

Durability of Concrete Structures

Dr. Safeer Abbas

Assistant Professor

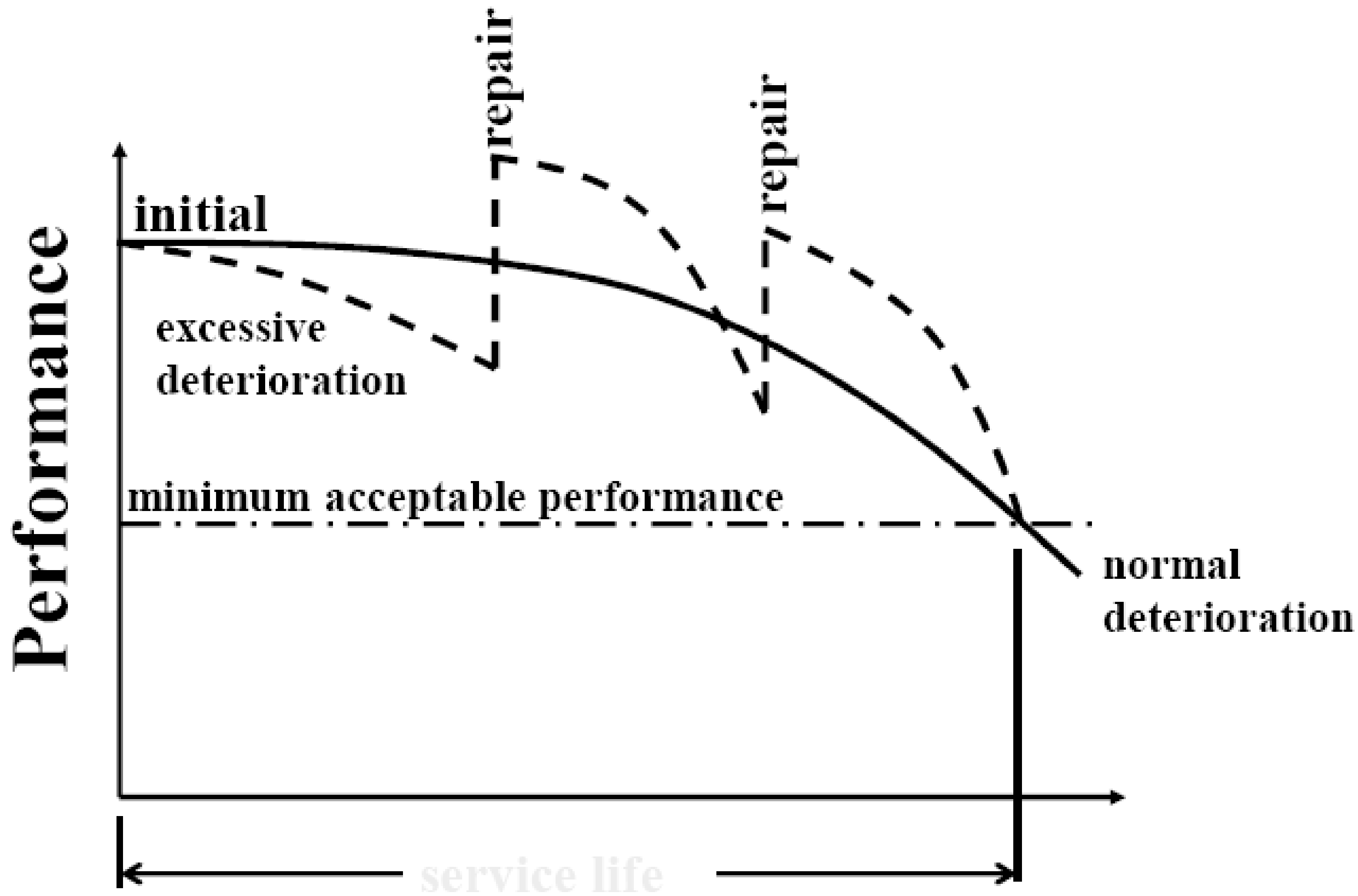
Civil Engineering Department

UET Lahore, Pakistan

Durability of Concrete

- Ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration.
- Durable concrete will retain its original form, quality, and serviceability when exposed to environment

Service Life Objectives



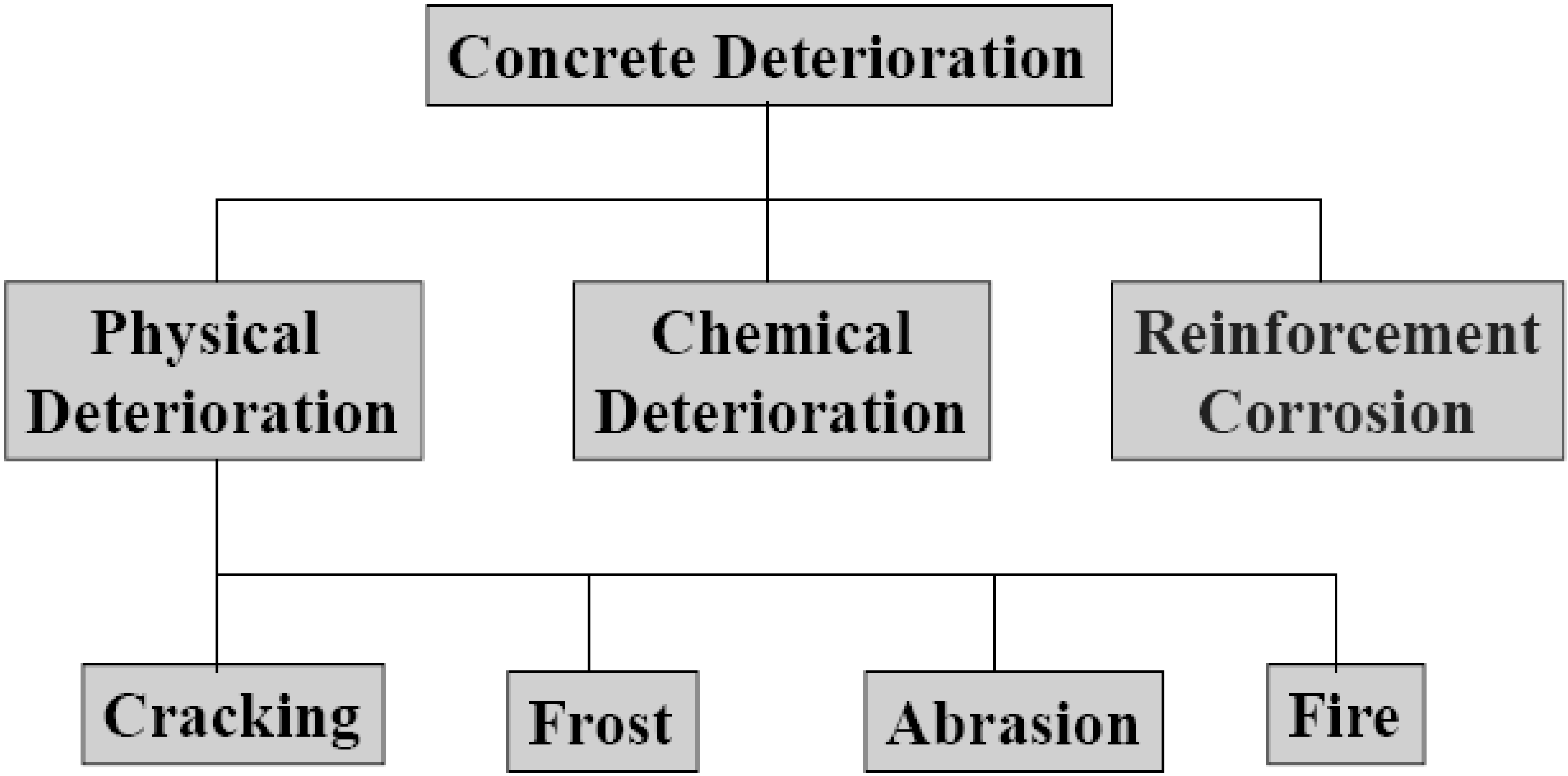
Deterioration and its Causes

- *Physical manifestation of failure of a material* (cracking, spalling, delamination, pitting)
- *Decomposition of material* (disintegration, weathering)

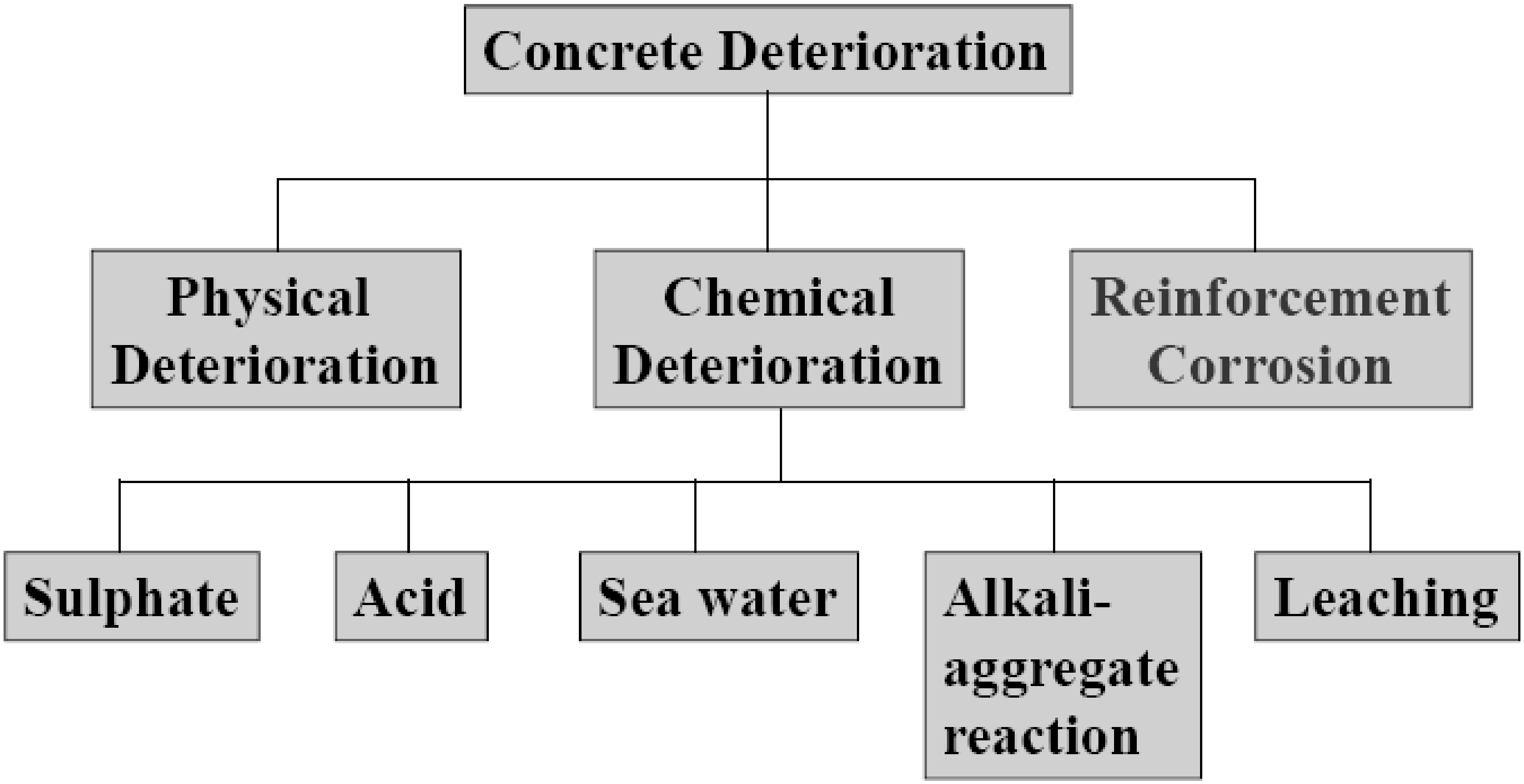
Causes of deterioration:

- *Interaction with environment* (external)
- *Interaction with constituents* (internal)

