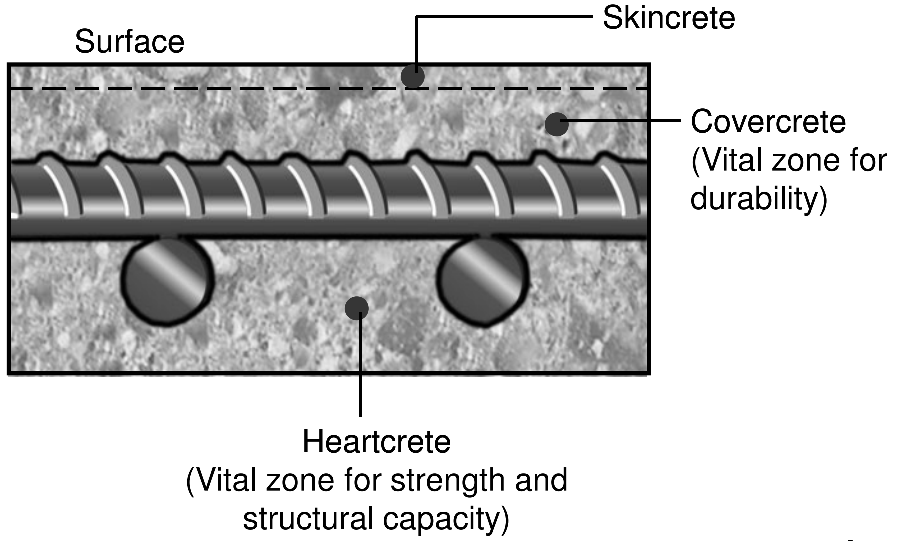
Contents

What is "Concrete Durability"?

ACI Manual – "The ability of a structure or its components to maintain serviceability in a given environment over a specified time"

Browne (1986) – "Ability of the concrete in preventing steel corrosion. The attack process can be regarded as a battle between the environment and the concrete cover which acts as the defense system for steel. The enemies range from chlorides, moisture, oxygen…"

The "Cretes" of Concrete Structural Element



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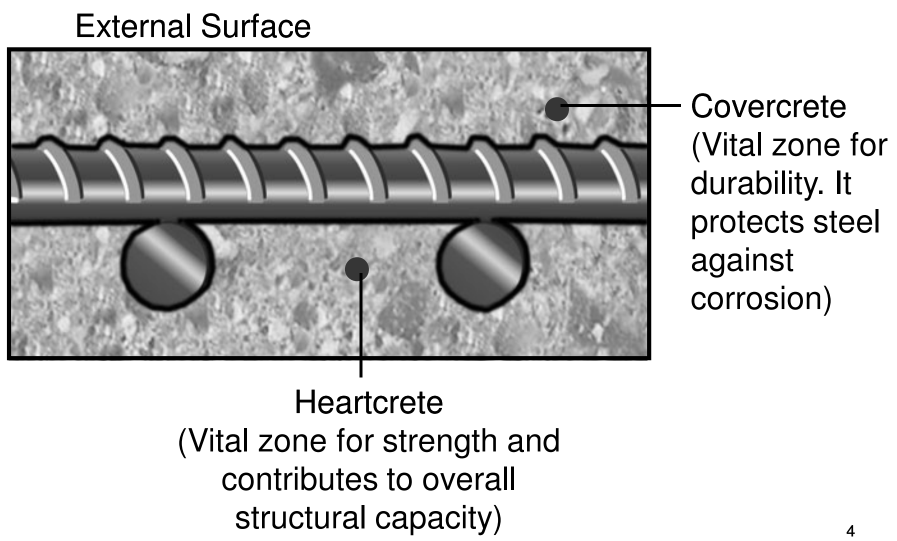
What is "Concrete Durability"?



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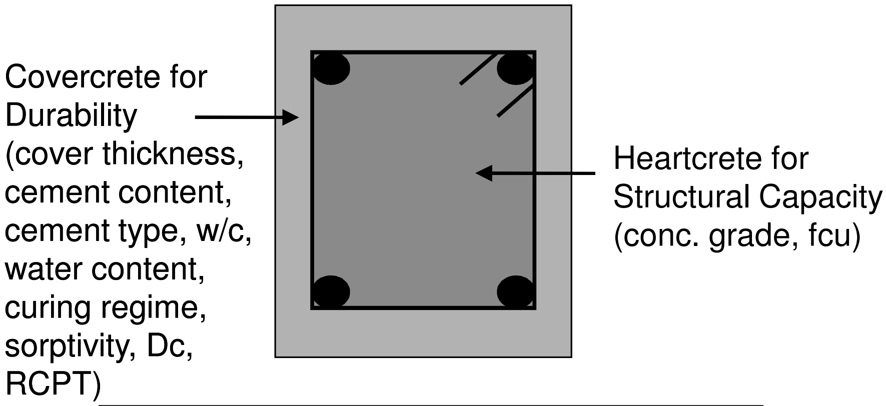

Typical Cross-Section of Reinforced Concrete

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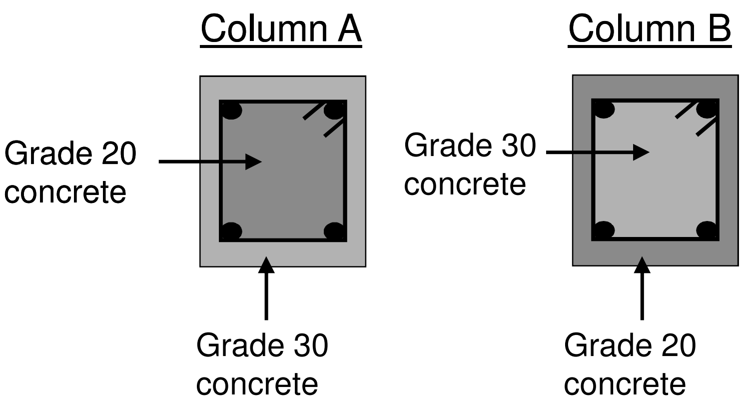

Which is more durable ?

