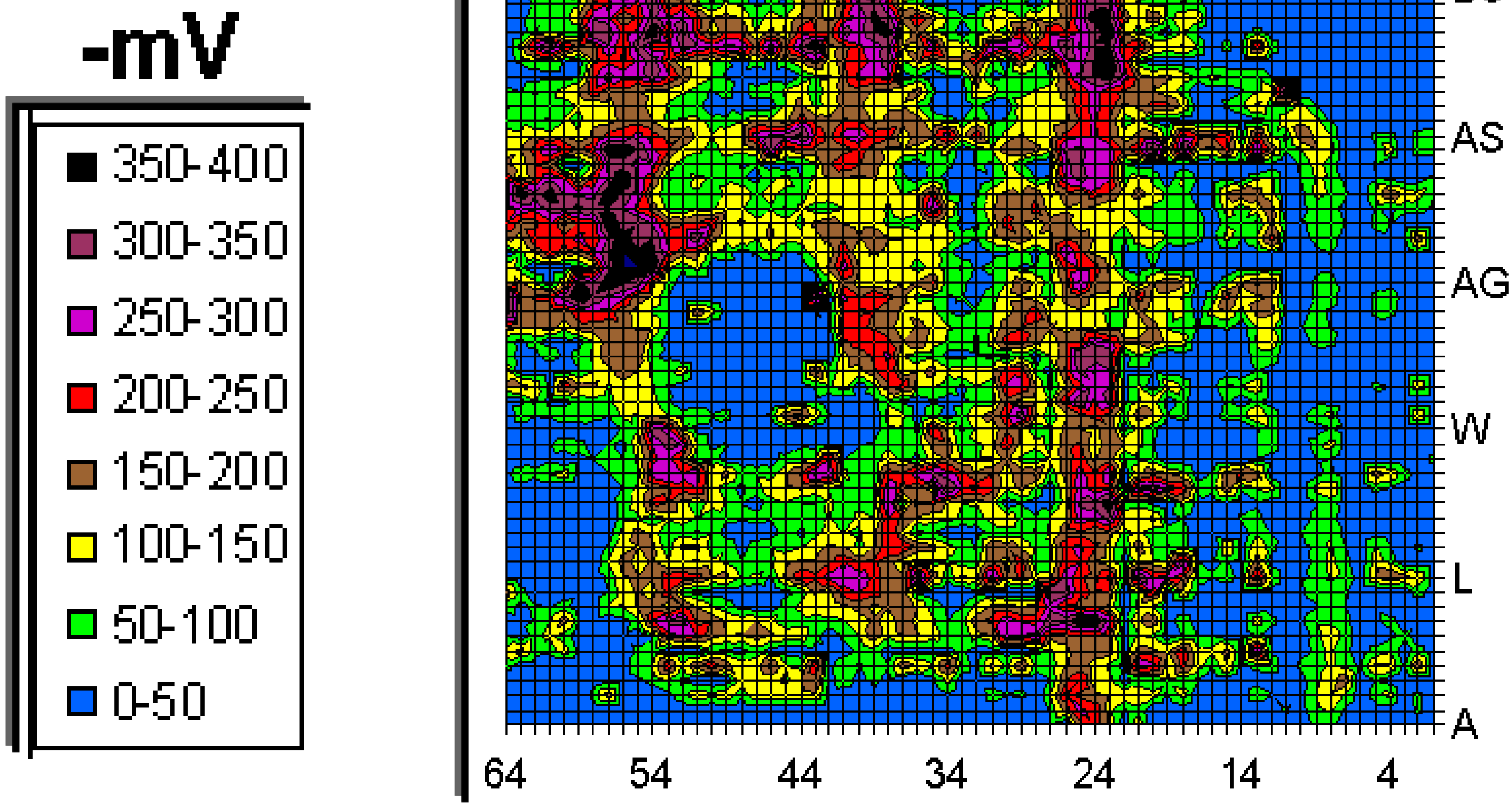
Potential Test Setup



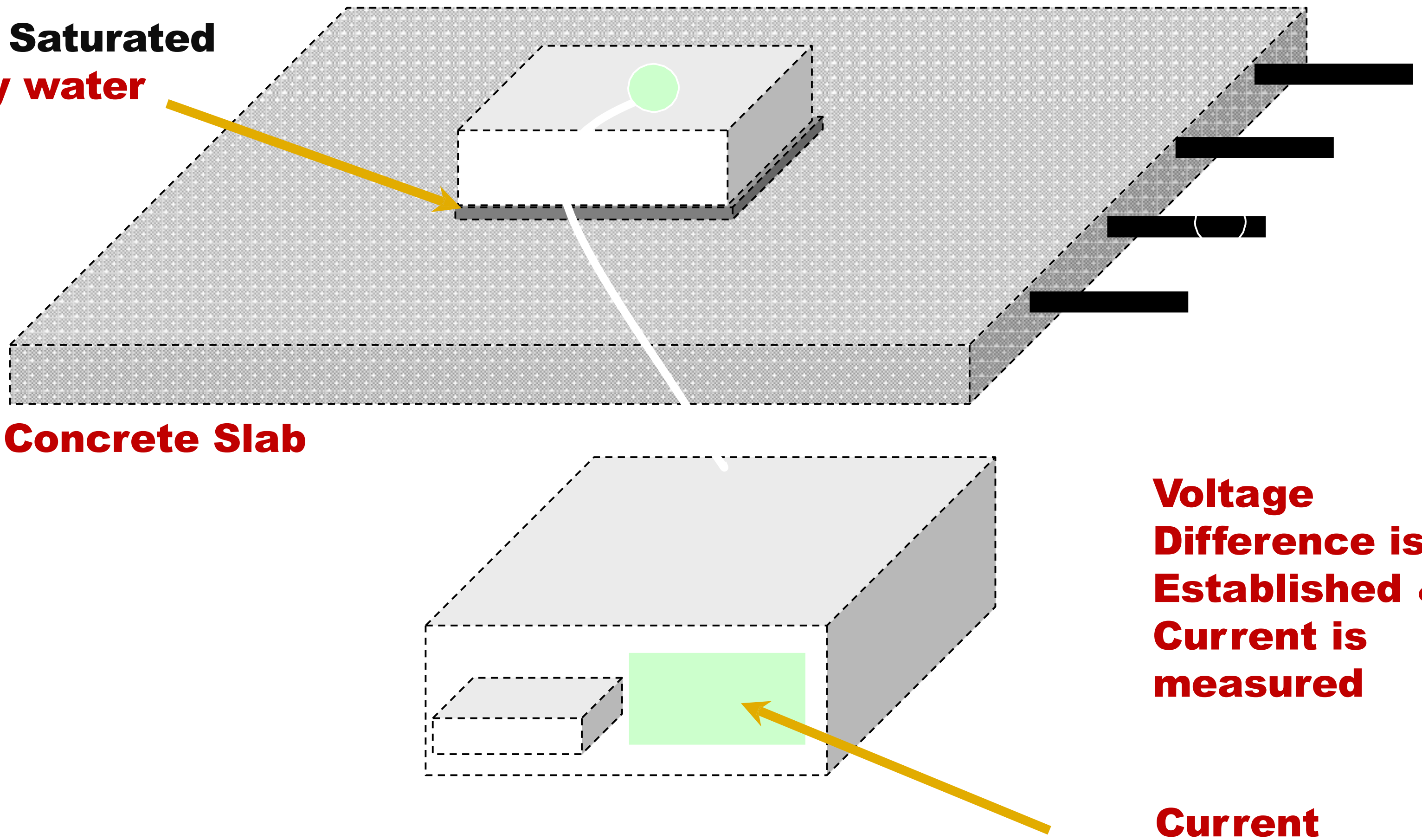
None-Structural Faults

Contour Plot

Potential Test Setup



Linear Polarization Resistance (LPR)



LPR Apparatus

The weight loss W_t of the steel is calculated as follows:

$$w_t = \frac{At_m}{zF} \sum \Delta t I_{ave}$$

where At_m is the atomic mass of the metal, z is its valency, F is Faraday's constant (96487 C/mol), Δt the time step, and I_{ave} is the average uniform current measured. For reinforcing steel, which is primarily iron, the atomic mass is 55.85 g/mol and the valency is 2.

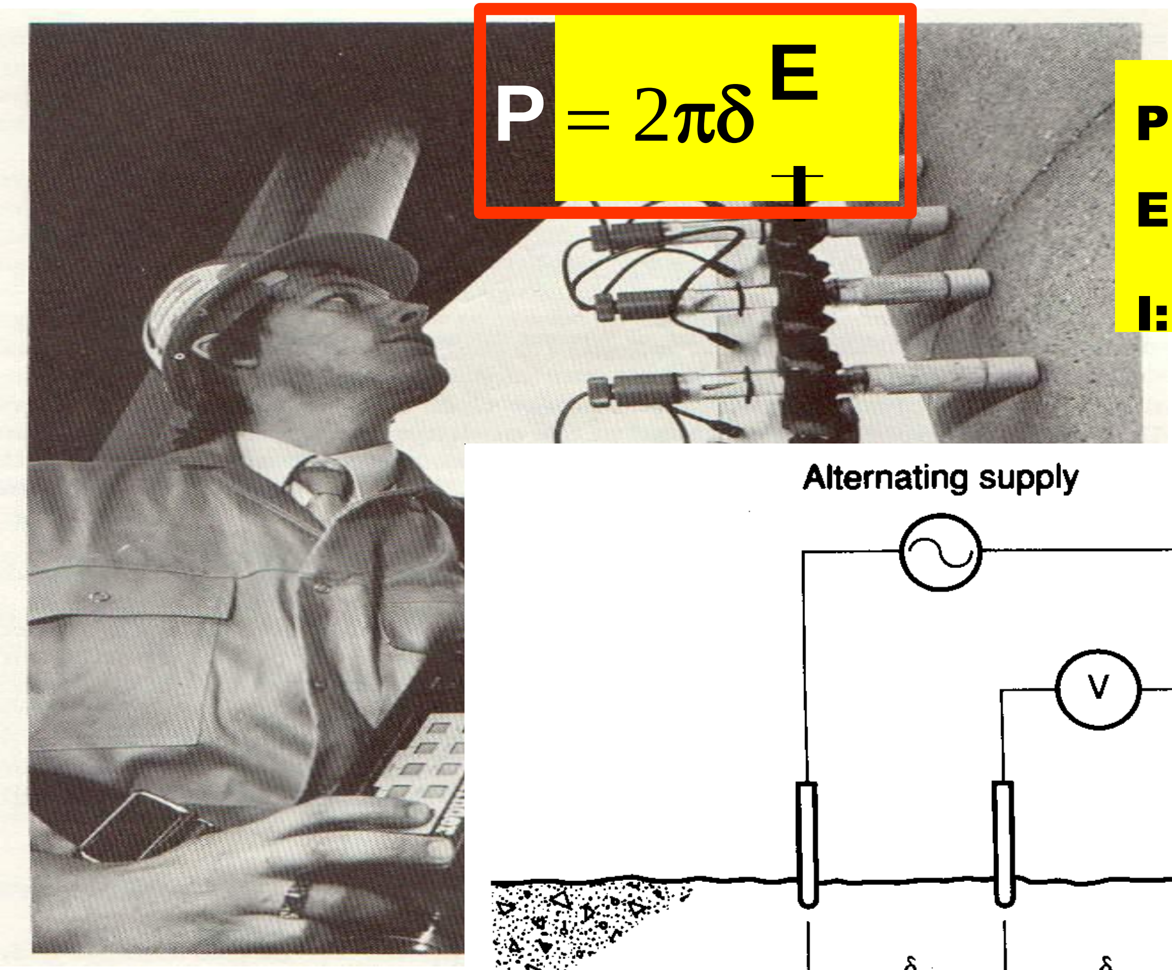
Four-Probe Wenner Array

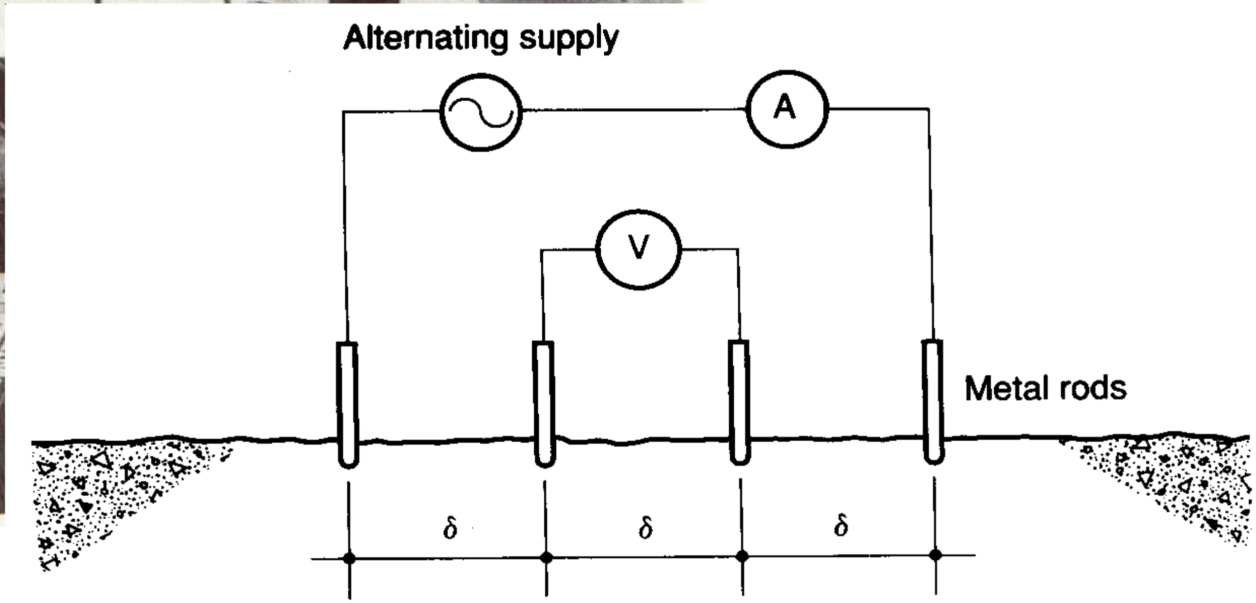
$$P = 2\pi\delta \frac{E}{I}$$

P: Resistivity, ohm cm

E: Voltage Drop

I: Current





Four-Probe Wenner Array

Surface Resistivity - Permeability	
Chloride Ion Permeability	Surface Resistivity Test kΩ–cm
High	< 12
Moderate	12 – 21
Low	21 – 37
Very Low	37 – 254
Negligible	> 254

None-Structural Faults

Reinforced Concrete Corrosivity Monitor (RCCM)

None-Structural Faults

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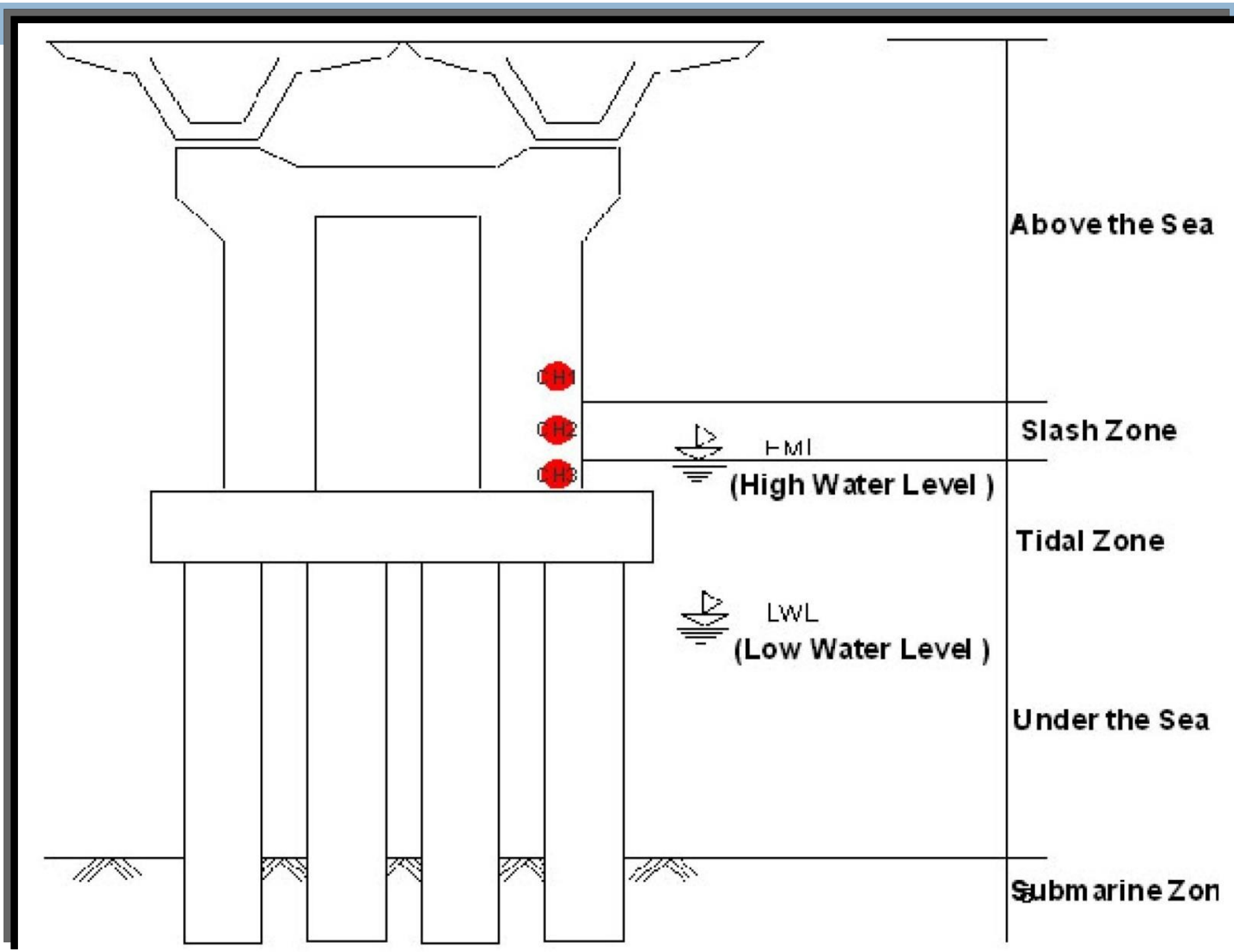