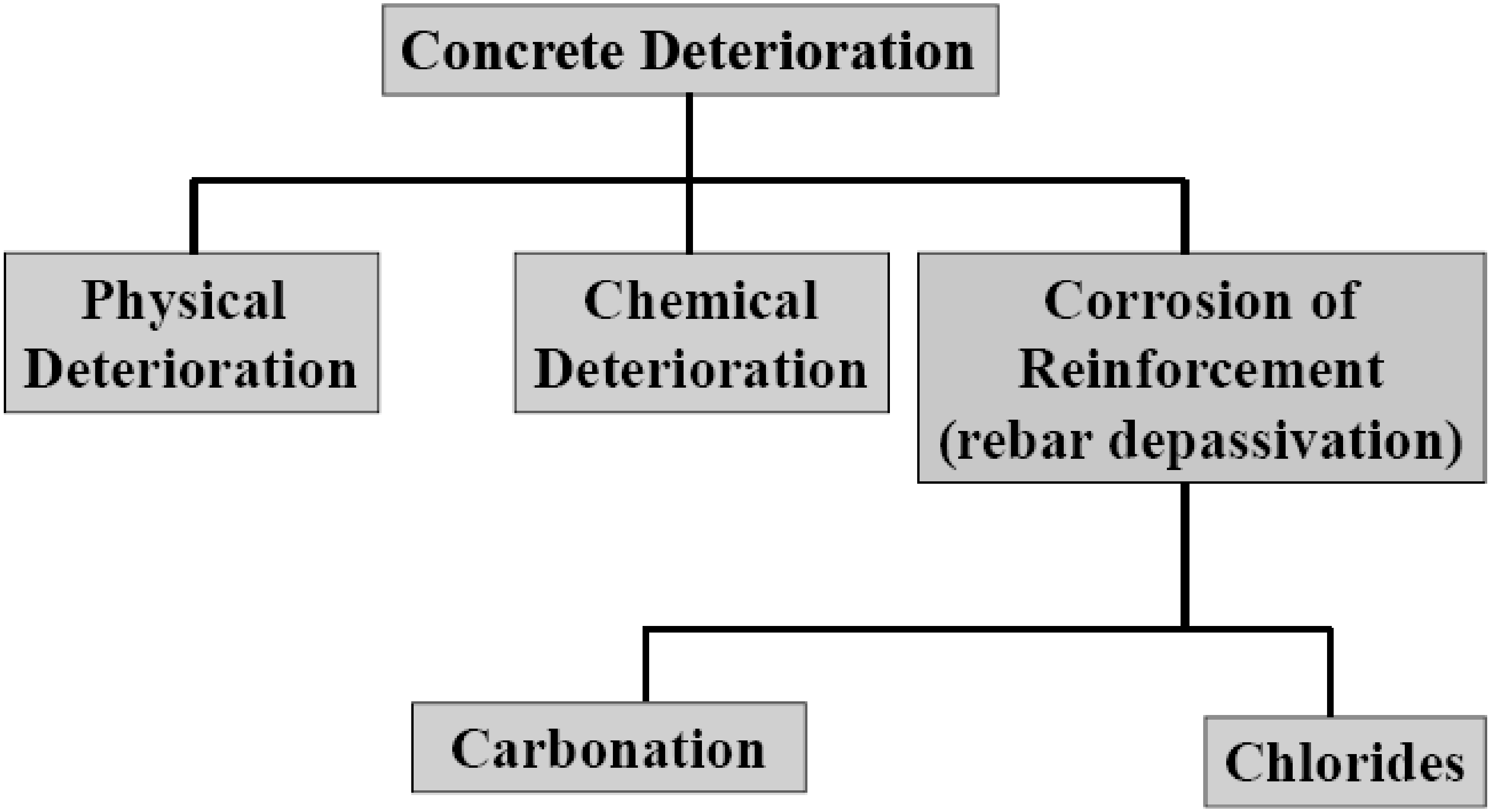
Physical Deterioration



Chemical Deterioration



Reinforcement Corrosion



Durability Issues

- Corrosion
- Freeze-thaw
- Alkali-Silica reaction
- Sulphate

Corrosion: Extent of Problem

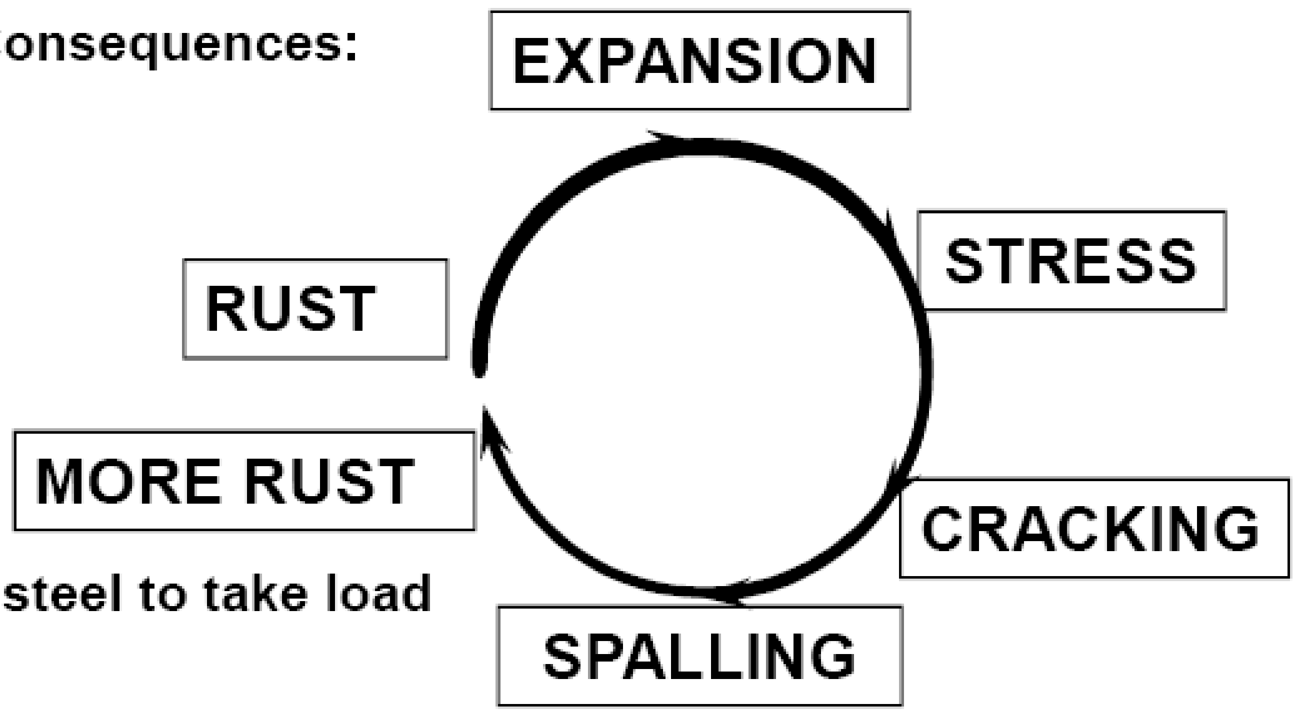
- 40% of steel annually produced in the world is used to repair corrosion damage.
- Costs are around 2000$ to 3000$ per inhabitant
- More than annual income in many countries

What is Corrosion?

Conversion of:

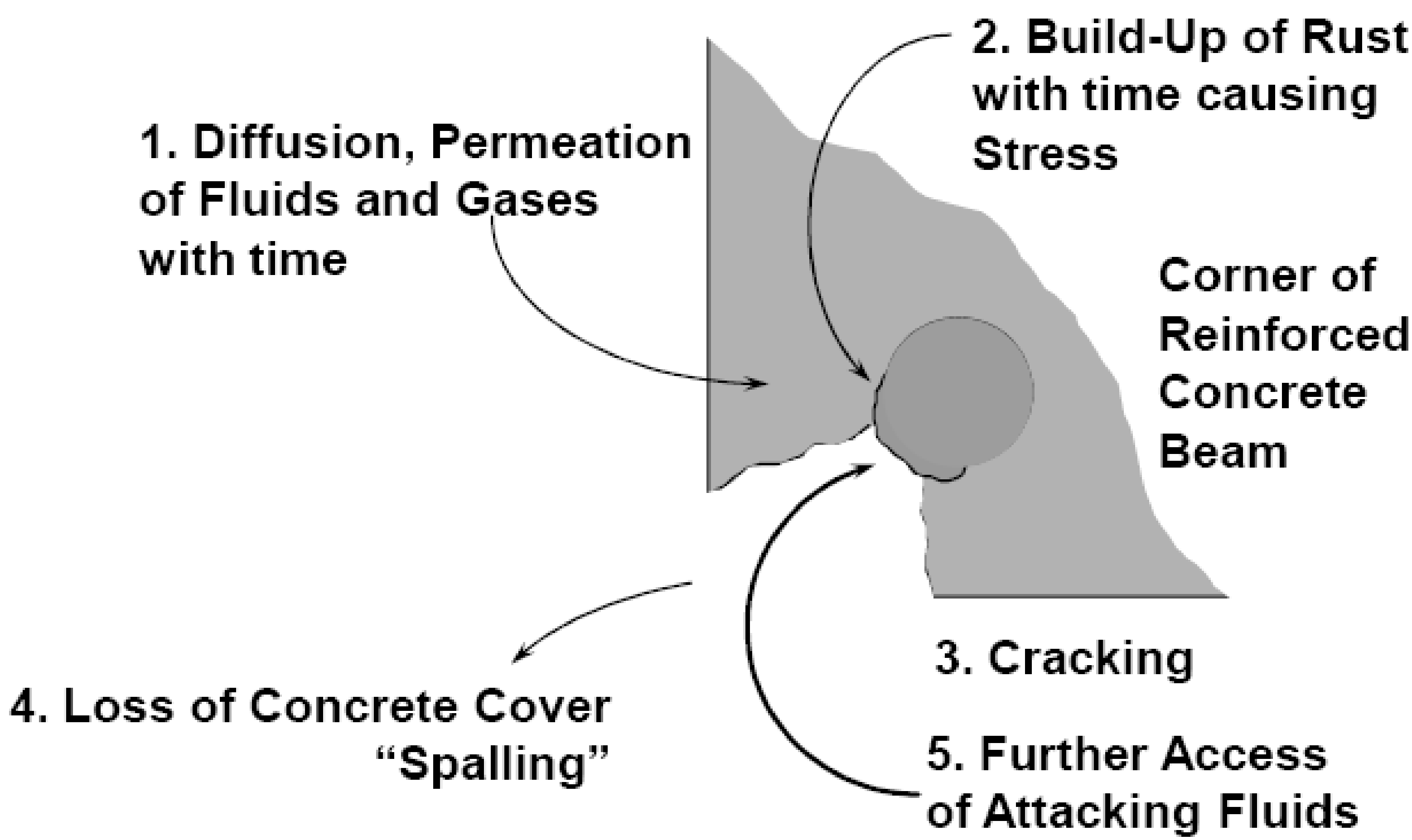
IRON → IRON OXIDE (rust)

Consequences:



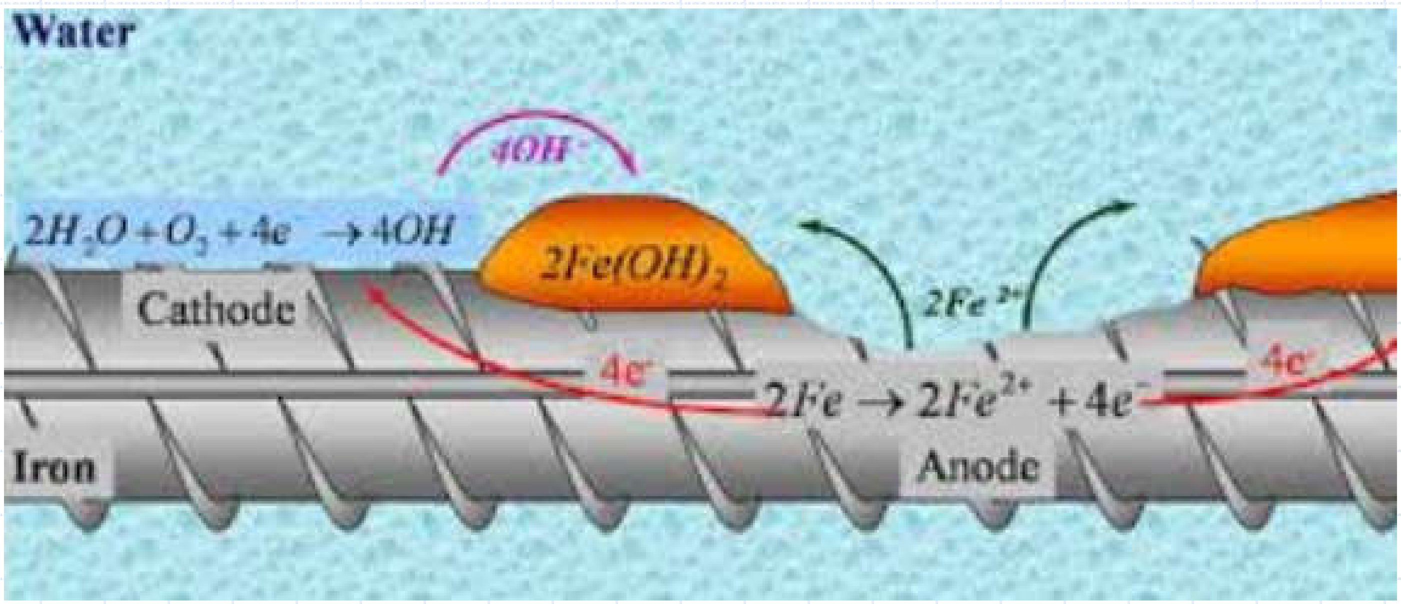
Less steel to take load

Illustration of Spalling



Corrosion of Reinforcement

- Reinforcement normally passivated (oxide film)
- *Chloride ingress*
- *Carbonation*

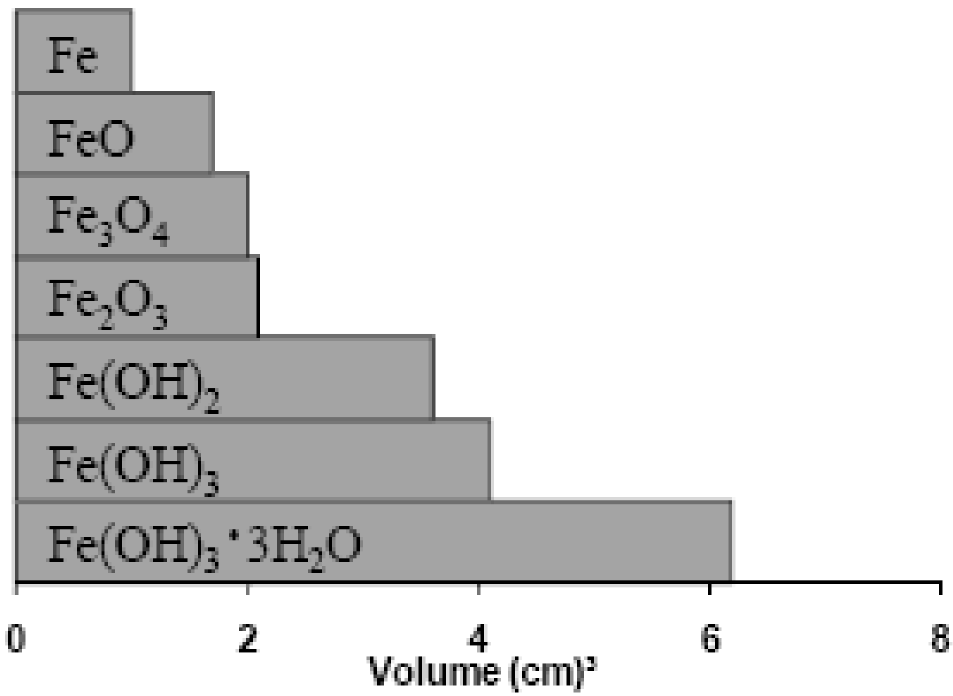


Electrochemical Corrosion

- Similar reaction take place in flash light battery
- Electrochemical reaction are:
  - ✓ *Anode: electrochemical oxidation takes place*
  - ✓ *Cathode: electrochemical reduction*
  - ✓ *Electrical conductor: rebar*
  - ✓ *Aqueous medium: water, seawater*

Corroded Steel

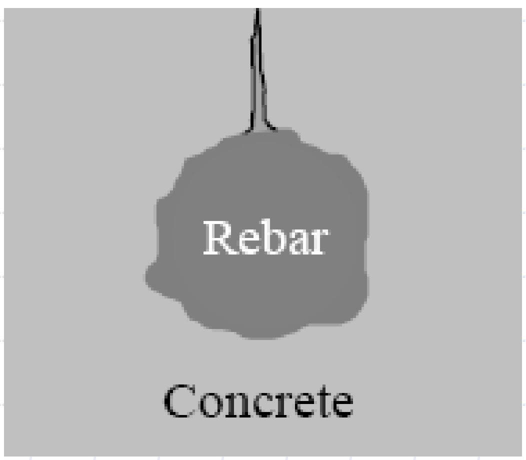
- Fe^{++} react with OH^- and dissolved oxygen to form iron oxides and hydroxides. As the electrochemical reactions continue, more and more Fe-OH compounds pile up.
- Rust occupy more volume than steel. Depending on the compound formed, volume can increase by six times over the original steel.