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Concrete Durability Issues

1. Very often, the quality of covercrete is poorer than the heartcrete because of inadequate curing. As a result, the covercrete is more porous and prone to development of cracks making it permeable to harmful agents.
2. However, a larger part of the durability issue is attributed to poor design and construction practice, such as poor detailing, low cover achieved at site, poor compaction and inadequate curing of concrete.
3. The tendency to use higher yield strength steel (up to 500 MPa) as reinforcement in concrete and at larger spacing would result in wider surface crack width and more microcracks in the covercrete. These cracks serve as potential pathway for ionic transport between the concrete surface and the steel reinforcement.

The 2Qs for Durability

1. QUANTITY of cover
   * Is the Code's provision adequate?
   * What is the achievement of the specified cover at site?
2. QUALITY of cover
   * Is curing and compaction adequate?
   * Is the concrete mix acceptable?

Factors Affecting Durability

1. Mix proportions – binder type, binder content, w/c ratio, water content, sand-aggregate ratio
2. Curing and compaction
3. Chemical admixture
4. Mineral admixture

Why Curing of Concrete?

"Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration."

Curing shall be carried out immediately after concrete has been placed in position, thus, providing time for the hydration of the cement to take place.

Since the hydration of cement does take time – days, and even weeks rather than hours, curing shall be undertaken for a reasonable period of time if the concrete is to achieve its POTENTIAL STRENGTH and DURABILITY.

Methods of Curing Concrete

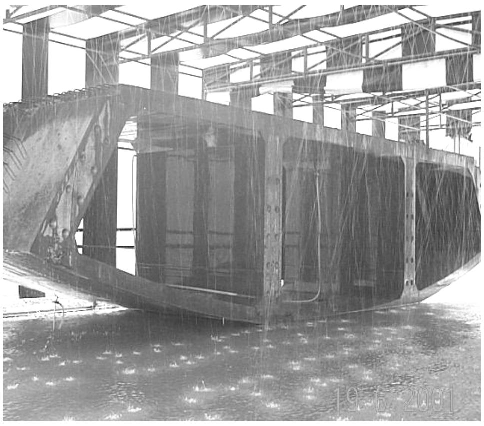
1. Wet or moist curing – preventing moisture loss by continuously wetting the exposed concrete surface eg. Wet burlaps, fogging, water-ponding, plastic sheets, etc.
2. Curing compounds – are liquids usually sprayed directly onto concrete surfaces which then dry to form an impermeable membrane that retards the loss of moisture from concrete.
3. Internal curing admixtures – are admixtures incorporated into fresh concrete to inhibit moisture loss. These are relatively new products and care should be taken to use them.

Wet or Moist Curing of Concrete

Wetting by water sprinkler

Using plastic sheet to cover concrete

Wet or Moist Curing of Concrete



Wetting by water sprinkler

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Wet or Moist Curing of Concrete

Fogging (in a chamber)

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Wet or Moist Curing of Concrete

Water Ponding

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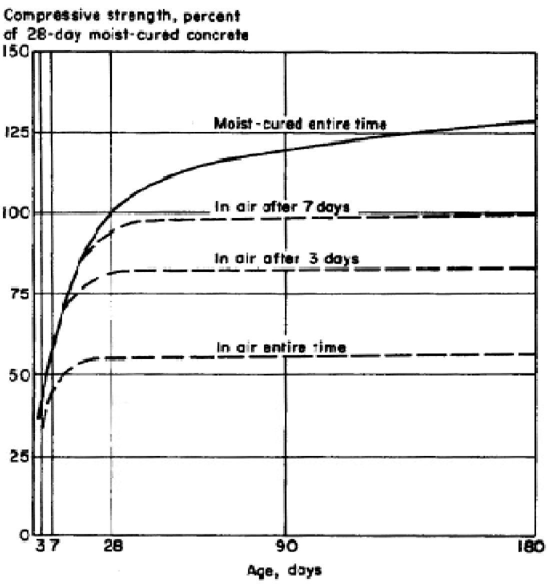

Compressive strength as a function of age for a variety of curing condition (ACI 308R-01)

