DURABILITY OF CONCRETE AND CONCRETE STRUCTURES – THE KEY FACTORS

By

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1. **Introduction:** For a long time, concrete was considered to be very durable material requiring little or no maintenance. Emphasis was mostly on compressive strength of concrete. However many structures world over have shown deterioration during the last 60-70 years. Lot of studies have been carried out. Exposure conditions also have been found to play a vital role on the durability of concrete. Accordingly IS 456: 2000 has been amended. It has been amended further based on experience in other countries

One of the main reasons for deterioration of concrete, is the component materials used in the manufacture of concrete, method of manufacture, placing, compacting, and curing, environmental conditions, loading patterns, various pollutants like carbon dioxide, chemicals that have pervaded the environment. Soils and subsoil water in certain locations in India have deleterious chemicals and salts which will affect the durability of concrete.

FACTORS AFFECTING DURABILITY

Durability: As per IS 456: 2000, durable concrete is one that performs satisfactorily in the working environment during the anticipated exposure conditions and during its service life. It is the ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration which will alter the original form and quality. The materials and mix proportions specified and used should be such as to maintain its integrity and, if applicable, to protect embedded metal from corrosion.

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Durability: Durability to a great extent is influenced by its permeability to ingress of water, oxygen, carbon dioxide, chloride, sulphate and other potentially deleterious substances. Impermeability is greatly governed by the constituents, workmanship in making concrete.

Factors influencing durability:

- The environment (Rain, heat, cold, fire, snow)
- The cover to the embedded steel
- The type and quality of constituent materials
- The cement content and water/cement ratio of the concrete
- Workmanship, to obtain full compaction and efficient curing
- The shape and size of the members
- Permeability, and abrasion

Types of durability conditions:

External	
Physical	**Chemical**
Freezing & Thawing	**Alkali aggregate reaction**
Percolation & Permeability	**Sulphate attack**
Temperature stresses (High heat of hydration)	**Chloride ingress**
	Delayed ettringite formation (DCF)
	Corrosion of reinforcement
Causes:	
Extreme weather conditions, Extreme temperatures, Extreme humidity, Abrasion, Electrolytic action, Attack by natural or industrial liquids/gases	

Types of durability conditions:

Internal	
Physical	**Chemical**
Volume changes due to different thermal properties of aggregates, and cement paste	Alkali silica reaction
Frost action	Alkali silicate reaction
	Alkali carbonate reaction

GENERAL DESIGN REQUIREMENTS

Durability of Concrete and Concrete Structures

Sl.No.	Environment	Exposure condition
1	Mild	▪Concrete surfaces protected against weather or aggressive conditions except those situated in coastal areas
2	Moderate	▪Concrete surfaces sheltered from severe rain or freezing whilst wet ▪Concrete exposed to condensation and rain ▪Concrete continuously under water ▪Concrete in contact or buried under non aggressive soil/ground water ▪Concrete surfaces sheltered from saturated salt air in coastal areas

Environmental conditions:

Sl. No.	Environment	Exposure condition
3	severe	▪Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation ▪Concrete completely immersed in sea water ▪Concrete exposed to coastal environment
4	Very severe	▪Concrete surfaces exposed to sea water spray corrosive fumes or severe freezing conditions whilst wet ▪Concrete in contact with or buried under aggressive sub-soil/ground water
5	Extreme	▪Surface of members in tidal zone ▪Members in direct contact with liquid/ solid aggressive chemicals

Shape and size of members:

1. Shape or design details shall be such that proper drainage is provided/avoid standing pool of water, junctions of members properly designed
2. Minimize cracks that will transmit water
3. Proper compaction and curing
4. Concrete is prone to deterioration due to climatic and chemical attack when the sections of members are thin

Shape and size of members:

5. Deterioration in sections under hydrostatic pressure from one side, in partially immersed sections, at corners and edges of elements
6. Life of structure can be lengthened by providing extra cover to steel, by chamfering corners, using circular cross sections or by surface coatings which prevent or reduce ingress of water, carbon dioxide, or aggressive chemicals

Stiffness factors: Span to effective depth ratios up to 10m

Cantilever beams	7
Simply supported beams	20
Continuous beams	26

For spans above 10m, the ratios above shall be multiplied by 10/ span in meters

STRENGTH OF CONCRETE

Strength of concrete:

Strength: It is defined as the ability to withstand stress without failure. Some of the main parameters are:

- Water cement ratio
- Cement type
- Aggregate grading, shape, surface texture
- Proportions of materials
- Porosity and air entrainment

Strength of concrete:

- Mixing water
- Admixtures
- Curing conditions
- Humidity, temperature

Strength of concrete: M 25 grade

Permissible stresses:

- Compressive stress 6.0 N/mm^2 (Direct)
- Compressive stress in bending 8.5 N/mm^2
- Tensile stress 3.2 N/mm^2
- Flexural stress 3.5 N/mm^2
- Shear stress 0.5 N/mm^2
- Bond stress 0.9 N/mm^2

Strength of concrete: Design bond stress

Grade of concrete	Bond stress N/mm^2
M 20	1.2
M 25	1.4
M 30	1.5
M 35	1.7
M 40 and above	1.9

Acceptance criteria: Standard deviation

M 10	3.5 N/mm^2
M 15	3.5 -do-
M 20	4.0 -do-
M 25	4.0 -do-
M 30	5.0 -do-
M 35	5.0 -do-
M 40	5.0 -do-
M 45	5.0 -do-

Acceptance criteria: Standard deviation

M 50	5.0 N/mm^2
M 55	5.0 -do-
M 60	5.0 -do-

Acceptance criteria: Standard deviation

Compressive strength – Four consecutive test results shall comply with appropriate limit

Characteristic strength compliance:

M 15 $\geq f_{ck} + 0.825 \times SD$ (Rounded of to nearest 0.5 N/mm^2) or $F_{ck} + 3$ whichever is greater

M 20 or above $f_{ck} + 0.825 \times SD$ or $f_{ck} + 4$ N/mm^2 whichever is greater