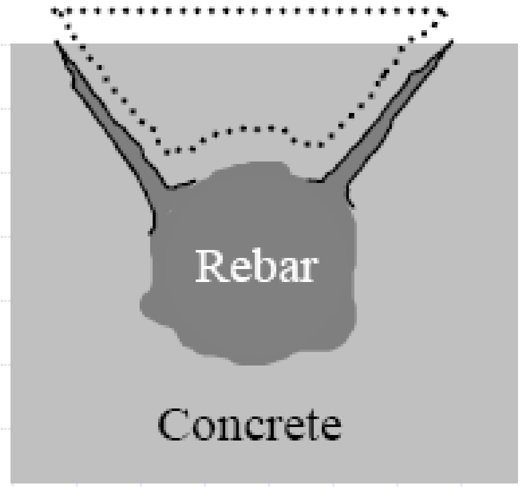


Concrete Fracture

Due to tensile stresses generated by rust

- Single crack
- Coordinated cracks

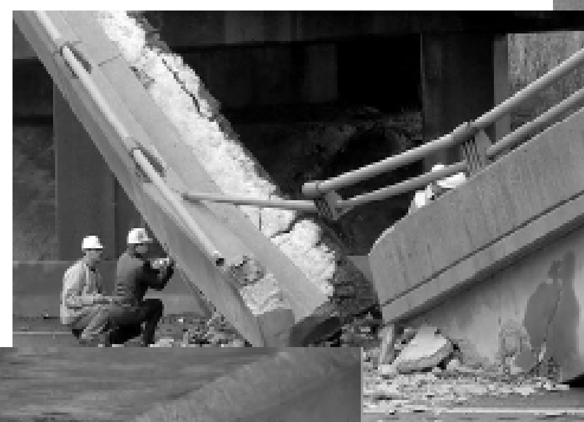


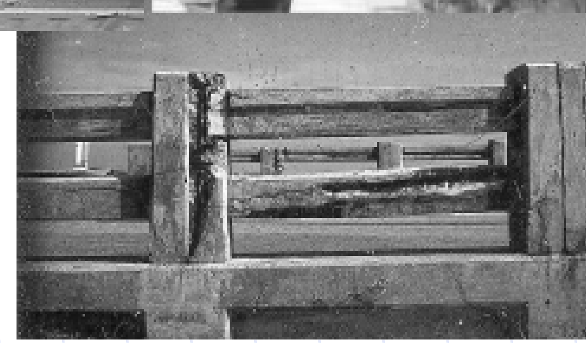


Manifestation (Consequences) of Corrosion

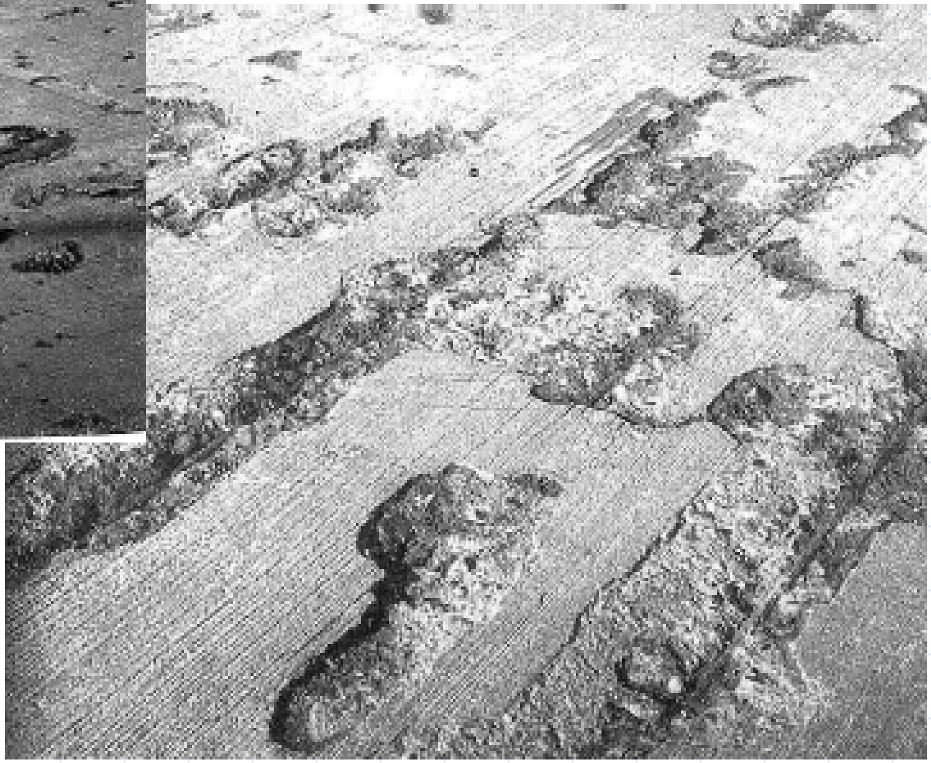
- Corrosion induced cracking, spalling and delamination (reduces effective cross-section of concrete member, effect structural capacity).
- Fine cracks followed by rust strains reflecting the pattern of underlying reinforcement.
- Visible rust strain at the surface.
- Loss of cross-section of rebars.