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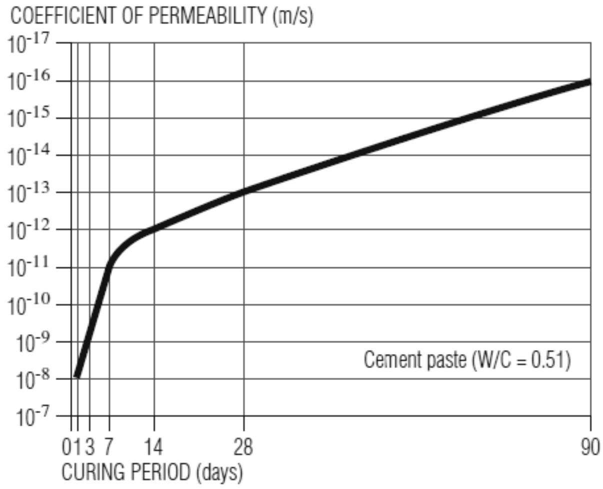

Effect of curing period on permeability of cement paste (Cement Concrete & Aggregates Australia)

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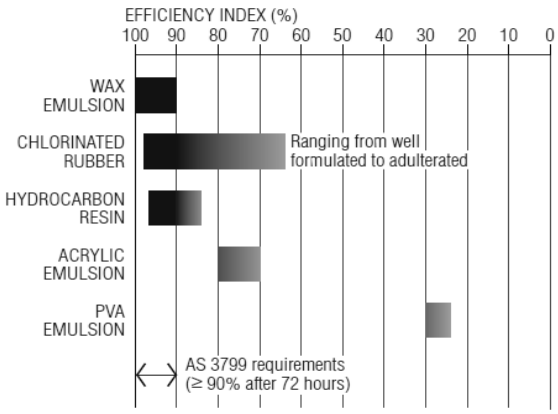
Curing Compounds

Curing compounds are generally formulated from wax emulsion, chlorinated rubber, synthetic and natural resins.



Comparative efficiency of curing compounds (Cement Concrete & Aggregate Australia)

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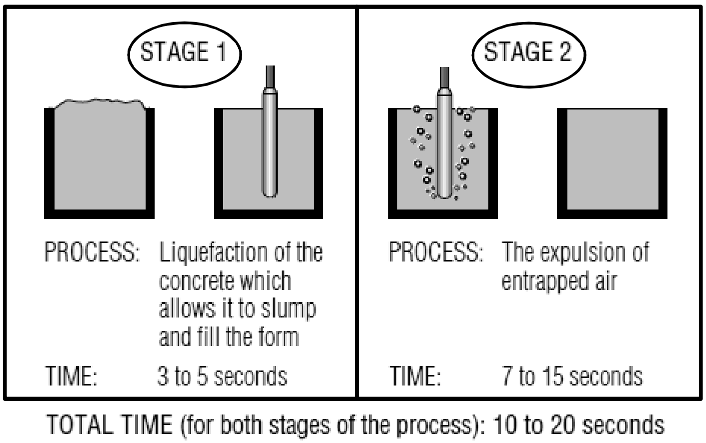
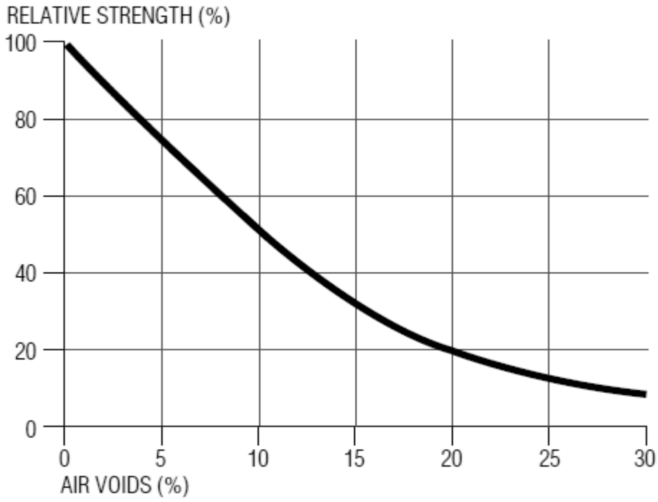
Why Compaction of Concrete?

"Compaction is the process which expels entrapped air from freshly placed concrete and packs the aggregate particles together so as to increase the density of concrete."

Proper compaction increases concrete strength, improves impermeability and durability of concrete.



Compaction of concrete is a 2-stage process. Firstly, aggregates are set in motion and slump to fill the form. Secondly, entrapped air is expelled (Cement Concrete & Aggregates Australia)



Typical Loss of Strength in Concrete Through Incomplete Compaction (Cement Concrete & Aggregates Australia)

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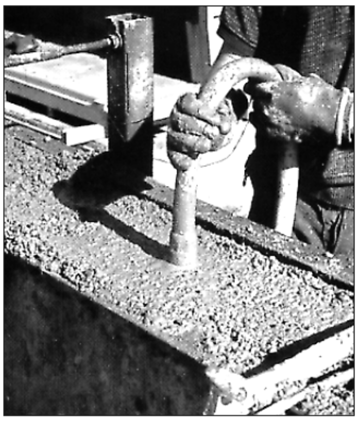
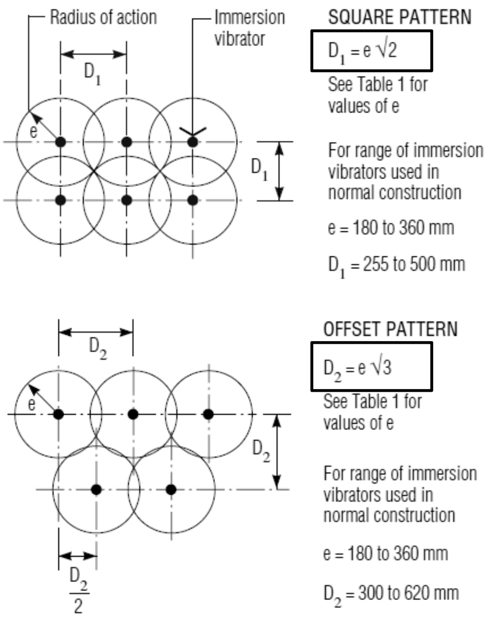


