Concrete Durability and Its Control

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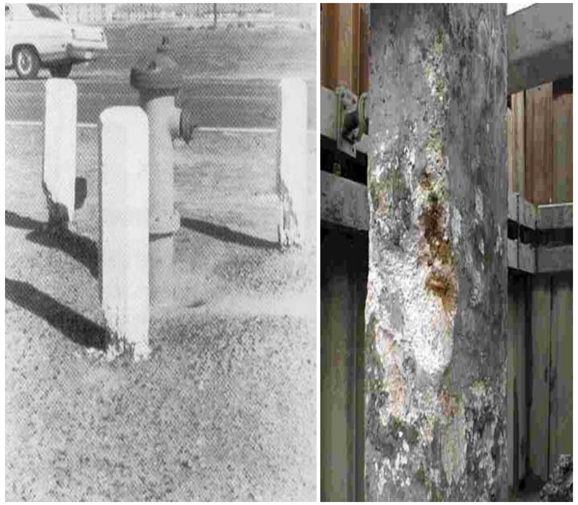
Outline

- Common durability problems of concrete, and their underlying mechanisms
  - Understanding of major durability problems
  - Transport mechanisms driving these issues
  - Tests to measure the transport properties
- Control of concrete durability
  - Durability planning

Durability problems in concrete



Sulphate attack

All durability problems in concrete are associated with water → impermeability of concrete is the first line of defence!

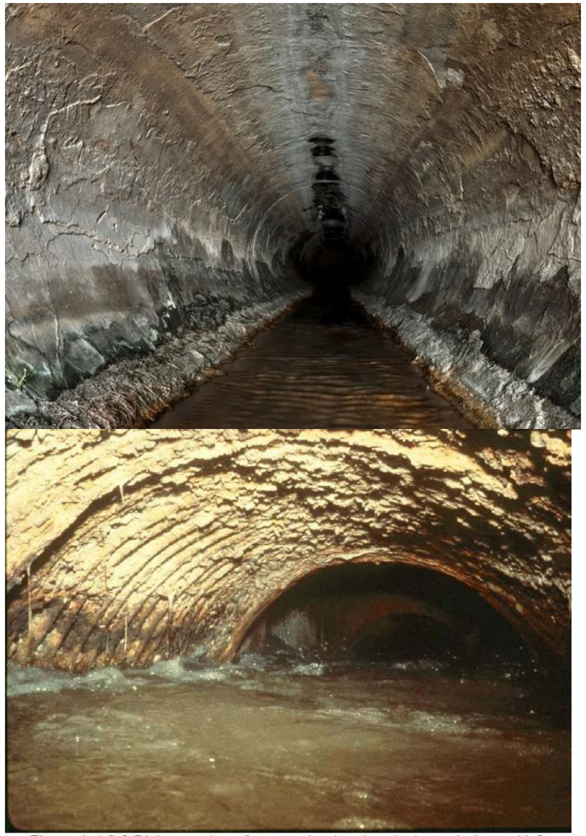


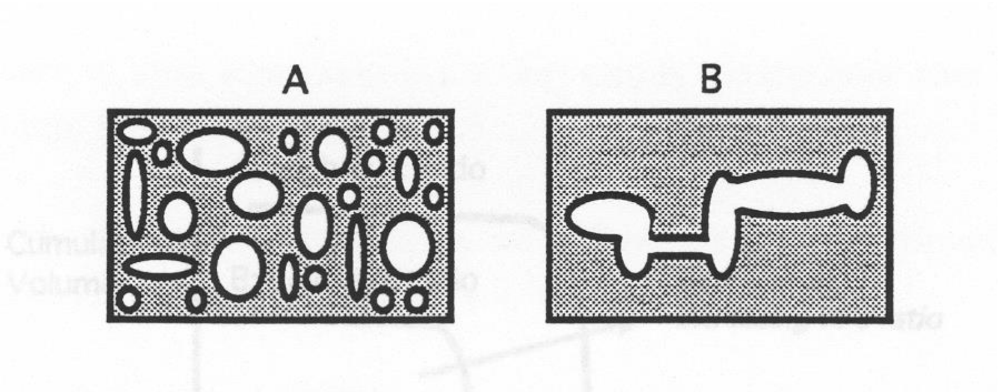
Figure A.4.2.2 Disintegration of sewer pipe by chemical attack due to H_2S.

Acid attack

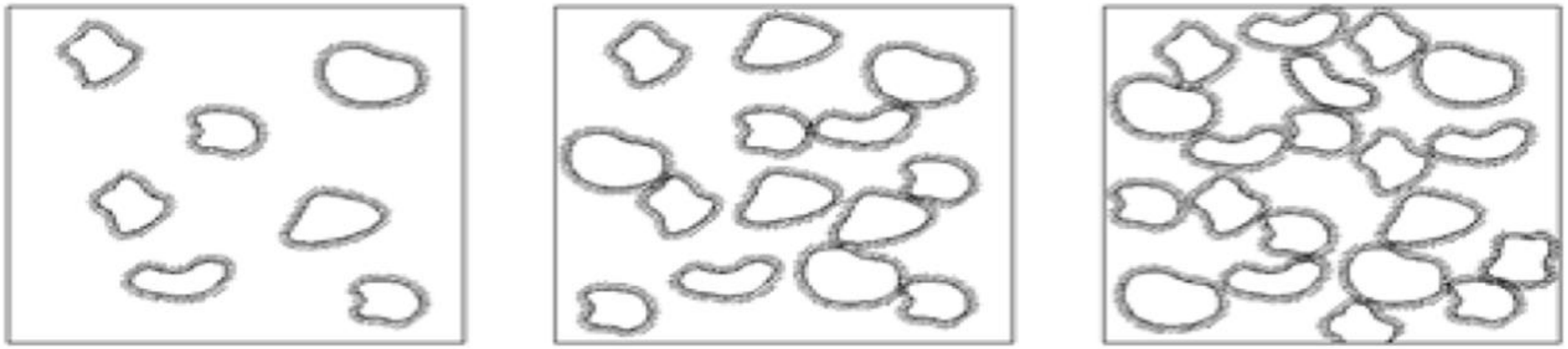
Corrosion of steel

Permeability and porosity

- Permeability of concrete is a function of the permeability of the cement paste, of the aggregate, and of the interfacial transition zone. The permeability of these components is in turn related to the porosity.
- Porosity and permeability need not be directly related. The interconnectivity of pores is generally responsible for a high permeability.
- Both porosity and permeability increase with an increase in the water to cement ratio. The permeability also depends on the degree and nature of curing, and the presence of mineral admixtures, which can act as fillers densifying the transition zone.