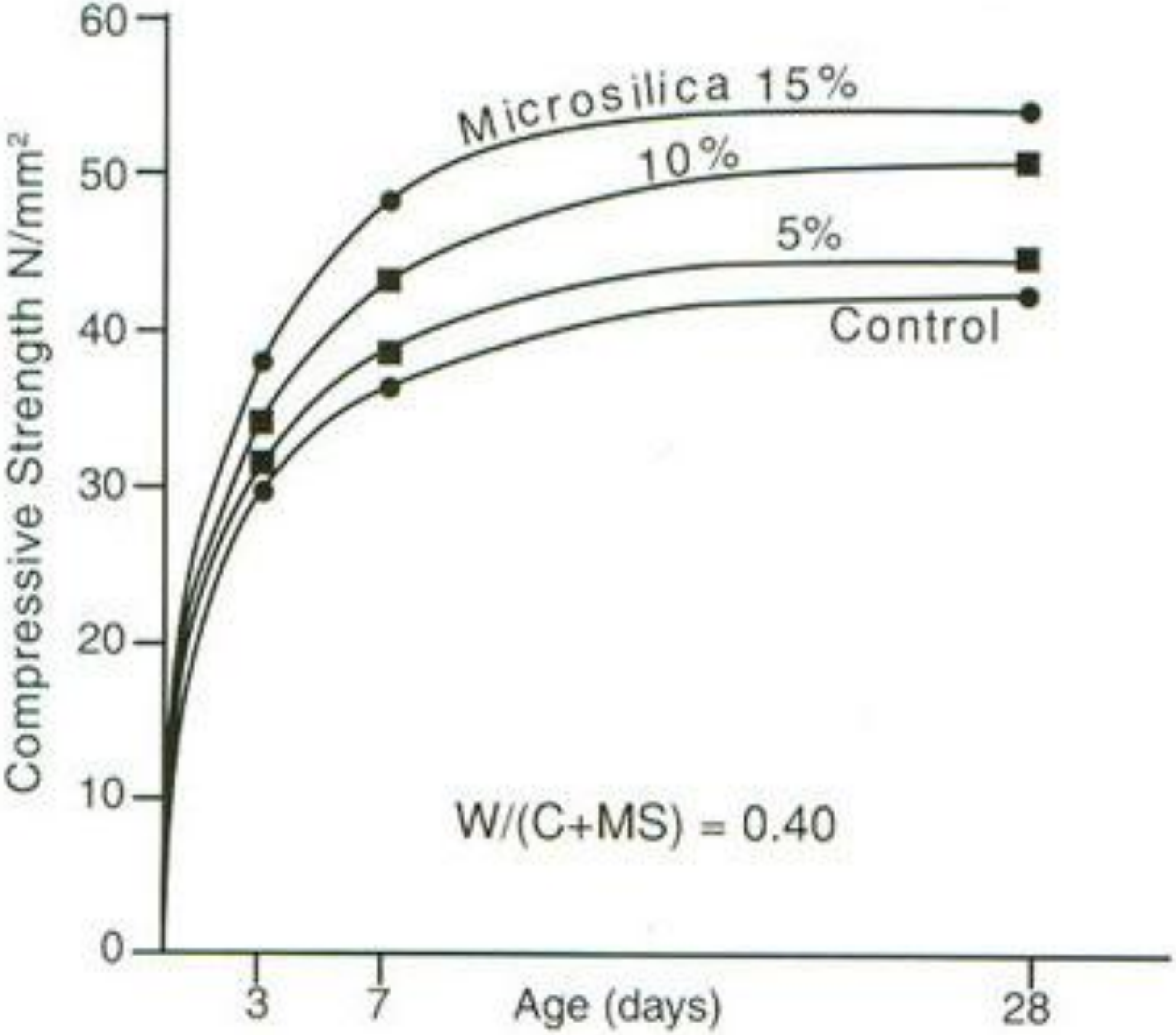
Individual specimen $\geq f_{ck}$ N/mm^2

Strength of concrete: Main constituents of cement

Name of compound	Formula	Percent age	Action
Tricalcium silicate	C_3S	54%	Early strength
Dicalcium silicate	C_2S	16%	Slow strength
Tricalcium aluminate	C_3A	10%	Flash set
Tetra calcium aluminoferrite	C_4AF	9%	Resistance to sulfate attack

Hydration due to addition of water:

- C_3S produces more heat, early strength and more calcium hydroxide
- C_2S hydrates slowly produces less heat and later strength and better product
- Calcium hydroxide $Ca(OH)_2$ (20 – 25% of the volume) is also produced in the process of hydration which is unstable, undesirable and responsible for deterioration of concrete



Microsilica / Plasticiser Dosage
(% by weight of cement)

MICRO SILICA

CODAL PROVISIONS

Standard codes on construction practices:

- SP 62 (S&T) : 1997
- CPWD Standard Specifications
- IS 456: 2000
- NBC 2005

Minimum cement content, max. w/c for RCC

Exposure	Min. Cement content kg	Max. w/c	Min. grade of concrete
Mild	300	0.55	M20
Moderate	300	0.50	M25
Severe	320	0.45	M30
Very severe	340	0.45	M35
Extreme	360	0.40	M40

Table 5.1 Graded Aggregate

(*Clause* 2.2.7.1)