Diameter of Head (mm)	Radius of Action, e (mm)
20 – 40	75 – 150
30 – 65	125 – 250
50 – 90	175 – 350



(Cement Concrete & Aggregates Australia)

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Mineral Admixtures

Mineral Admixtures

TYPES : pulverised fuel ash (pfa), condensed silica fume (csf), ground granulated blastfurnace slag (ggbs),

PFA : A by-product from the combustion of pulverised coal in thermal power stations

CSF : A by-product from the smelting process in the production of silicon metal alloys

GGBS : A by-product of iron manufacturing

Industrial wastes !!

Mineral Admixtures

Pulverised Fuel Ash (Flyash)

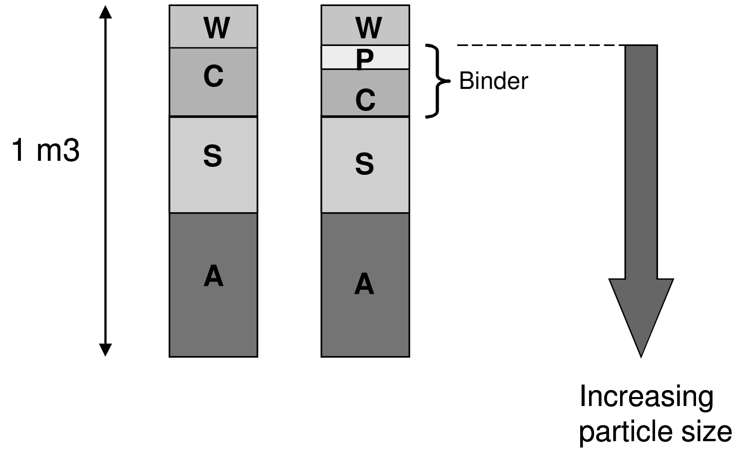
Ground Granulated Blast Furnace Slag (GGBS)

Silica Fume

Typical Chemical Composition

% by mass	OPC	CSF	PFA	GGBS
SiO_2	20	92	50	38
Fe_2O_3	3.5	1.2	10.4	0.3
Al_2O_3	5	0.7	28	11
CaO	65	0.15	3	40
MgO	0.1	0.2	2	7.5
Na_2O	0.1	1.0	0.7	0.4
K_2O	0.7	1.5	2.5	0.8
Fineness (m^2/kg)	300 - 400	20,000	400 - 700	350 - 600

Concrete Composition



Hydration of cement

$$\underset{(C_3S,\ C_2S)}{\text{Cement}} + \text{Water} \longrightarrow \underset{\text{(gel)}}{\text{CSH}} + Ca(OH)_2$$

Pozzolanic reaction

$$\underset{(SiO_2)}{\text{Pozzolan}} + Ca(OH)_2 + \text{Water} \longrightarrow \underset{\text{(gel)}}{\text{CSH}}$$

Mix Designation	% wt. of FA	% wt. of Cement	Initial Setting Time hours : minutes	Final Setting Time hours : minutes
330K2	0	100	5 : 40	7 : 00
330W2	0	100	5 : 20	6 : 40
454WE2	40	60	6 : 20	7 : 50
454WV2	40	60	6 : 30	8 : 00
555Q	50	50	10 : 30	13 : 00
555R	50	50	10 : 50	14 : 00

Effect of Flyash on Setting Times of Concrete (Sirivivatnanon et al)

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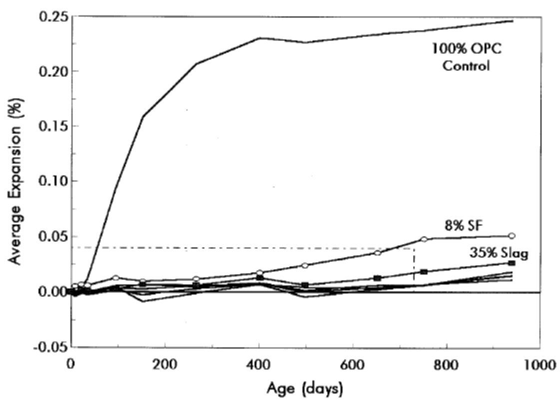
Alkali-Silica Reactivity (ASR) of Blended Cement Concrete



Concrete Prism Expansions After 2 Years at 38°C and 100% RH (Roland Bleszynski et al, 2002)

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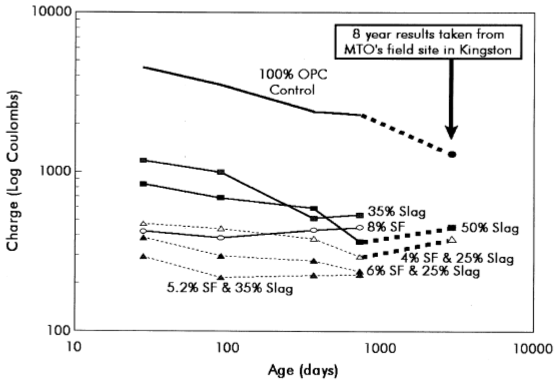
Chloride Penetration Resistance of Blended Cement Concrete