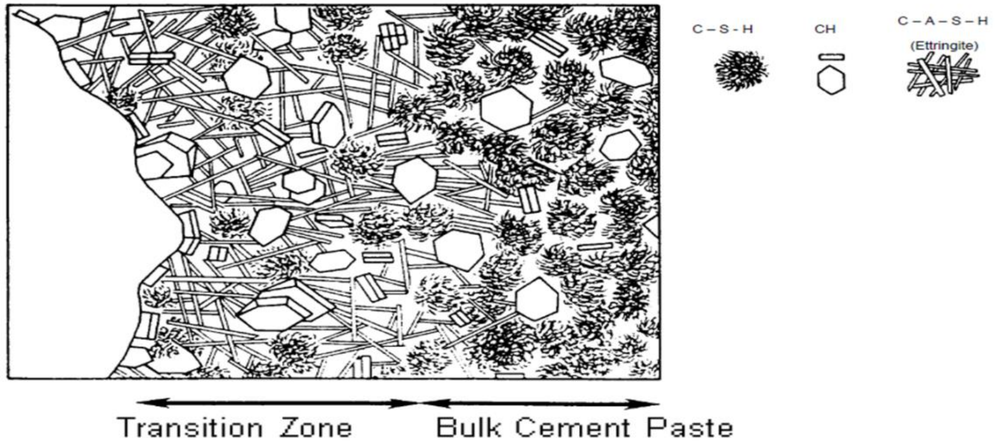
Interfacial transition zone



(a) Unpercolated, discrete

(b) Unpercolated, some continuous

(c) Percolated, continuous ITZ

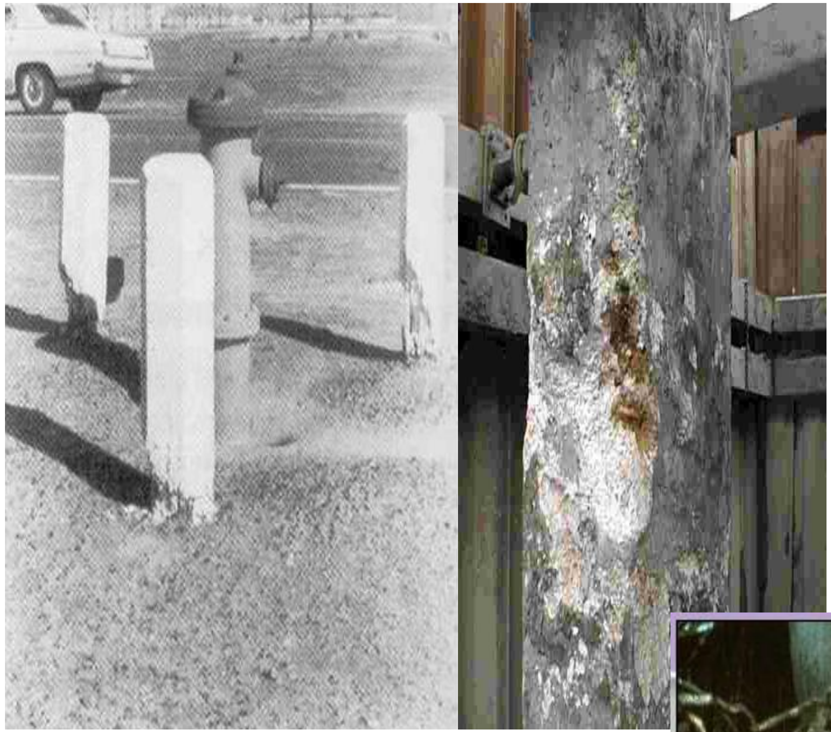


Major durability problems in concrete

- Sulphate attack and DEF
- Chloride / acid / seawater attack
- Freezing and thawing / Alkali Silica Reaction
- Corrosion

Sulphate attack: Introduction

- External sulphate attack: When the sulphate ions are from an external source
- Internal sulphate attack: When attack occurs from an internal source of sulphates, as in Delayed Ettringite Formation
- Common chemicals carrying sulphate ions: Na_2SO_4, $MgSO_4$, $CaSO_4$, $(NH_4)_2SO_4$ and $FeSO_4$ – these are present in various concentrations in seawater and groundwater
- Hydrated cement phases react in an aqueous medium with the sulphate ions
- Primary products formed are gypsum and ettringite
- Other reactions result in a progressive loss of stability of the calcium silicate hydrate (CSH), which is the primary strength-giving compound of hydrated cement



Photos courtesy Prof. P. Paramasivam / Prof Doug Hooton

Protection against sulphate attack

- Use of low C_3A cements (sulphate resisting cements are proportioned based on this concept); low C_3S would also help
- Use of high alumina cement
- Use of supersulphated cement
- Use of pozzolanic materials and mineral admixtures
- Low w/c and good impermeability!!

Chloride attack

- Solutions bearing chloride ions can also react with cementitious compounds, although the products that form as a result do not cause any expansions
- Consumption of cementitious phases could lead to increase in porosity, reduction of pH, etc.
- C_3A can bind Cl^- ions; thus, high C_3A cements are good against chloride attack

Acid attack

- Primarily a problem in sewer pipes
- Typically related to H_2SO_4
- Gypsum formation, and an associated softening and strength loss of the structure observed
- Loss of cementitious nature due to deterioration of CSH because of low pH

Photos courtesy Prof. P. Paramasivam

Figure A.4.2.1 Disintegration by chemical attack from muriatic acid

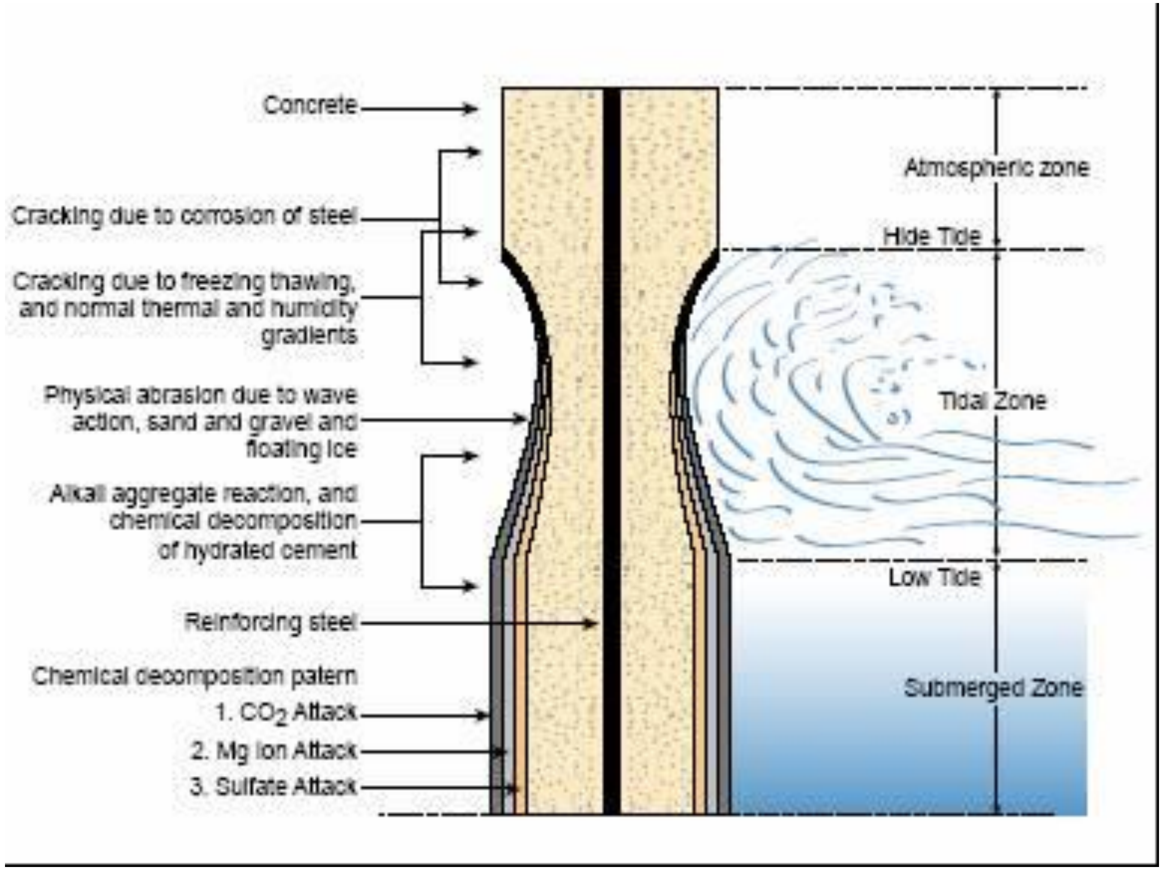
Figure A.4.2.2 Disintegration of sewer pipe by chemical attack due to H_2S.