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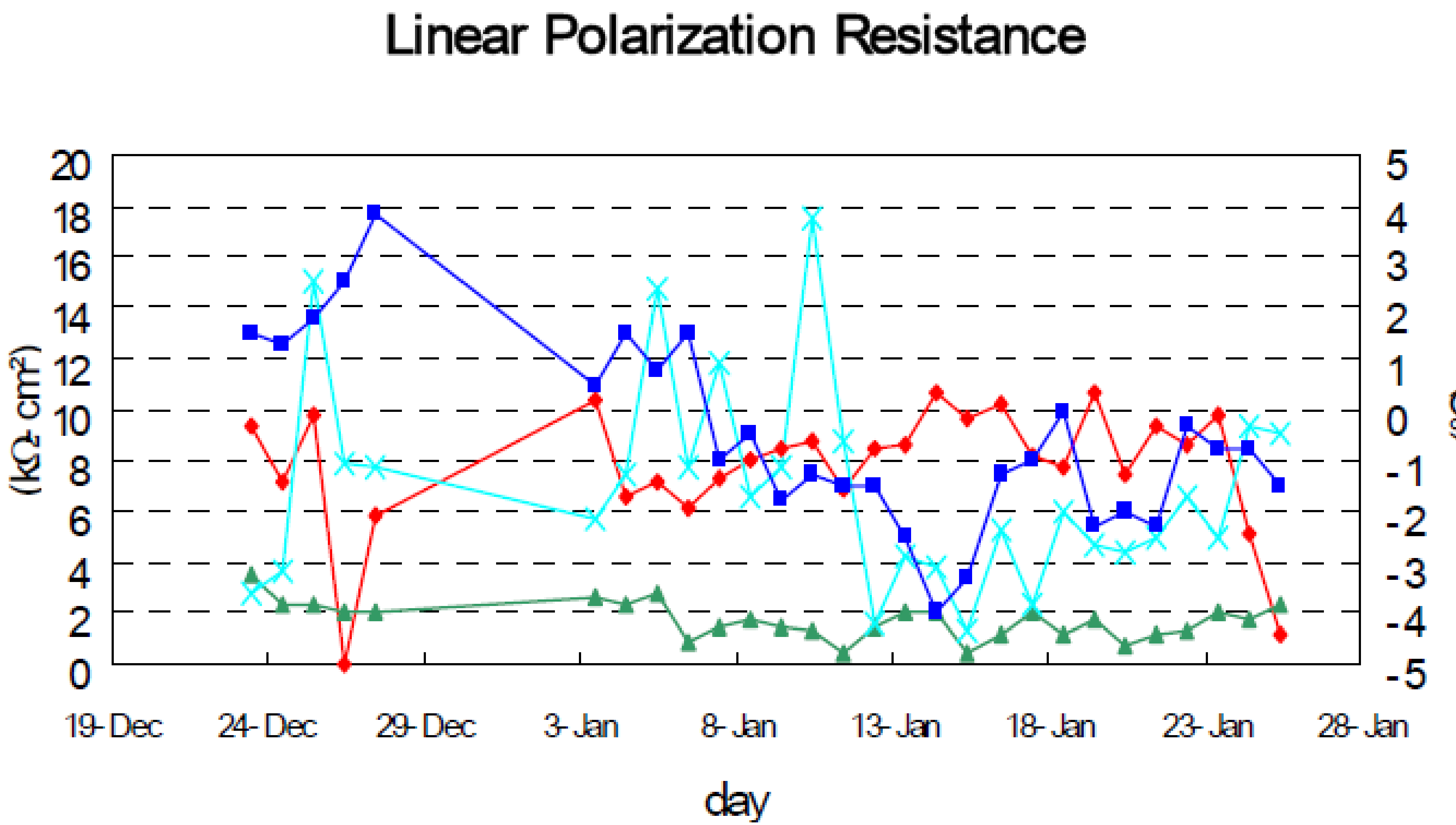

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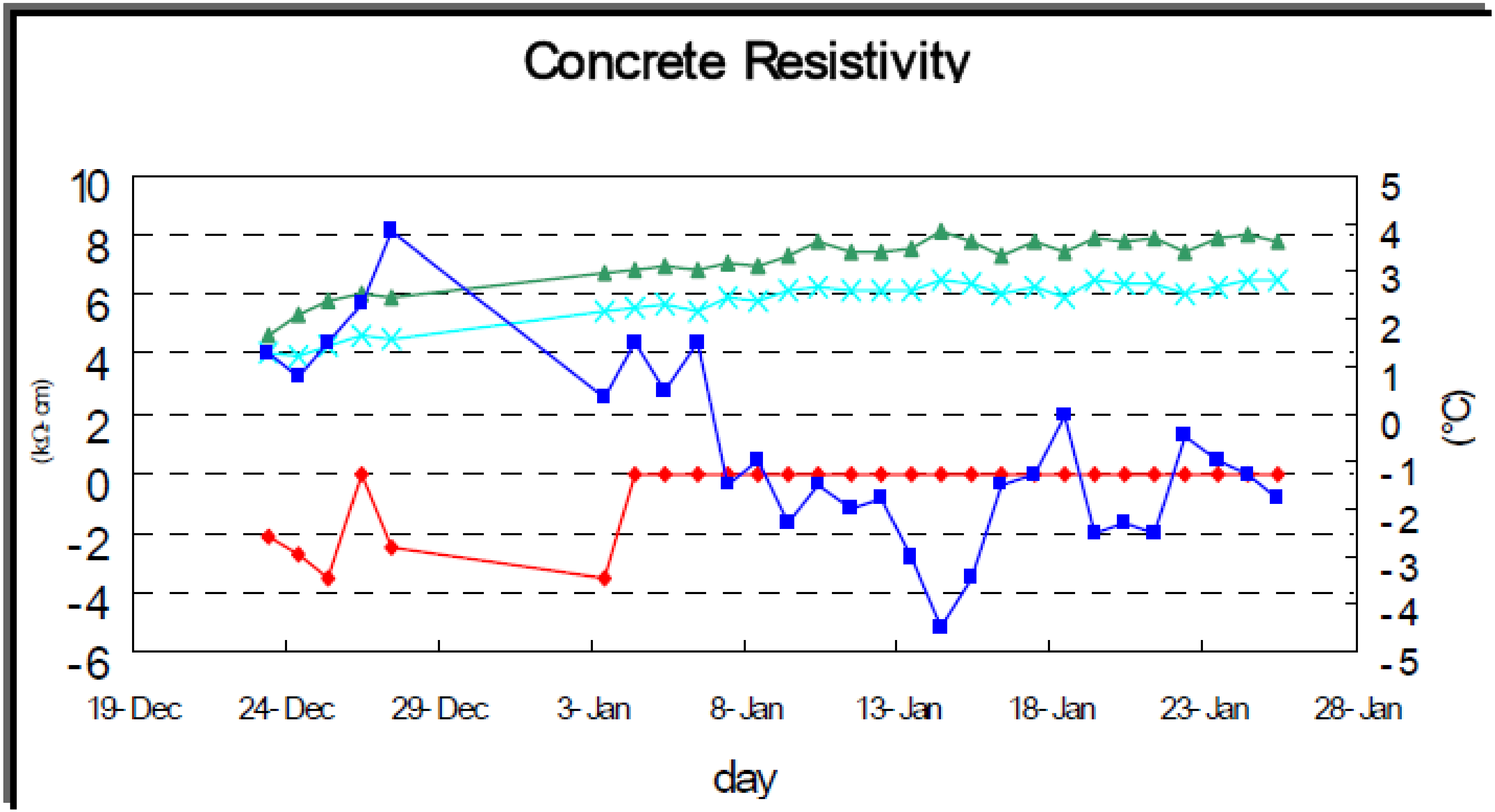

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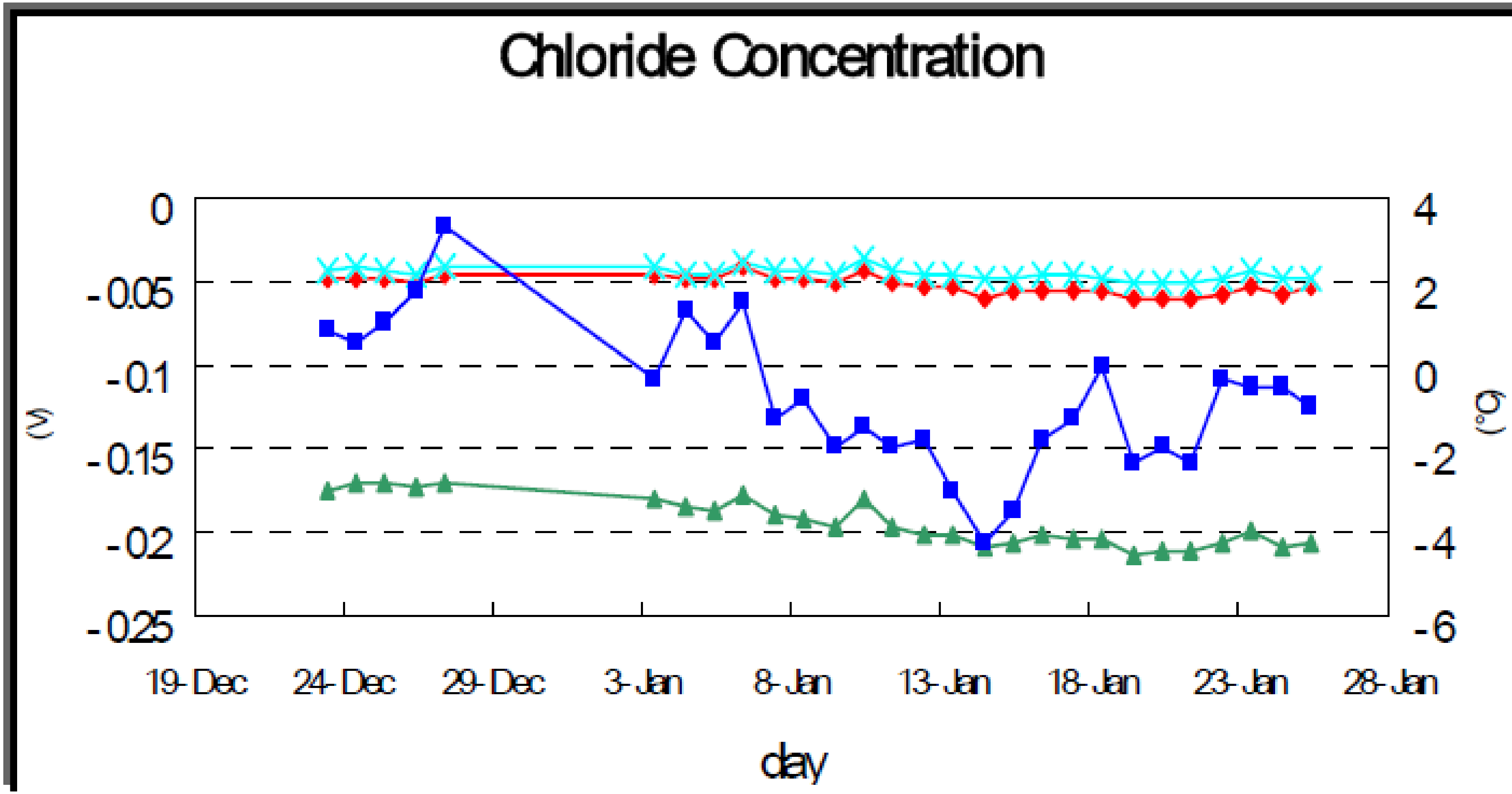

None-Structural Faults

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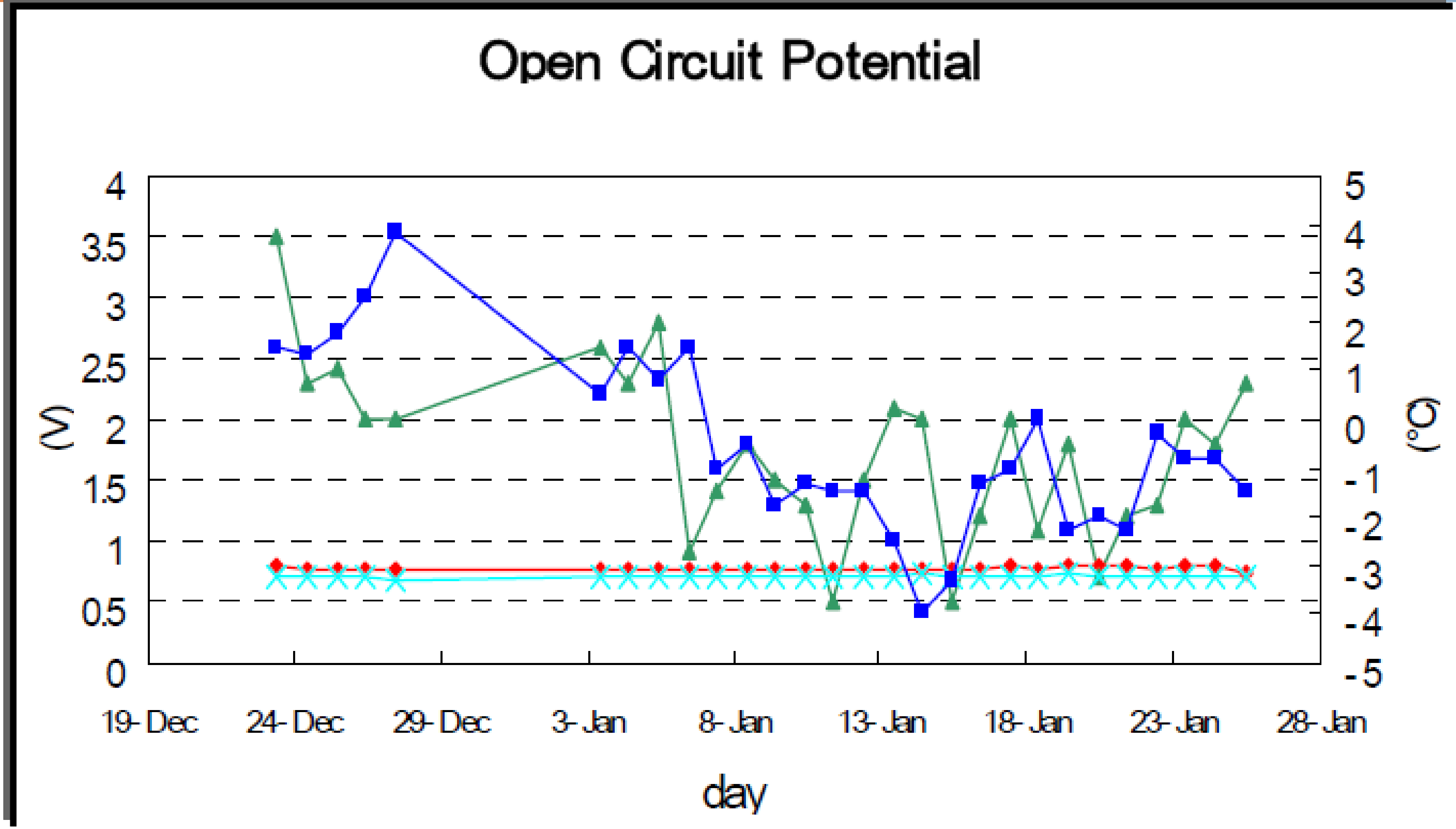


Reinforced Concrete Corrosivity Monitor (RCCM)

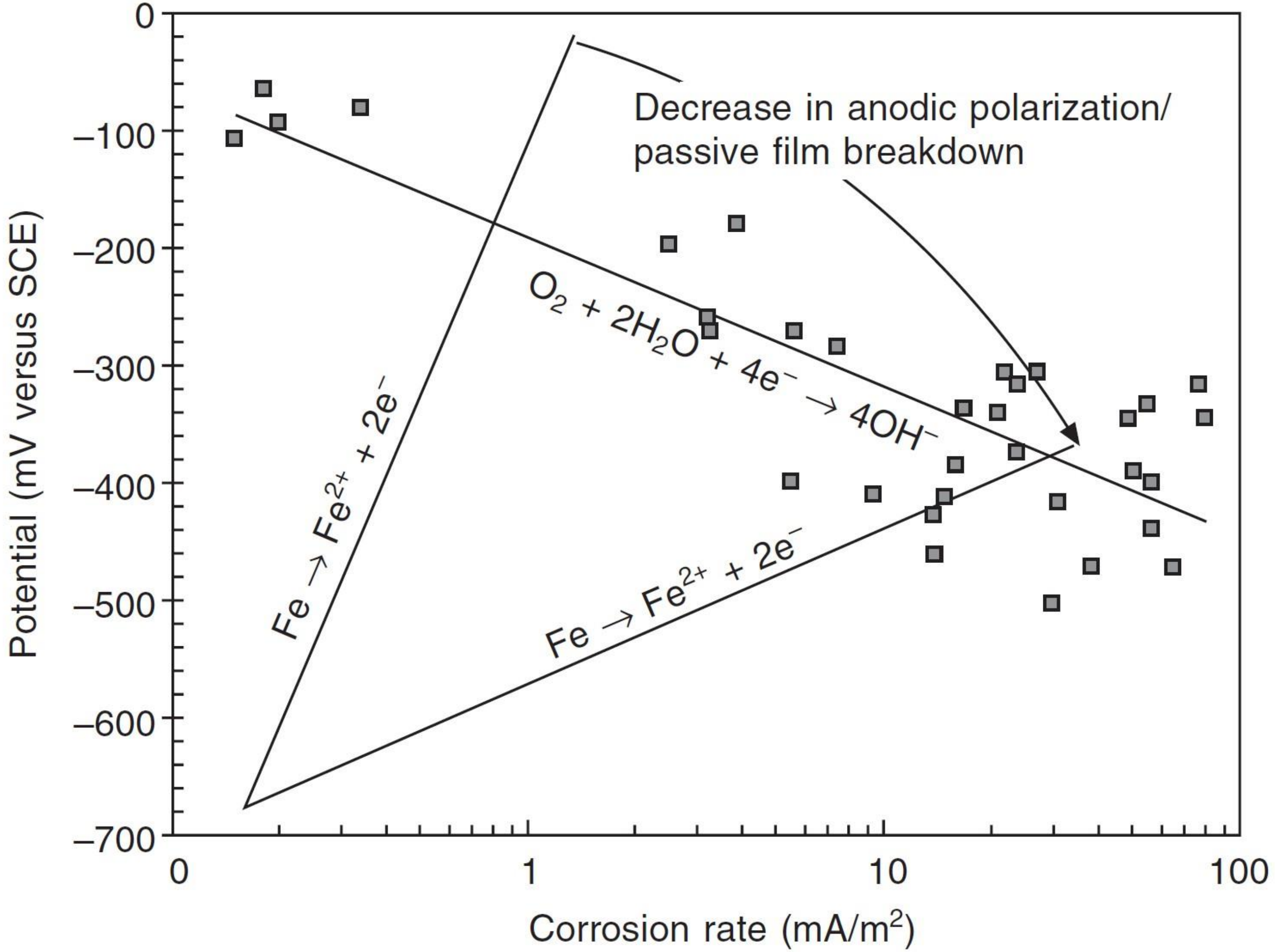
PROBABILITY OF CORROSION FOR DIFFERENT E_{CORR} VALUES[14]

Probability of corrosion	E_{corr} (vs $Cu/CuSO_4$)	E_{corr} (vs SCE)	E_{corr} MnO_2
> 95 %	< -350 mV	< -276 mV	< -430 mV
< 5 %	> -200 mV	> -126 mV	> -280 mV
approx. 50%	-200 to –350 mV	-126 to –276 mV	-280 to –430 mV