Bridge Corrosion

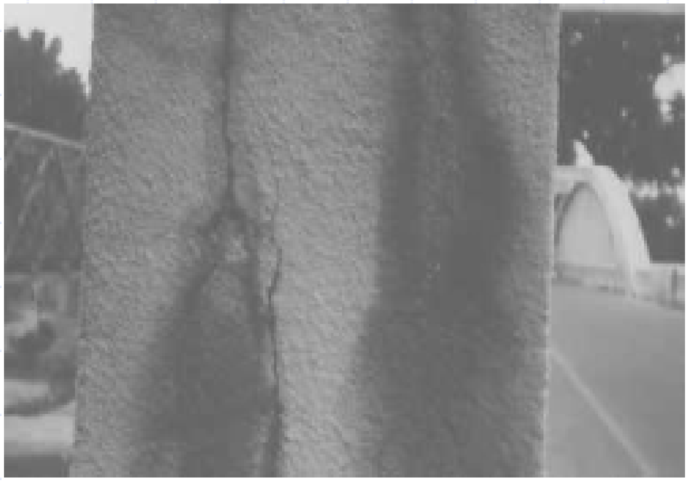


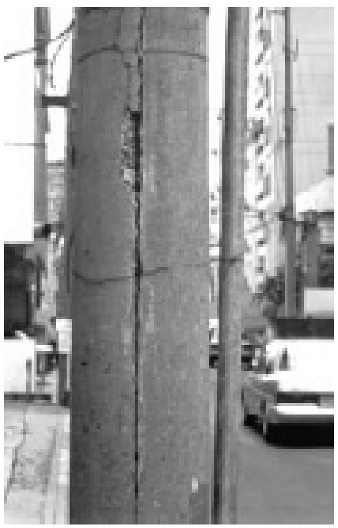


Severe Spalling of Bride Deck

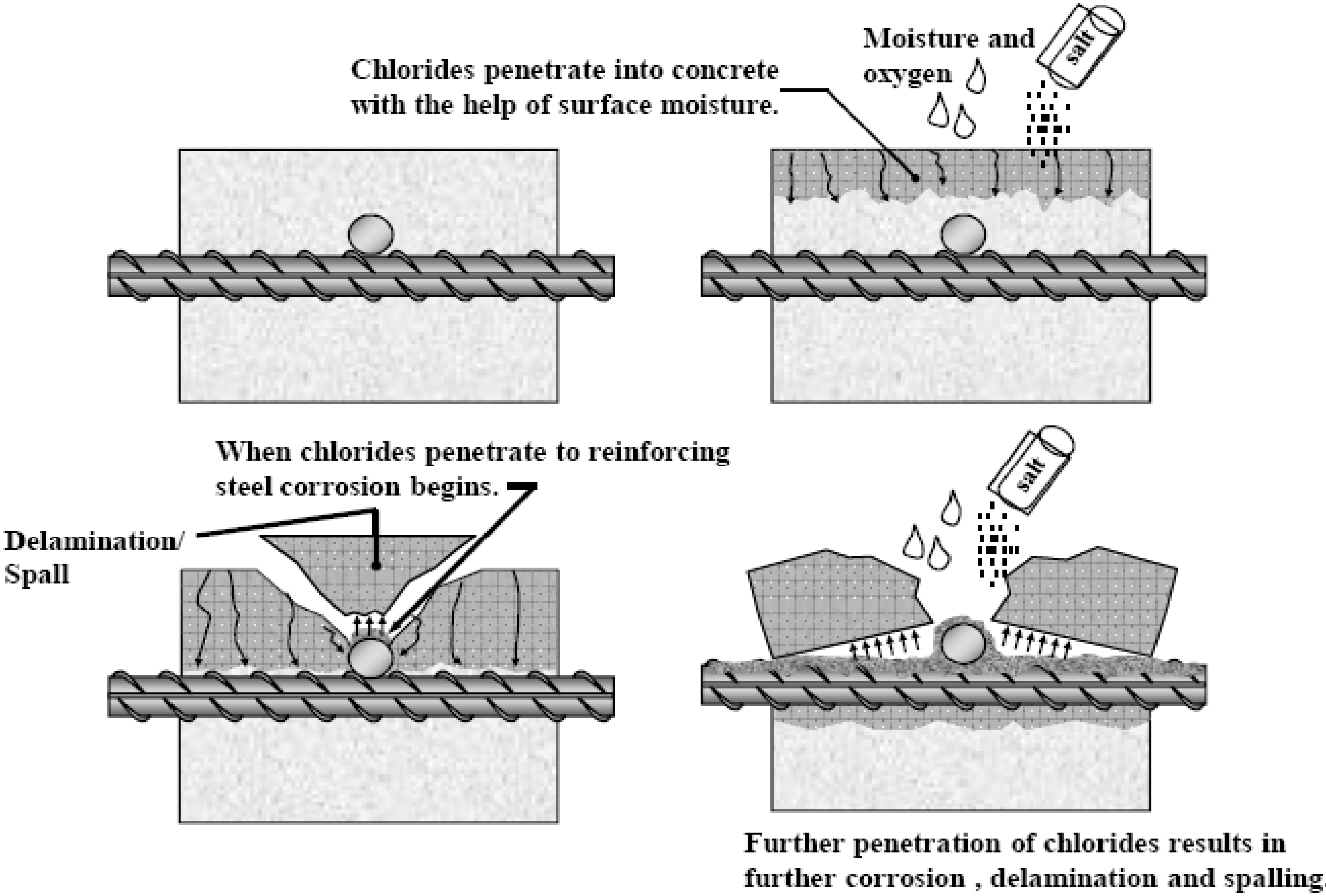


Straining due to Corrosion

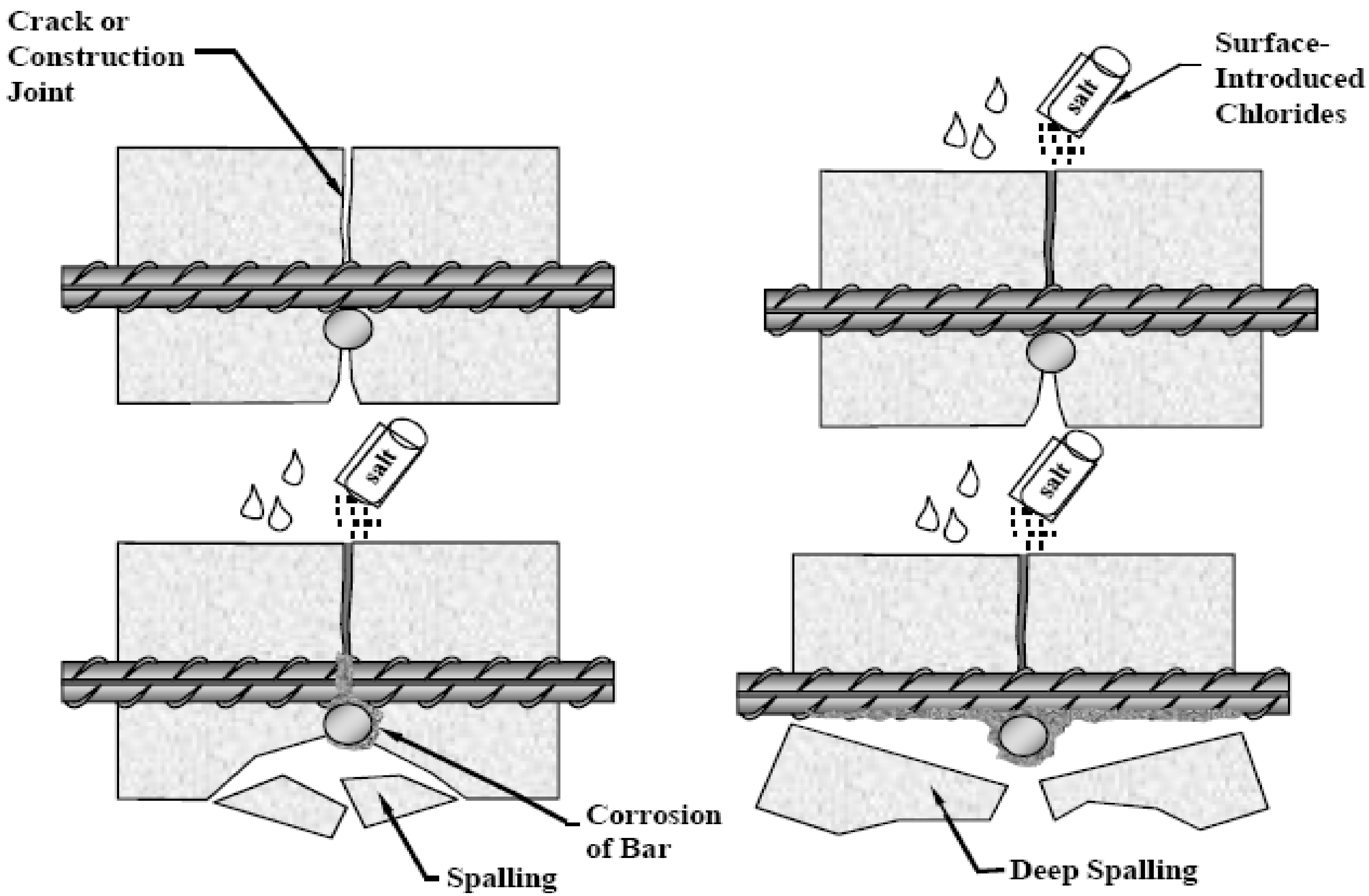




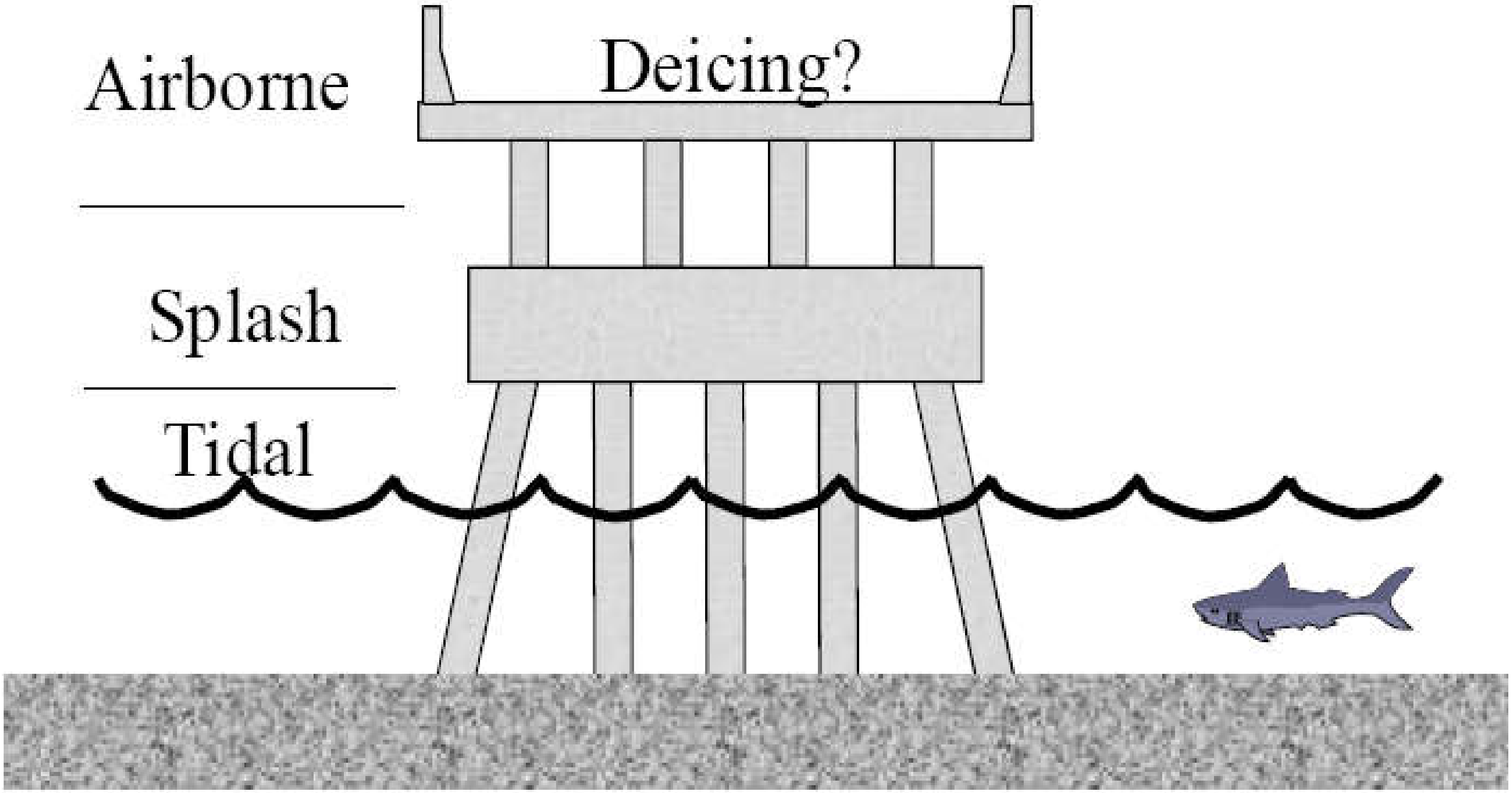
Chloride Induced Corrosion



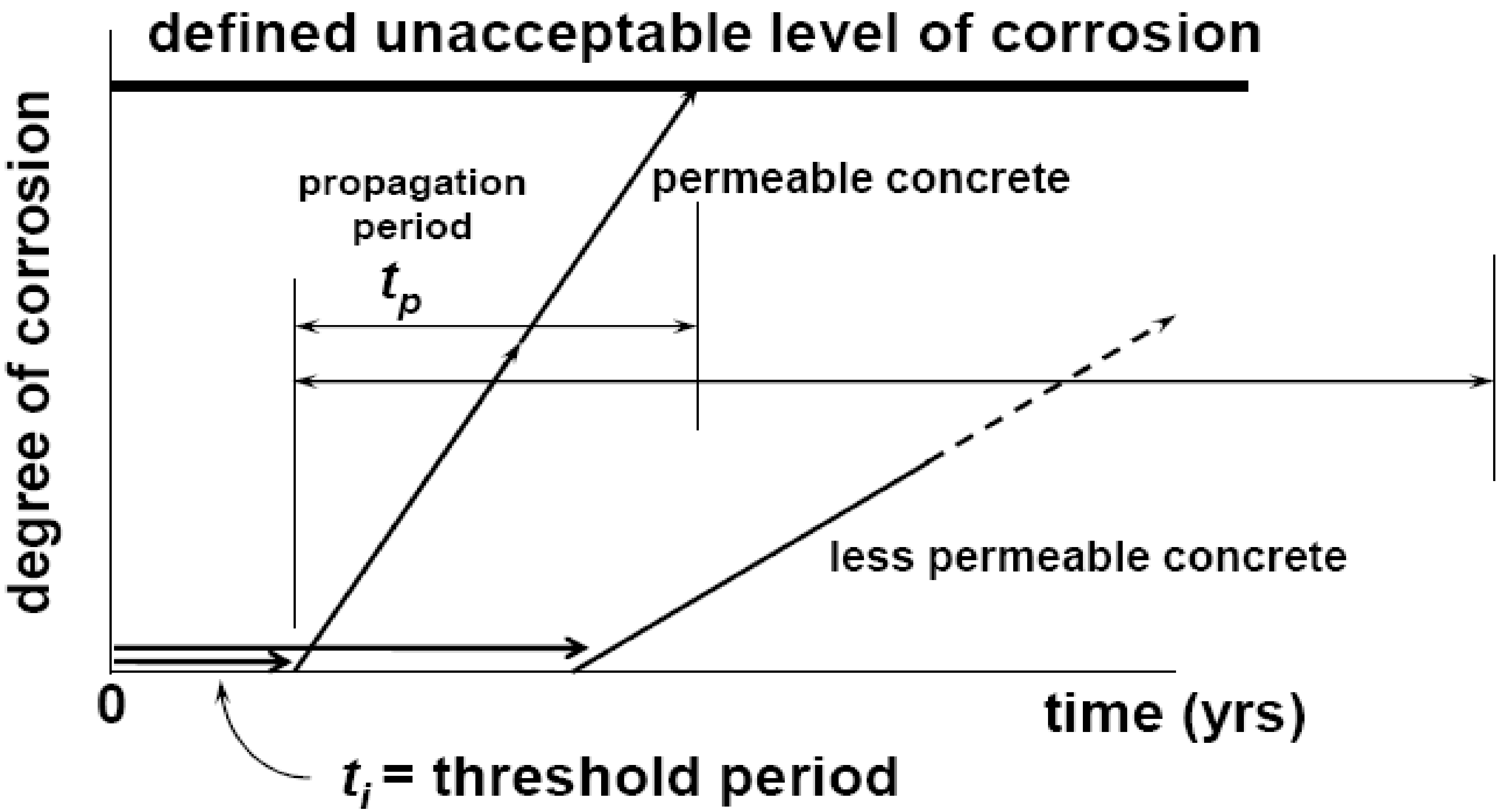
Chloride Induced Corrosion



Macro Environment: Corrosion Scenarios



Schematic of Corrosion Process



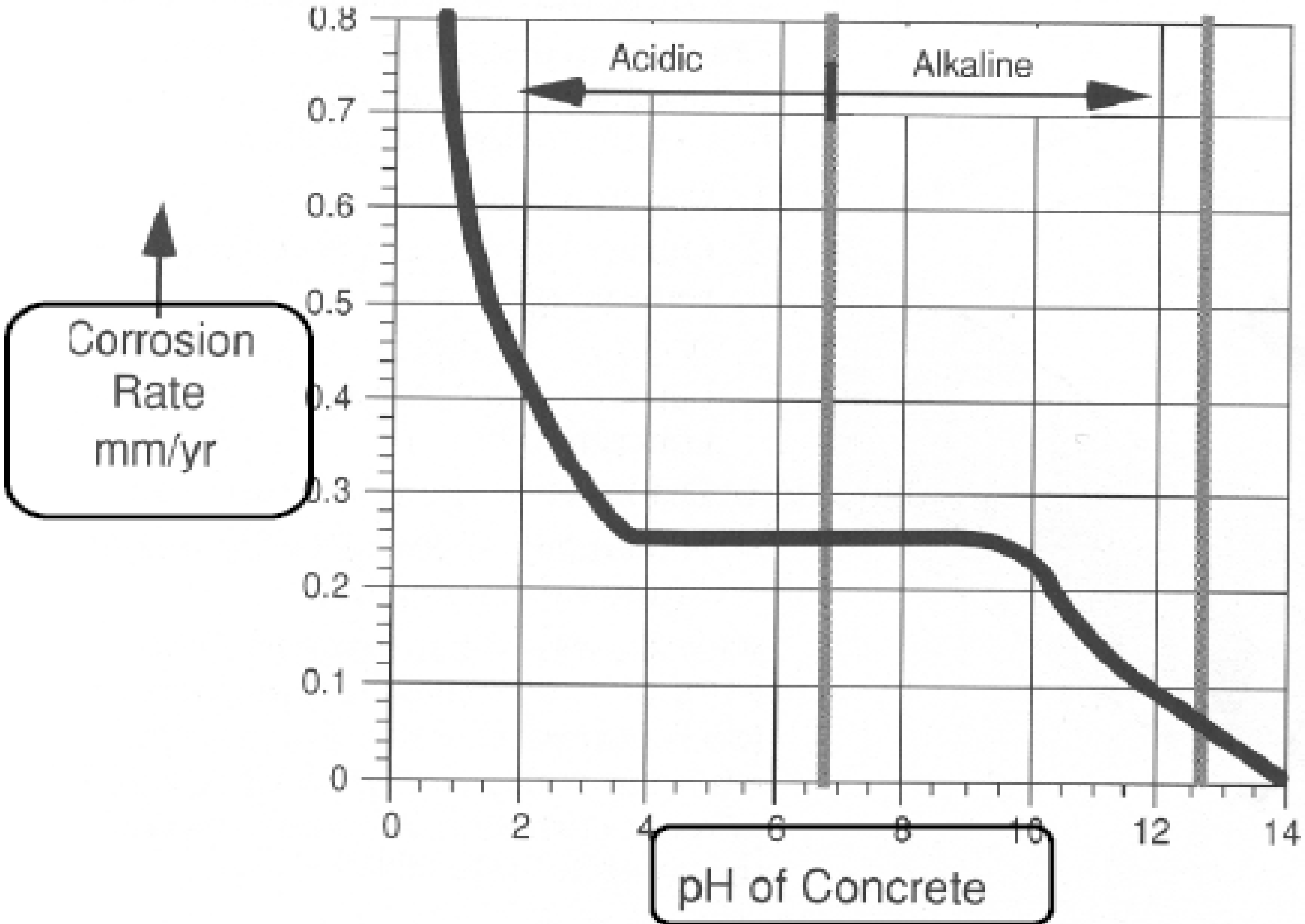
Service life = $t_i + t_p$

after Bakker, van der Wegen and Bijen, 1994

Factors Effecting the Chloride Build-up Process

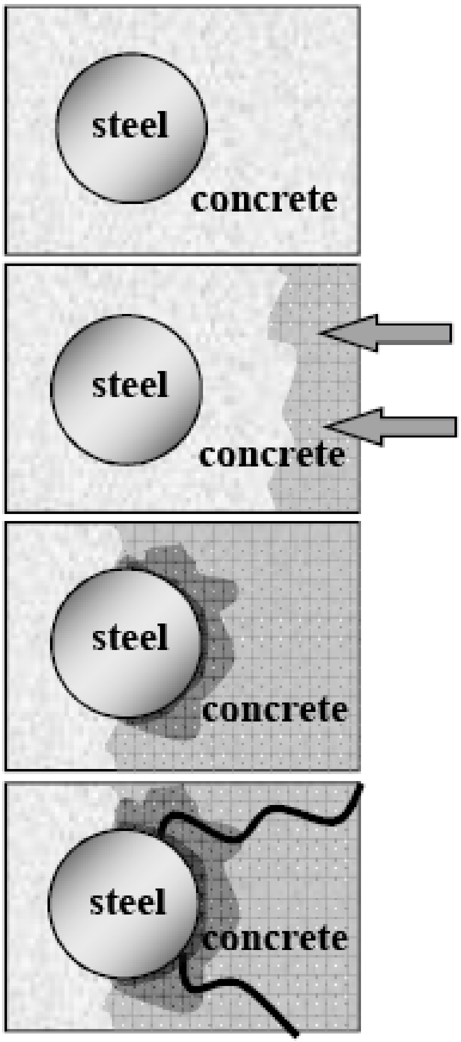
- Absorption
  - Lower absorption reduces build-up rate
  - Longer curing and low w/cm reduces absorption
- Environment
  - Wide variability within an area
  - Micro climates on each structure
- Paste Volume
  - Higher binder content increases C_s
- Testing Procedure

Effect of pH on Corrosion Rate



Relationship between pH and corrosion rate

Carbonation Corrosion



Good quality concrete (pH=12-13) steel is passivated.

Carbon dioxide enters, pH begins to drop. Steel is not yet affected.

pH at steel drops below 9.5, corrosion begins.

Volume expansion of rust causes cracking and spalling.