Seawater attack

- Combined effect of sulphates and chlorides
- In addition to chemical attack, other complications are also involved:

- Tidal zones subjected to drying and wetting (salt crystallization)

- Splashing action of waves leads to mechanical degradation



Source: Mehta, 1997

Carbonation

- Carbon dioxide diffuses into the pores of concrete and reacts with calcium hydroxide; as a result, the alkalinity (pH) of the concrete is reduced
- Reduction of pH causes the passivity of reinforcing steel (protective layer) to be destroyed
- Carbonation typically occurs in a range of relative humidity (40 – 80%); too dry or too wet a concrete does not have a carbonation problem
- Moisture is essential during this process, to convert the CO2 into carbonic acid
- $Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$
- $CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O$
- $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$

Aggregate issues in concrete

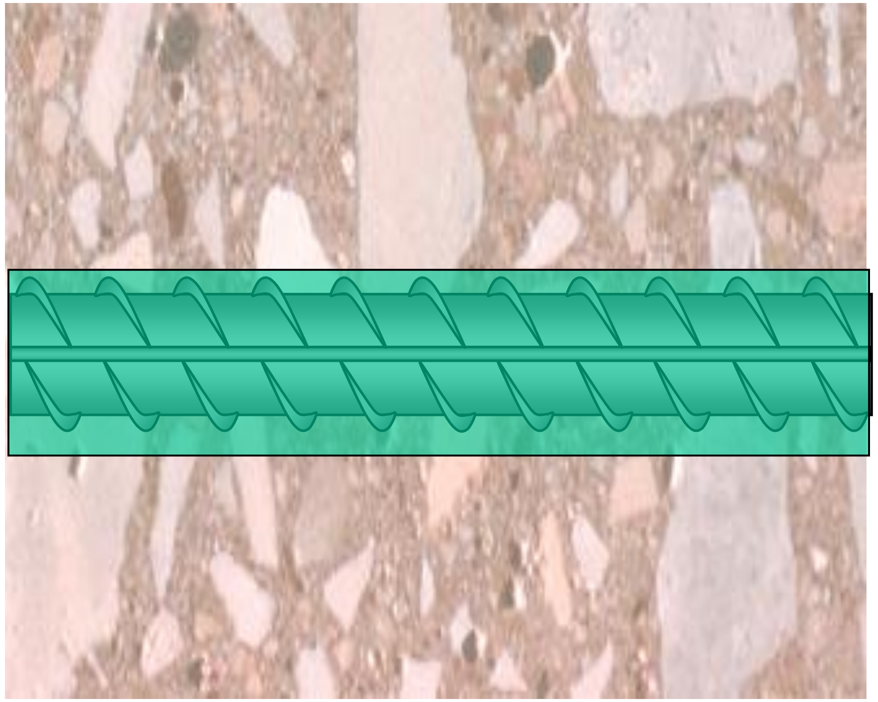
Matrix of deterioration mechanisms relating to aggregates in concrete

	Physical Mechanisms	Chemical Mechanisms
Intrinsic Mechanisms	Dimensional Incompatibility:- • Thermal effects • Moisture effects	**Alkali Aggregate Reaction** Sulphides in aggregates Thaumasite sulphate attack
Extrinsic Mechanisms	Freeze-Thaw Surface Wetting and Drying (Moisture Cycles) Surface Abrasion and Erosion	Acid Attack Alkali Attack Other Aggressive Chemicals, e.g. Sulphates

Alexander, 2014

Why steel embedded in uncontaminated concrete does not corrode?

- Steel does not corrode due to high pH of concrete pore solution
- A protective layer ("Passive film") is formed
  - A thin, invisible, and stable layer of initial corrosion products (i.e., iron oxides and hydroxides)



However, corrosion can occur when exposed to aggressive conditions

Hoar (1967)

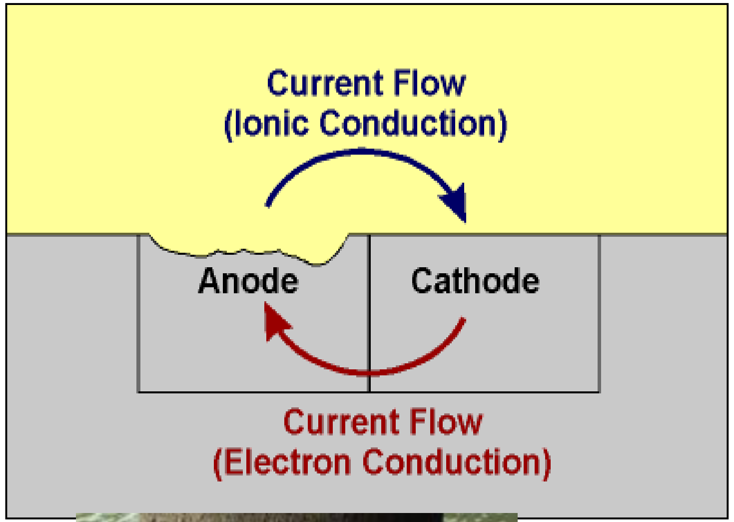
Reactions of corrosion

- Anodic (oxidation) reaction

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

- Cathodic (reduction) reaction

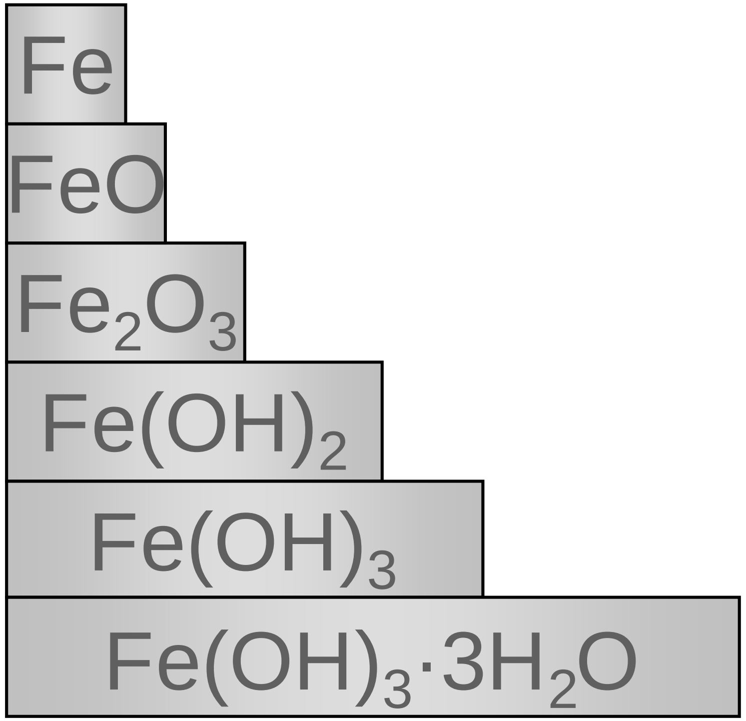
$$\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2(OH)^{-}$$