TYPICAL E_{CORR} VALUES OF THE DIFFERENT CORROSION STATES OF STEEL IN CONCRETE

Corrosion state	Range of possible E_{corr} /$mV_{(SCE)}$	Converted to $mV_{(MnO2)}$
Passive state	+200 to -200	40 to –360
Pitting corrosion	-200 to -500	-360 to -510
General corrosion	-450 to -600	-610 to –760
Corrosion with limited oxygen access	Around -1000	-1160

Corrosion Potential Evaluation

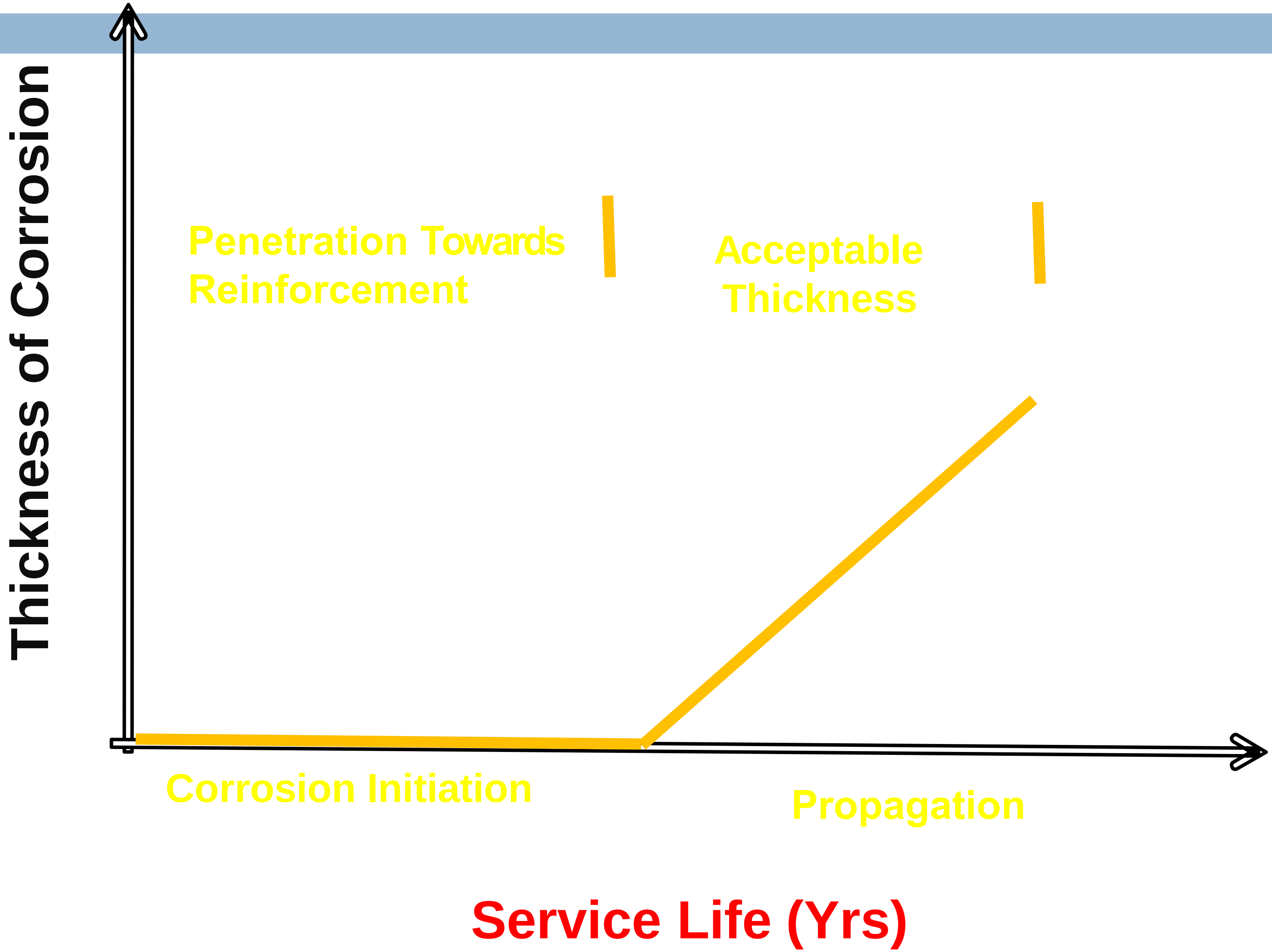


Steel Corrosion: Chloride Induced

Factors Affecting Corrosion:

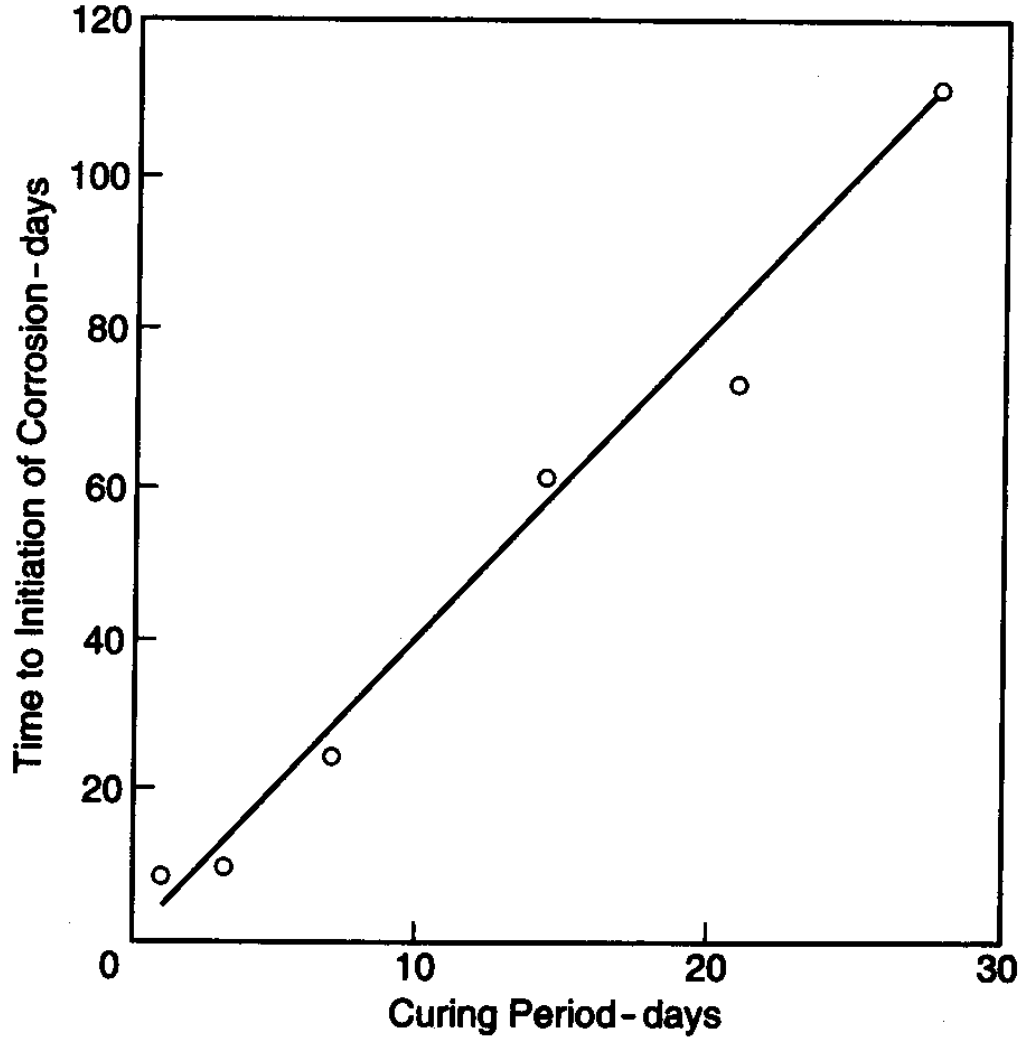
- Curing Period
- C3A content
- Concrete cover thickness
- Porosity and Pore size distribution
- W/C ratio
- Pozzolan Addition
- Moisture Content
- Temperature

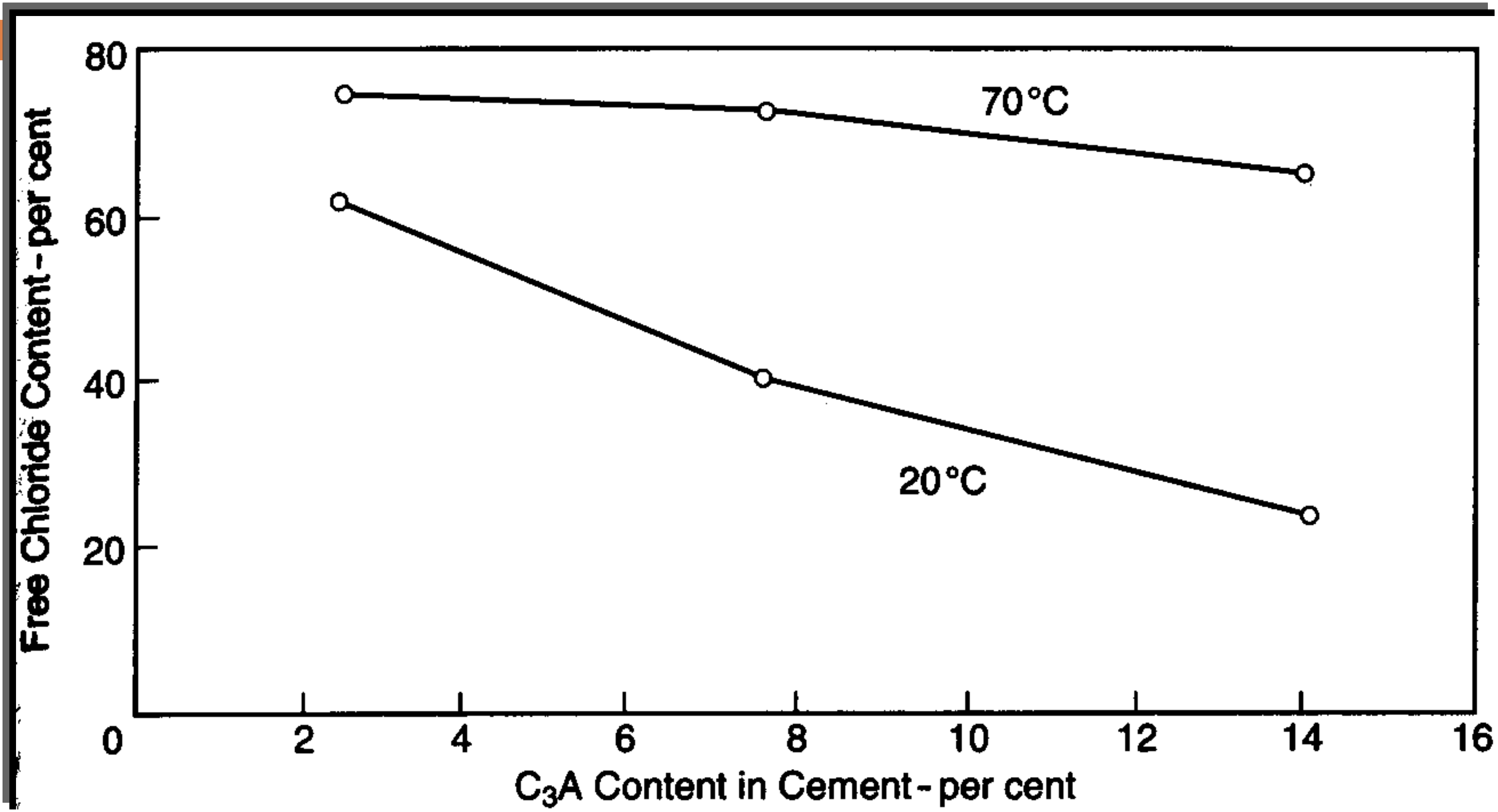
Steel Corrosion: Service Life



Factors Affecting Corrosion:

Curing Period





Factors Affecting Corrosion:

C_3A Content

Crystallization of Salt

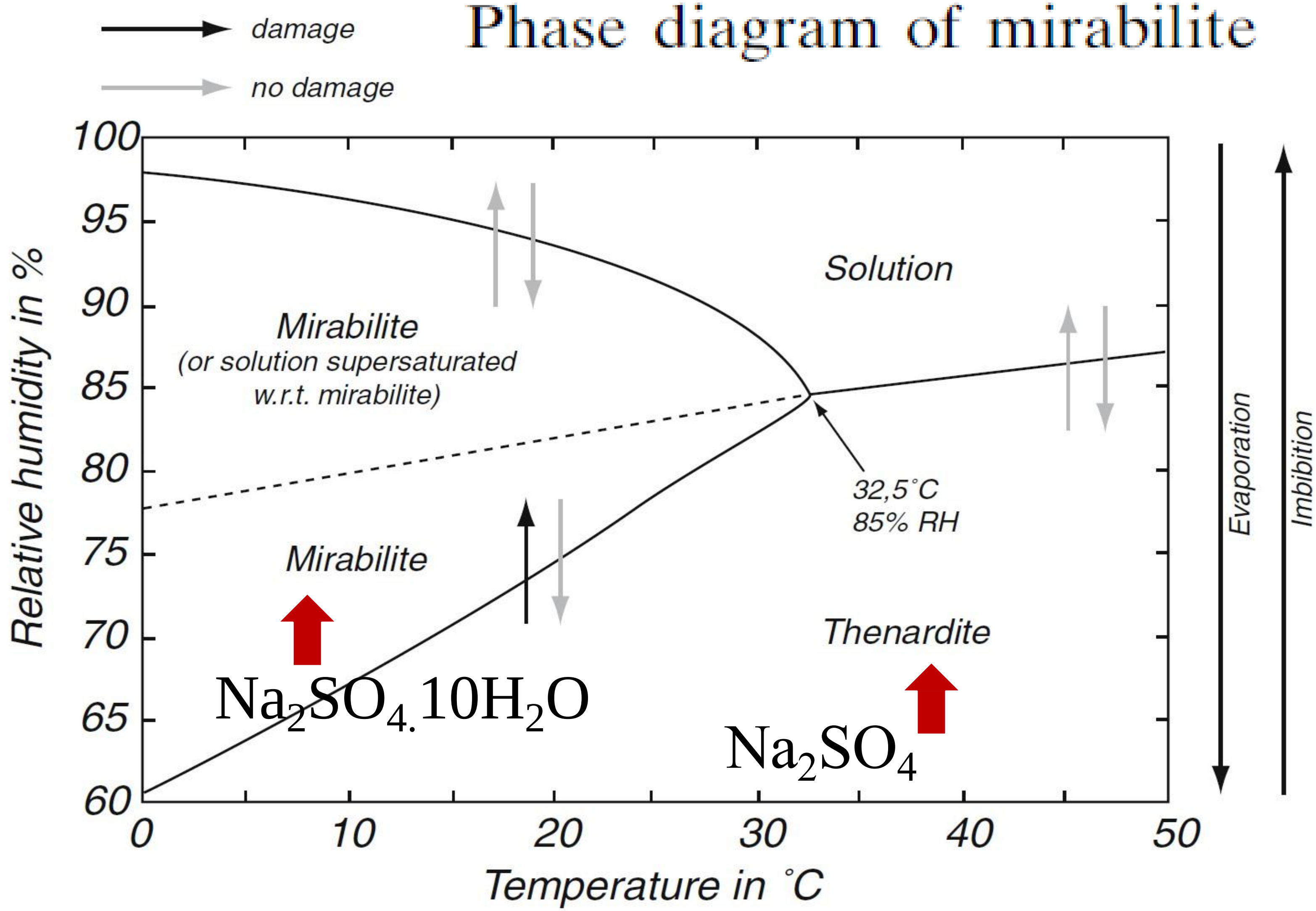
- **Repeated or continuing evaporation of salty water from concretes in marine environments or from concrete foundation resting on salt contaminated soil cause salt deposits to build up in the concrete pore system to the point where they cause concrete cracking.**

Remedy

- ✓ **Sealing the concrete, either to prevent ingress of moisture or subsequent evaporation .**
- ✓ **Concrete below ground may be surrounded by an impervious clay fill to keep salts from coming in contact with the concrete (reduce concrete permeability).**