Rapid Chloride Penetration Test Results
(Roland Bleszynski et al, 2002)

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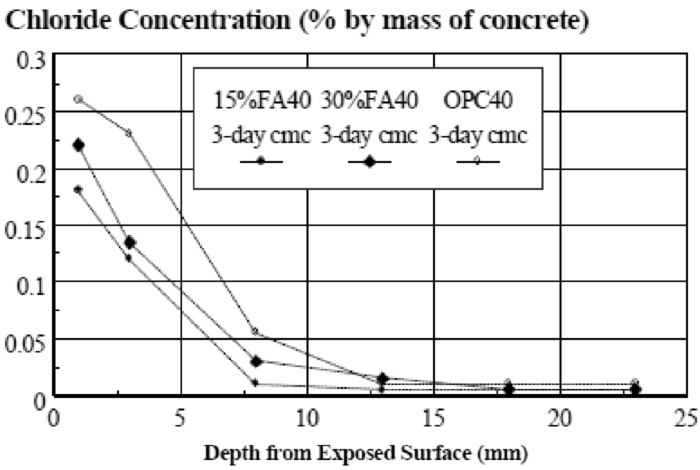

Effect of Flyash on Chloride Penetration of Concrete Partially Immersed in 3% NaCl Solution for 90 Days (Sirivivatnanon et al)

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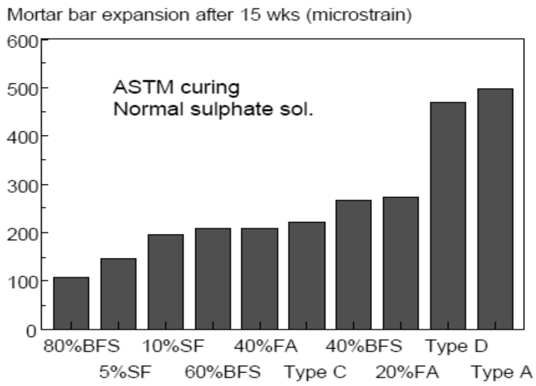
Sulphate Resistance of Blended Cement



Expansion of Mortar Bars After 15 Weeks in 5% Na_2SO_4 Solution Tested to ASTM C1012 (Sirivivatnanon et al, 1996)

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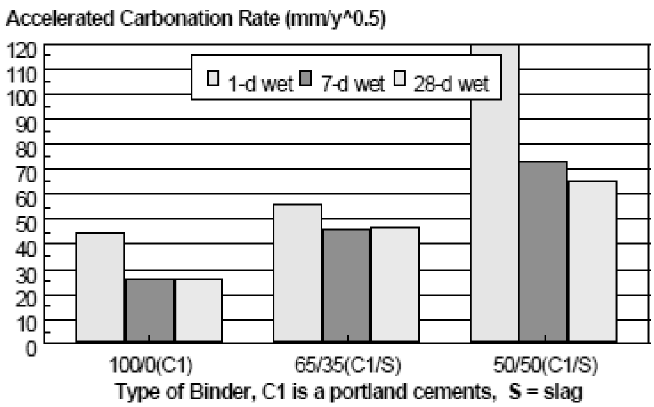

Effect of Slag Content on Accelerated Carbonation Rate of Concrete in 4% CO_2 (Sirivivatnanon et al)

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Chemical Admixtures

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History of HRWR Development

Year	Chemical Base	Generation	Water Reduction
1930	Ligno-sulphonates, Gluconates	1st	10%
1970	Sulphonated Melamine/Naphtalin polymers	2nd	20%
1990	Vinyl-copolymers	3rd	30%
2000	Modified Polycarboxylates	4th	40%

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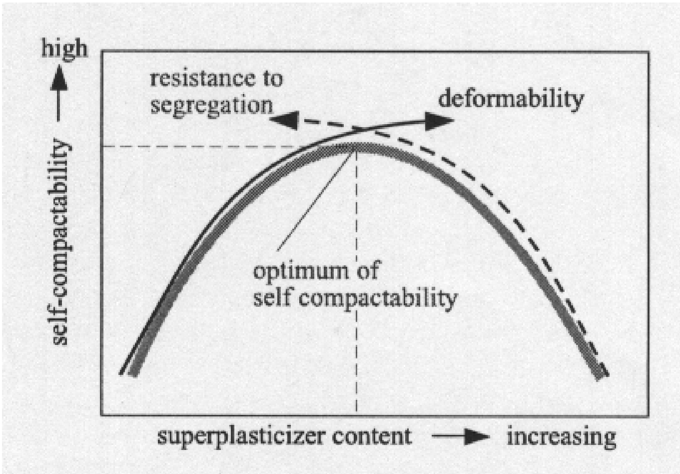
An Illustration of Superplasticiser Content on Self-Compactibility