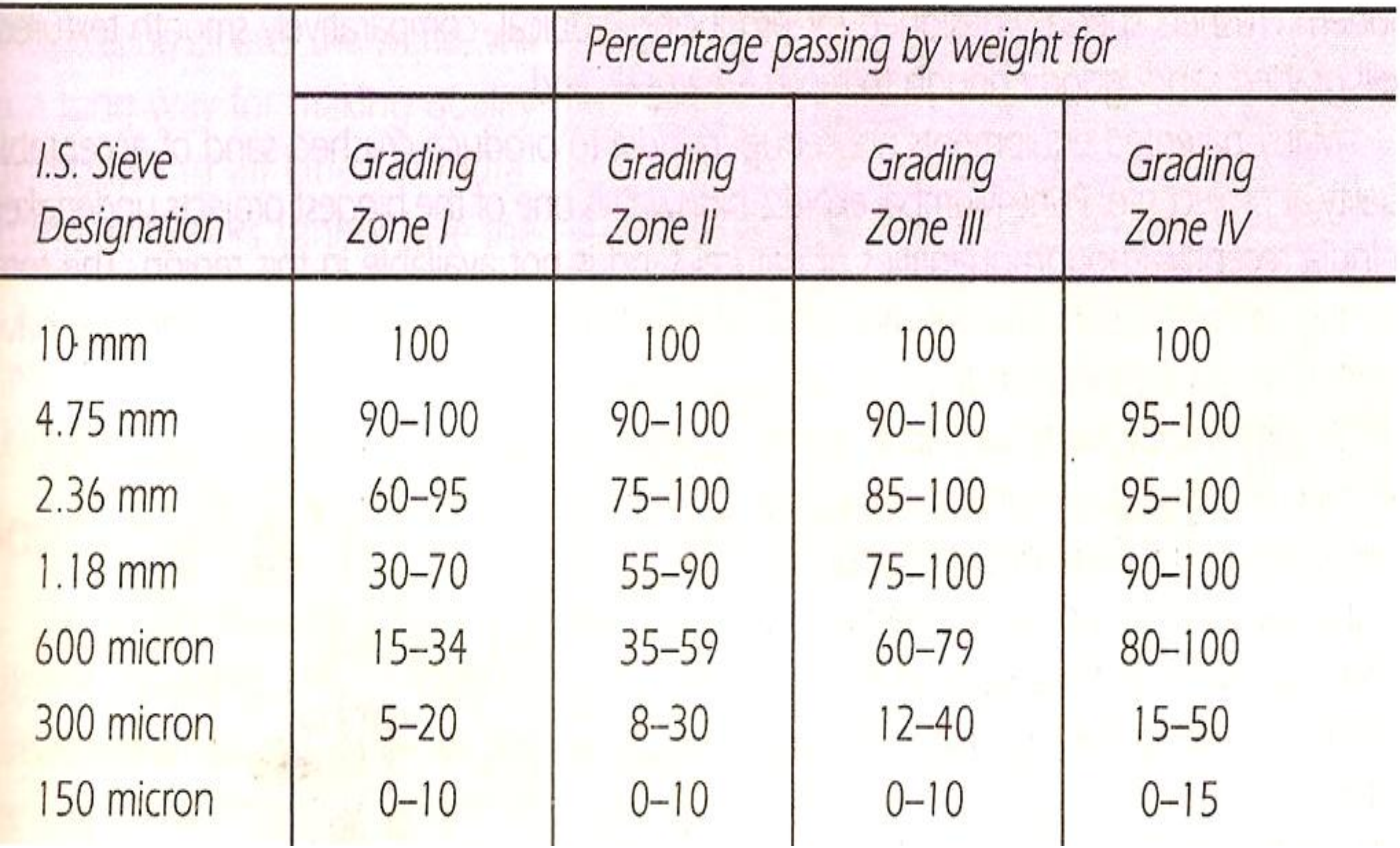
IS Sieve Designation	Percentage Passing for Normal Size of Aggregate			
mm	40 mm	20 mm	16 mm	12.5 mm
80	100	—	—	—
40	95-100	100	—	—
20	30-70	95-100	100	100
16	—	—	90-100	—
12.5	—	—	—	90-100
10	10-35	25-55	30-70	40-85
4.75	0-5	0-10	0-10	0-10
2.36	—	—	—	—

Table 5.2 Single Sized Aggregate (Ungraded)

(*Clause* 2.2.7.1)

IS Sieve Designation	Percentage Passing for Normal Size of Aggregate					
mm	63 mm	40 mm	20 mm	16 mm	12.5 mm	10 mm
80	100	—	—	—	—	—
63	85-100	100	—	—	—	—
40	0-30	85-100	100	—	—	—
20	0-5	0-20	85-100	100	—	—
16	—	—	—	85-100	100	—
12.5	—	—	—	—	85-100	100
10	0-5	0-5	0-20	0-30	0-45	85-100
4.75	—	—	0-5	0-5	0-10	0-20
2.36	—	—	—	—	—	0-5

Table 3.15. Grading limits of fine aggregates IS: 383-1970



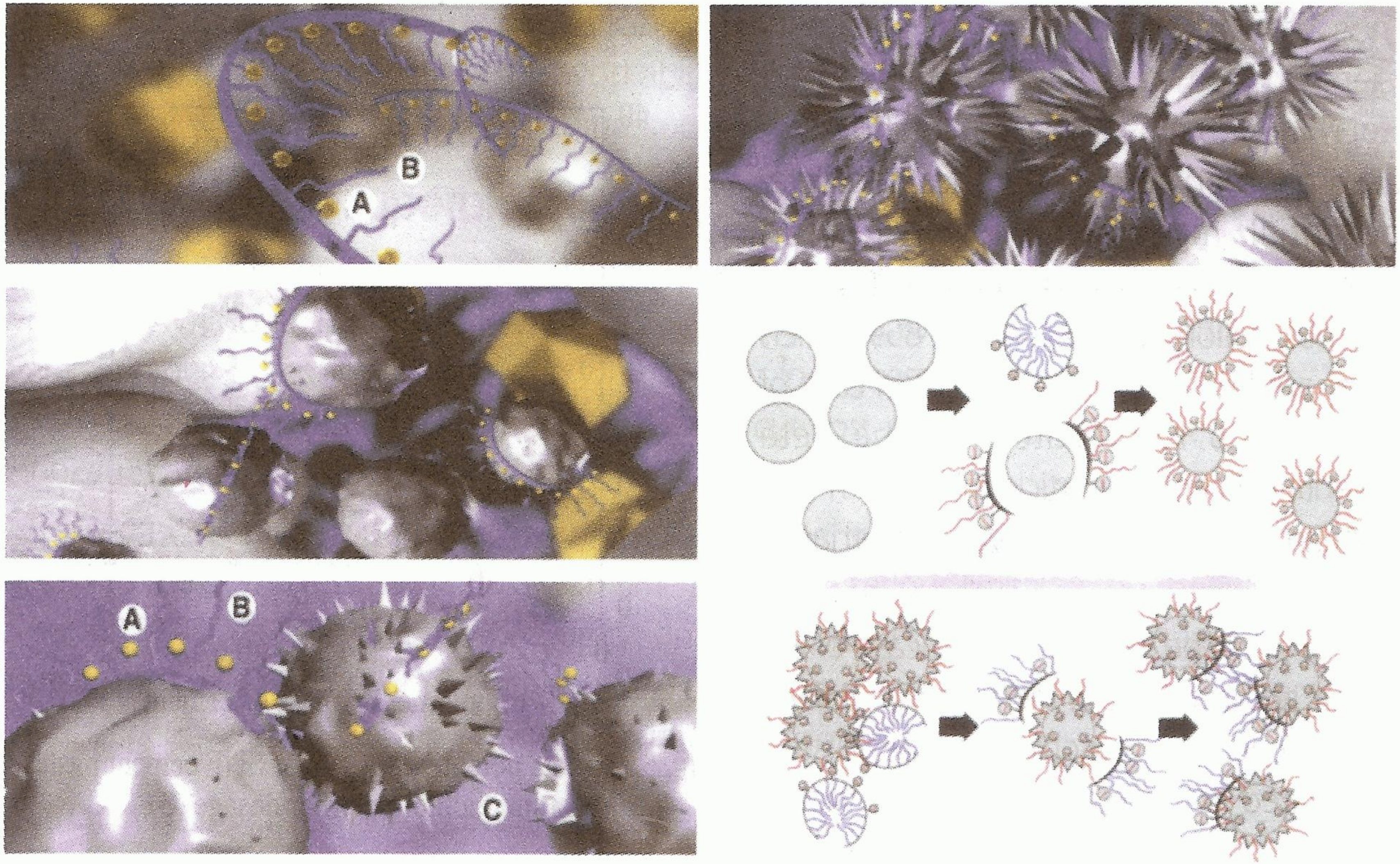
	Percentage passing by weight for			
I.S. Sieve Designation	*Grading Zone I*	*Grading Zone II*	*Grading Zone III*	*Grading Zone IV*
10 mm	100	100	100	100
4.75 mm	90–100	90–100	90–100	95–100
2.36 mm	60–95	75–100	85–100	95–100
1.18 mm	30–70	55–90	75–100	90–100
600 micron	15–34	35–59	60–79	80–100
300 micron	5–20	8–30	12–40	15–50
150 micron	0–10	0–10	0–10	0–15