Crystallization of Salt

Phase diagram of mirabilite



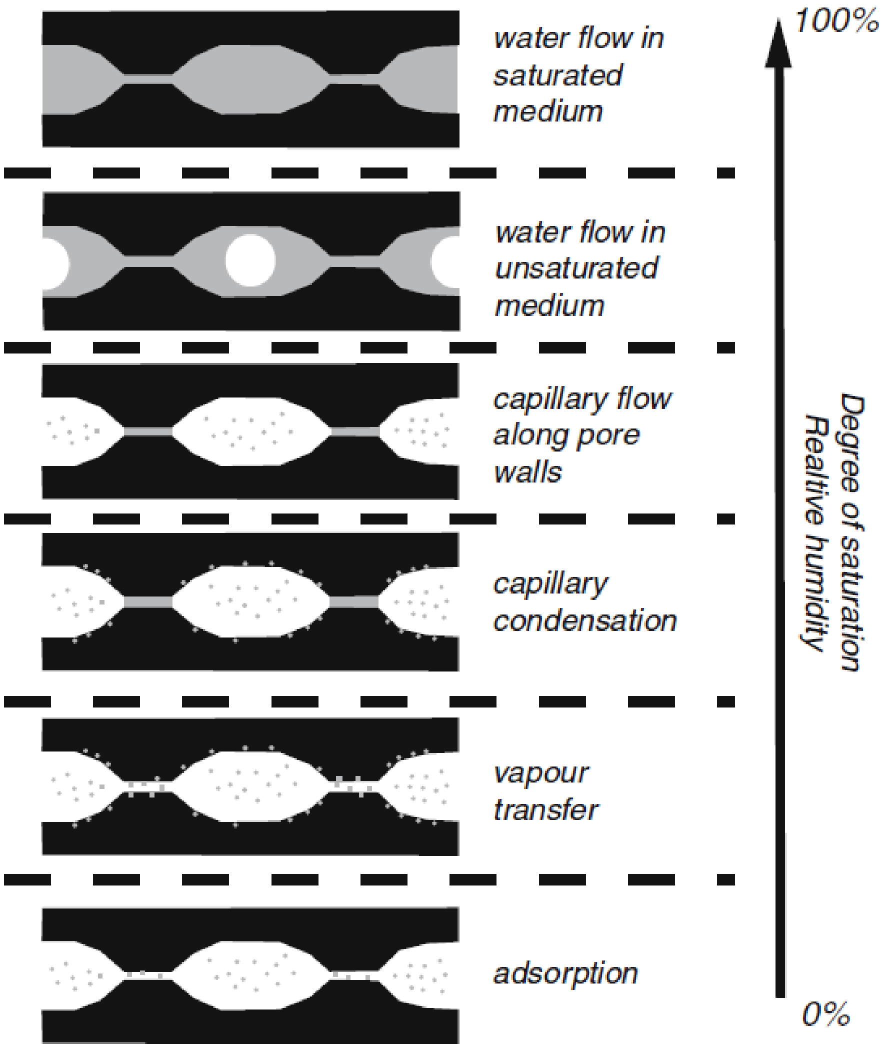
Crystallization of Salt

Cycles of Wetting and Drying Cause damage and loss in weight

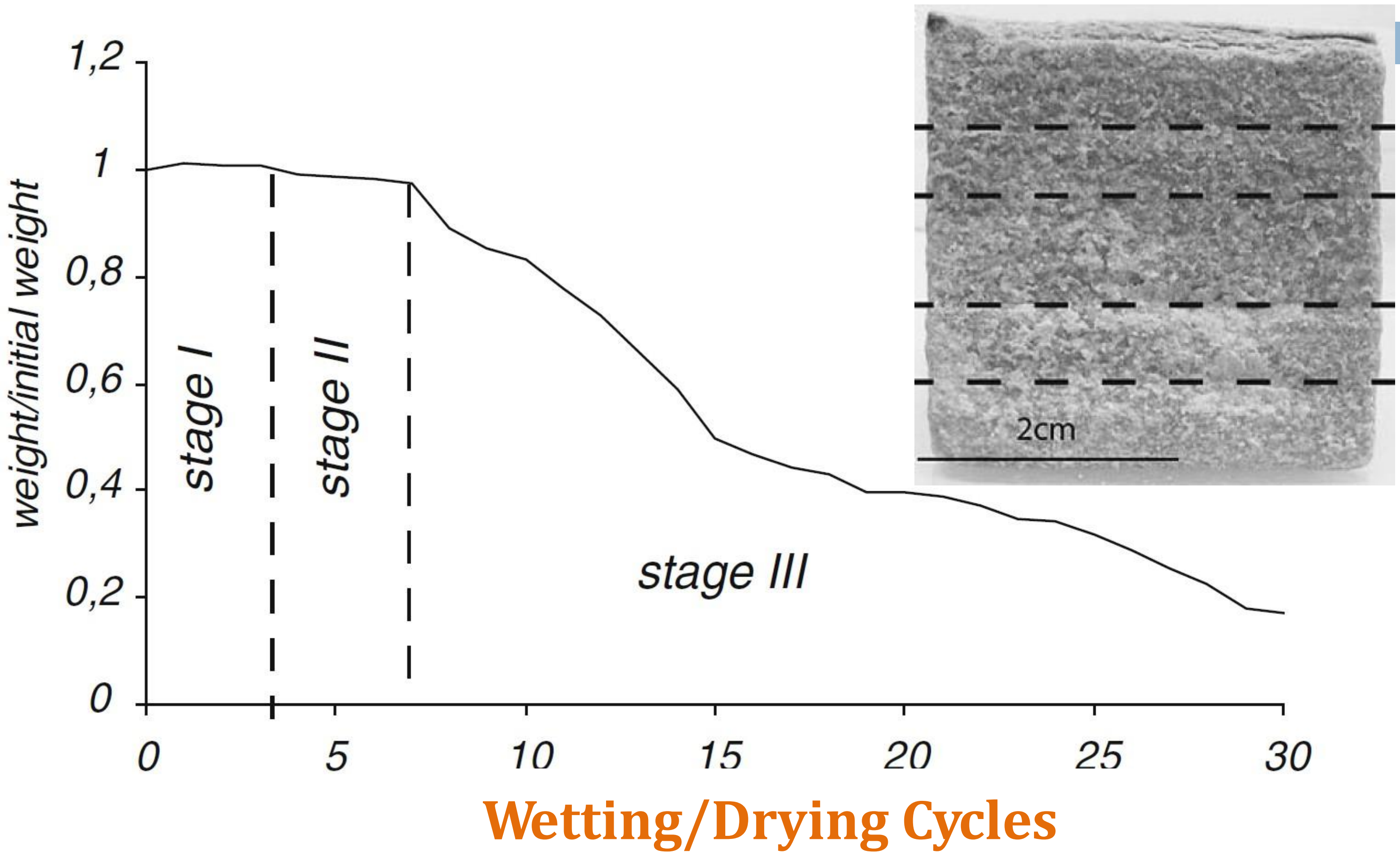
Start of Crystallization

Efflorescence

Stages in the wetting of a porous system



Crystallization of Salt



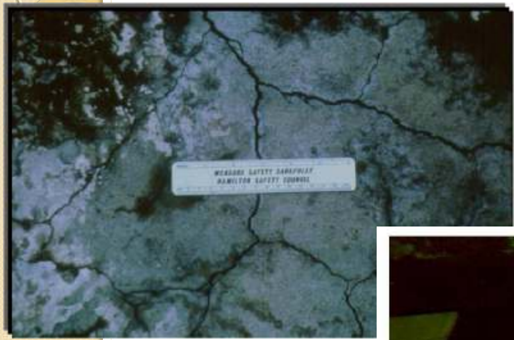
WETTING/DRYING CYCLES VS WEIGHT LOSS OF CONCRETE

Alkali-Silica Reaction

None-Structural Faults

Alkali-Silica Reaction

None-Structural Faults



Alkali-Silica Reaction

Causes:

- **Reaction between alkalis, usually from cement and certain siliceous aggregates**
- **Reaction forms silica gel inside or round the periphery of the aggregate**
- **Silica gel absorbs water and swells**
- **Swelling eventually bursts the concrete and typical "map" cracks form**

Alkali-Silica Reaction

Alkali Content:

ASTM specifies the maximum alkalis content as 3 kg/m^3 or 0.6% of the cement composition.

- Some concretes have alkalis in their aggregates.
- Opinion is divided on the availability of these alkalis.
- Cement replacements can contribute to alkalis

Alkali-Silica Reaction

ASR

The alkali - silica reaction occurs between the alkalis in the cement paste and reactive silica found in aggregates. The three necessary ingredients of ASR expansion are the following:

- ✓ **Reactive forms of silica**
- ✓ **Sufficient alkali (usually from the cement)**
- ✓ **Sufficient moisture within the concrete**

The expansion leading to deterioration can be prevented if any one of these ingredients is removed from the concrete.

Alkali-Silica Reaction

Reactive Aggregate

- The reactivity of silica (silicon oxide) in an aggregate depends on the type and forms of silica that are present in the aggregate.
- Completely crystalline silica is chemically and mechanically stable; although there are some exceptions. Quartz is stable unless it is microcrystalline or highly strained.

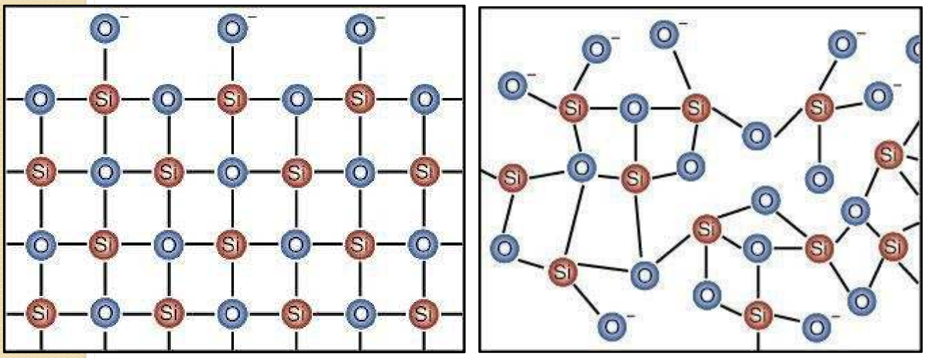
Alkali-Silica Reaction

Completely amorphous silica is more porous and very reactive. An aggregate that is poorly crystalline, amorphous, glassy, and micro-porous, and that has many lattice defects presents a large surface area for reaction and is susceptible to attack from alkali hydroxides. Aggregates containing the following constituents in the quantities listed are considered potentially reactive:

Opal – more than 0.5% by mass
Chert or chalcedony – more than 3.0%
Tridymite or cristobalite – more than 1.0%
Optically strained or microcrystalline quartz – more than 5.0%
Natural volcanic glasses – more than 3.0%

Alkali-Silica Reaction

Crystalline Form of Silica

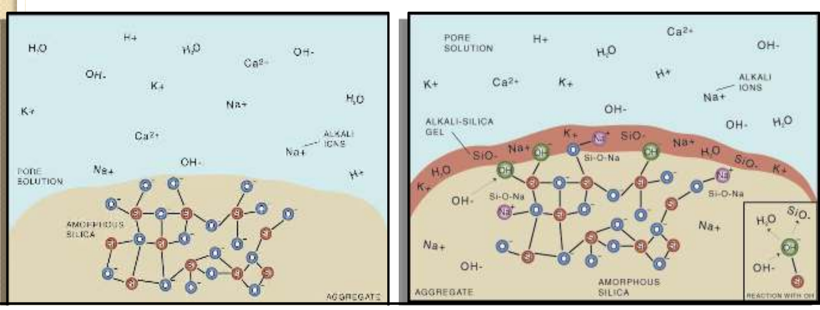


Alkali-Silica Reaction

Idron and Roy (1986) explained the hydration of silica as being catalyzed by the presence of hydroxide ions in the cement paste. The following reactions describe the formation process of the alkali-silica gel:

$$Si - O - Si + Na^{+} + OH^{-} \rightarrow Si - O^{-} Na^{+} + H_2O$$

$$Si - O - Si + 2NaOH \rightarrow Si - O^{-} Na^{+} + Na^{+} O^{-} - Si$$



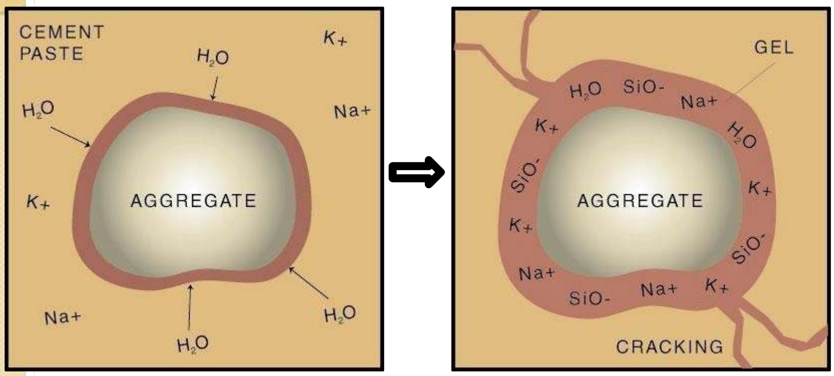
Alkali-Silica Reaction

Damage Mechanisms: Two Theories

Absorption Theory: Expansion depends on the volume concentration, rate of growth and physical properties of the complex alkali-cement gel. The more rapid the gel growth, the more damage in the Portland cement concrete. A high growth rate of the gel leads to stresses that build up, and when they exceed the tension strength of Portland cement concrete, cracking occurs.

Osmotic cell Pressure : Hansen (1944) suggested that the cement paste acts as an impermeable membrane for the silicate ions. The membrane, thus, allows water, hydroxyl ions, and alkali metal ions to diffuse through it, but does not permit the diffusion of silicate ions. Under these conditions, any reacting site would exert an increasing pressure against the restraining paste.

Alkali-Silica Reaction



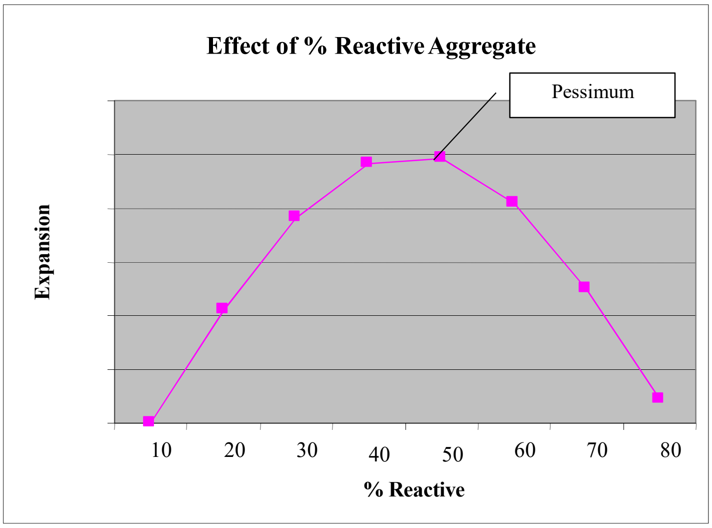
Alkali-Silica Reaction

Assessment of Damage

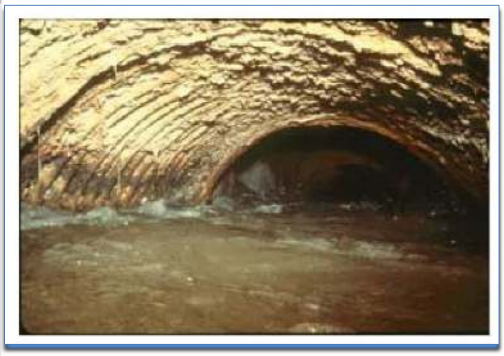
- Expansion measurements
- Compressive Strength of Concrete Cores
- Non-destructive Testing
- Full-scale loading

Alkali-Silica Reaction

“Pessimum” Effect of ASR



Forms of Sulfate Attack



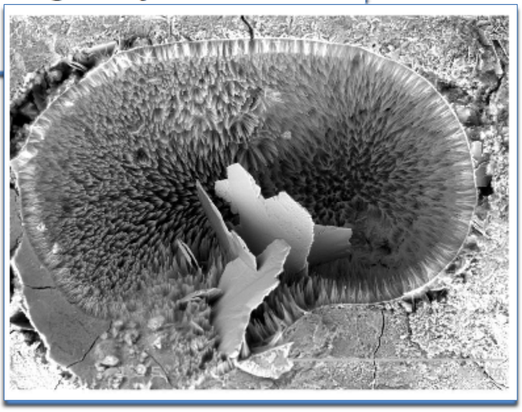
Forms of Sulfate Attack

$$C_3A + 26H + 3C\bar{S}H_2 \rightarrow C_6A\bar{S}_3H_{32}$$

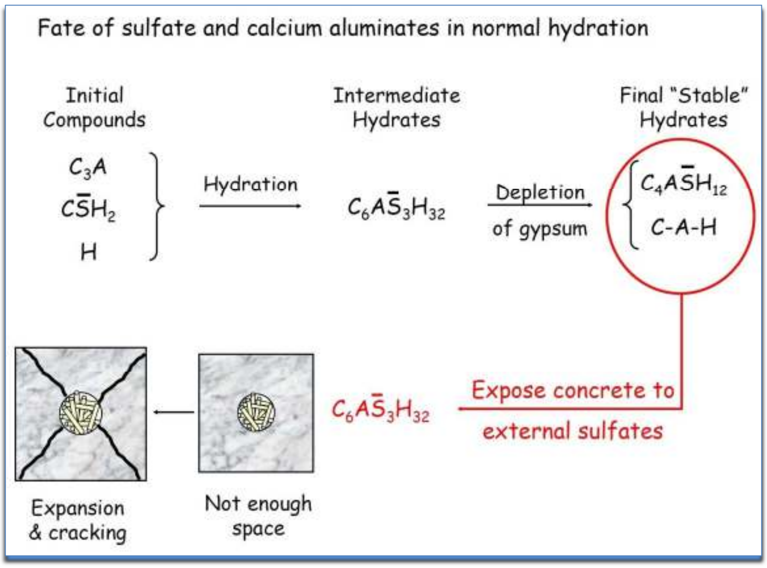
Tricalcium aluminate + Water + Gypsum → Calcium sulfoaluminate (Ettringite)

Forms of Sulfate Attack

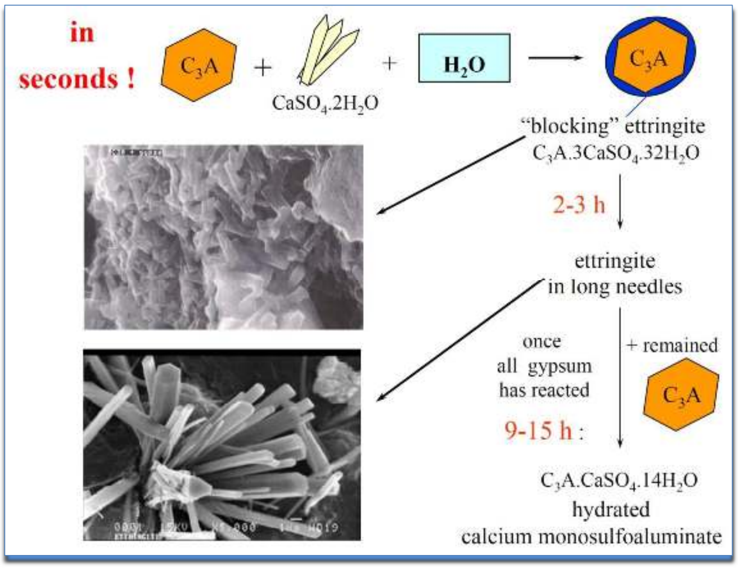
In the presence of gypsum, C_3A reacts to form **ettringite**, which coats the C_3A grains and prevents rapid hydration and flash set.



Forms of Sulfate Attack



For ms of Sulfate Attack



Forms of Sulfate Attack

Sources of sulfate?

- Naturally occurring sulfates may be found in soils and groundwaters

anhydrite	$CaSO_4$	**thenardite**	Na_2SO_4
bassanite	$CaSO_4 \cdot \frac{1}{2}H_2O$	mirabilite	$Na_2SO_4 \cdot 10H_2O$
gypsum	$CaSO_4 \cdot 2H_2O$	**arcanite**	K_2SO_4
kieserite	$MgSO_4 \cdot H_2O$	glauberite	$Na_2Ca(SO_4)_2$
epsomite	$MgSO_4 \cdot 7H_2O$	langbeinite	$K_2Mg_2(SO_4)_3$

- Ammonium sulfate - $(NH_4)_2SO4$ - found in agricultural soils and fertilizers
- Various sulfates found in wastewaters, water-treatment and sewage-treatment plants and other industrial processes
- Organic waste can produce H2S which can be oxidized to bacteria to form sulfuric acid – H_2SO_4
- Seawater

Forms of Sulfate Attack

Manifestation of sulfate attack

- Cracking, expansion
- Mass loss
- Reduction in strength
- Scaling of surface
- Warping

Forms of Sulfate Attack

Sulphate Attack by Alkali Sulfates

$$CH + N_2\bar{S}H_{10} \rightarrow C\bar{S}H_2 + 2NH + 8H$$

Calcium Hydroxide + Sodium Sulphate → Gypsum + Sodium Hydroxide + Water

$$C_3A(C\bar{S})H_{12} + 2C\bar{S}H_2 + 16H \rightarrow C_3A(C\bar{S})_3H_{32}$$

Calcium Monosulphoaluminate + Gysum + Water → **Ettringite**

$$2C_3AH_6 + 3N_2\bar{S}H_{10} \rightarrow C_3A(C\bar{S})_3H_{32} + 2AH_3 + 6NH + 5H$$

Tri-Calcium Aluminate Hydrate + Sodium Sulphate → **Ettringite** + Aluminum Hydroxide + Sodium Hydroxide + Water

Forms of Sulfate Attack

Sulphate Attack by Alkali Sulfates

Once the $Ca(OH)_2$ has been consumed, the Ca^{2+} ions required may be provided by the decomposition of the C-S-H phase

This results in a gradual lowering of the CaO/SiO_2 ratio of the C-S-H and a gradual loss of its bonding properties

Calcium Silicate + Sodium Sulphate →

$$3CaO \cdot 2SiO_2 + 3N_2\overline{S}H_{10} \rightarrow$$

$$3C\overline{S}H_2 + 6NH + 2SiO_2 \cdot aq + 18H$$

Gypsum + Sodium Hydroxide + Silica Gel + Water

Forms of Sulfate Attack

$$C_3A\left(C\overline{S}\right)H_{12} \rightarrow C_3A\left(C\overline{S}\right)_3 H_{32}$$

$$312.7 \rightarrow 714.9$$

130% volume increase

Forms of Sulfate Attack

Mechanisms of Expansion

- Increase in solid volume
- Expansion in a topochemical reaction
- Oriented crystal growth
- Crystallization pressure
- Swelling phenomena
- Osmotic pressure
- Reversal of local desiccation

} Common wisdom?