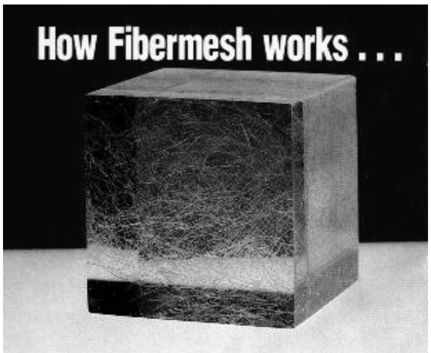


Fibres

Polypropylene Fibers

❑ Developed in the early 1980's

Polypropylene fibers



Dispersion of fibers

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Benefits of PP Fibers in Concrete (1)

❑ Inhibits cracking due to plastic and drying shrinkage

❑ A cost effective alternative to wire mesh for crack control

❑ Reduces concrete permeability and improves durability

❑ Improves impact and abrasion resistance

❑ Reduces rebound and material loss in gunite and shotcrete application

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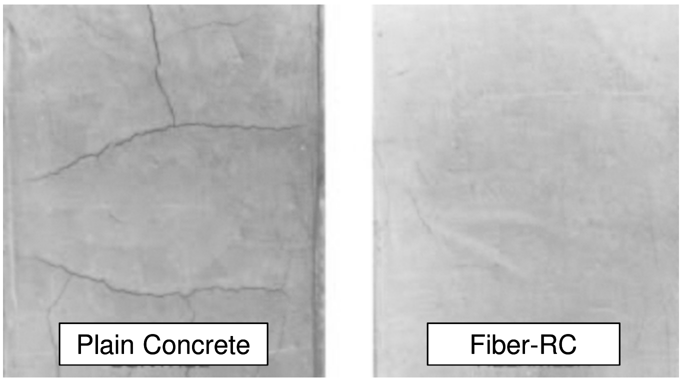
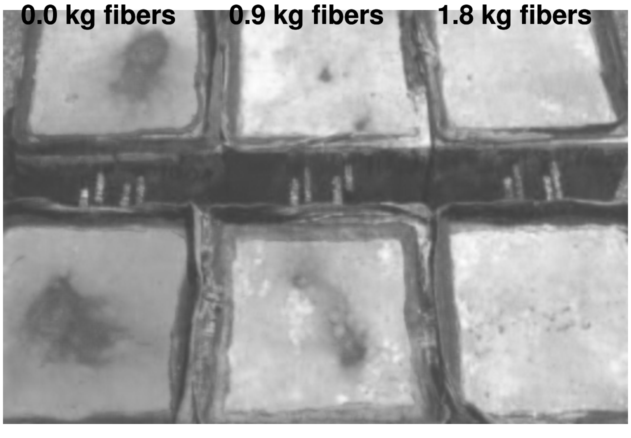
Benefits of PP Fibers in Concrete (2)



PP fibers inhibit cracking

Benefits of PP Fibers in Concrete (3)



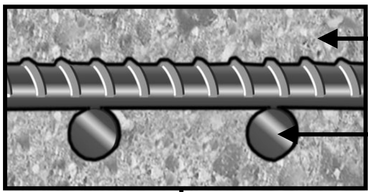
PP fibers improve durability

Do Not Use PP Fibers For

- Replacement for structural steel reinforcement
- Higher structural strength development
- Reducing the number of contraction joints

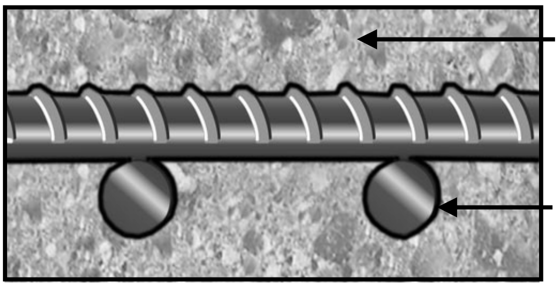
Deterioration of Reinforced Concrete Structures

Deterioration of Reinforced Concrete



- Concrete Deterioration
  - Corrosion of Reinforcement
    - Chloride Attack
    - Carbonation
  - Degradation of Concrete Matrix
    - Sulphate Attack
    - Acid Attack
    - Alkali-Aggregate Reaction

Protection of Steel in Concrete



❖ High Alkalinity Environment In Concrete Protects Steel From Corrosion

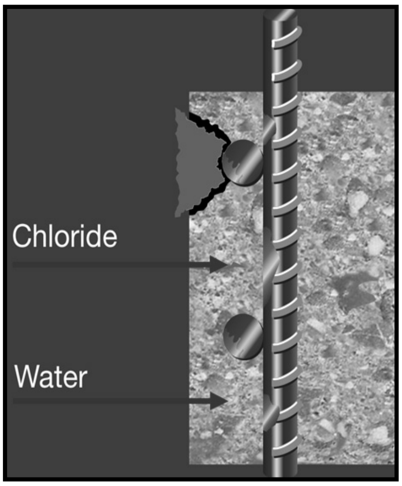
Destruction of Passivating Layer

❖ Two mechanisms that can destroy the passivating layer :

(1) Chloride Attack

(2) Carbonation

Chloride Attack (1)



Sources of chlorides:

- ✓ Sea water / sea water spray
- ✓ Contaminated aggregates
- ✓ Chloride-based admixture
- ✓ De-icing salt

Transport mechanisms:

- ✓ Diffusion
- ✓ Permeation
- ✓ Absorption

Chloride Attack (2)