Types of cement in common use:

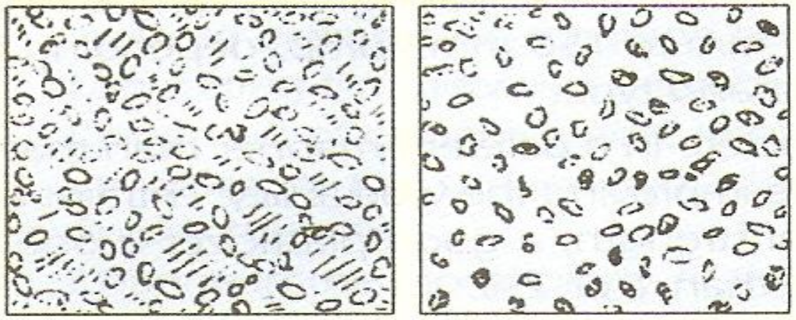
OPC	IS 269 1989
PPC	IS 1489 1991
Sulphate resisting cement	IS 12330 1988
Rapid hardening cement	IS 8041 1990

Admixtures: IS 9103: 1999

- **Accelerating admixtures:** Added to hasten the early strength development to facilitate early removal of formwork
- **Retarding admixtures:** To slow down setting of cement
- **Water retarding or plasticizers:** To improve workability for a given W/C ratio. When used in sufficient quantity act as set retarders.
- Admixtures should not impair durability of concrete nor combine with the constituents to form harmful compounds

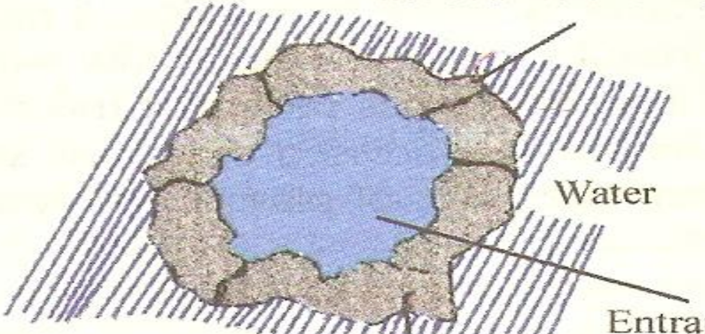


Mechanism of action of acrylic based new generation superplasticizers works on both electrostatic repulsion and steric hindrance *(Courtesy : MBT)*



Flocculated Dispersed

Schematic representation of flocculation of cement grain in plain concrete and effect of S.P. for dispersion



Cement Particles Flocculate in the absence of a dispersing agent

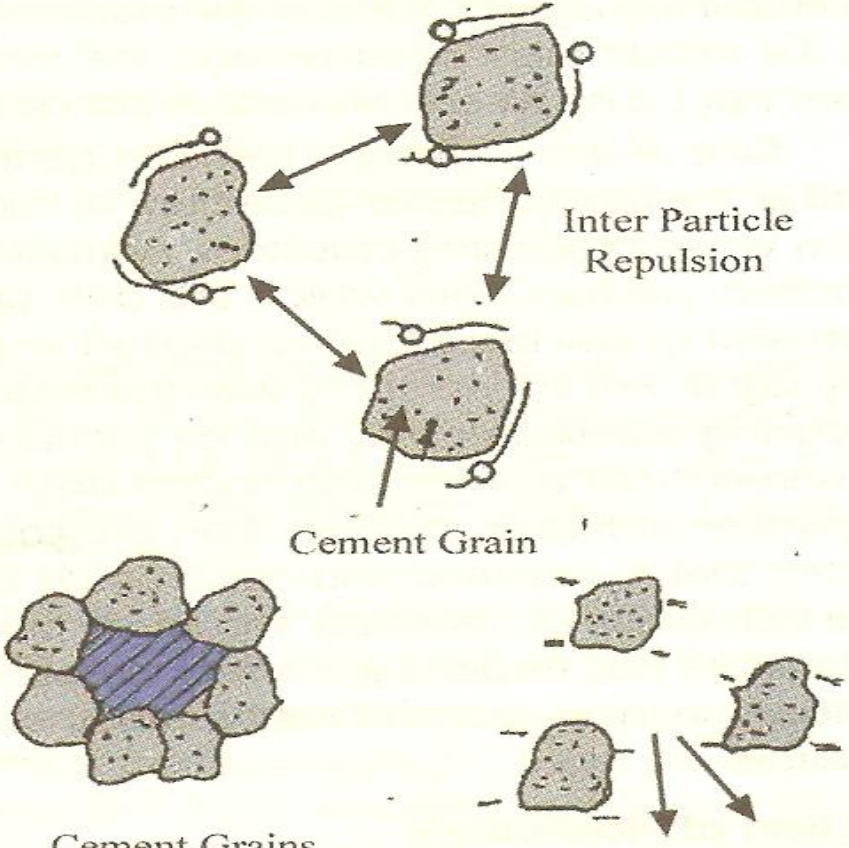


Fig. 5.1. Effect of surface-active agents on deflocculating of cement grains.

Admixtures: IS 9103: 1999

- Air-entraining admixtures: (0.1 to 0.3% by weight of cement) These are used to entrain a controlled quantity of air in concrete without altering the setting or hardening of concrete. Their use improves durability, water tightness and workability. 2-3% air entrainment for normal concrete and 4% for combating freezing and thawing is advised.