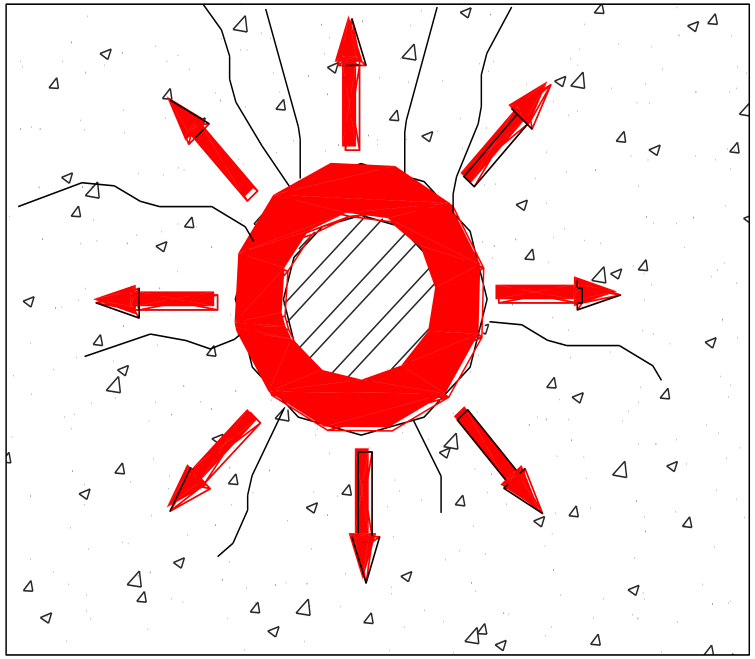


At the splash zone, corrosion can occur at a higher rate

http://www.corrosion-club.com/images/corrosioncell.gif, http://www.tfhrc.gov

Why corrosion causes cracking of concrete?



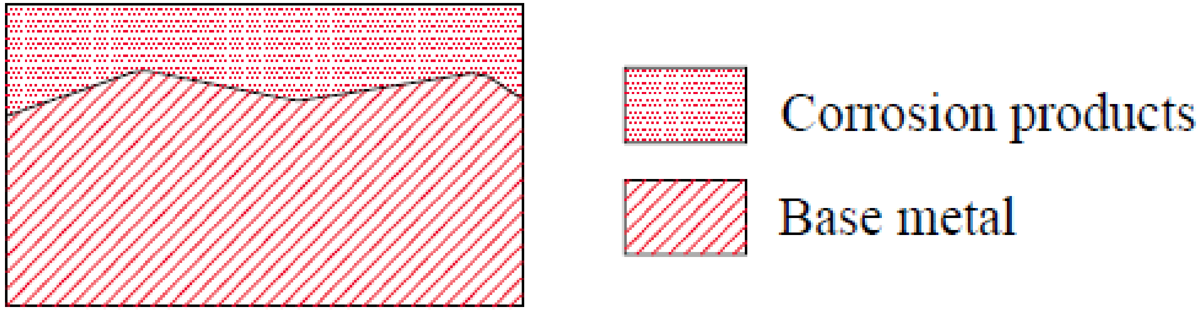


When steel corrodes, its volume increases by approximately 6 times

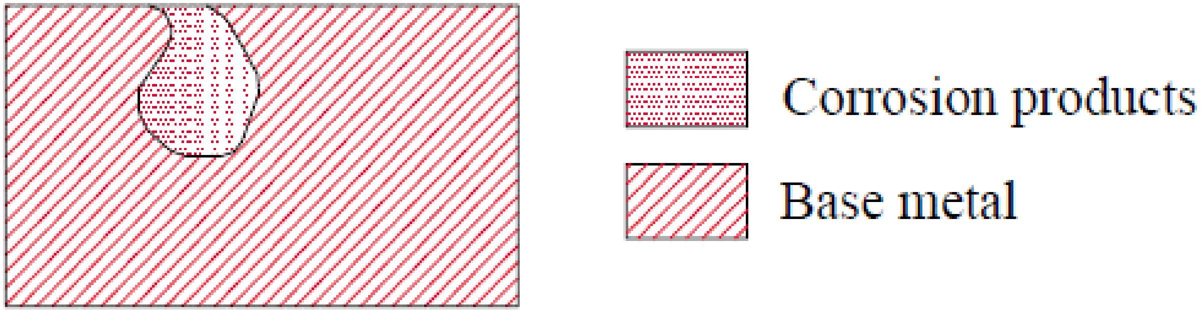
Courtesy: R G Pillai

Two major types of corrosion in concrete structures

- Carbonation-induced corrosion
    - General or uniform section loss



- Chloride-induced corrosion
    - Localized, pitting or non-uniform section loss



Courtesy: R G Pillai

Carbonation-induced corrosion and testing carbonation depth using phenolphthalein indicator