Forms of Sulfate Attack

Sulphate Attack by Magnesium Sulfate

Calcium Silicate + Magnesium Sulphate →

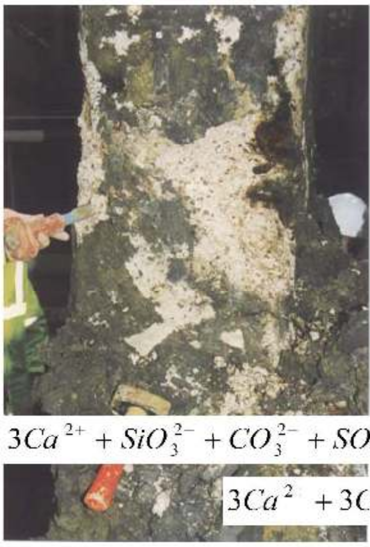
$$3CaO \cdot 2SiO_2 + MgSO_4 \cdot 7H_2O \rightarrow$$

$$3(CaSO_4 \cdot 2H_2O) + 3Mg(OH)_2 + 2SiO_2 \cdot aq$$

Gypsum + Magnesium Hydroxide + Silica Gel

Low solubility of $Mg(OH)_2$ – brucite – and low solubility of solution in equilibrium with this phase result in rapid degradation of C-S-H

Forms of Sulfate Attack



Thaumasite Form of Sulfate Attack

30-year-old bridge column exposed to wet Lower Lias clay in S.E. England

$$3Ca^{2+} + SiO_3^{2-} + CO_3^{2-} + SO_4^{2-} + 15H_2O \rightarrow$$

$$3Ca^{2} + 3CaO \cdot SiO_2 \cdot CO_2 \cdot SO_3 \cdot 15H_2O$$

Clark et al. 1999

Forms of Sulfate Attack

Sulfates + Calcium Aluminates + Calcium Hydroxide

Ettringite

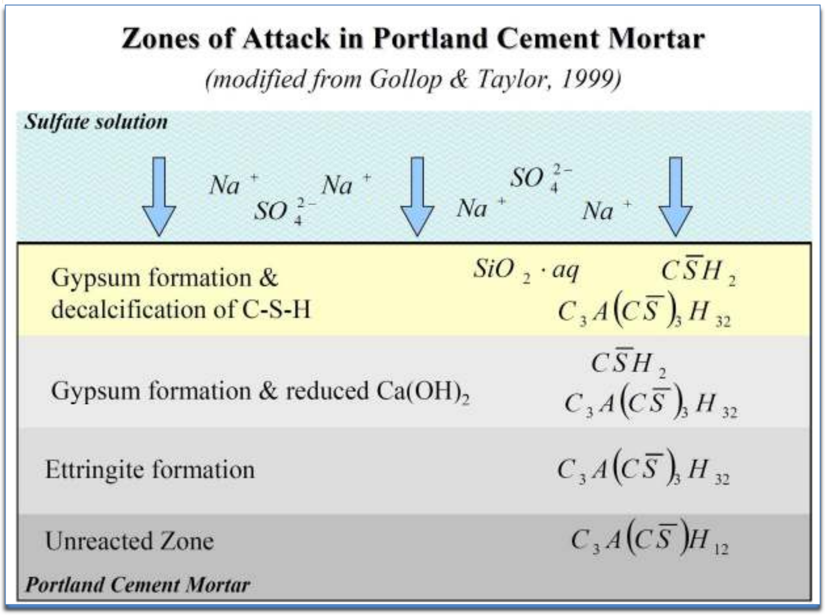
$$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$$

Sulfates + Calcium Silicates + Calcium Carbonate

Thaumasite

$$CaSiO_3 \cdot CaCO_3 \cdot CaSO_4 \cdot 15H_2O$$

Forms of Sulfate Attack



Fire Attack

There are two principal effects of fires on structural concrete:

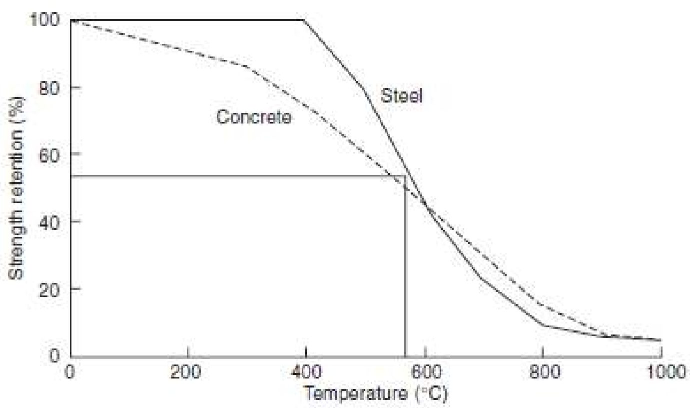
Loss in strength of matrix by degradation of hydrate structure. This occurs at various stages from 300°C upwards but the main losses are seen at 500°C plus.

Fire Attack

- Spalling and 'shelling' of the outermost concrete. This can occur with most concretes but the extent and rate is influenced by aggregate type, moisture content, concrete quality, fire severity and imposed stress condition.
- The complexity of the interactions under fire makes precise prediction of behavior of concrete in structures extremely difficult.

Fire Attack

Strength loss in the cement matrix



Fire Attack: Physical and Chemical Changes

- 100°C: Loss of Free Water — 10% Loss in Strength
- 150°C: Loss of bound Water from C-S-H and CH — Further Loss in Strength by Vapor Pressure of Water
- 300°C: Dehydration of CH and Combination with water — Further Loss in Strength; Swelling leading to cracking
- 400°C: Dehydration of CH and Combination with water
- 500°C: Loss in Strength (50%-75%)
- 600°C: Dehydration of CSH; Upper Limit for Useful Strength — 70-80% Loss in Strength
- 800-900°C: Friable & Loose Concrete

Fire Attack: Spalling

Spalling of concrete in fires is the breaking-off of layers of the concrete surface in response to the applied heat. Spalling can be either localized or widespread depending upon the fire and/or concrete condition, particularly moisture content, and the susceptibility to break-up of heat-unstable aggregate particles. On prolonged heating areas of concrete cover can also just fall away, a process that is sometimes called 'sloughing'. The processes causing sloughing are not generally reported, although it is noted that it occurs from corners of beams and slabs and seems to spread along a plane of weakness parallel to the outer surface. Because 'sloughing' occurs late in a fire exposure it is considered by some as being of less concern than explosive spalling that occurs earlier upon exposure to fire. Understanding explosive spalling is important because of the potential for loss in section of the concrete element, the depth of fire affected concrete and the reduced protection to embedded steel.

Spalling is a frequently observed phenomenon in fire; more prominently on soffits of slabs and on beams because of the greater exposure to heat and possibly heat 'entrapment'. It is not certain that this frequent observation is fully anticipated by design codes and this is discussed in more detail below, in the section on design codes.

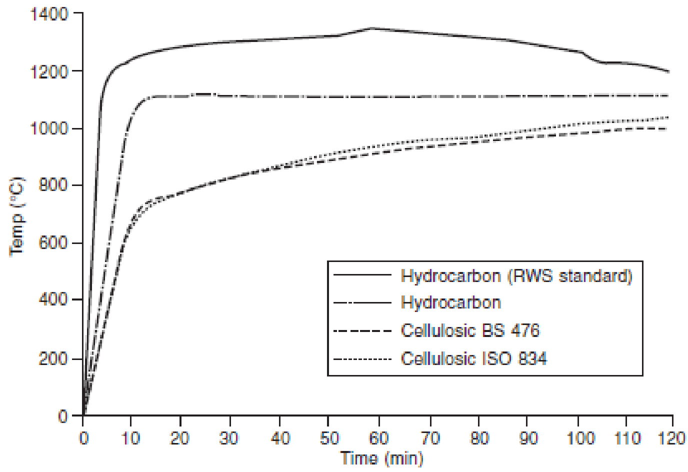
None-Structural Faults

Fire Attack

There are mixed views and experiences expressed in the literature on the influence of reinforcement bars and concrete cover depth on spalling. These are briefly discussed later in the section on design codes. In general the presence of normal structural bars does not seem to influence spalling of concrete until after the cover has spalled off, although the greater the depth of cover (it is believed), the greater the risk of spalling. There is some evidence that using a smaller non-structural mesh in the cover zone reduces the ability of spalled concrete to fall away.

None-Structural Faults

Fire Attack: Fire Source



Comparison of typical 'cellulosic' and 'hydrocarbon' time/temperature curves.

None-Structural Faults

Fire Attack

Many factors have an influence on the performance of concrete in hydrocarbon fire but those with a primary influence are:

- the rate of temperature rise in the concrete
- the moisture content of the concrete
- the permeability of the concrete

Fire Attack: Evaluation of Fire Damage

The three principal concerns in evaluating the effect of the fire on a concrete structure are:

- depth of damage (spalling) or loss in strength of the concrete matrix
- loss in strength of steel reinforcement or embedded structural steel elements
- damage or distress to the structure from movement, settlement or imposed loads

Fire Attack: Concrete Status

T	Color Change	Change in Physical and Benchmark Temperature	Concrete Condition
0-290°C	None	Unaffected	Unaffected
290-590°C	Pink to red	Surface crazing- 300°C Deep cracking-550°C Popouts over Chert and Quatz aggregate-575°C	Sound but strength significantly reduced
590-950°C	Whitish Grey	Spalling, exposing not more than 25% of reinforcing steel-800°C Powdered, light colored, dehydrated paste-575°C	Weak & Friable
950+°C	Buff	Extensive spalling	Weak & Friable

Fire Attack: Concrete Status

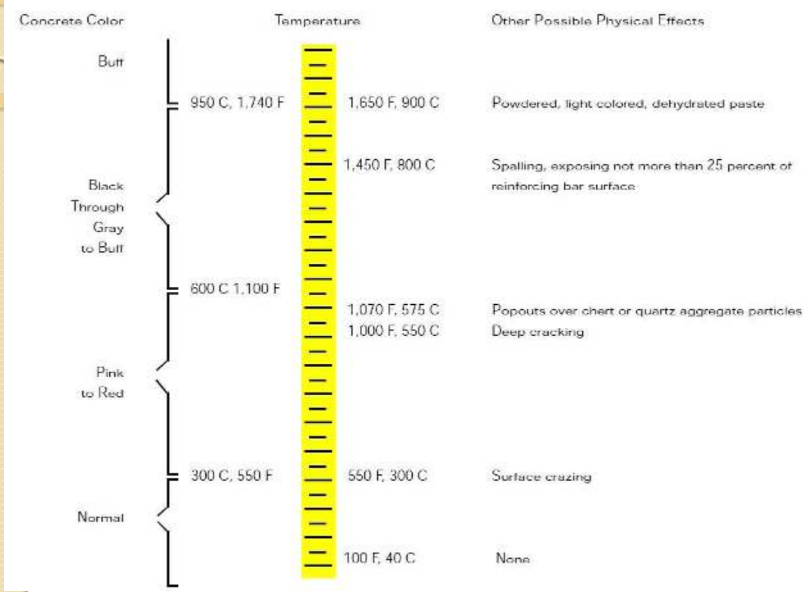


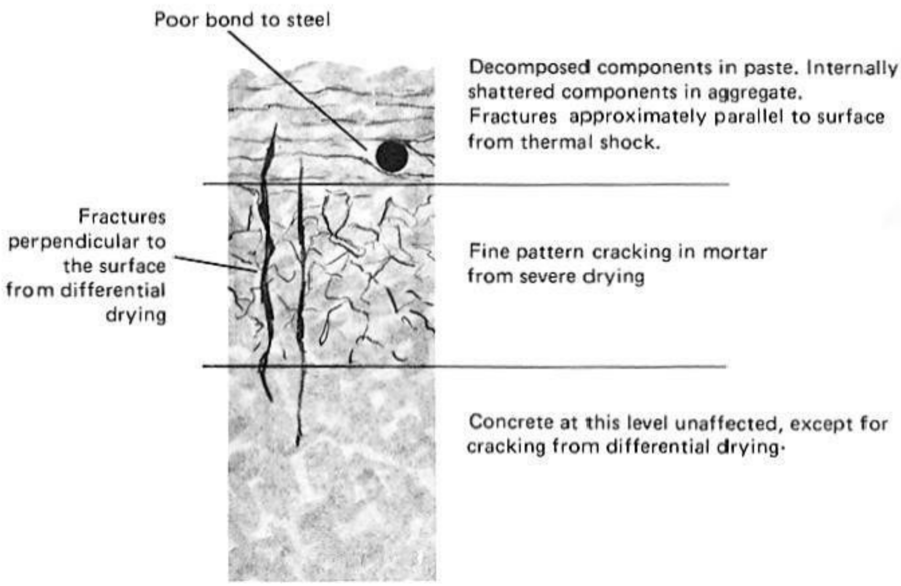
TABLE III Methods for Details Appraisals of Condition of Fire-Damaged Concrete

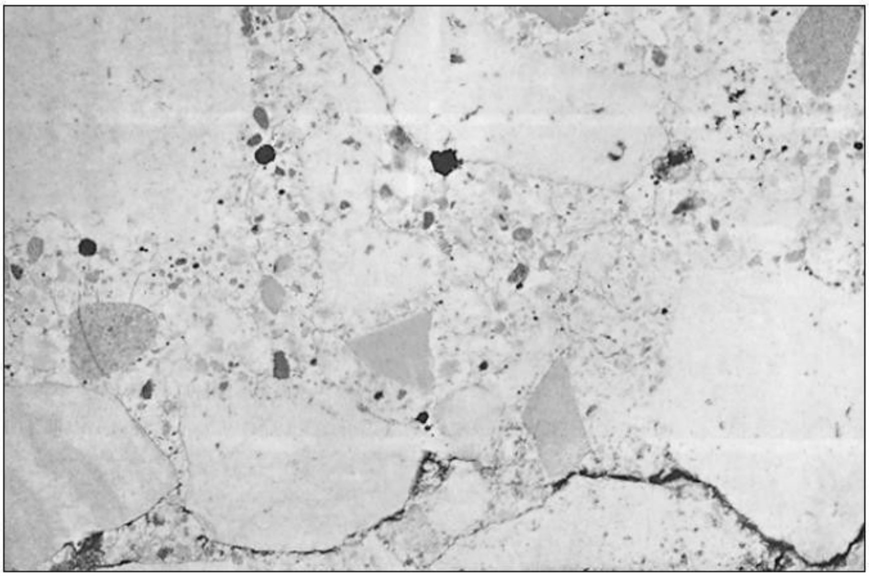
Condition of Property	Methods	Notes
Actual temperature reached in building	Examination of building contents	See Tables 1 and 2
Actual temperature reached in concrete	Visual examination of concrete, Petrographic, DTA, and metallurgical studies of steel.	See Fig. 1
Compressive strength	Tests on cores. Impact hammer studies. Penetration resistance. Soniscope studies.	

Soundness at highly stressed areas (upper side at center of beam; beam supports; anchorages for reinforcement near support; frame corners)	Hammer and chisel. Visual examination. Soniscope studies.
Modulus of elasticity	Tests on cores. Soniscope studies.
Dehydration of concrete	DTA. Petrographic analysis. Chemical analysis.

Surface hardness	Dorry hardness or other tests
Abrasion resistance	Los Angeles abrasion test on concrete chips*
Depth of damage	Visual examination for spalling, cracking. Color variation in cores. Chipping. Petrographic analysis.
Deformation of beams,	Visual examination. Straightedge and scale. Dial gages or theodolite if needed.
Gross expansion	Visual examination. Checking of dimensions and levels.
Differential thermal movements	Visual check of cores for loss of bond to steel. Color change in concrete next to steel.
STEEL CONDITION Reinforcing steel, structural steel or prestressing steel	Physical tests. Metallurgical studies. Dimensional changes, displacement and distortion.
Load carrying capacity	Load tests on structure

* Of uncertain value for this purpose.


Poor bond to steel
Decomposed components in paste. Internally shattered components in aggregate. Fractures approximately parallel to surface from thermal shock.
Fractures perpendicular to the surface from differential drying
Fine pattern cracking in mortar from severe drying
Concrete at this level unaffected, except for cracking from differential drying.



STRUCTURAL FAULTS:

SOURCES AND TYPES

Structural Faults: Sources

- **Sources**
  - Over-Loading
  - Excessive Deflection
  - **Soil Problem**
    - Improper Foundation Design
    - Over-Estimation: Bearing Capacity
    - Expansive Soil
    - Improper Base Depth
    - Soil Movement
  - **Design Faults**
    - Loads Estimation
    - Concrete Dimensions
    - Design & Safety Factors
    - Reinforcement Quantities & Details
  - **Construction Faults**
    - Honey-Combing
    - Insufficient Concrete Cover
    - Insufficient Compaction Segregated Concrete
    - Pre-stressing Force Less than Required

Structural Faults: Sources

Causes & Consequences

Over-Loading

Excessive Deflection

Cracking

Cracking and Reduced Structural Capacity

Sc

Materials Faults

esign Faults

Construction Faults

Differential Settlement

Reduction In Structural Capacity

Reduction In Structural Capacity

Cracking of Girders

Cracking-Bursting of Columns

Failure of Foundation

Cracking of Slabs

Common Design Faults

- Underestimation of loads on columns {Using Areas Methods Instead of Using Reactions}.
- Insufficient Development Length of Reinforcement in Concrete.
- Termination of Steel in Zones of High Tension.
- Constructing Stiffening Beams in Slabs {Increasing Deflecting}.

Common Design Faults

- Termination of Negative Steel in Zones of High Tension.
- Adjustments on Design with Consulting with Engineers.
- Reduce Concrete Cross Sections.
- Reduce quantities of Steel by Number or Size.
- Over-loading.
- Lack of adequate number of expansion joints.