Slump:

Placing conditions	Degree of workability	Slump (mm)
Blinding concrete, Shallow sections, pavements (Slump not appropriate)	Very low	Compacting factor 0.75-0.80
Mass concrete, lightly reinforced sections in slabs, beams, columns, floors	Low	25-75
Heavily reinforces sections in slabs, beams, columns	Medium	50-100
Slipform work, pumped concrete	Medium	75-100

CHEMICAL ACTION ON CONCRETE

Requirement for concrete exposed to sulphate attack:

Class	Concentration of sulphate as SO3	Min. cement content Kg	Max. W/C ratio	Type of cement
1	<0.2%	280	0.55	OPC,PPC,PSC
2	0.2-0.5%	330	0.50	OPC,PPC,PSC
3	0.5-1.0	330	0.5	SSC,PPC,PSC
4	1.0-2.0	370	0.45	SSC, SRPC
5	>2.0	400	0.4	SRPC,SSC with protective coating
PPC-Portland pozzolana cement, SSC-Super sulphated cement, PSC-Portland slag cement, SRPC- Sulphate resisting Portland cement				

Chloride content:

Sl. No.	Type of use of concrete	Max.Chloride Kg/Cum
1	Concrete containing metal, Steam Cured PSC	0.4
2	RCC or PCC with embedded metal	0.6
3	Concrete not containing embedded metal or any material requiring protection from chloride	3.0

Water used in Concrete:

	Permissible limit as per IS: 456
Organic	200mg/l
Inorganic	3000mg/l
Sulphates	400mg/l
Chlorides (PCC)	2000mg/l
-d0- (RCC)	500mg/l
Suspended Matter	2000mg/l

Concrete in aggressive soils and water:

The destructive action of aggressive waters is progressive. The rate of deterioration decreases as the concrete is made stronger and impermeable, and increases as the salt content of the water increases. Where structures are partially immersed or are in contact with aggressive soils or water on one side only, evaporation may cause serious concentrations of salts with subsequent deterioration.

Sulphate attack: Most soils contain some sulphate in the form of calcium, sodium, potassium, and magnesium. They occur in the soil and ground water. Solubility of calcium sulphate is low. Solid sulphates do not attack concrete severely but when the chemicals are in solution, they find entry into porous concrete and react with hydrated cement products. Of all sulphates magnesium sulphate causes maximum damage. A characteristic whitish appearance is the indication of suphate attack.

Magnesium sulphate reacts not only with calcium hydroxide and hydrated calcium aluminates but also decomposes the hydrated calcium silicates completely. As a result the hardened volume can go up to up to 227% and gradual disintegration of concrete takes place.

Methods of Controlling Sulphate attack:

- Use of suphate resisting cement with low C_3A content of 5%
- Quality concrete
- Use of air-entrainment of about 6%
- Use pozzolana
- High pressure steam curing

Chloride attack: Due to high alkalinity in concrete a protective layer is created which will protect reinforcement. This protective layer is lost due to carbonation as also due to presence of chloride in the presence of water and oxygen. While sulphates attack concrete chlorides attack reinforcement.

Concrete in aggressive soils and water:

The destructive action of aggressive waters is progressive. The rate of deterioration decreases as the concrete is made stronger and impermeable, and increases as the salt content of the water increases. Where structures are partially immersed or are in contact with aggressive soils or water on one side only, evaporation may cause serious concentrations of salts with subsequent deterioration.

Sample of water collected in 22 km stretch between Palla-Okhla, Delhi due to pollutants discharged from sewage and Industrial wastes from River Yamuna

Pollutant	Result Mg/L	Max. permissible Mg/L
Nitrate	174	400
Sulphate	680	400
Fluoride	3.10	1.50
Mercury	4.60	1.00
Arsenic	69.50	50.00

Sample of ground water collected in Rohatak & Jhajjar Districts, Haryana

Pollutant	Result	Max. permissible as per IS 456
Chloride	1.29%	0.05%
Sulphate	0.49%	0.20-0.50% Class.2

Alkali aggregate reaction:

Some aggregates containing particular varieties of silica may be susceptible to attack by alkalis (Na_2O and K_2O) originating from cement or other sources, producing an expansive reaction which can cause network of cracks and disruption of concrete by spalling. Damage to concrete will normally occur when the following are present:

Alkali aggregate reaction:

i) A high moisture level within concrete

ii) A cement with high alkali content

iii) Aggregate containing an alkali reactive constituent

EFFECTS OF ALKALI AGGREGATE REACTION

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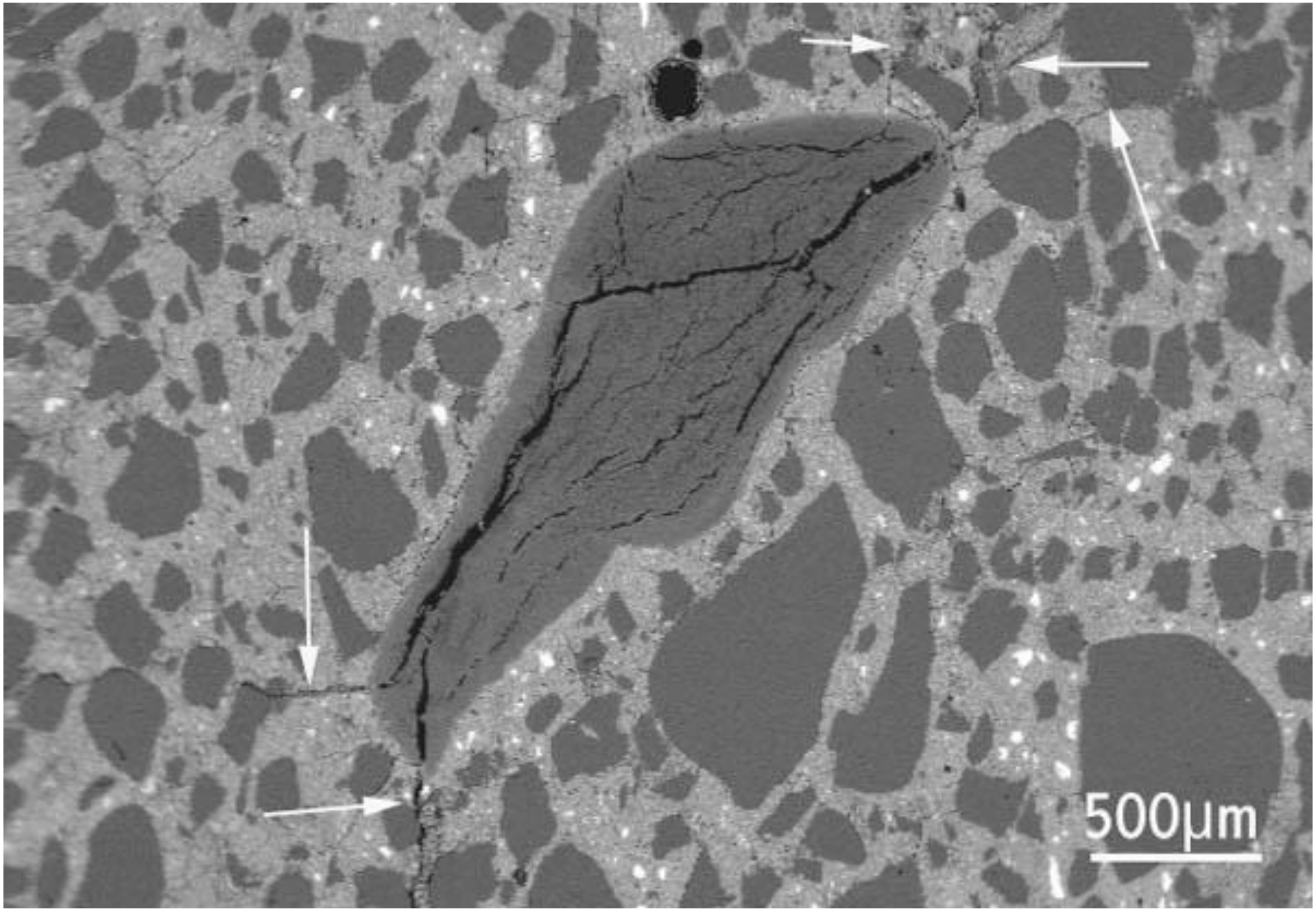
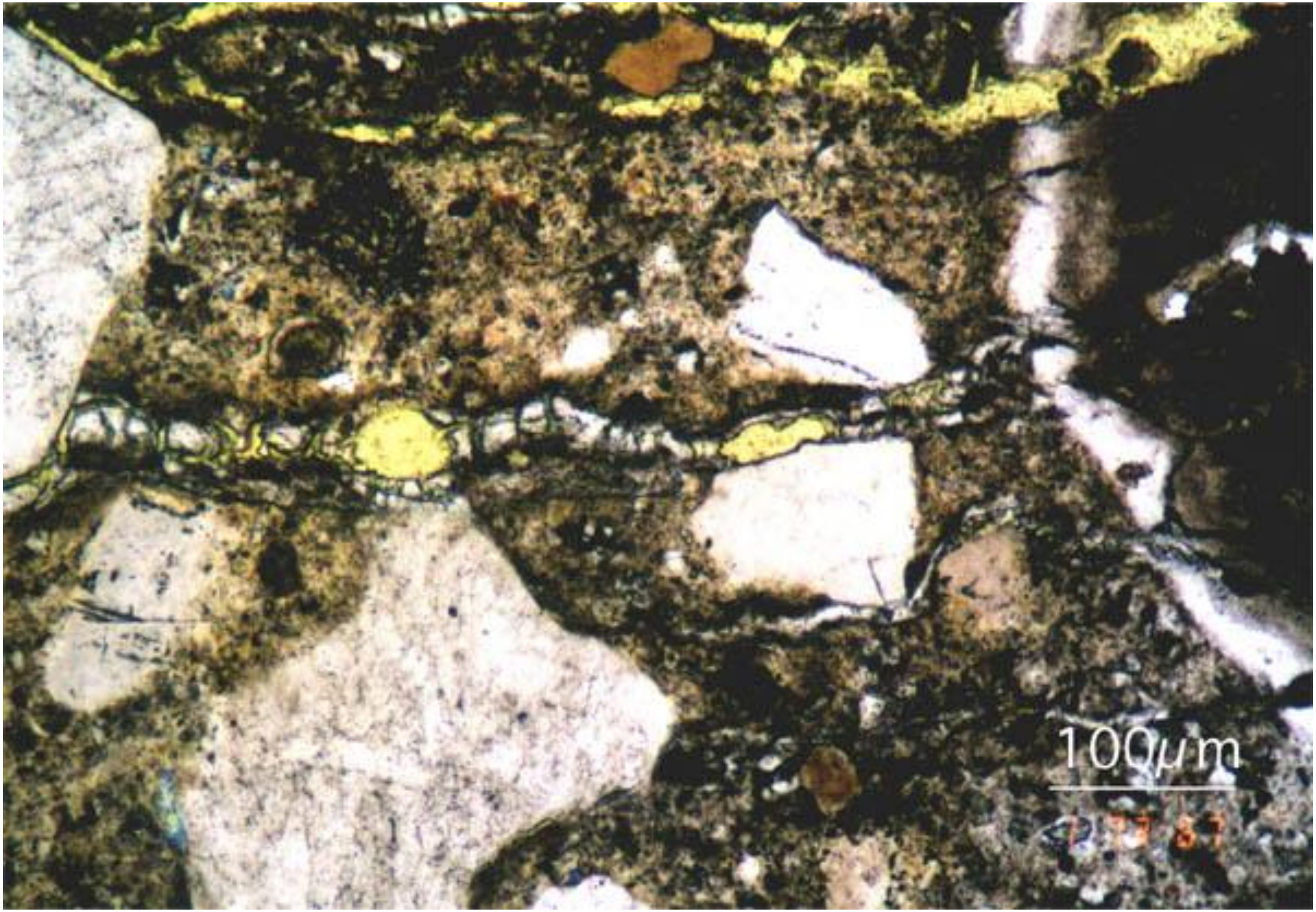


Cracks through chert aggregate due to aggregate silica Reaction



AGGREGATE SILICA REACTION

Delayed ettringrite formation(DCF): The ettringite (Calcium alumino sulphate) normally forms during hydration. However when concrete is cured at high temperature >70°C as in steam curing, mass concreting in dams, the hydration process is decomposed then subsequently reformed in the hardened concrete. Damage occurs when ettringite crystals exert an expansive force within the concrete as they grow.