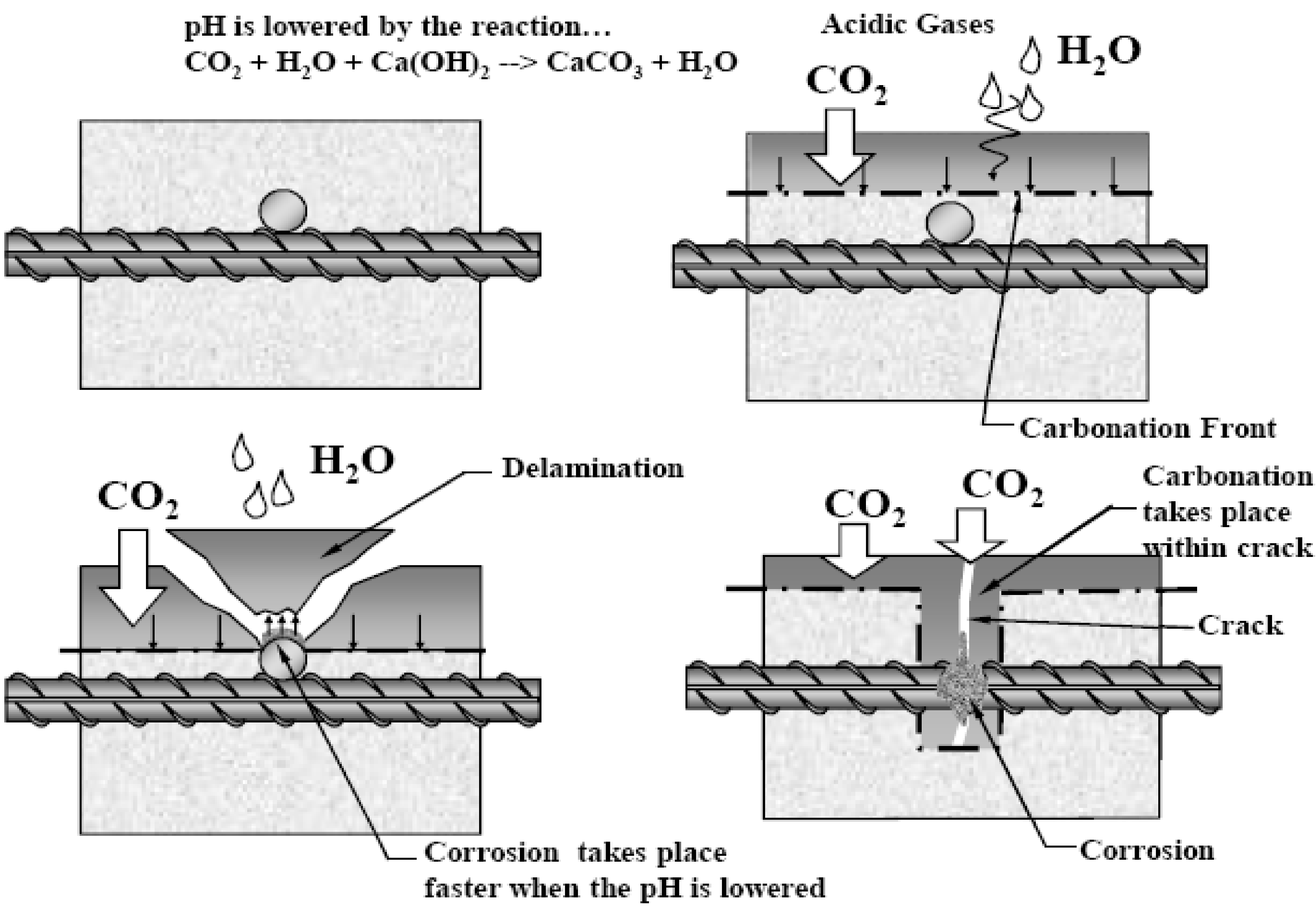
Carbonation Corrosion

- **Reaction between CO_2 in the atmosphere and Calcium hydroxide in the concrete**

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

- Process does not occur at a significant rate if:
  - the concrete is completely saturated
  - the concrete is dry
- Process most rapid when concrete is subjected to wetting—drying cycles
- Result: removal of CH = reduction in pH

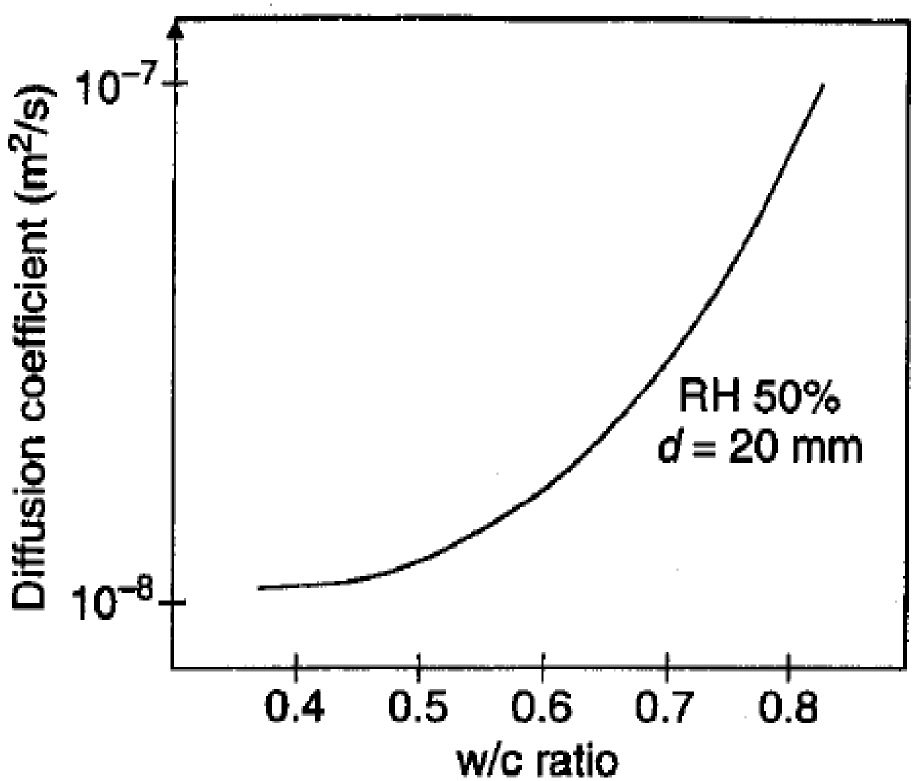
Carbonation Corrosion

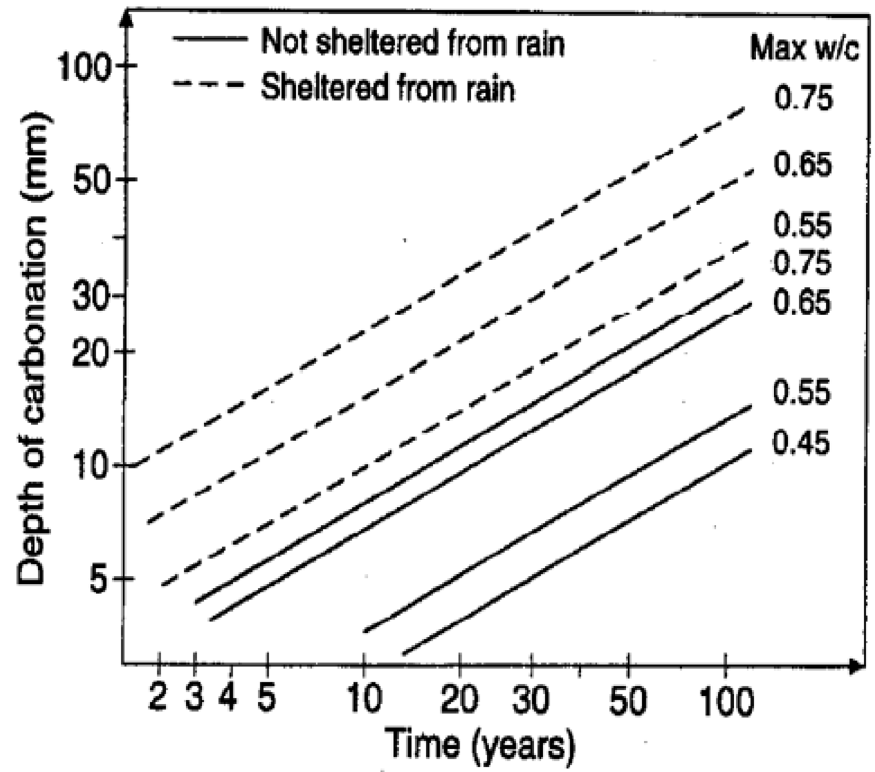


Carbonation corrosion: Phenolphthalein Test

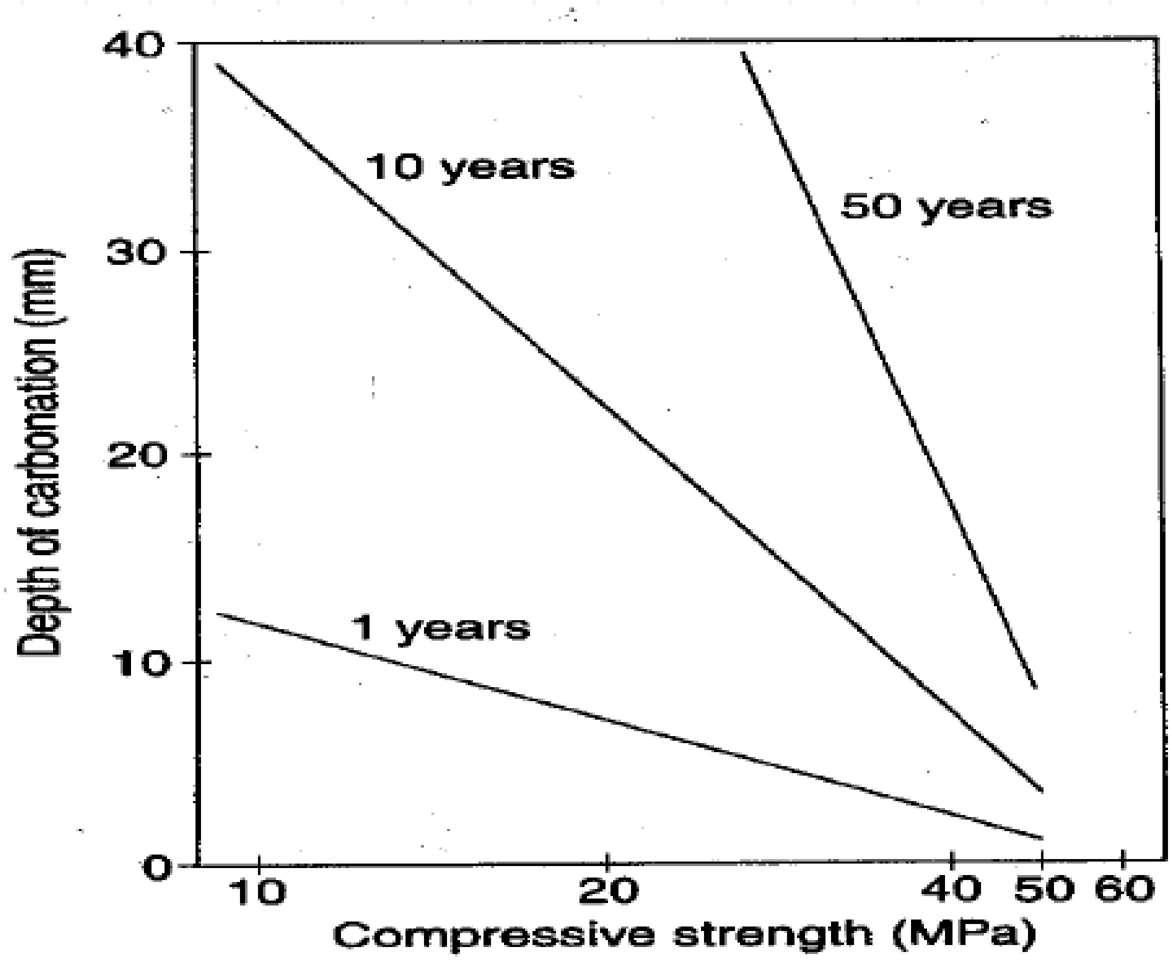
The carbonation depth is determined by spraying phenolphthalein on a freshly broken concrete surface. Non-carbonated surfaces turn red or purple, carbonated areas stay colorless.

Corrosion of Steel in Concrete

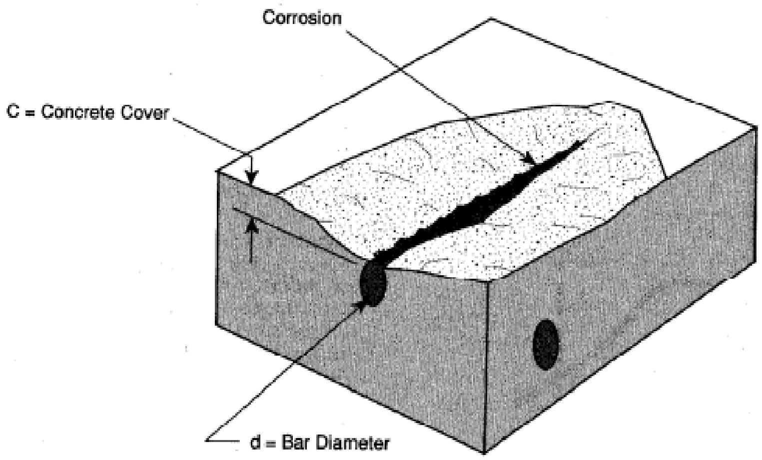




Corrosion of Steel in Concrete



Concrete Cover is Critical



Assessing Causes and Extent Corrosion

- Visual inspection
  - Signs: staining, cracking, delamination, pop-outs, erosion, softening
  - Is problem local or wide?
  - Effect of orientation, elevation, vertical vs. horizontal, environment (proximity to sea, wind direction, temperature, precipitation, etc.)
  - **General corrosion with flaking rust over long length: usually due to carbonation**
  - **Short length with deep (pitting corrosion) normally due to chlorides**
  - Hammer test can reveal location of delaminations

Solving the Corrosion Problem Require

- Identification and correction of potential corrosive situations during design
- Application of effective preventative measures in young structures
- Use of appropriate repair methods for older deteriorating structures

Effective Design
requires an understanding
of the mechanisms at work

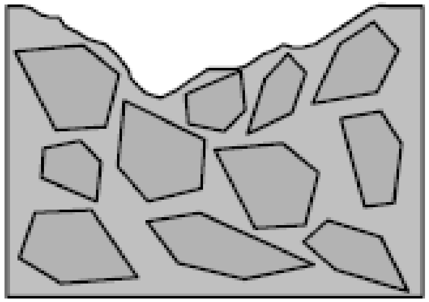
Freeze-Thaw Problem

- Porous and saturated concrete
- Water expands by 9% as it freezes, applies tensile stresses in concrete
- Two distinct mechanism occur: internal micro-cracking and disruption, and surface scaling.