OTHER CASUES OF FAULTS: SOURCES AND TYPES

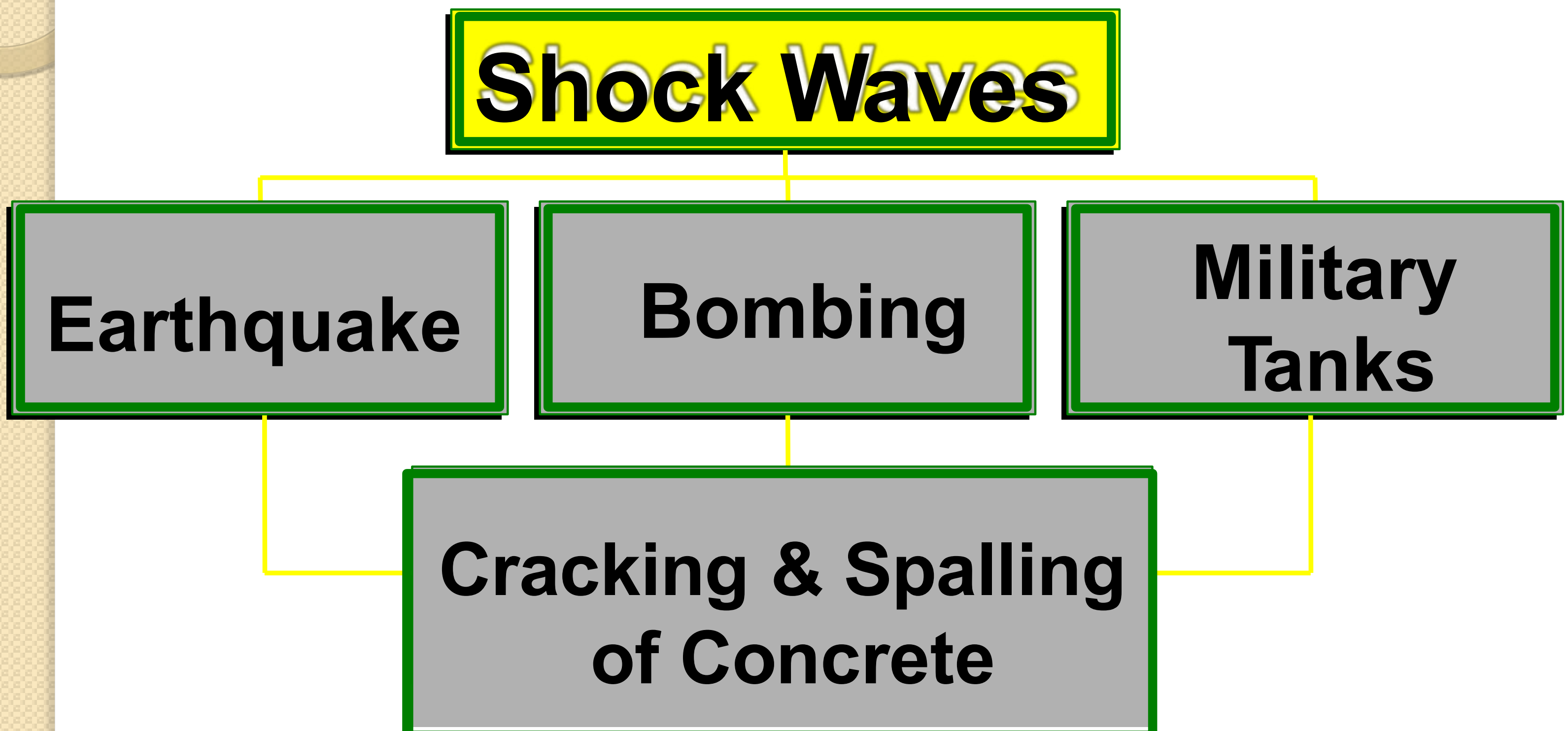
Other Causes of Materials & Structural Faults

Fire Related Incidents

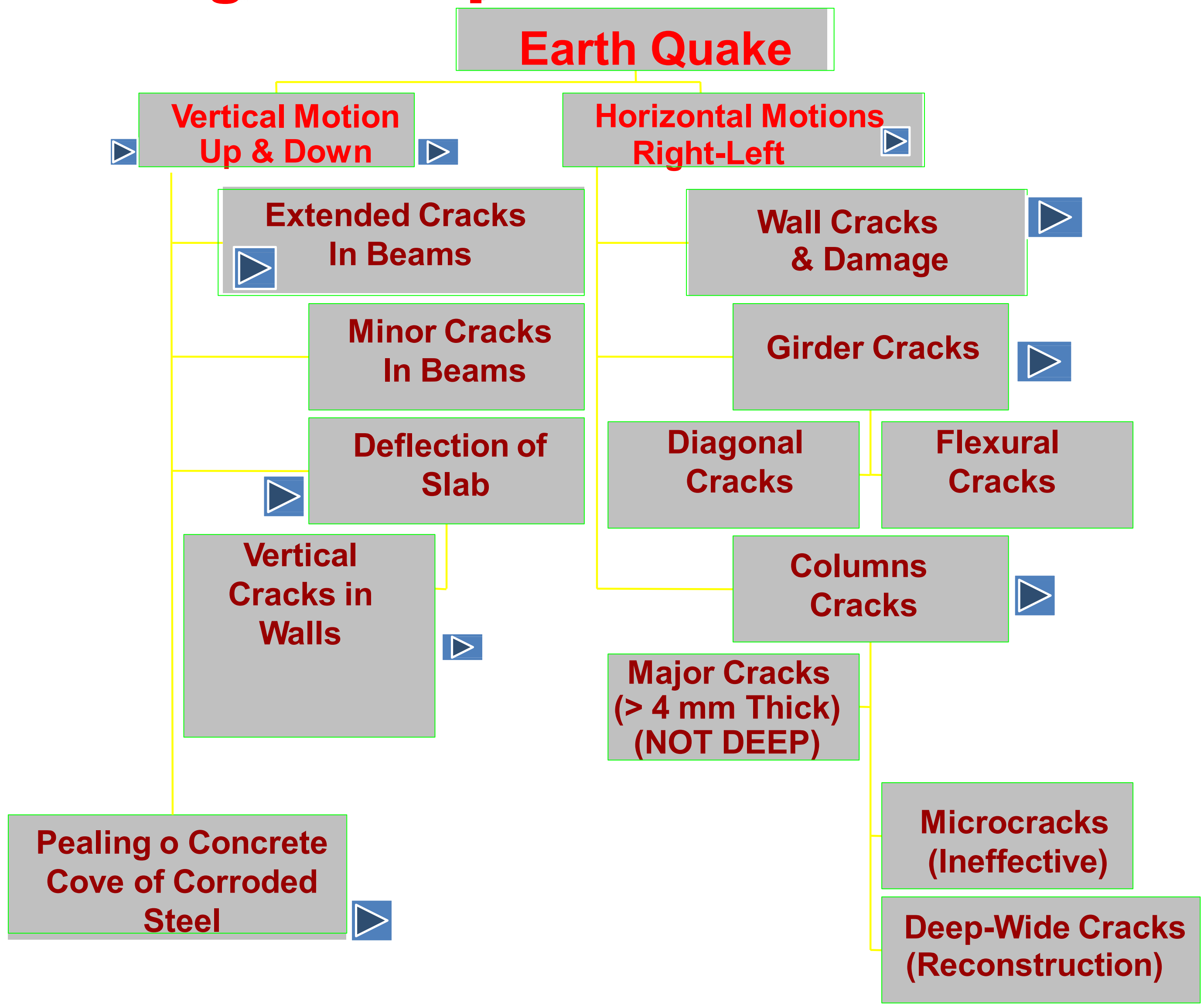
- Poor concrete strength
- Cracked or Spalled concrete
- Yielded & Damaged steel

Erosion and Cavitations

- Wearing and loss of materials
- E rosion of Soil Underneath Foundations
- Erosion of Wing walls & Stabilized Surfaces


Shock Waves
Earthquake
Bombing
Military Tanks
Cracking & Spalling of Concrete

Cracking: Earthquake



Common Construction Faults

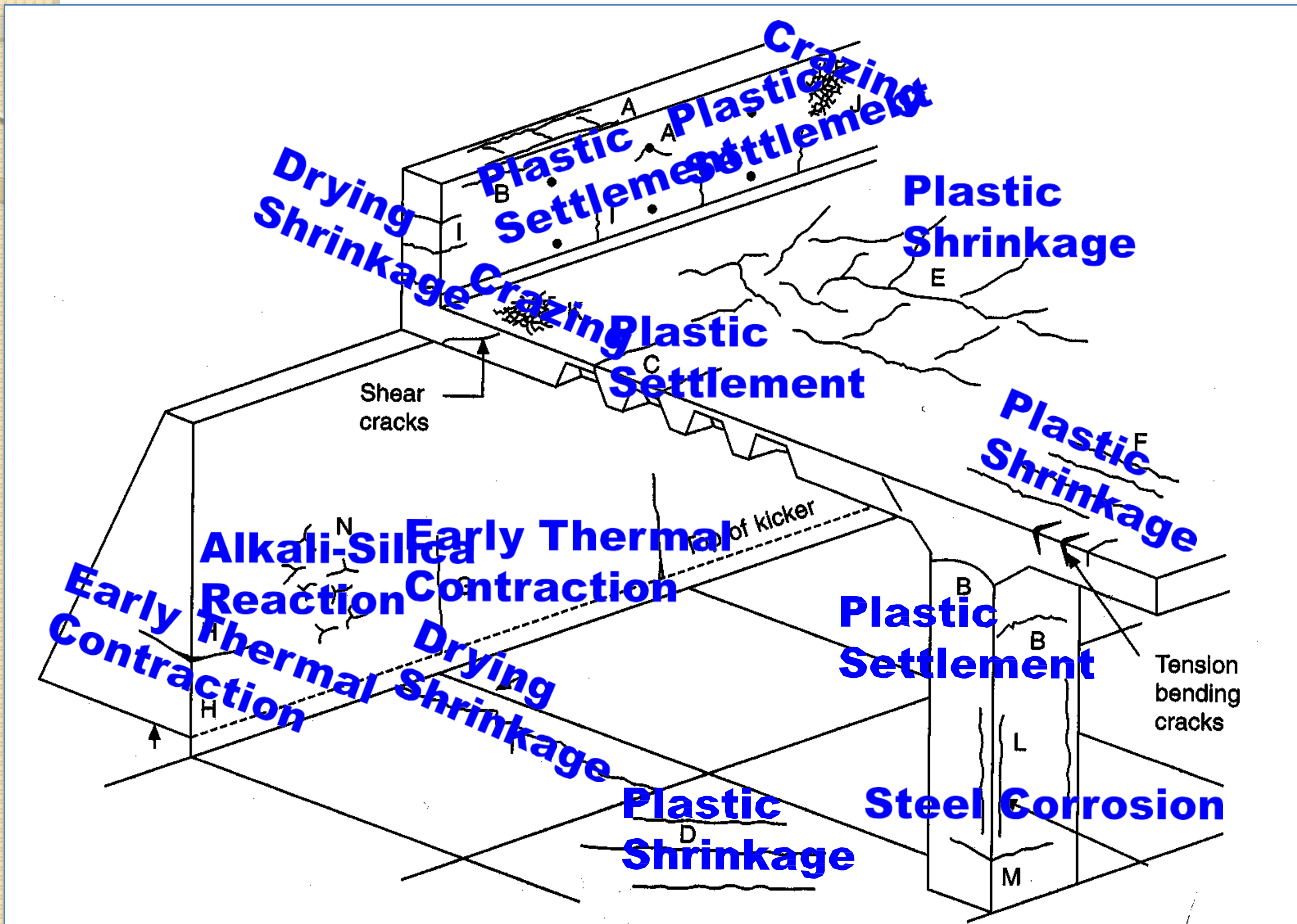
- Use of improper Concrete Ingredients.
- Structural Members are Not Proportioned According to Engineering Plans.
- Insufficient Compaction of Members.
- Use of Improper Cement in Casting Concrete.
- Use of Contaminated Water.
- Use Low quality Reinforcing Steel.
- Improper Distribution of Reinforcing Steel.

CRACKS: CLASSIFICATION & CAUSES

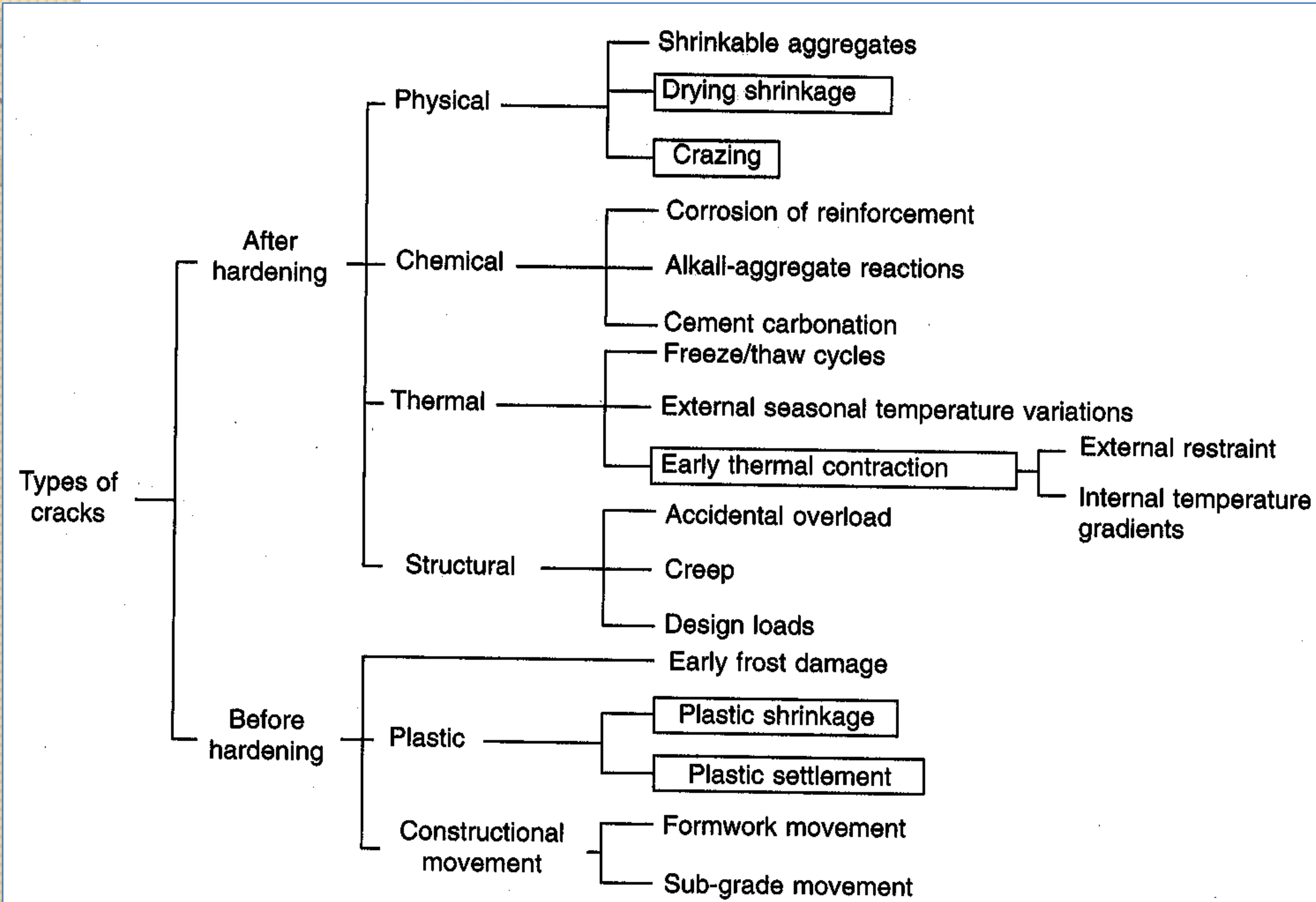
Classification of Intrinsic Cracks

Type of cracking	Letter (See Figure 6.13	Subdivision	Most common location	Primary cause (excluding restraint)	Secondary causes/ factors	Remedy (assuming basic redesign is impossible) In all cases reduce restraint	Time of appearance
Plastic settlement	A	Over Reinforcement	Deep sections	Excess bleeding	Rapid early drying conditions	Reduce bleeding (air entrainment) or re-vibrate	10 minutes to 3 hours
	B	Arching	Top of columns				
	C	Change of depth	Trough and waffle slabs				
Plastic shrinkage	D	Diagonal	Roads and slabs	Rapid early drying	Low rate of bleeding	Improve early curing	30 minutes to 6 hours
	E	Random	Reinforced concrete slabs				
	F	Over-reinforcement	Reinforced concrete slabs	Ditto plus steel near surface			
Early thermal contraction	G	External restraint	Thick walls	Excess heat generation	Rapid cooling	Reduce heat and/or insulate	One day to two or three weeks
	H	Internal restraint	Thick slabs	Excess temperature gradients			
Long-term drying shrinkage	I		Thin slabs (and walls)	Inefficient joints	Excess shrinkage, inefficient curing	Reduce water content, improve curing	Several weeks or months
Crazing	J	Against formwork	Fair-faced concrete	Impermeable formwork	Rich mixes, poor curing	Improve curing and finishing	One to seven days, sometimes much later
	K	Floated concrete	Slabs	Over-trowelling			
Corrosion of reinforcement	L	Natural	Columns and beams	Lack of cover	Poor-quality concrete	Eliminate causes listed	More than two years
	M	Calcium chloride	Pre-cast concrete	Excess calcium chloride			
Alkali–silica reaction	N		(Damp locations)	Reactive aggregate plus high-alkali cement		Eliminate causes listed	More than 5 years

Classification of Intrinsic Cracks



Cracks Types :



Materials and Structural Cracks

Problematic Cracks

- Aesthetically Unacceptable
- Non-Water Tight of The Structure
- Affect The Structure's Durability
- Structural Significance

Types of Crack

- **Dormant Crack: Constant Width**
  - Causes
    - Event in past
    - Shrinkage
- **Active Crack**
  - Width changes with Temperature change
  - Width changes with loads
- **Growing Crack**
  - Causes
    - Foundation Settlement
    - Reinforced Corrosion