The ettringite is destroyed when

- High temperature during curing > 65-70°C
- Water intermittent or permanent saturation
- Commonly associated with alkali silica reaction

DEF expansion has been shown to correlate positively with cement related factors including:

a) High sulphate b) High alkali c) High MgO d) Cement fineness e) High C_3A f) High C_3S

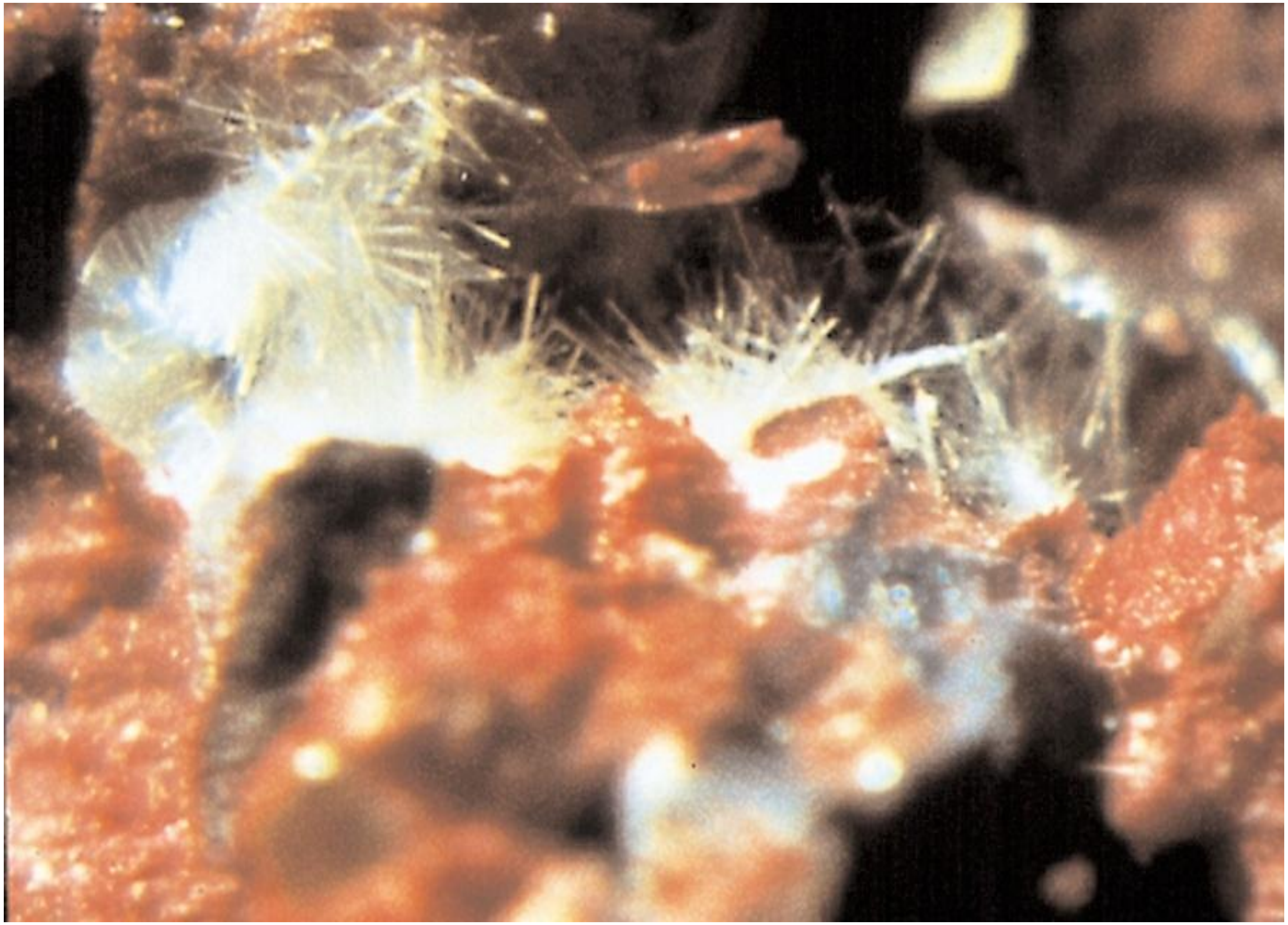


Fig. 2. Ettringite (white, needle-like crystals) are commonly found in samples taken from concrete in service, especially in concrete from moist environments. Secondary ettringite is not detrimental to concrete performance. [Concrete in photo exposed to phenolphthalein stain to highlight features.]