- Severe when the relative humidity is ~ 60 to 70%

Courtesy: R G Pillai

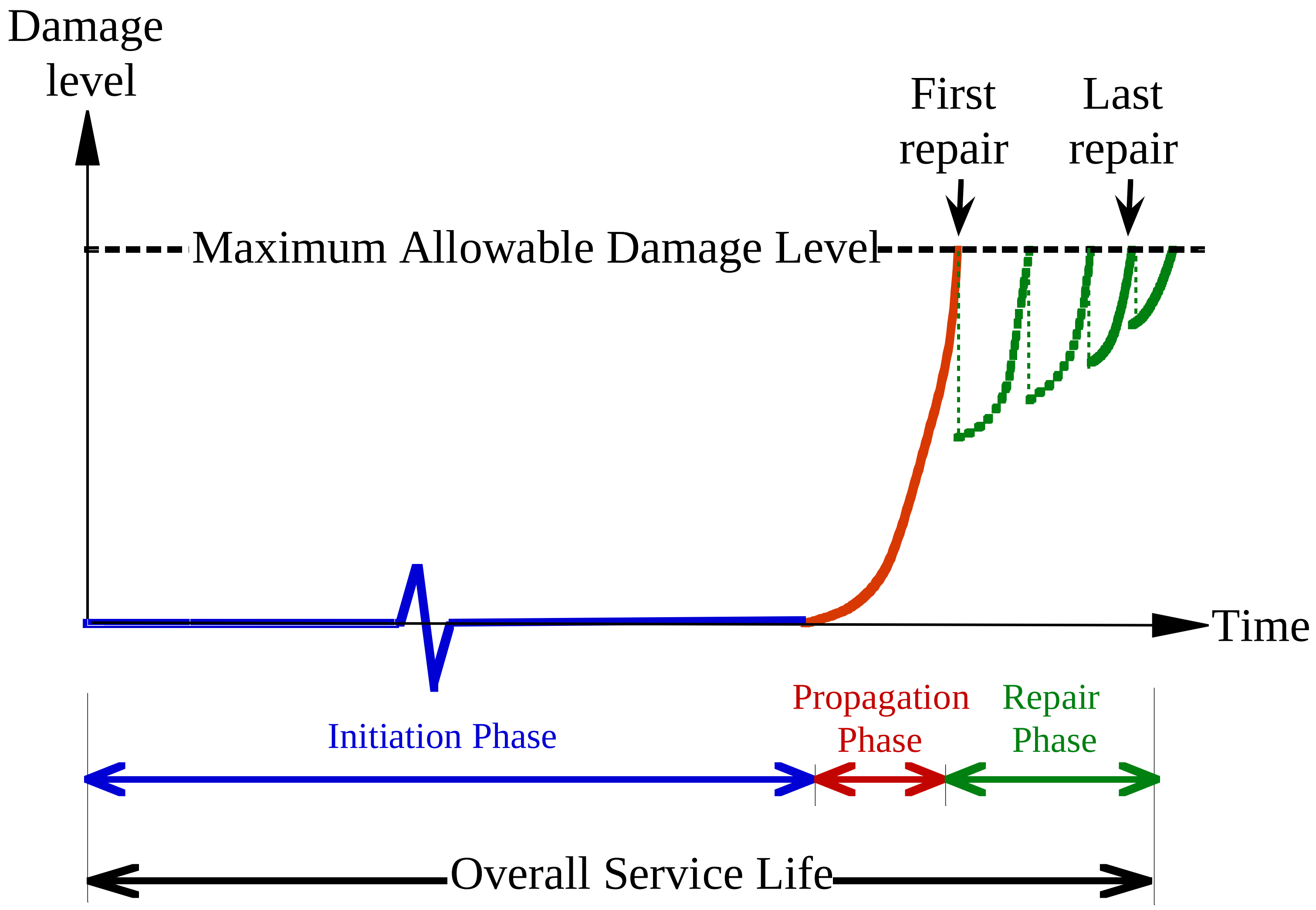
Pitting corrosion on strands and deformed bars due to chloride attack

- 7-wire strand →

- Deformed bar →

Courtesy: R G Pillai

Service life = the time during which the structure is able to safely meet the user requirements

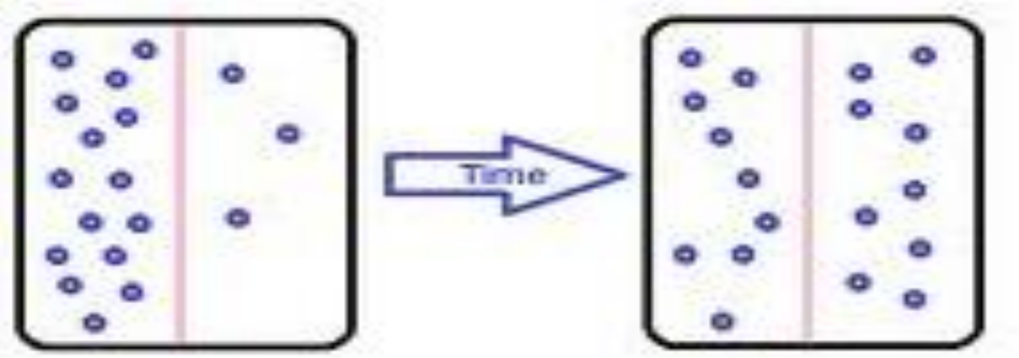


Courtesy: R G Pillai

Transport Mechanisms

Diffusion

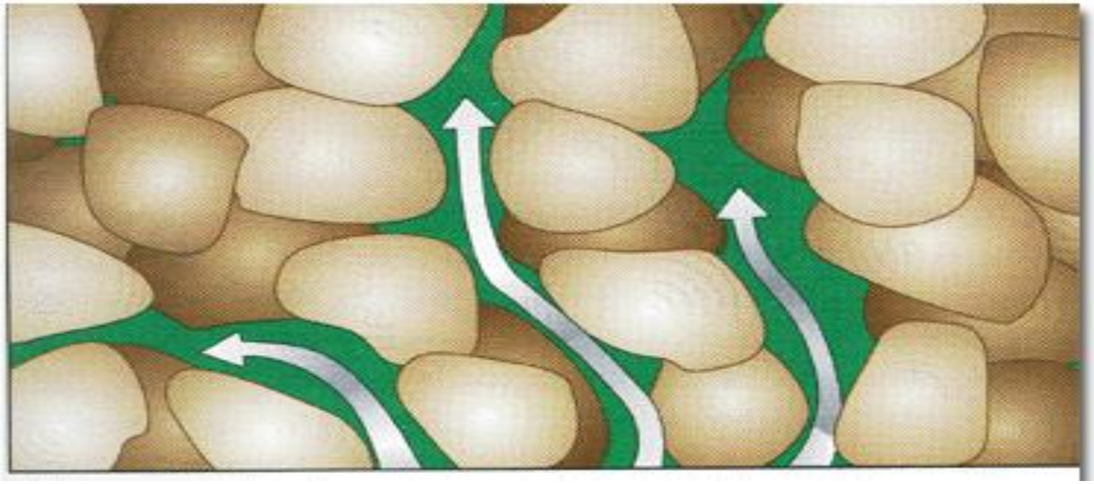
- Flow under concentration gradient



- Gaseous diffusion
  - Through unsaturated concrete
- Ionic diffusion
  - Through saturated and partially saturated concrete
- Molecular diffusion
  - If the pores are relatively large

Permeation

- Saturated liquid transfer controlled by a pressure gradient across the concrete
- Ionic species dissolved in water also can move by permeation of water
- Permeation higher when cracks and defects are present

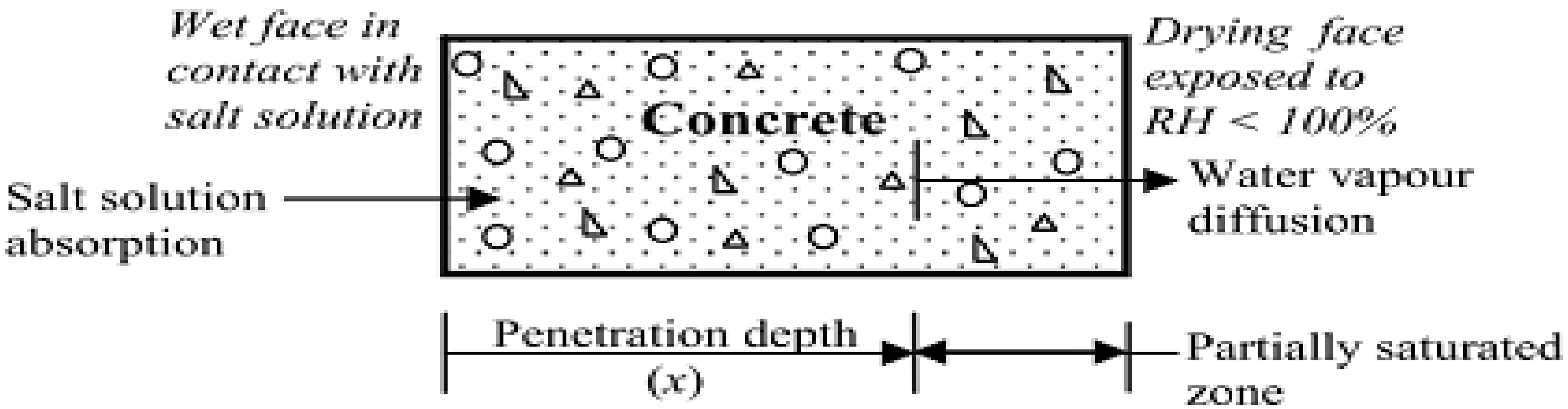


Sorption / Capillary water absorption

- Uptake of liquid into unsaturated or partially saturated solids
- Influenced by large capillaries and degree of continuity, compaction, aggregate orientation and distribution, mix composition etc.
- Measure the mass of water absorbed by the concrete over time