Location	Chloride Content (gm/litre)
Gulf of Finland (Vesikari, 1988)	3.0 - 3.5
Baltic Sea (Vesikari, 1988)	7.0 - 10.0
Oceans (Vesikari, 1988)	20.0 - 35.0
North Sea (Pettersson, 1996)	17.0
Singapore (Liam et al, 1992)	12.0
Gulf of Mexico (Castro et al, 1993)	37.6

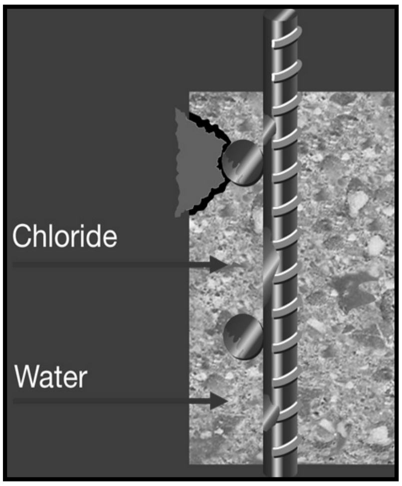
Typical Chloride Content of Sea Water

Chloride Attack (3)

	Chemical composition (gm/litre)		
	Lumut	Johor Bahru	Kuantan
Sodium	8.58	7.92	10.44
Potassium	0.45	0.41	0.38
Calcium	0.39	0.36	0.40
Magnesium	1.14	1.05	1.16
Sulphate	**2.44**	**2.15**	**2.32**
Chloride	**17.16**	**15.54**	**15.91**
Bromide	0.06	0.06	0.06

Typical Chemical Compositions of Sea Water in Malaysia

Chloride Attack (4)



Chloride content on steel surface ≥ 0.4% by wt. of cement

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Destruction of passivating layer

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Steel corrosion and volume expansion

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Concrete cracking and spalling

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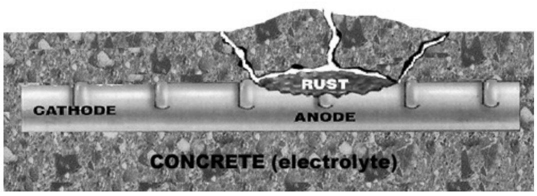
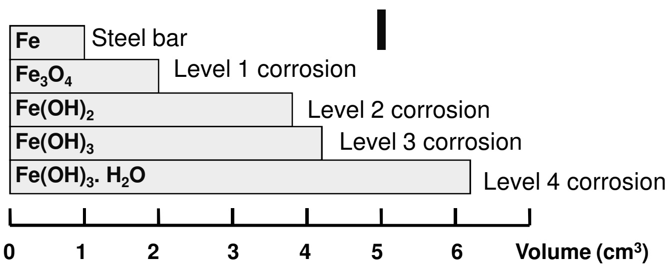
Corrosion of Steel: Volume Change





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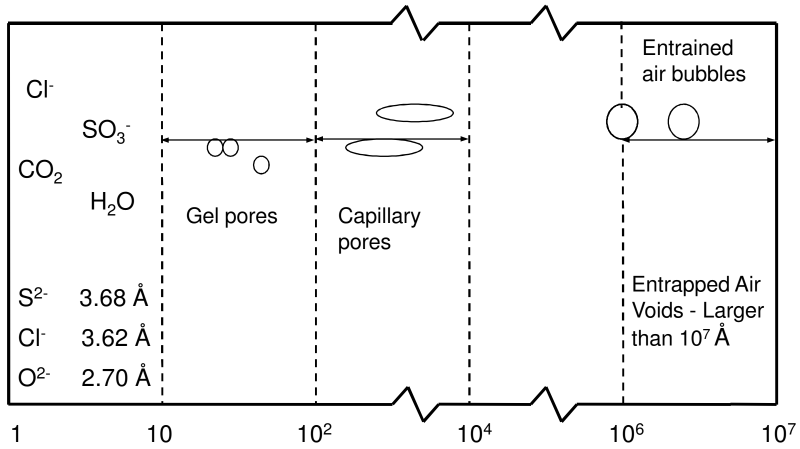
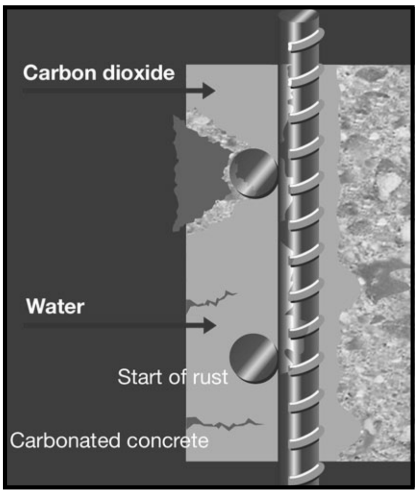
Pore Size Distribution of Concrete



$1\ \text{Å} = 10^{-10}$ m

<u>Carbonation</u> (1)