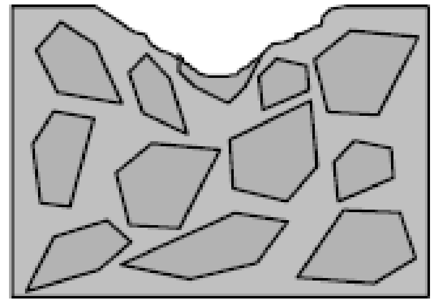
Influencing factors on Freeze-Thaw

- Increased porosity increases rate of degradation.
- Increased moisture saturation.
- Increased number of freeze-thaw cycling.
- More rapid freezing rate, more damage.
- Horizontal surface entrap more water & salt.
- Aggregate with small capillary pores and high absorption aggravate problem.
- Often occurs in horizontal surfaces or at the water line of vertical submerged portions of structure.

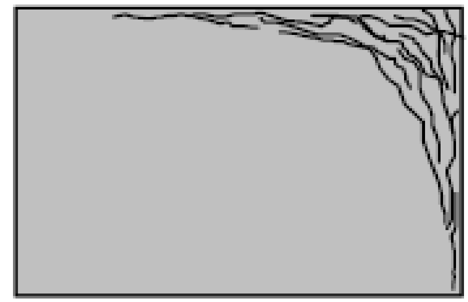
Signs of Freeze-Thaw Damage



Cross-section



Cross-section



Top view

1- Paste failure - broken paste often undisturbed aggregate faces.

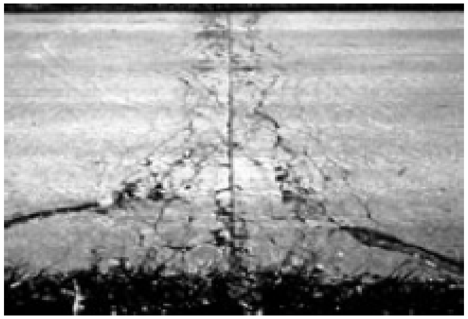
2- Aggregate failure - broken aggregate at bottom of fracture surface pit. Paste fractures due to aggregate expansion.

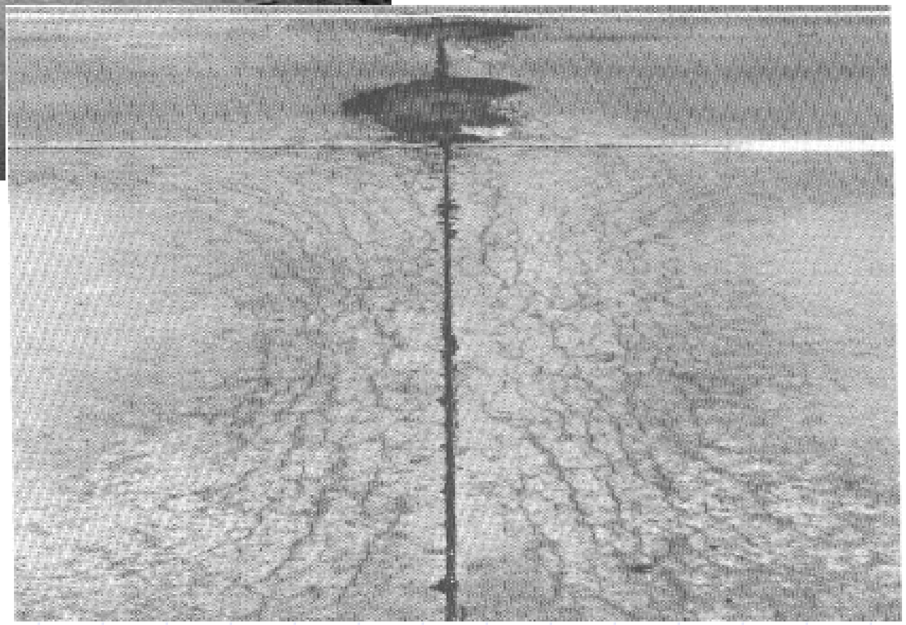
3- D-cracking and scaling

D-Cracking: often occurs at expansion joints.

D-cracking

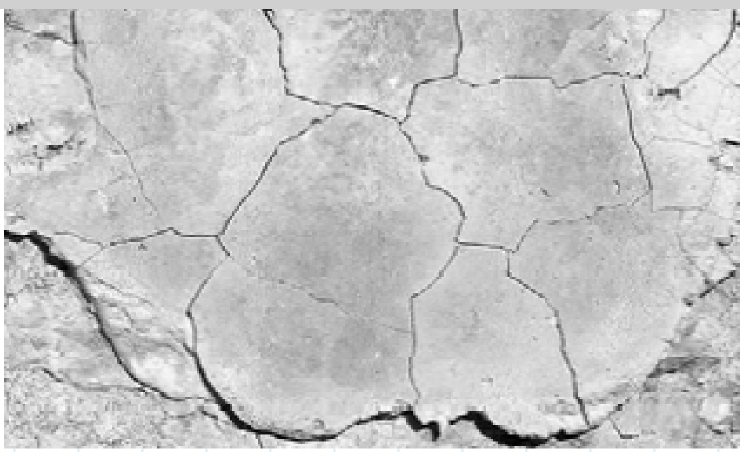
D-Cracking



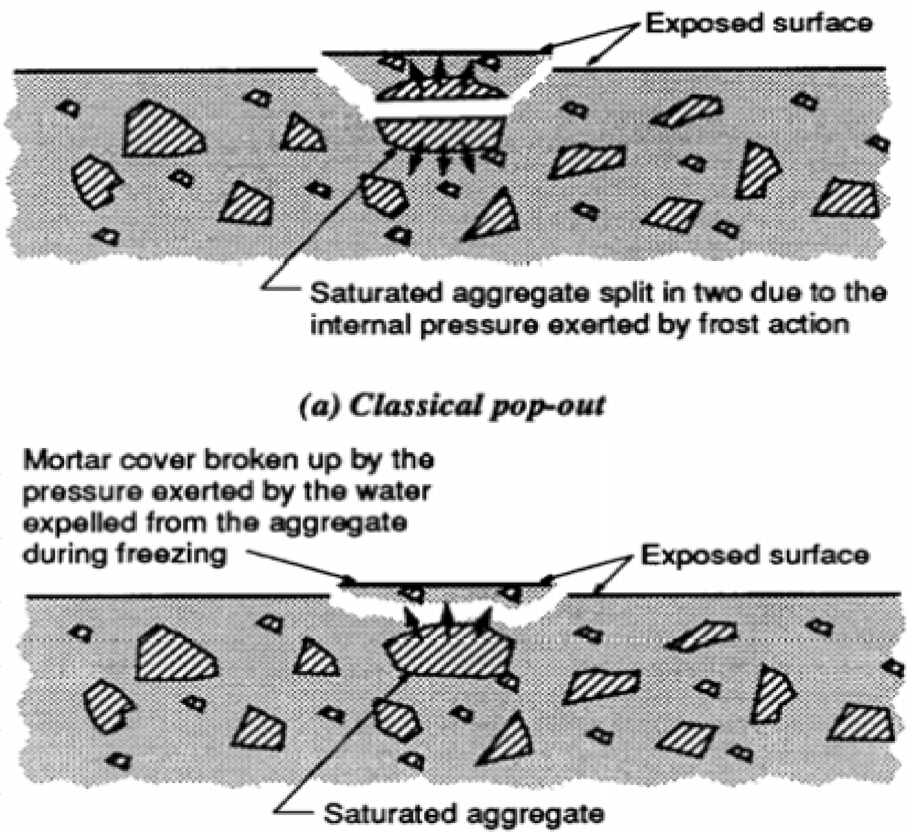


Freeze Thaw Damage

Map-cracking due to severe freezing of non-air entrained concrete



Pop-outs: Freeze Thaw Damage

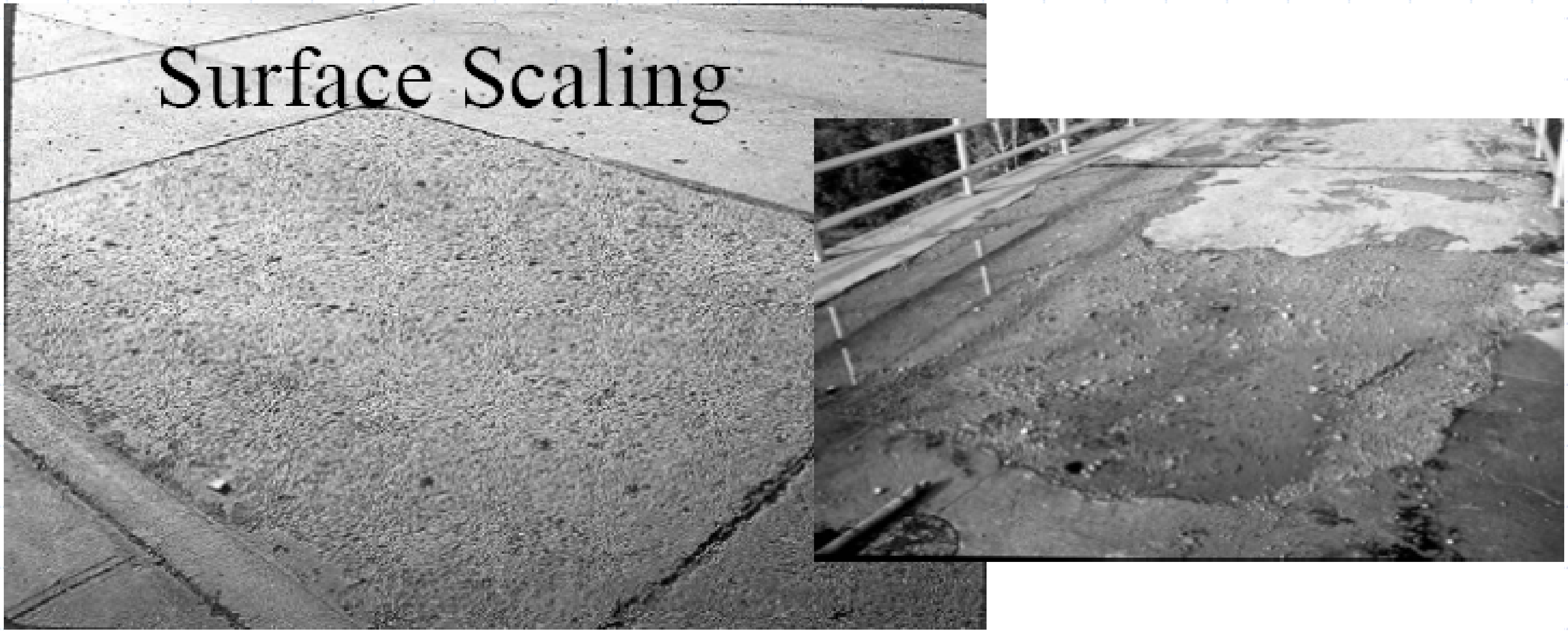


(a) Classical pop-out

(b) Type II pop-out

Pop-outs often occur when concrete contains frost susceptible aggregates or simply when aggregates are too weak or have cleavage plans.

Surface Scaling: Freeze Thaw Damage



Excessive bleeding, bad finishing procedures, overworking the surface during finishing, lack of curing, early exposure to high temperatures, plastic shrinkage cracking, can all be indirect causes of rapid surface scaling of concrete

How to Protect Concrete: Freeze Thaw Damage

- Keep concrete dry (not always possible)
- Reduce the amount of freezable water (by reducing capillary porosity, feasible)
- Provide a relief for pressure (air entrainment)
- Combinations of the above

Air Entrainment

- Network of air bubbles
- Using a chemical admixture (surfactant) mixed with concrete
- Size of bubbles usually 10 µm to 100 µm
- Dosage, type of cement, compatibility with other admixtures used, etc. can influence volume and spacing of air bubbles

Specimen subjected to Freeze Thaw

- Non-air-entrained
- High water-cement ratio

- Air-entrained
- Low water-cement ratio

Alkali-Aggregate Reaction

- AAR correspond to chemical reactions between the hydroxil (OH^-) ions associated with the alkalis (Na_2O & K_2O) in the concrete pore fluid and some mineral phases in the aggregates

- Alkalis are supplied to the concrete pore fluid from sources such as the cement, chemical additives, aggregates (medium to long term), SCMs, sea water and de-icing salts.