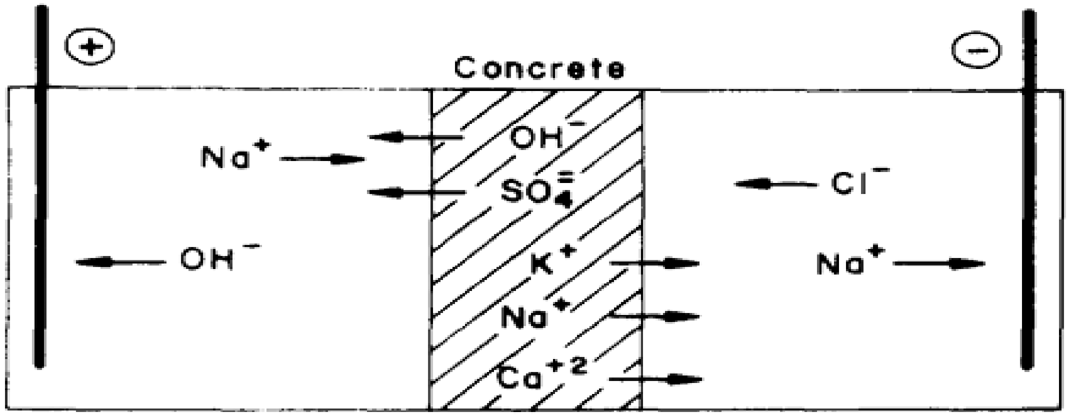
Wick action

- Transport of liquid from a face in contact with liquid to drying face, where the liquid evaporates and dissolved ions precipitate as salts in the pores or on the surface of the medium
- Wetting and drying cycles



Migration/ Conduction

- Movement of ionic species driven by difference in electrical potential



- Nernst Planck Equation

$$\vartheta = D \frac{zF}{RT} \frac{dU}{dx}$$

Tests for durability

Useful resources

- RILEM TC230 State of the Art Report on Performance Based Specifications and Control of Concrete Durability – available from www.rilem.net
- ICI Technical Committee Handbook on Durability
- Santhosh G Cheriyan and M. Santhanam, "Demystifying durability testing for Indian concrete construction industry," *Indian Concrete Journal*, Vol. 87, No. 7, **2013**, pp. 18 – 34.
- Santhosh G. Cheriyan, B S Dhanya and Manu Santhanam, "Durability Indices of Concrete with Different Mineral Admixtures," *Indian Concrete Journal*, Vol. 88, No. 3, **2014**.
- B S Dhanya, Manu Santhanam, Vijay Kulkarni, Prakash Nanthagopalan, Shashank Bishnoi, S P Singh, Indu Siva Ranjani, P Dinakar, and S Bhaskar, "Round Robin Testing of Durability Parameters – Towards Identification of Suitable Durability Tests for Concrete," Indian Concrete Journal Vol. 91, No. 7, **2017**, pp. 11 – 22.

Wenner 4 Probe Resistivity Test

Method	Merits	Demerits
•Consists of four probes •Through two outer probes current is applied while the inner two points measure the potential	• Fast • Resistivity is used to calculate the corrosion rates in concretes •Avoids heating • Very low voltage (10V or lower) is applied for a short time	•Depends on pore solution conductivity and degree of saturation •Inclusion of conductive materials affect the results

Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Resistivity, kΩcm	Concrete quality
> 100	Good
50 - 100	Normal
10 – 50	Poor
< 10	Very poor

Rapid Chloride Permeability Test (ASTM C 1202)

Method	Merits	Demerits
•Specimen is subjected to a 60V potential, for 6 hours • -ve side is filled with 3% NaCl solution and +ve side is with 0.3M NaOH solution •Current is measured in each half hour	•Widely used test method •Gives qualitative classification of concrete	•Current passed is related to all ions in the pore solution •Increase in temperature •Presence of conductive materials affects the test results •Many transport mechanisms act together

Classification Criteria (ASTM C 1202)

TABLE 1 Chloride Ion Penetrability Based on Charge Passed (1)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

Accelerated Chloride Migration Test (NT Build 492)

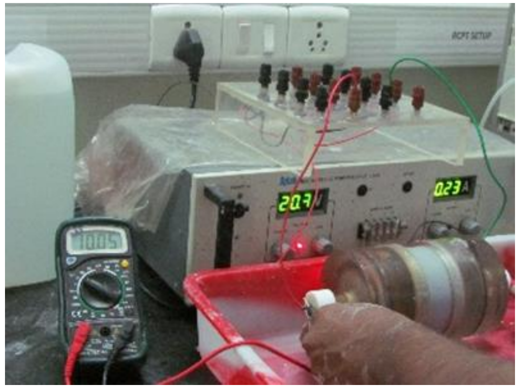
Method	Merits	Demerits
•30 V potential is applied initially and after measuring the initial current, voltage is adjusted. •After specified duration the specimen is split and silver nitrate solution is sprayed •Depth of chloride penetration is used to calculate the non-steady state diffusion coefficient	•Capable of addressing some of the criticisms of RCPT related to the examination of actual chloride ion movement and temperature rise.	•Presence of conductive materials affects the test results •Many transport mechanisms acts together

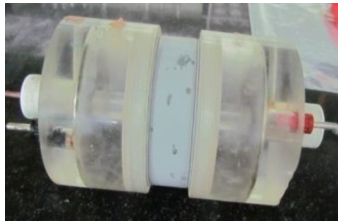
Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Nordtest Method BUILD 492, Migration coefficient (m^2/s)	**Concrete quality**
$< 2 \times 10^{-12}$	Very good
$2 – 8 \times 10^{-12}$	Good
$8 – 16 \times 10^{-12}$	Normal
$> 16 \times 10^{-12}$	Poor

Chloride Conductivity Test (DI Manual, SA)

Method	Merits	Demerits
•Consists of a two cell conduction rig in which concrete core specimens are exposed on either side to a 5M NaCl solution •Chloride conductivity is determined by measuring the current flowing through the specimen due to the application of 10V potential difference	•Specimens preconditioned before testing to standardize the pore water solution •Nullify the effect of other ions in the pore solution	•Destructive •Can not be applied on site





Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Chloride conductivity	Concrete quality
< 0.75	Very good
0.75 – 1.50	Good
1.50 – 2.50	Poor
> 2.50	Very poor

Bulk diffusion test (ASTM C 1556)

Method	Merits	Demerits
•Natural diffusion under a very high concentration gradient •Specimens saturated with saturated lime water is immersed in 3% NaCl solution for 35 days •Uni-directional diffusion •Chloride profiling with profile grinder •Chloride ion concentration determined	•Identical to natural diffusion process •Other transport mechanisms are avoided	•Slow process •Powder can be lost during profiling •Effect of aggregates is unavoidable