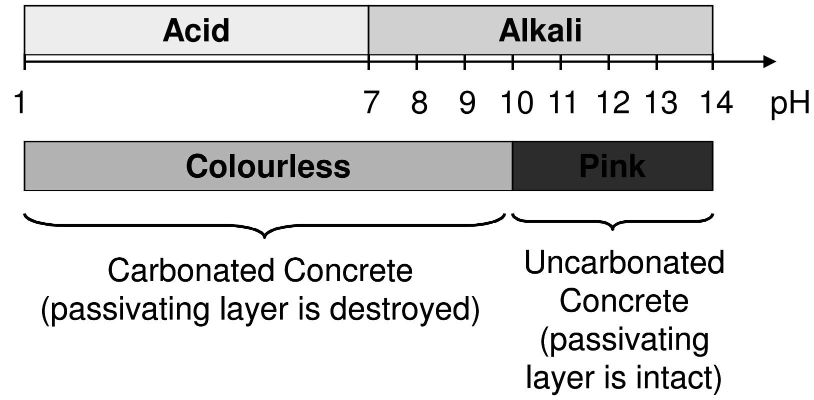


a) $CO_2 + H_2O$ = Carbonic acid

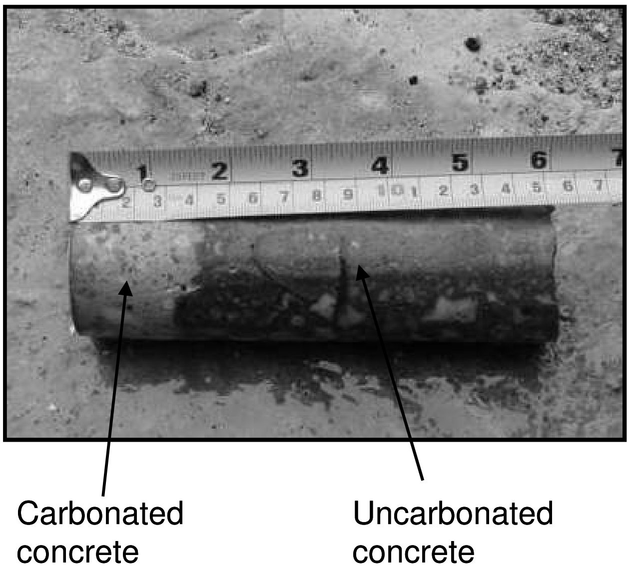
b) This carbonic acid neutralises the alkalinity of concrete in the cover

c) When pH of concrete falls <u>below 10</u>, passivating layer is destroyed & corrosion can take place

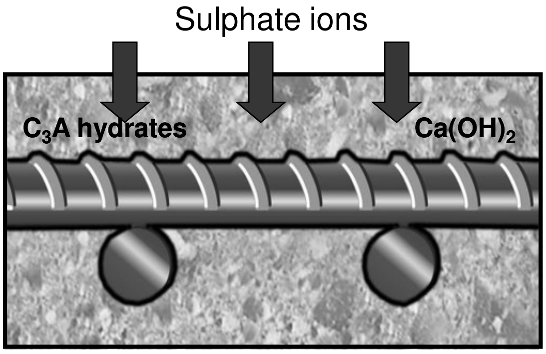
Carbonation (2)



Phenolphthalein Indicator for Carbonation Test



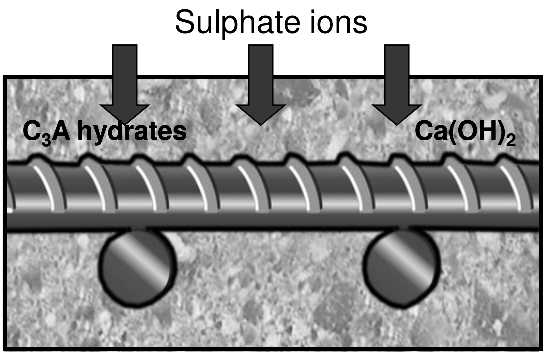
Sulphate Attack (1)



Sources of sulphates:

- ✓ Sewerage
- ✓ Groundwater and seawater
- ✓ Rocks and soils

Sulphate Attack (2)



1. Sulphate ions + $Ca(OH)_2$ = Gypsum
2. Sulphate ions + C_3A hydrates = Ettringite

Sulphate Attack (3)

1. Gypsum + Water = 120% Volume Increase
2. Ettringite + Water = 230% Volume Increase

Delayed Ettringite Formation (DEF)

Main Compounds In Portland Cement

C_3S	Tricalcium Silicate (54%)	Contribute to early strength development
C_2S	Dicalcium Silicate (17%)	Contribute to later age strength development
C_3A	Tricalcium Aluminate (12%)	Insignificant to strength development. Can cause "flash-set"
C_4AF	Tetracalcium aluminoferrite (8%)	Insignificant to strength development. Reacts with gypsum and helps to accelerate C_3S and C_2S hydration

Fresh Concrete (Temp < 70°C)

$$\underset{(C_3A)}{\text{Cement}} + \underset{(SO_4^{2-})}{\text{Gypsum}} + \text{Water} \longrightarrow \text{Ettringite}$$

Added to cement during production to prevent flash set

Internal sulphate attack. Harmless because fresh concrete can accommodate volume change

Fresh Concrete (Temp > 70°C)

Cement (C_3A) + Gypsum (SO_4^{2-}) + Water ⟶ No reaction

When temp. drops back < 70°C, concrete has hardened and the reaction occurs

Cement (C_3A) + Gypsum (SO_4^{2-}) + Water ⟶ Delayed Ettringite Formation