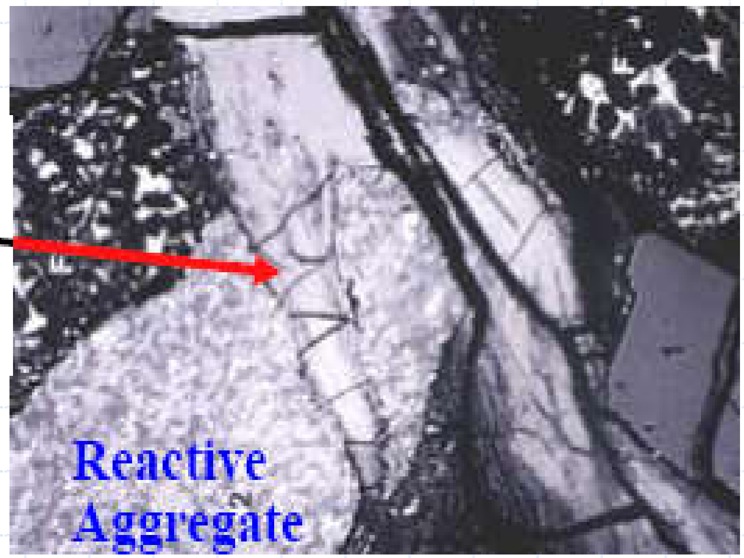
Types of Alkali-Aggregate Reaction

- Alkali-Silica Reaction
- Alkali-Carbonate Reaction

Alkali-Silica Reaction

- ASR is a chemical reaction between the Na, K - OH from concrete pore fluid and <u>siliceous phases</u> in the aggregates

Alkali-silica reaction product: alkali-silica gel



- Creates internal forces of expansion (swelling of <u>alkali-silica gel</u>), thus inducing cracking and distress of affected concrete

Alkali-Silica Reaction

Alkali-Carbonate Reaction

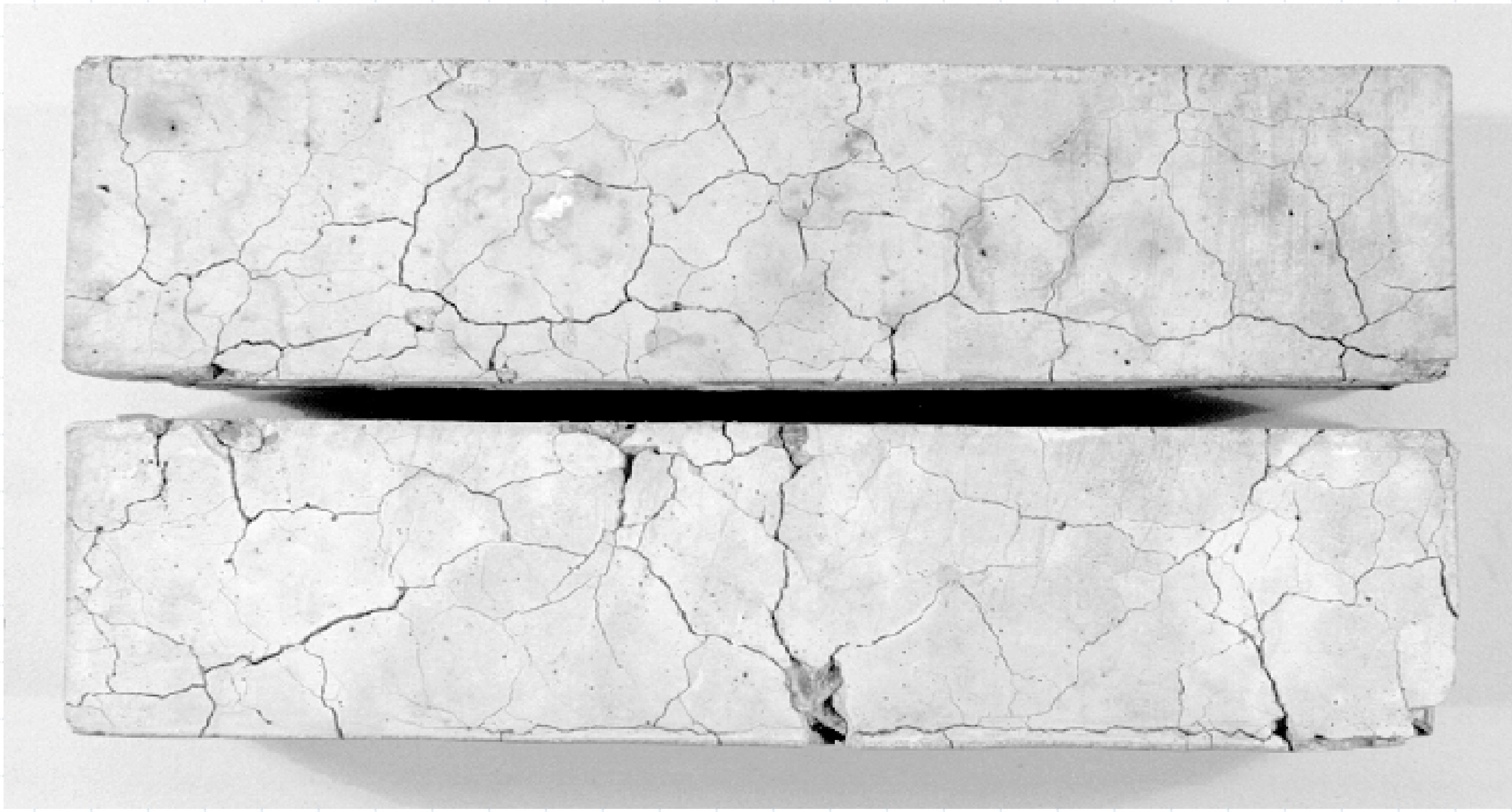
- Mechanisms of reaction not well understood
  - Alkali-hydroxides from the concrete pore fluid attack the dolomite crystals disseminated in the rock matrix
  - Expansion associated with re-organization of dedolomitization reaction products (brucite and calcite) and/or swelling of clay minerals in the rock matrix.

- Very deleterious reaction that can cause damage in the field within two years after construction

Time for Distress due to AAR

- Less than 5 to more than 25 years
- Depends on various factors
  - Type and reactivity level of the aggregate (non reactive, marginally reactive, moderately reactive, highly reactive)
  - Alkali content and design of the concrete mixture (cement content & alkali content of the cement have an effect on the pH of the pore solution)
  - Exposure conditions (availability of moisture is critical for excessive expansion due to AAR to develop and be sustained)

Concrete Prisms Tested for ARR



AAR damage in Calgary

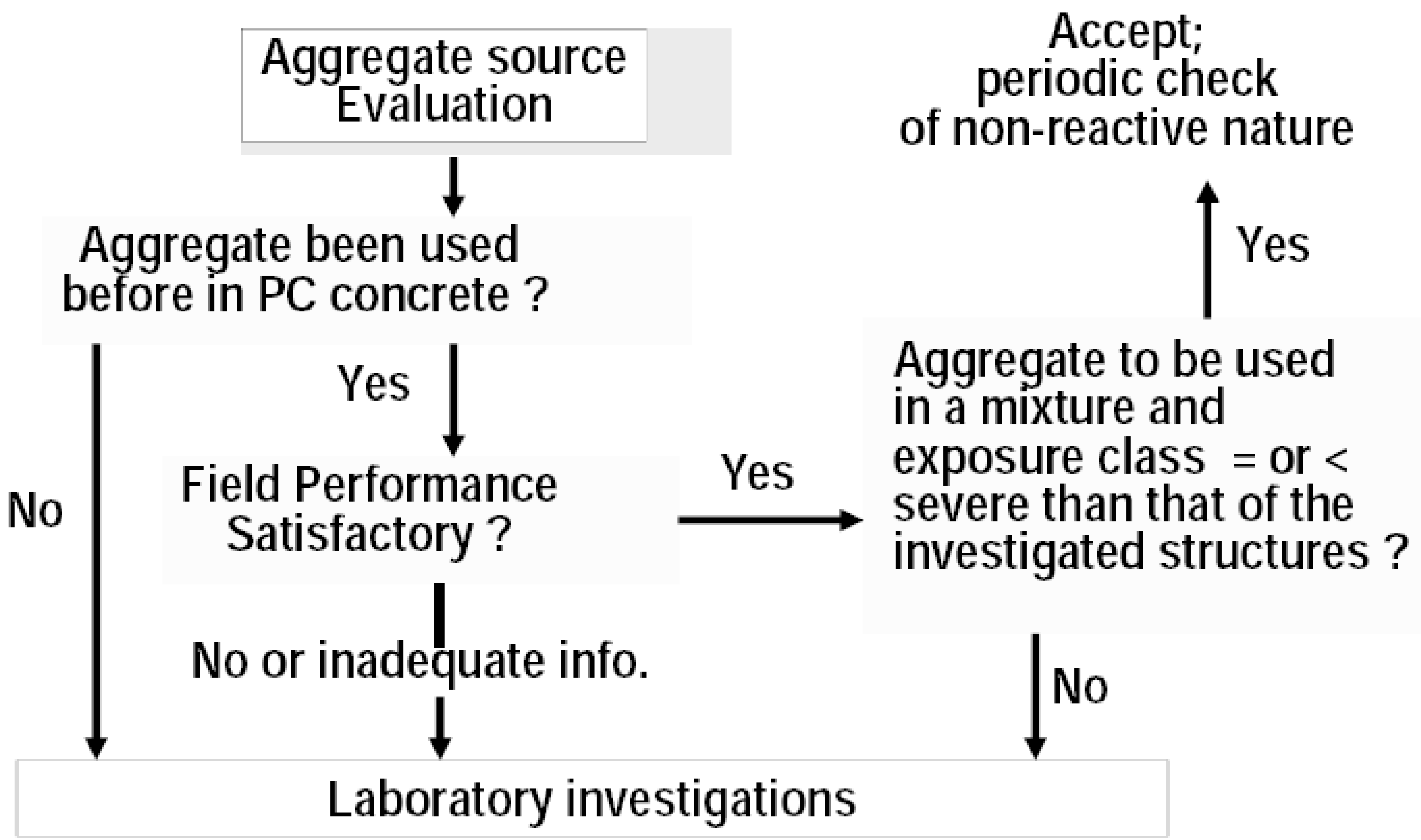
Testing for AAR

- Recommended Practices (CSA A23.2-27A, RILEM AAR-0)
  - Petrographic Examination: ACR & ASR
    (ASTM C 295, RILEM AAR-1)
  - Chemical Method: ACR
    (CSA A23.2-26A)
  - Accelerated Mortar Bar Test: ASR
    (CSA A23.2-25A, ASTM C 1260, RILEM AAR-2)
  - Concrete Prism Test: ACR & ASR
    (CSA A23.2-14A, ASTM C 1293, RILEM AAR-3)

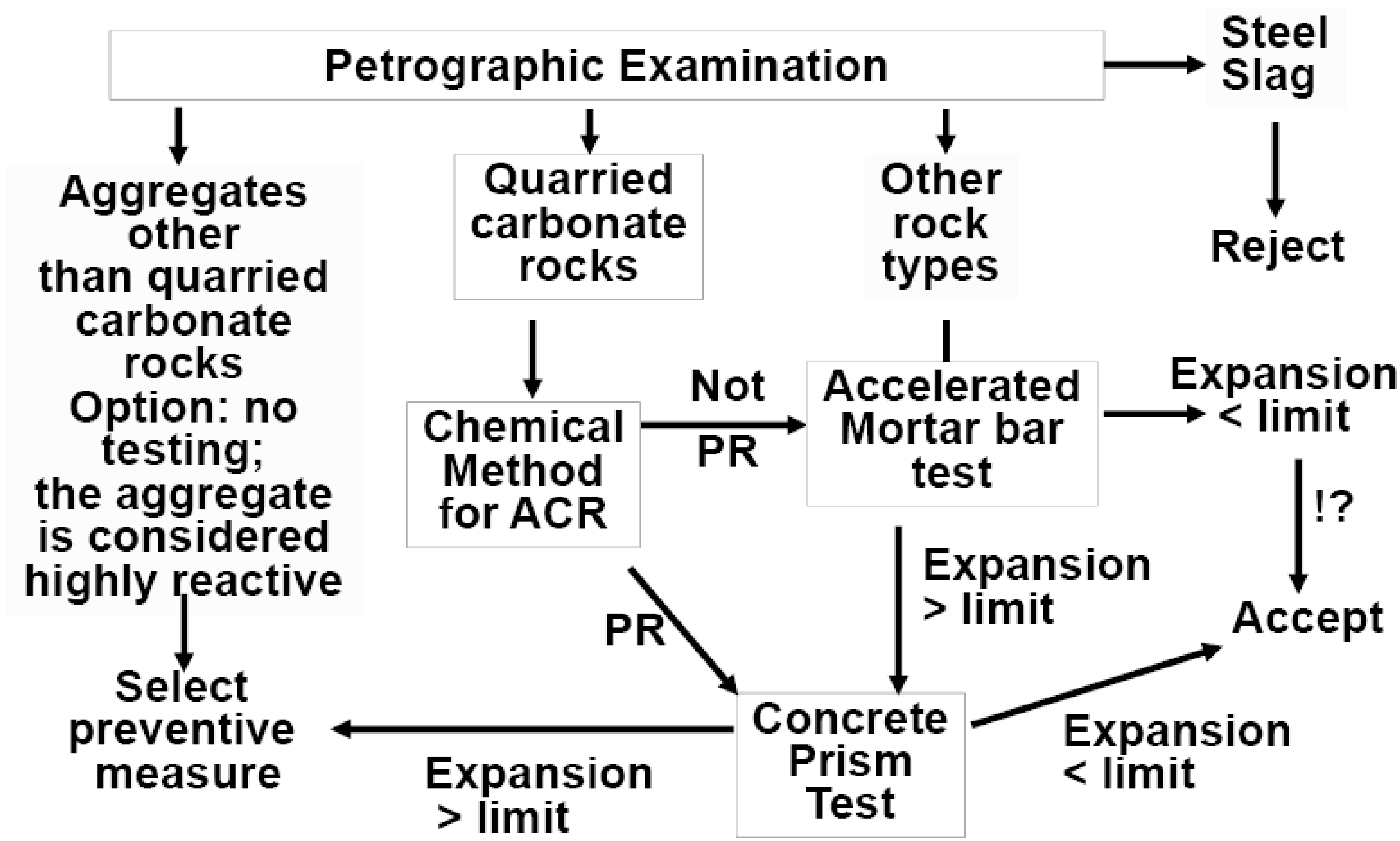
CSA Standard Practice for Testing AAR

- Step by step procedure for evaluating potential and degree of alkali-reactivity of concrete aggregate
- Field performance survey
- Laboratory test program
  - ✓ Petrographic examination
  - ✓ Chemical method for ACR
  - ✓ Accelerated mortar bar test (ASR)
  - ✓ Concrete prism test (ACR & ASR)