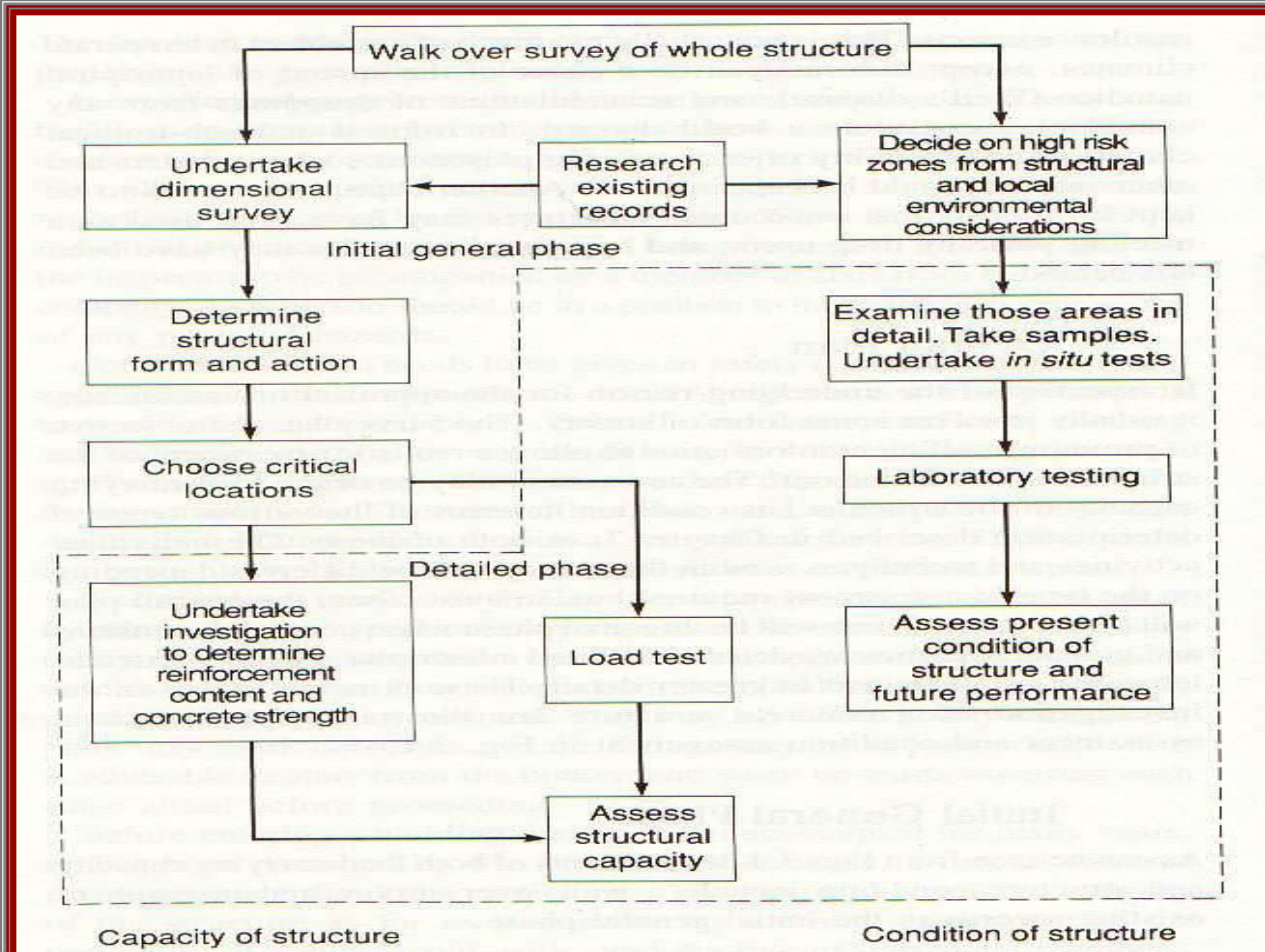
Sources & Characterization of Cracks

1	Crack width is under 0.2 mm. Cracks are small, mainly surface cracks.
2	Crack width is 0.2 to 0.4 mm. Cracks are small structural cracks, generally due to shrinkage.
3	Crack width is 0.3 to l.0 mm. Structural cracks are generally due to deflection, exceeding of the shear capacity, or creep.
4	Crack depth is over 1.0 mm. Structural cracks are due to uneven settlement or a large deformation.

SURVEY & ASSESSMENT METHODS

Engineering Judgment is very fundamental in directing the evaluation process of a deteriorated buildings. Therefore the following fundamental information must be well known:

- **History of the concrete structure: time constructed, materials used and their properties, repair performed, general problems.**
- **History of construction practices.**
- **History of the surrounding region: earthquakes, floods, aggregate quality in the region.**
- **Type of loads.**
- **Topography of the region.**
- **Climate and use of deicing agents.**
- **Accidents**


Walk over survey of whole structure
Undertake dimensional survey
Research existing records
Decide on high risk zones from structural and local environmental considerations
Initial general phase
Determine structural form and action
Examine those areas in detail. Take samples. Undertake *in situ* tests
Choose critical locations
Laboratory testing
Detailed phase
Undertake investigation to determine reinforcement content and concrete strength
Load test
Assess present condition of structure and future performance
Assess structural capacity
Capacity of structure
Condition of structure

Visual Inspection Form for A concrete Building				
Building Name:	Location:	Date Built:	Occupancy:	Owner:
Occupancy: ☐ Residential ☐ Commercial ☐ Offices	☐ Parking ☐ School ☐ Hotel	☐ Public Services ☐ Church ☐ Storage	☐ Industrial ☐ Agricultural ☐ Other…….	
Type of Structure: ☐ Reinforced Concrete	☐ Masonry bearing wall with floor of RC, steel, or wood.	☐ Mixed RC and Masonry vertical members.	Soft Story Stories Below Ground The building is in use	☐ Yes ☐ No ☐ Yes ☐ No ☐ Yes ☐ No
Sketch of the building Plan with distances.				
Condition	Slab: S1 S2 S3 S4 S5	Beams: B1 B2 B3 B4 B5	Column: C1 C2 C3 C4 C5	Wall: W1 W2 W3 W4 W5
1. Surface General Good Satisfactory Poor	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
2. Cracks: Frequency Vertical Horizontal Random	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
Size: Fine (<1mm) Medium (1-2 mm) Wide (>2mm)	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3. Scaling Light (<5mm) Medium (5-10mm) Severe (>10mm) Extensive Localized	☐ ☐	☐ ☐	☐ ☐	☐ ☐

4. Spalling Small Large Many Few	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □
5. Previous Repair Present None Good Satisfactory Poor	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □
6. Signs of: Settlement Expansion Deflection (Buckling) Note Locations:	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □	□ □ □ □ □ □ □ □ □ □ □ □ □ □ □
7. Building Usability Classification	□ Usable- Occupancy Permitted.	□ Temporarily Unusable: Not to be used on continuous basis until a second evaluation.		□ Unusable (Dangerous)

General Comments and Recommendations for NDT and other tests.

Date of Inspection:

Signature of Inspection Team Leader:

Field & Laboratory Evaluation Methods

I. Visual Inspection:

II. Testing Techniques

III. Laboratory Testing.

IV. Coring Testing (ASTM C 42).

V. Fall-Scale Loading

I. Visual Inspection

Useful Tools

- HIUV Lamp
- Gauges
- Tamping Hammer
- Camera & Telescopic Lenses
- Good Quality Binoculars
- Measuring Tape
- Crack Width meter
- Steel Roller
- Pocket magnifier
- Borehole TV Camera

II. None-Destructive Techniques

- Surface Hardness Tests (Schmidt Hammer "Impact Hammer").
- Penetration Resistance (Windsor Probe Test).
- Pull-off Test.
- Ultrasonic Plus Velocity Measurements.
- Resonant Frequency Method(suitable for Freezing and Thawing)
- Impact -Echo Method.
- Acoustic Emission.

9- Corrosion activity test.

Radar.

Covermeter (measures concrete cover to reinforcing steel).

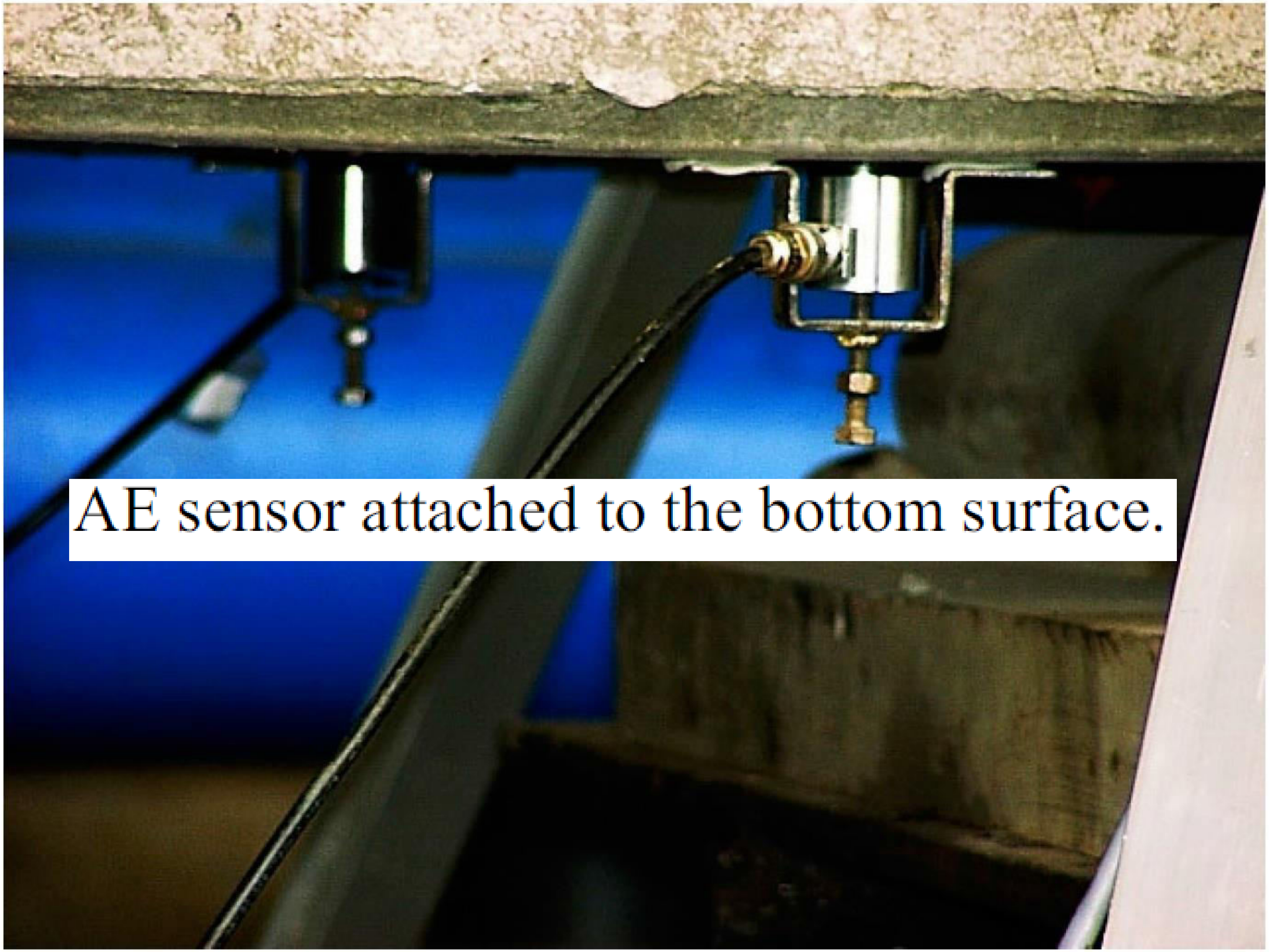
Relative Humidity in Concrete

13- Delaminating Detection. Tools:

- -Tapping Hammer. .
- Electromechanical Devices.
- Infrared Themography .
- Chain Drag Techniques.

Assessment Methods

Pre-cast Prestressed T-beam


AE sensor attached to the bottom surface.

Historic index is a measure of the changes in Signal Strength throughout the test, defined by

$$H(t)=\frac{N}{N-K}\frac{\sum_{i=K+1}^{N} S_{Oi}}{\sum_{i=1}^{N} Soi}$$

where $H(t)$ is the historic index at time t, N is the number of hits up to and including time t, S_{Oi} is the signal strength of the i-th event, and K is an empirically derived factor that varies with the number of hits. For $N < 50$, $K = 0$: for $50 \leq N < 200$, $K = N - 30$: for $201 \leq N < 500$, $K = 0.85N$: and for $501 \leq N \leq 2000$, $K = N - 35$ [8]. The second parameter used for this analysis is known as severity (S_r) and is defined as the average signal strength for the 50 events having the largest numerical value of signal strength and is defined by the following equation:

$$S_r = \frac{1}{50}\sum_{i=1}^{i=50} S_{Oi}$$

where S_r is severity and S_{Oi} is the signal strength of the i-th event as above.

III. Laboratory Testing and Evaluation

- Strength test, Density, Absorption , Void ratio and Permeability determination.
- Petrography's and Image analysis.
- Air voids system.
- Chloride content determination.
- Condition of rebar.
- Ultrasonic plus velocity determination.
- Determination of cement and aggregate contents and aggregate size distribution.
- Chemical analysis of cement paste.

IV. Core Testing

Testing Cores For Compressive Strength: ASTM C42

Example: The data obtained from a compressive strength test of three concrete 100 mm-diameter cores are listed in the Table below. If the specified cylinder strength is 25 MPa, would the concrete pass or fail the test?!.

Solution: The average σ_{cyl}=21.6 MPa (86% of Specified Strength) > 85%, Yet σ_{cyl} of core III is 71% < 75% of specified strength. Decision: The concrete fails the test.

Core	Load	σ_{core}	L (mm)	L/D	CF	σ_{cyl}
I	200 kN	25.6 MPa	150	1.5	0.96	24.6 MPa
II	180 kN	23.0 MPa	175	1.75	0.96	22.5 MPa
III	155 kN	19.8 MPa	113	1.13	0.96	17.8 MPa

V. Full-Scale Loading: ACI 318

- **Loading Structures that failed to attain the required concrete core strength.**
- **Loading Structures that had been repaired for lack of bearing capacity of its major components.**
- **What should you measure under load effect?**

✓ Deflection

✓ Induced strain

✓ Monitor crack formation and widening (if any)

✓ Regained deflection

V. Full-Scale Loading: ACI 318

General-Test Conditions:

- Slabs and beams of age (56 days and less).
- Loading in Field is carried out by a party of recognized expertise.
- The structure should be loaded by design superimposed dead loads (excluding own weight of slabs & beams) before 48 hours of of loading test.

V. Full-Scale Loading: ACI 318

Loading Procedure:

- Slabs and beams are loaded with 0.85(1.4 DL+1.7LL) minus the dead load that is already applied.
- LVDTs of dial gauges are placed under the slabs and beams at critical locations to measure deflection. These are maintained at their specified positions through a special frame work.
- Before loading, the LVDTs or dial gages are set to zero readings, then the load calculated is applied equally at four stages. The loads are left above the slabs and beams for 24 hours, before deflection readings are taken.
- The loads calculated are removed, and deflection readings are taken after 24 hours. The difference between these readings and those before lifting the loads represents Self-Recovery.

V. Full-Scale Loading: ACI 318

Specification Requirements:

The slabs and beams fail the test if extensive cracking or failure signs appeared during loading or if it do not achieve the following requirements:

A. Deflections measured $\leq 50L^2/h$, where L is the span of loading expressed as the center-center distance between supports or the loading span+ the depth of the slab or beam. In case of cantilevers, the span is the double distance between the support and the free end.

B-If the deflection in A is violated, Self-Recovery should not be less than 75% of ultimate deflection.

V. Full-Scale Loading: ACI 318

Example: The core testing, obtained from the second floor- Prince Rashed Hospital, failed the Jordanian Specifications regarding core strength, although equivalent strength remained above 15 MPa. Therefore, the contractor and the supervising team had agreed on carrying out a loading test for the floor.

Loads Calculations:

Superimposed Dead Load:

Tiles ▸	0.03 x 2000	=	60 kg/m^2
Mortar ▸	0.02 x 2000	=	40 kg/m^2
Sand ▸	0.10 x 1800	=	180kg/m^2
Total ▸		=	280 kg/m^2

Dead Load of Ribs & Slabs:

Rib ▸	0.24 x 0.15 x 2500	=	90 kg/m^2
	0.07 x 0.55 x 2500	=	96 kg/m^2
Slab ▸	15 x 5	=	75 kg/m^2
Total ▸		=	475kg/m^2

Live Load: 400 kg/m^2

V. Full-Scale Loading: ACI 318

- The superimposed loads (280 kg/m2) are placed before 48 hours. These were achieved using 25 (100 voided Bricks) on 1 m^2 {mass of each brick = 11.5 kg).
- After 48 hours, six dial gages were placed at certain points under the roof and were set at a reference reading.
- The the following load is placed directly at four stages:

  $= 0.85\{1.4(475+280)+1.6(204)\} - (475+280) = 421\ kg/m^2$

  This load was achieved by placing 28 100-mm Bricks + 2 (50-kg Bags) ▸ $28 \times 11.5 + 2 \times 50 = 422\ kg/m^2$.
- After 24 hours, dial gages reading were taken. Results are summarized in the following Table.

V. Full-Scale Loading: ACI 318

Example:

Dial Gage #	Deflection, mm	Allowable Deflection, mm
1	3.115	5.47
2	3.35	4.27
3	1.95	5.37
4	1.01	6.29
5	2.55	4.38
6	0.58	5.42

Conclusion: The floor showed no cracking, and deflection are below allowable values. Therefore, the floor passes the load test.