Classification criteria – Nilsson et al.1998

Apparent diffusion coefficient (x 10^{-12} m^2/s)	Resistance to chloride penetration
> 15	Low
10 – 15	Moderate
5 – 10	High
2.5 – 5	Very High
< 2.5	Extremely High

Oxygen Permeability Test (DI Manual, SA)

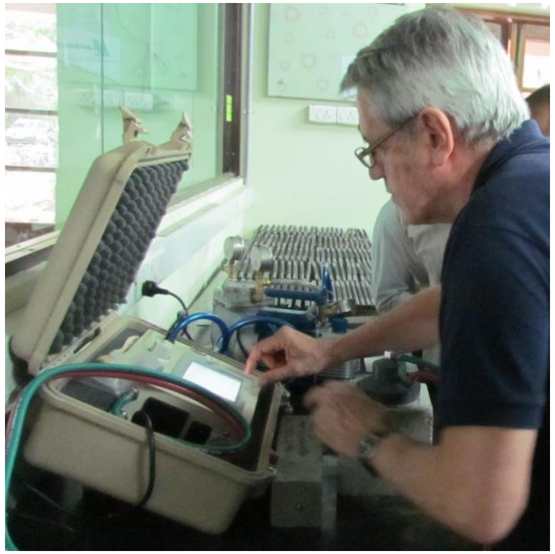
Method	Merits	Demerits
•Measures the pressure decay of oxygen passed through an oven dried, 30 mm thick slice of a 70mm diameter core placed in a falling head permeameter •The oxygen permeability index is defined as the negative log of the coefficient of permeability	•Good correlation with accelerated carbonation test	•Sensitive to macro- voids and cracks •Sensitive to the edges of the specimen

Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Oxygen permeability index OPI	Concrete quality
> 10	Very good
9.5 - 10	Good
9.0 – 9.5	Poor
< 9	Very poor

Torrent Air Permeability Test
Swiss Standard SIA 262/1-E:2003

Method	Merits	Demerits
•Method is based on creating a vacuum on the surface of the concrete and monitoring the rate at which the pressure is raising in the test chamber after the vacuum pump has been disconnected	•Simple •Non destructive •Both lab and site application	•Sensitive to the moisture condition of the specimen •Test is more sensitive to the surface condition of the specimen



Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Torrent kT $\times 10^{-16} m^2$	**Concrete quality**
< 0.01	Very good
0.01 - 0.1	Good
0.1 - 1.0	Normal
1.0 - 10	Poor
> 10	Very poor

Accelerated Carbonation Test

Method	Merits	Demerits
•Measuring the depth of carbonation at different sections of the prismatic samples at different time intervals (70,98, 112 and 154 days) •Phenolphthalein used as indicator – colourless implies carbonated	•Mechanism is diffusion, which is similar to the natural phenomena	•High degree of carbonation may lead to microstructural alterations at high CO_2 concentrations

Sorptivity Test (DI Manual, SA)

Method	Merits	Demerits
•Measures the rate of movement of a water front through the concrete under capillary suction	•Simulates natural phenomena •Applicable to drilled cores	•Sensitive to macro-voids and cracks •Sensitive to the micro-structural properties of the near-surface zone of concrete •Destructive

Classification Criteria (RILEM TC PSC STAR, Chapter 5)

Water sorptivity test, mm/√h	Concrete quality
< 6	Very good
6 - 10	Good
10 - 15	Poor
> 15	Very poor

Germann Water Permeability Test (GWT)

Method	Merits	Demerits
•A sealed pressure chamber is attached to the concrete surface. •Water is filled into the pressure chamber and a specified water pressure is applied to the surface •Pressure is kept constant using a micro-meter gauge with an attached pin that reaches into the chamber	•Non-destructive •Both field and lab test	•Pressure is not sufficient for impermeable concretes •Water flow may not be parallel to the gasket if pores are present

Classification Criteria (RILEM TC PSC STAR, Chapter 5)

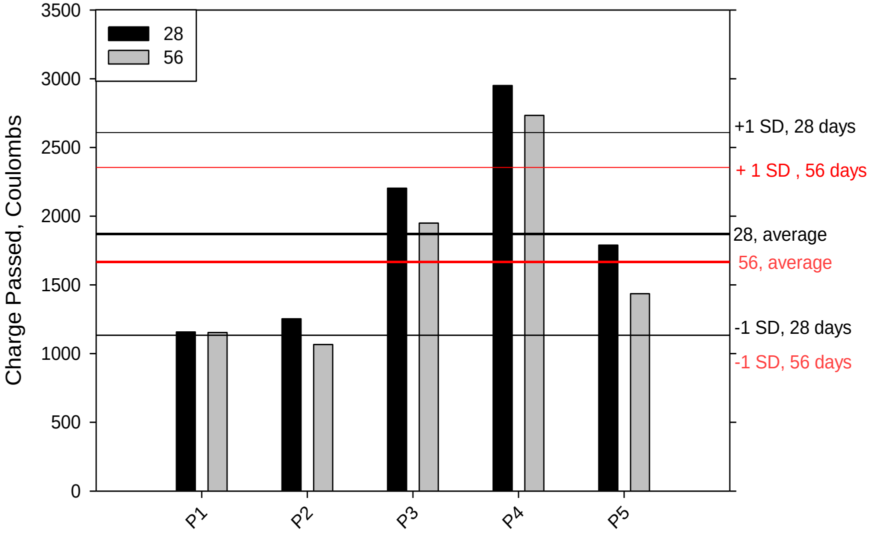
Coefficient of water permeability, m^2	Concrete quality
$< 10^{-12}$	Good
10^{-12} - 10^{-10}	Normal
$> 10^{-10}$	Poor

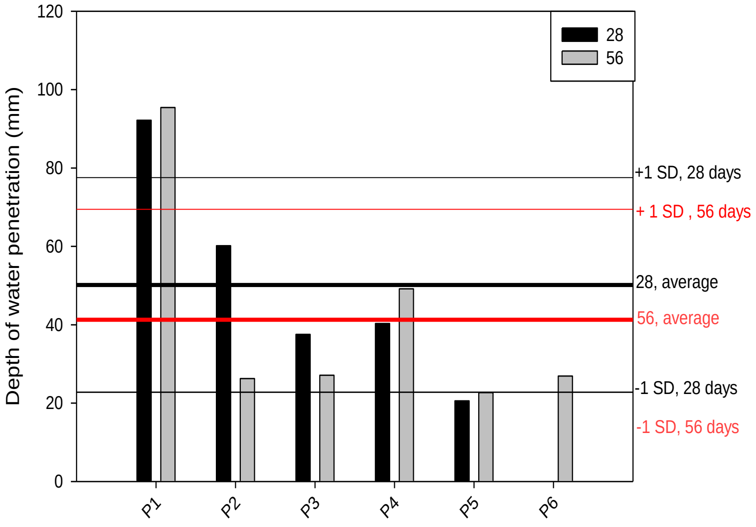
Water Permeability Test (DIN 1048 Part 5)

Method	Merits	Demerits
•Measure of the resistance of concrete against the penetration of water under pressure •The test should be done when the age of concrete is between 28 and 35 days •A water pressure of 0.5 N/mm^2 is applied for a period of 3 days •After the pressure is released, the specimen is split into two and the depth of water penetration is measured	•Depth of water penetration is measured	•Destructive •Air compressor is needed to keep the pressure constant