Evaluating Potential Alkali-Reactivity



Laboratory Investigation



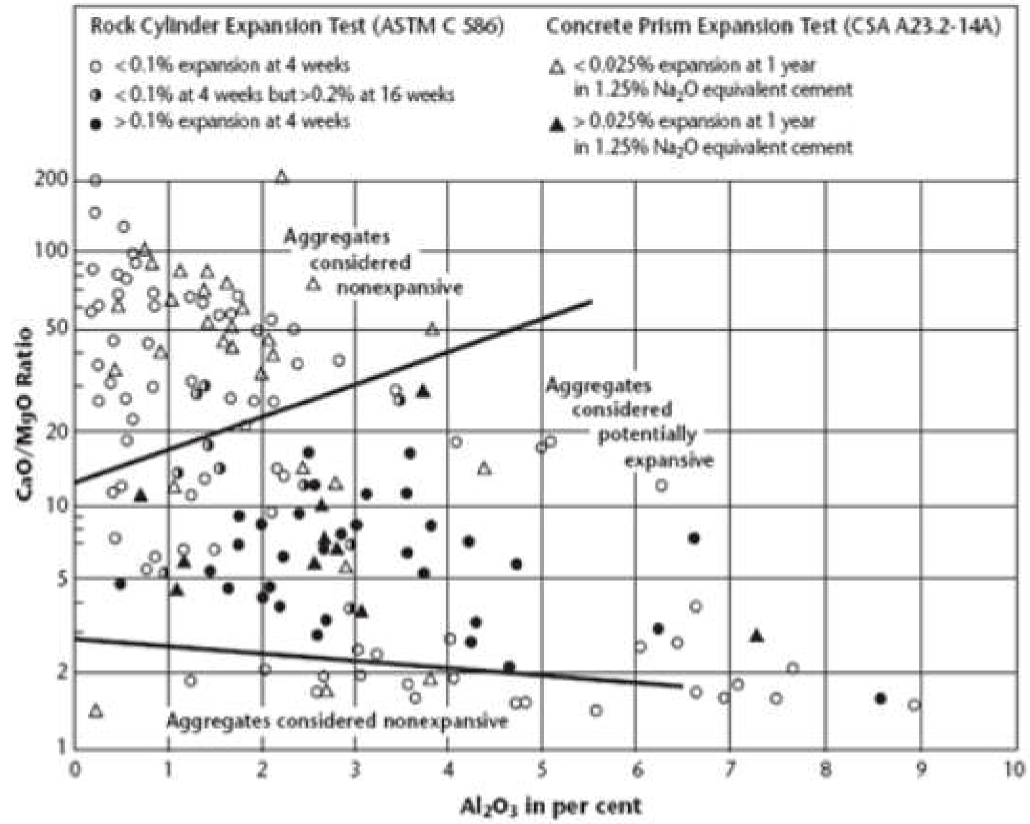
Petrographic Examination

- First essential step in the process of evaluating the potential alkali-reactivity of concrete aggregates.
- Allows to recognize the nature of the aggregate (rock types), the presence of potentially reactive rock types or particles in a gravel aggregate, and to select the best test procedure to use.
- Main approaches
  - **Macroscopic examination (naked eye or with the use of a stereobinocular microscope)**
  - **Microscopic examination (under the petrographic microscope – thin sections)**

Chemical Method for ACR

- Screen test for quarried carbonate rocks
- Chemical analysis for Al_2O_3, MgO and CaO

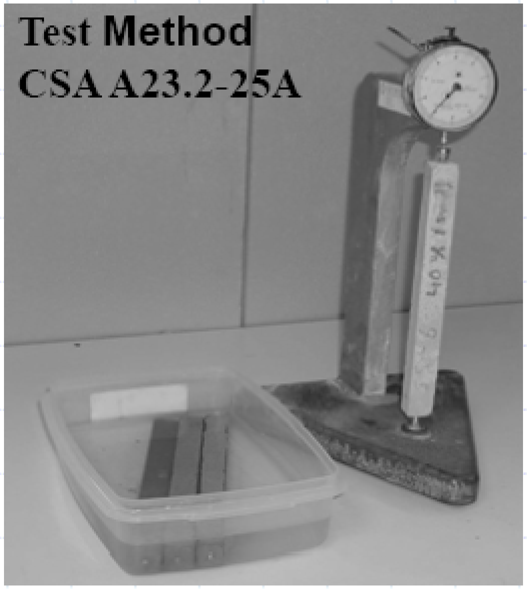
- Plot the results on a graph with zones for aggregates considered potentially expansive or non-expansive
- Screening test only; confirmation of potential ACR to be done through the Concrete Prism Test



http://www.fhwa.dot.gov/pavement/concrete/asr/hif09001/03.cfm

Accelerated Mortar Bar Test

- Severe test conditions: mortar bars, 25 x 25 x 285 mm in size, are immersed 1N NaOH @ 80°C for 14 days
- Expansion limit of 0.08-0.20% at 14 days
- Testing potential alkali-silica reactivity of coarse or fine aggregates
- Good screening test but not to be used for rejecting aggregates

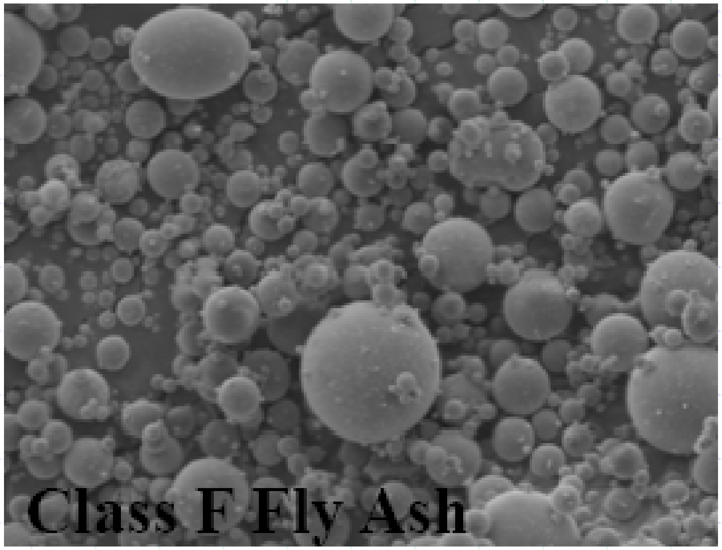


Concrete Prism Test

- Test conditions: concrete prisms, 75 x 75 x 300-400 mm in size, are stored at 38°C and R.H. > 95% for one year
- Expansion limit of 0.04% at one year
- Testing potential of ASR and ACR coarse or fine
- Best test method but considered long (one year)

Preventive Measures against AAR

- Use a non-reactive aggregate
- Selective quarrying & aggregate beneficiation
- Limit the alkali content of the concrete mixture
  - Use a low-alkali cement
  - Limit alkali content of concrete
- Use an adequate proportion of supplementary cementing materials (SCMs)



Selecting Preventive Measures against AAR

CSA Standard Practice A23.2-27A

- For ACR: best and most practical preventive measure is to avoid the use of aggregates susceptible to ACR
- For ASR: step-by-step procedure for selecting preventive measures against ASR using a risk analysis approach based on:
  - Degree of reactivity of the aggregate
  - Size of element and environmental conditions
  - Expected service life of the structure

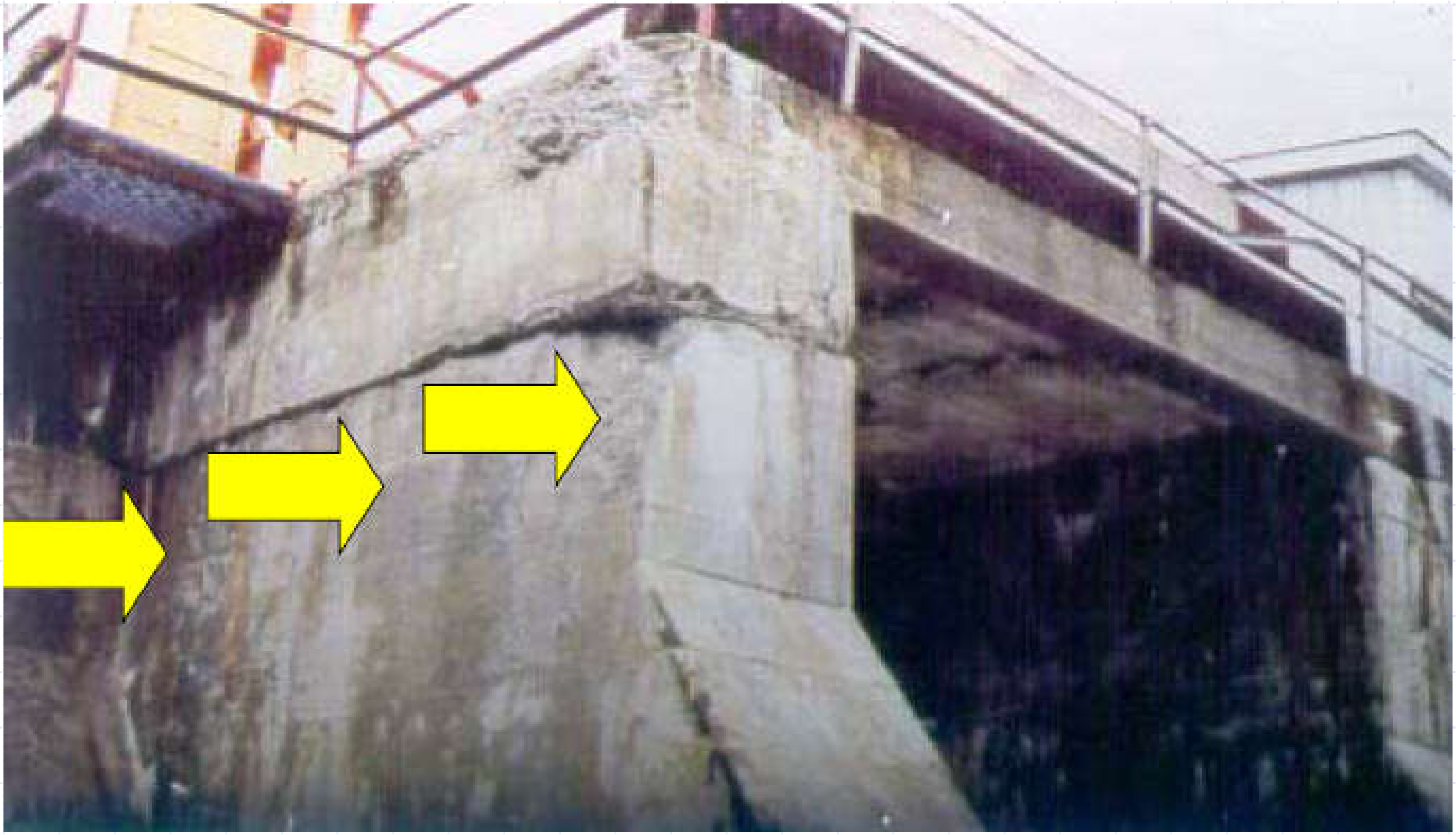
Global Management Approach for ASR

- Field inspection (field symptoms of deterioration, assessment of the environmental conditions)
- Sampling (components with & without visual signs of deterioration)
- Laboratory test program (petrographic examination, physical & mechanical tests)
- In-situ testing (structural investigations & monitoring → may not be required in a preliminary stage)

Field Symptoms of AAR

- Differential expansion of concrete elements (deformation, movements, displacements)
- Surface macro-cracking
- Surface discolouration around cracks
- Gel exudations (vs. efflorescence)
- Pop-outs

Field Symptoms of AAR



Displacement caused by AAR induced expansion in Dam structure

Field Symptoms of AAR

Map cracking in Wing Wall; surface discoloration around cracks

Displacement caused by ASR-induced expansion in bridge structure; spalling and extrusion of jointing material

Field Symptoms of AAR

Map cracking pattern
Bridge Pier, Medicine Hat, Alberta

ASR Induced Longitudinal Cracking in Soffit of Bridge Deck

Field Symptoms of AAR

Map cracking and discoloration due to ASR –
Parapet wall, Northern Ontario

AAR Induced Cracking in
Concrete Pavement.

Field Symptoms of AAR

Exudations of alkali-silica gel - Bridge Foundation, Nova Scotia

ASR in Concrete Pavement

Laboratory Investigation

- Petrographic examination (macroscopic and microscopic signs of AAR ➔ examination of polished concrete sections and broken concrete pieces under the stereo-binocular microscope and the scanning electron microscope)
- Mechanical testing (compressive strength, direct or splitting tensile strength, modulus of elasticity and stiffness tests)
- Expansion test on cores taken from the affected structures

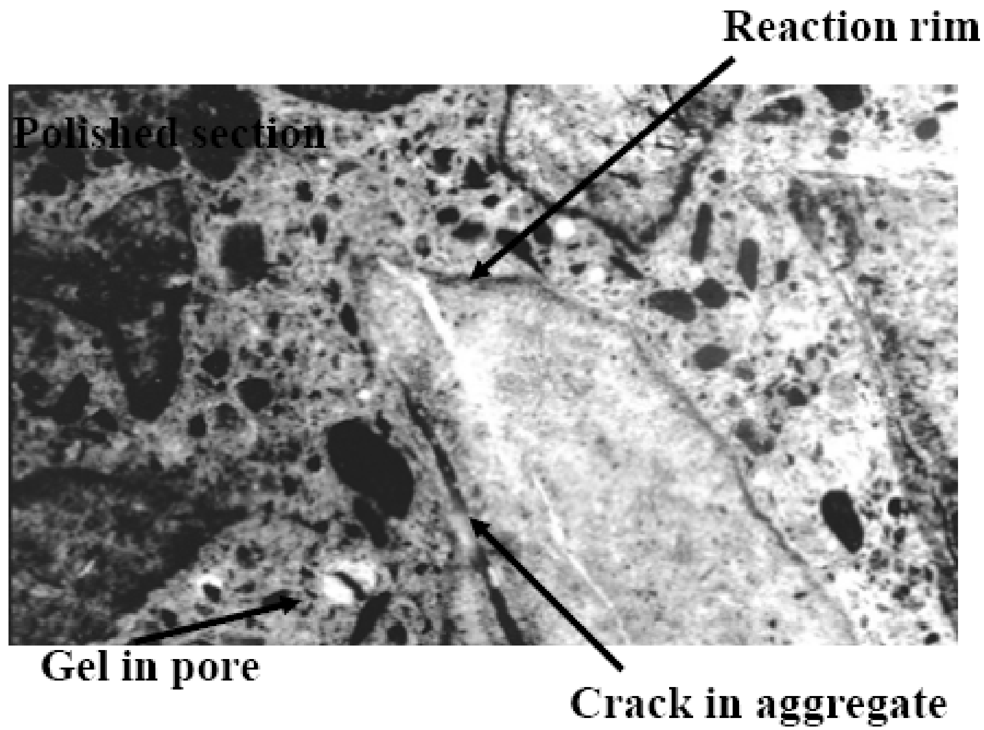
Petrographic Examination

- Macroscopic description of cores (cracking, reaction rims, gels in pores of the concrete, etc.)

Pavement Cores Vertical Cracking

Petrographic Examination

- Petrographic examination of polished sections under stereobinocular microscope (cracking, reaction rims, gels in pores of the concrete, etc.)



Mechanical Properties of Concrete affected by AAR

- Compressive strength: +/- conclusive on the degree of damage due to AAR
- Tensile strength to compressive strength ratio: gives better indication of AAR related deterioration
- Modulus of elasticity: badly affected by AAR; will show rapid reduction when AAR expansion and cracking develop
- Stiffness damage rating (stress-strain hysteresis of damage vs undamaged concrete)

Management Action on AAR

- Plan inspection programs
  - Routine visual surveys (damage severity rating using sketches and photographs)
  - Special surveys for critical structures (in-situ testing/monitoring - crack mapping, small scale deformation measurements)
  - Sampling and laboratory testing (petrography, mechanical testing, expansion tests on cores)