Survey & Assessment Methods

Concrete Chemical & Physical Properties: Guide

Evaluation Procedure / Chemical And Physical Properties	Acoustic Impact (Table 1.3)	Air Content test (ASTM C457)	Cement Content Test (ASTM C1084)	Chemical Tests	Core Testing	Electrical potential measurements (Table1.3)	Electrical resistance measurements (Table1.3)	Flexural tests(ASTM C42)	Freeze thaw test (ASTM C666)	Gamma radiography (Table 1.3)	Nuclear moisture meter (Table 1.3)	Permeability test (CRD C48)	Petrographic analysis (ASTM C856)	Pullout testing(ASTM C900)	Rebound hammer (ASTM C805)	Ultrasonic pulse (ASTM C597)	Windsor probe (ASTM C803)
Acidity				●									●				
Air content		●											●				
Alkali-Carbonate Reaction													●				
Alkali-Silica Reaction													●				
Cement content			●	●									●				
Chemical Composition				●									●				
Chloride content				●	●								●				
Compressive strength					●									●	●	●	●
Contaminated Aggregate				●									●				
Contaminated Mixing water				●									●				
Corrosion environment				●		●											

Survey & Assessment Methods

Concrete Chemical & Physical Properties: Guide

Evaluation Procedure / Chemical And Physical Properties	Acoustic Impact (Table 1.3)	Air Content test (ASTM C457)	Cement Content Test (ASTM C1084)	Chemical Tests	Core Testing	Electrical potential measurements (Table1.3)	Electrical resistance measurements (Table1.3)	Flexural tests(ASTM C42)	Freeze thaw test (ASTM C666)	Gamma radiography (Table 1.3)	Nuclear moisture meter (Table 1.3)	Permeability test (CRD C48)	Petrographic analysis (ASTM C856)	Pullout testing(ASTM C900)	Rebound hammer (ASTM C805)	Ultrasonic pulse (ASTM C597)	Windsor probe (ASTM C803)
Creep					●												
Density					●					●							
Elongation					●												
Frozen components													●				
Modulus of elasticity					●											●	
Modulus of rupture					●			●									
Moisture Content					●		●				●						
Permeability												●	●				
Pullout strength														●			
Quality of aggregate													●				
Resistance to Freezing and Thawing					●				●				●				
Soundness					●					●			●				

Survey & Assessment Methods

Concrete Chemical & Physical Properties: Guide

Evaluation Procedure / Chemical And Physical Properties	Acoustic Impact (Table 1.3)	Air Content test (ASTM C457)	Cement Content Test (ASTM C1084)	Chemical Tests	Core Testing	Electrical potential measurements (Table1.3)	Electrical resistance measurements (Table1.3)	Flexural tests(ASTM C42)	Freeze thaw test (ASTM C666)	Gamma radiography (Table 1.3)	Nuclear moisture meter (Table 1.3)	Permeability test (CRD C48)	Petrographic analysis (ASTM C856)	Pullout testing(ASTM C900)	Rebound hammer (ASTM C805)	Ultrasonic pulse (ASTM C597)	Windsor probe (ASTM C803)
Splitting tensile strength					●												
Sulfate resistance				●									●				
Tensile strength					●			●									
Uniformity	●												●		●		●
Water cement ratio													●				

Survey & Assessment Methods

Concrete Physical Condition: Guide

Evaluation Procedure / Physical condition	Acoustic Emissions (Table 1.3)	Acoustic impact (Table 1.3)	Chemical Tests	Core Testing(ASTM C42)	Fiber optics (Table 1.3)	Gamma Radiography (Table 1.3)	Infrared thermography (Table 1.3)	Load testing (ACI 437R)	Petrographic analysis (ASTM C856)	Physical measurement	Radar (Table 6.3)	Rebound hammer (ASTM C805)	Ultrasonic pulse (ASTM C597)	Ultrasonic pulse echo (Table 1.3)	Visual examination(ACI 201.1R, ASTM C823)	Windsor Probe (ASTM C803)
Bleeding channels									●						●	
Chemical Deterioration			●						●						●	
Corrosion of steel			●	●					●						●	
Cracking	●	●		●	●		●		●	●	●		●	●	●	
Cross-sect. Properties and thickness				●		●				●			●			
Delamination		●		●	●	●	●		●		●		●	●	●	
Discoloration			●						●						●	
Disintegration				●		●	●		●				●		●	
Distortion															●	

Survey & Assessment Methods

Concrete Physical Condition: Guide

Physical condition \ Evaluation Procedure	Acoustic Emissions (Table 1.3)	Acoustic impact (Table 1.3)	Chemical Tests	Core Testing(ASTM C42)	Fiber optics (Table 1.3)	Gamma Radiography (Table 1.3)	Infrared thermography (Table 1.3)	Load testing (ACI 437R)	Petrographic analysis (ASTM C856)	Physical measurement	Radar (Table 6.3)	Rebound hammer (ASTM C805)	Ultrasonic pulse (ASTM C597)	Ultrasonic pulse echo (Table 1.3)	Visual examination(ACI 201.1R, ASTM C823)	Windsor Probe (ASTM C803)
Efflorescence			●						●						●	
Erosion									●						●	
Freeze-Thaw damage									●						●	
Honeycomb				●	●	●	●		●				●		●	
Popouts															●	
Scaling															●	
Spalling				●		●	●								●	
Stratification		●			●									●	●	
Structural performance	●							●							●	
Uniformity of concrete					●				●			●	●		●	●

Survey & Assessment Methods

Concrete Physical Condition: Guide

	Acoustic impact(table 1.3)	Chemical analysis(ASTM A571)	Coating tests(ASTM A775,G12,14,20)	Cover meters pachometer(table 1.3)	Electrical potential measurements(table 1.3)	Gamma radiography(table 1.3)	Physical measurements	Radar(table 1.3)	Tension tests(table 1.3)	Ultrasonic pulse echo(table 1.3)	Visual inspection
Adhesion of epoxy coating			●								
Anchorage							●				
Bend test							●				
Breaking strength									●		
Carbon content		●									
Chemical composition		●	●								
Coating Properties		●									
Concrete cover				●		●	●	●			
Continuity of epoxy coating			●								

Survey & Assessment Methods

Reinforcing Steel Properties: Guide

	Acoustic impact(table 1.3)	Chemical analysis(ASTM A571)	Coating tests(ASTM A775,G12,14,20)	Cover meters pachometer(table 1.3)	Electrical potential measurements(table 1.3)	Gamma radiography(table 1.3)	Physical measurements	Radar(table 1.3)	Tension tests(table 1.3)	Ultrasonic pulse echo(table 1.3)	Visual inspection
Corrosion					●		●				●
Cross sectional properties and thickness							●				
Deformations							●				●
Elongation									●		
Exposure											●
Rebar location	●			●		●	●	●			
Reduction of area									●		
Shape							●				
Strength of connections							●				
Tensile strength									●		
Thickness of epoxy coating			●								
Weld shear strength							●				
Yield strength									●		

VI. Laboratory Testing of Steel

Stress-strain Diagram
Hardness Test
Corrosion Extent
Geometric Properties

VI. Laboratory Testing of Steel

Method: ASTM A 370

Objective: Determine properties of Wrought & Cast steel products used in Structures. These include:

- TENSION TEST.
- BEND TEST.
- HARDNESS TEST.

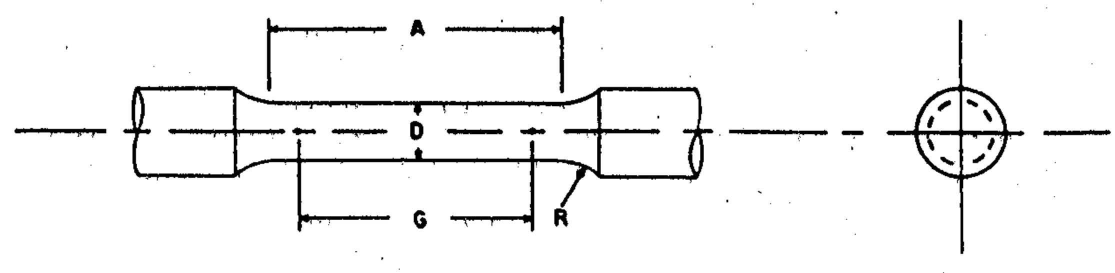
VI. Laboratory Testing of Steel

Tension Test

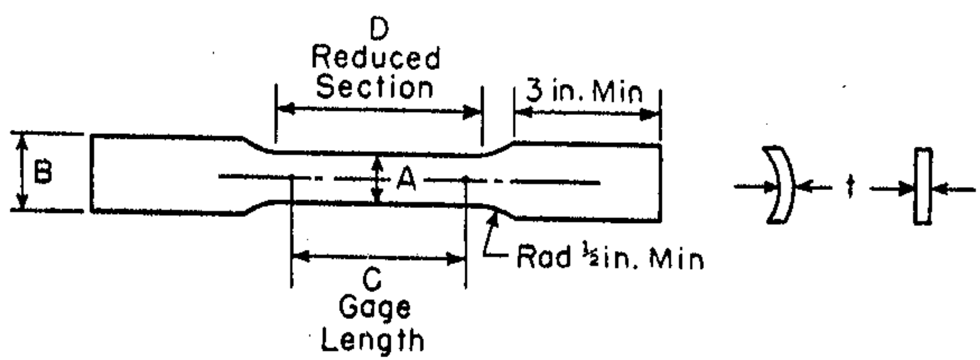
Objective: Determine properties of CHARACTERISITC OF STRESS-STRAIN DIAGRAM FOR Steel

Specimens:

Round Specimen



Flat or curved Specimen



VI. Laboratory Testing of Steel

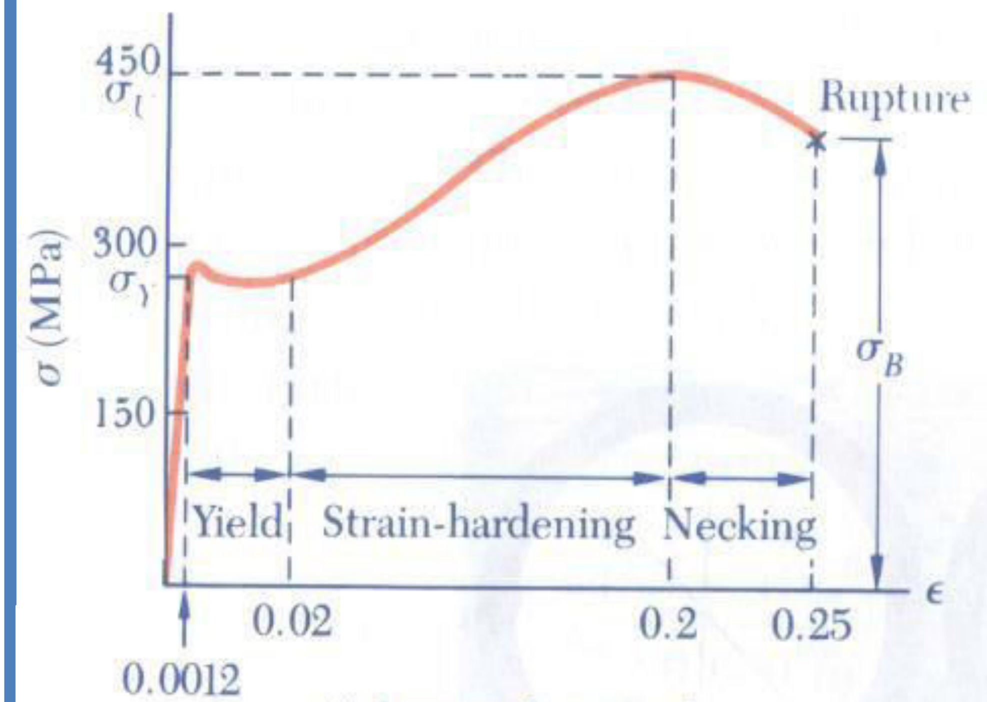
TENSION TEST

Procedure:

- The specimens are subjected to axial an increasing tensile force along with length and diameter changes measurements are acquired.

- The stress and strains are computed as:

$$\sigma = \frac{T}{A}; \text{and } \varepsilon = \frac{\delta}{L_o}$$



(a) Low-carbon steel

VI. Laboratory Testing of Steel

TENSION TEST

Characteristics of Stress-Strain Diagram

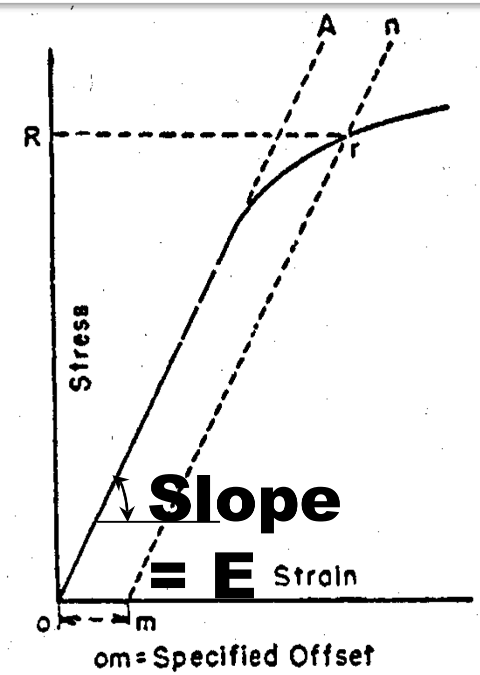
- Yield Point (Offset Method)
- Ultimate Strength
- Facture Strength
- Strain At Failure
- Modulus of Elasticity {E}
- Area Under Stress-Strain Diagram

▶ Toughness of Steel

VI. Laboratory Testing of Steel

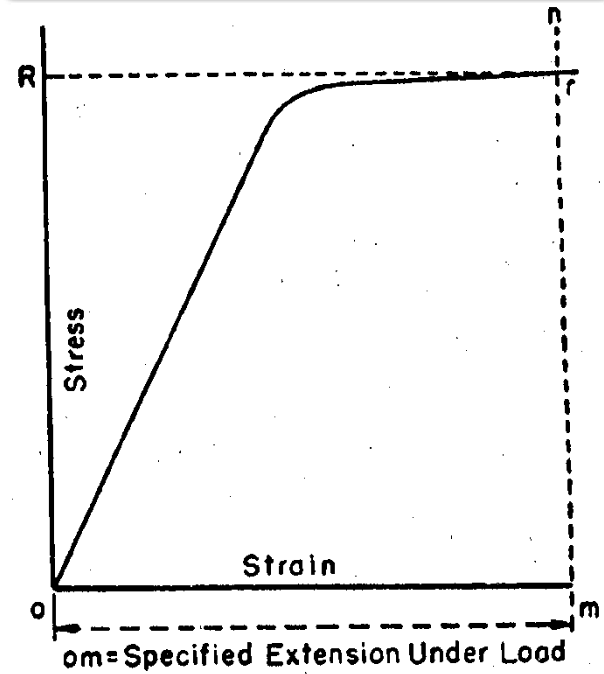
TENSION:
YIELD POINT

Offset Method:



Extension Method:

Load Producing A specified Extension:



Om=0.005 (Fy ≤ 550 MPa) OR 0.01 (Prestressed Steel)

VI. Laboratory Testing of Steel

BEND TEST

Objective: Evaluate QUALITATIVELY the Ductility of Steel

Procedure: The chemical composition, tensile properties, hardness type, and quality of steel specified, in addition to the bar size and the inside diameter to which the specimens is bend determine the severity of the bend. Pre-heat or aging treatment of steel is usually done in order to perform bending in field without major cracking on the outside of the bent portion.

Standard Specifications:

- For wires of sizes ≤ 7 mm, bend around a pin of diameter equal to that of the wire.
- For wires of sizes > 7 mm, bend around a pin of double the diameter of that of the wire.

VI. Laboratory Testing of Steel

HARDNESS TEST

Objective: Determine resistance to penetration & is occasionally employed to obtain A quick approximation of tensile strength

Specimens: Flat Surface Steel

Procedure: The hardness is evaluated by different scales; the most known of which are: Rockwell & Brinell.

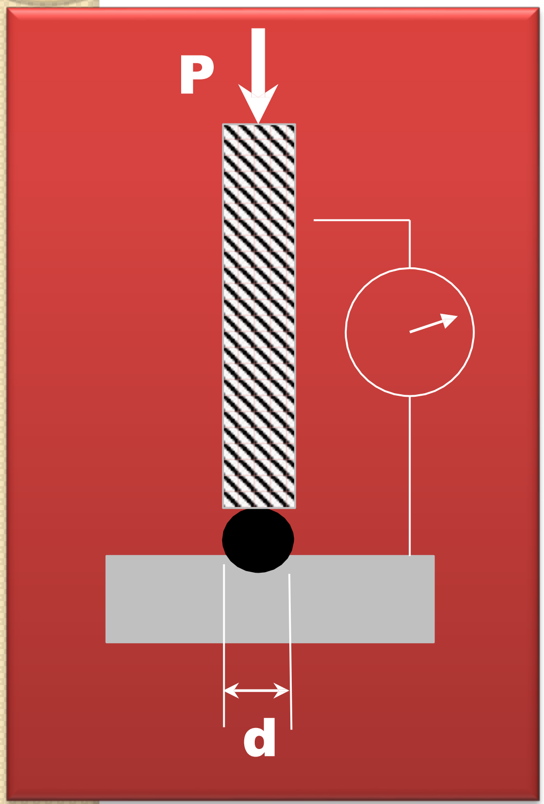
Rockwell: The hardness value is obtained by using a direct-reading testing machine which measures hardness by determining the depth of penetration of a diamond point or a steel ball into the specimen under certain arbitrary fixed conditions. A minor load is applied first, then a major load is applied. The difference in dial gage reading indicates the hardness. The number is proportional to hardness.

VI. Laboratory Testing of Steel

- Brinell: The hardness value is obtained by measuring the indentation resulting from pressing standard steel ball against a steel flat specimens. The smaller the indentation the harder is the steel.

VI. Laboratory Testing of Steel

HARDNESS TEST



Steel Ball (1/16")
Load 10-100

Diamond-Brale
Load 10-100 kgf

Steel Ball (Diameter =10mm)
Load 1500 or 3000 kgf

$$HB = P / [(\pi D/2)(D - \sqrt{D^2 - d^2})]$$

D: Ball Diameter (mm)

d: Indentation diameter (mm)

VI. Laboratory Testing of Steel

HARDNESS TEST

Hardness Numbers of Different Scales

Rockwell C Scale, 150-kgf Load, Diamond Penetrator	Vickers Hardness Number	Brinell Hardness, 3000-kgf Load, 10-mm Ball	Approximate Tensile Strength, ksi (MPa)
68	940	...	...
67	900	...	...
66	865	...	...
65	832	739	...
64	800	722	...
63	772	706	...
62	746	688	...
61	720	670	...
60	697	654	...
59	674	634	351 (2420)
58	653	615	338 (2330)
57	633	595	325 (2240)
56	613	577	313 (2160)
55	595	560	301 (2070)

Steel Mechanical Tests

TENSION TEST

Chemical Standard Specification - ASTM A 36
(Riveted, Bolted or Welded Constructions)

Element	Shapes	Plates	Bars
Carbon, max, %	0.25	0.25-0.25	0.26-0.26
Manganese, %	....	0.80-1.2	0.60-0.90
Phosphorus, max, %	0.04	0.04	0.04
Sulfur, max, %	0.04	0.04	0.04
Silicon, %	....	0.15-0.40	....
Copper, min, %	0.20	0.20	0.20

Steel Mechanical Tests

TENSION TEST: Standard Specifications

Carbon Steel: Riveted, Bolted or Welded Constructions - ASTM A 36

Property	Shapes	Plates	Bars
Tensile Strength (MPa)	400-550	400-550	400-550
Yield Stress (MPa)	250	250	250
Elongation	20-21%	20-23%	20-23%

Concrete Reinforcement - D ≥ 2 mm- ASTM A 82

Property y	Wires ≤ 16 mm	Welded Fabric
Tensile Strength, min, MPa	550	485[1]-515[2]
Yield Stress, min, MPa	485	385-450
Reduction of Area, Min, %	20-23%	....

1: Size ≤ 3 mm

2: Size ≥ 3 mm

Steel Mechanical Tests

TENSION TEST: Standard Specifications

Reinforcing Steel - ASTM A 615

Property	Grade 40	Grade 60
Tensile Strength, min, MPa	483	621
Yield Stress, min, MPa	276	415
Elongation, min, %	11-9*	9-7*

(Sizes Up to ϕ=32 mm)

Steel Mechanical Tests

TENSION TEST: Standard Specifications

Steel for Prestressed Concrete-ASTM C 421

D (mm)	Tensile Strength, min, MPa		Yield Stress, min, Extension at 1%, MPa		Initial Stress (MPa)
	Type BA	Type WA	Type BA	Type WA	
4.88	NA	1725	NA	1465	200
4.98	1655	1725	1407	1465	200
6.35	1655	1655	1407	1407	200
7.01	1655	1620	1377	1377	200