Many specifications put a penetration limit at 25 mm for HPC

Variability expected in tests





Test	COV (%)
Compressive strength	10 – 11
Rapid chloride permeability test	25 – 40
Chloride migration test	50 – 75
Sorptivity test	50 – 80
Water penetration test	55 – 80
Water absorption test	25 – 60

Dhanya et al. 2017

Summary - Durability test methods and parameters

Category	Test method	Parameter
Test methods to assess chloride penetration	**Rapid Chloride Permeability**	**Total charge passed**
	Accelerated Chloride Migration	**Non-steady state diffusion coefficient**
	Chloride Conductivity	**Chloride Conductivity**
	Bulk diffusion	**Chloride concentration profile**
Test methods to assess gas penetrability	**Oxygen Permeability**	**Oxygen Permeability Index**
	Torrent Air Permeability	**Coefficient of Permeability**
	Accelerated Carbonation	**Carbonation depth**
Test methods to assess water penetrability	**Sorptivity**	**Sorptivity index**
	Germann water Permeability	**Surface Permeability**
	German water Permeability	**Water penetration depth**
Test method to assess concrete resistivity	Wenner 4 Probe Resistivity	Surface Resistivity

Summary - Transport mechanisms in concrete and test methods

Mechanism	Definition	Test method
Sorption	Capillary action	Sorptivity
Permeation	Flow under pressure	Oxygen permeability, Torrent air permeability **(Gas permeability)**
		Germann water Permeability, DIN 1048 water penetration **(Water permeability)**
Diffusion	Flow under concentration gradient	Bulk diffusion, Rapid Chloride Permeability, Accelerated Chloride Migration, Accelerated carbonation
Migration/ Conduction	Movement due to applied electric field	Rapid Chloride Permeability, Accelerated Chloride Migration, Chloride conductivity, Wenner resistivity
Wick action	Transport of ions or water from a face in contact with water to drying face	Sorptivity
Absorption	Bulk intake of water	Sorptivity

Steps in durability design

- Identify the correct exposure environment, and the associated durability issues
- Understand how transport of liquids and gases will occur into the concrete (i.e. transport mechanism)
- Select tests that reflect the correct transport mechanism(s)
- Set the 'limiting values' for the tests that need to be achieved
- Perform mixture design studies to obtain the right combination of:
  - Workability
  - Compressive / flexural strength
  - Durability tests limiting value

  } Pre-qualification
- Set durability targets for the concrete in production – acceptance criteria!

Planning for durability – before starting

- Depending upon anticipated exposure conditions and local conditions, appropriate durability tests shall be chosen and specified
- A combination of test methods (appropriate to resist degradation mechanisms) shall be selected to ensure resistance to the ingress of liquid, gases and chemicals
- Initial testing work including durability testing shall be completed and co-relationships established between different test parameters (if any) before commencement of project

Planning for durability – during construction

- Sampling frequency
    - 3 samples for every 500 m^3 of concrete produced during initial production stage
    - On production stabilization and getting satisfactory results, frequency of sampling can be increased (say 3 samples for 1000 m^3) as agreed between stakeholders
- Conformity Assessment for Durability
    - Specify appropriate threshold values
    - Acceptance criteria
        - Average of consecutive five test results shall be below the threshold value
        - No single value to exceed the threshold by more than 35-40%*
    - Third-party testing
        - Lab shall have NABL and/or DST accreditation

* Based on experience from round-robin testing and practices followed in other countries

Testing protocol – some examples

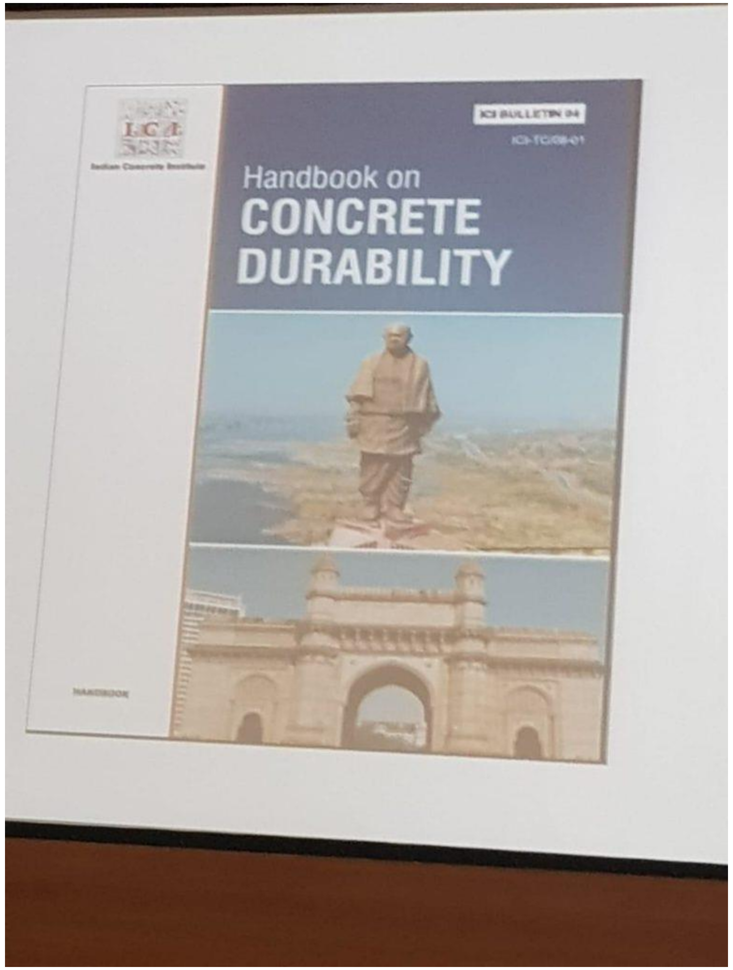
- Durability Testing on Constructed Elements
  - Cover meter survey
    - Cover to reinforcement is crucial in determining long-term durability
      - Tolerances over nominal cover shall be clearly specified
      - Minimum % of constructed elements shall be subjected to cover meter survey (as agreed in the contract)
  - Electrical Resistivity of Concrete
    - Useful parameter that links to permeability
    - Easy to perform in the field
    - Precautions – moisture saturation; reinforcement presence

Other preparations for durability

- Shape of exposed structural elements shall be capable of promoting proper drainage of water
- Concrete producer/contractor shall prepare detailed quality plan
- Third-party certification from accredited agency essential for RMC production facility
  - Audits at frequent interval (say every six month)
  - In-house audit once in a month
- Transportation, Handling, Placing & Compaction of Concrete
  - Quality Plan to include detailed procedures
  - Client/PMC to ensure strict implementation
- Curing of concrete
  - Adequate curing of concrete is a must to ensure long-term durability
  - Curing methodology and minimum duration shall be clearly specified and implemented

Summary

- Multiple durability problems and associated mechanisms in concrete
- Important to identify the correct mechanism and associated test method



Thank you!

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MANU SANTHANAM


KEERTHANA KIRUPAKARAN


KOSHY VARGHESE


BENNY RAPHAEL


RADHAKRISHNA PILLAI


PIYUSH CHAUNSALI


SURENDER SINGH


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