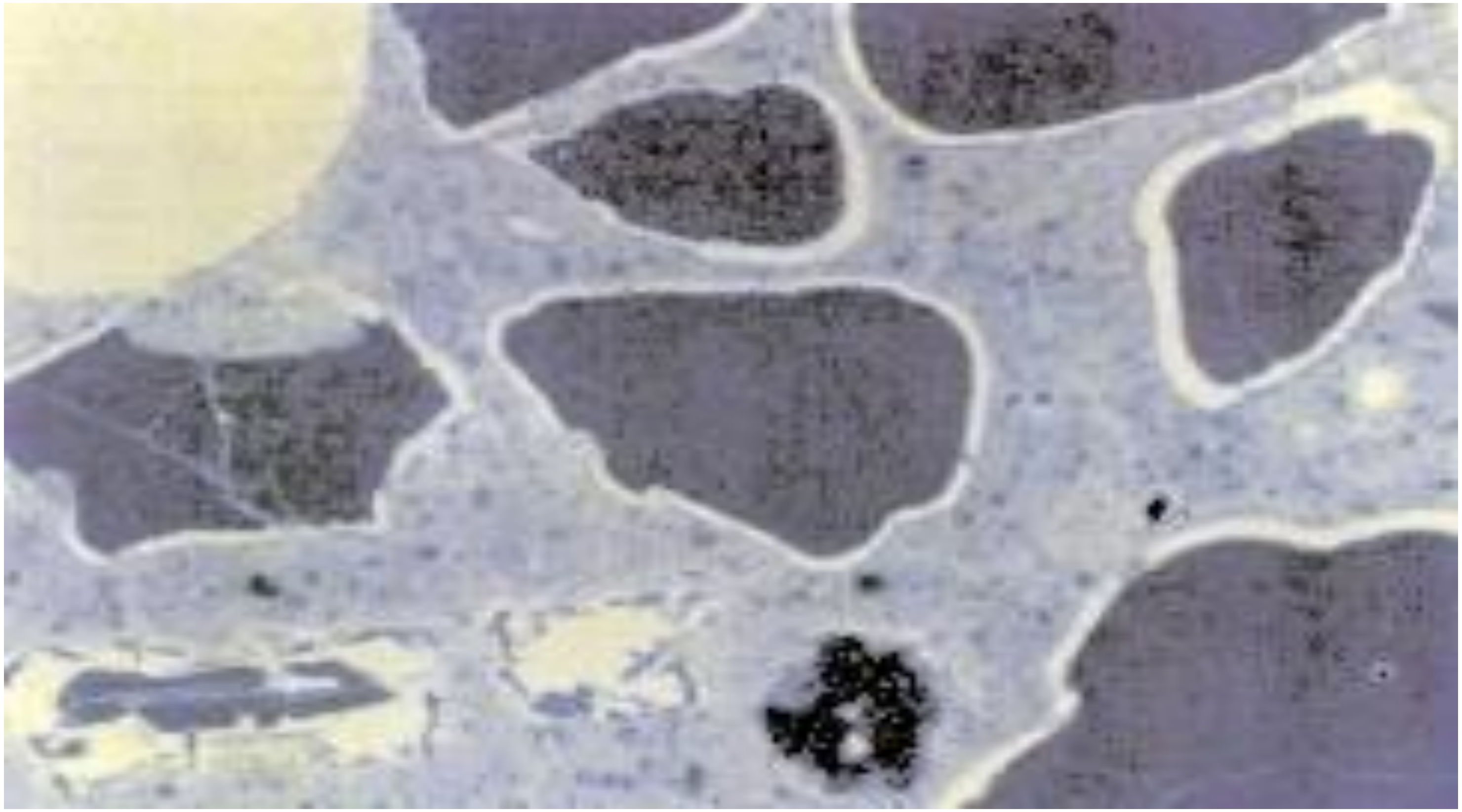


Fig. 3. This is a photomicrograph of a mortar sample that had been stored in water for six years at 20 °C. To simulate an over sulfated system, part of the sand was replaced by gypsum, and thus significant expansions occurred. Note that the gaps around the sand grains in the mortar are similar in appearance to those observed for delayed ettringite formation.

PERMEABILITY AND DURABILITY

Permeability: The cement paste consists of C-S-H (Calcium silicate hydrate) gel, $Ca(OH)_2$ (Calcium hydroxide) and water filled or empty capillary cavities. The permeability of gel pores is estimated to be about 7x10-16 m/s. i.e. approximately 1/100 of cement paste. The coefficient of permeability increases more than 100 times from w/c ratio 0.4 to 0.7. Unduly large cavities resulting from higher w/c ratio of 0.7 will not get filled up by hydration and results in higher permeability.

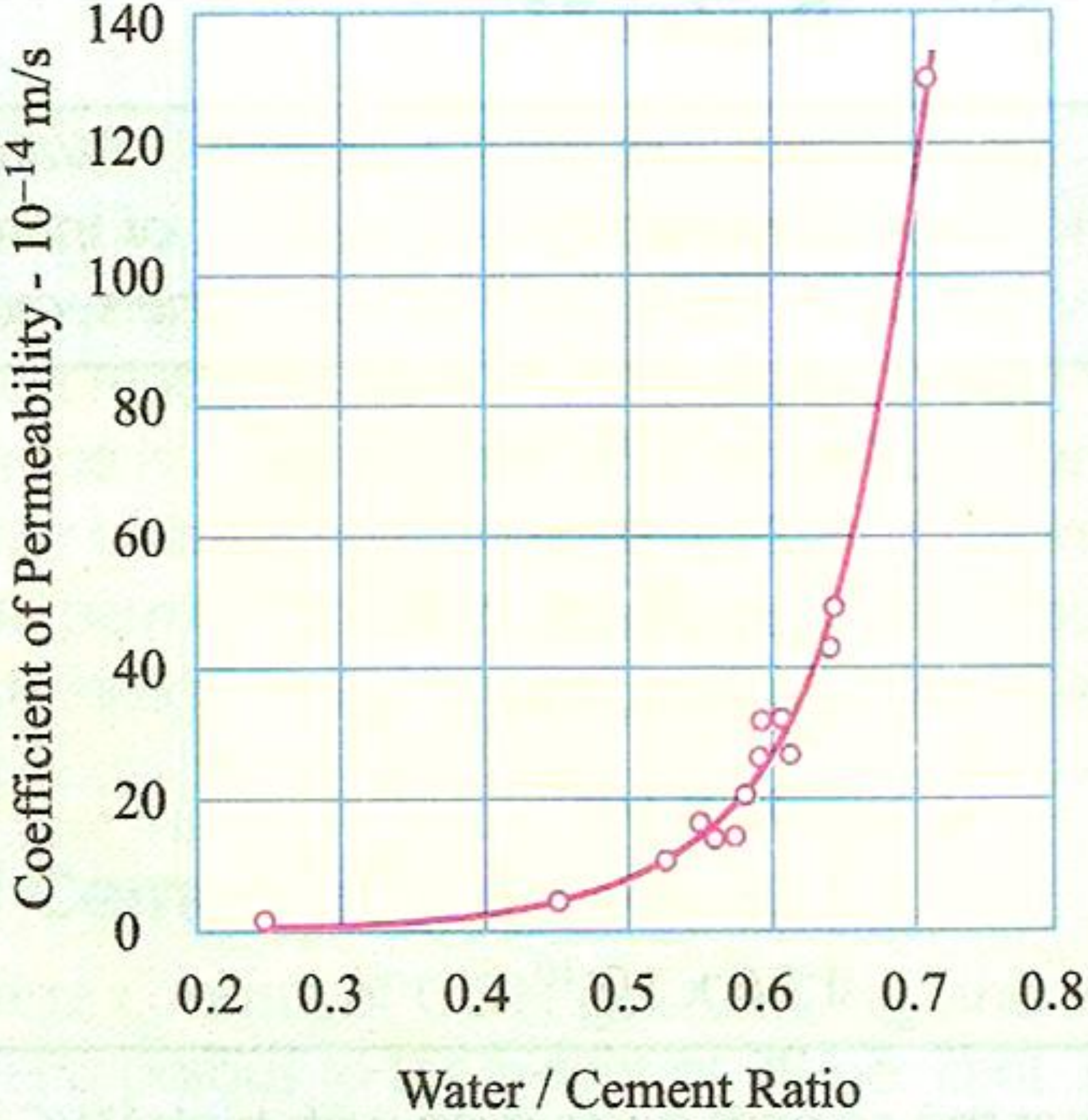


Fig. 9.2. Relation between permeability and water/cement ratio for mature cement pastes (93 per cent of cement hydrated) [9.3]

CONSTRUCTION CONSIDERATIONS

Production and control of concrete:

Batching:

Cement, aggregates shall be determined by mass. Grading of aggregate shall be controlled by obtaining coarse aggregate in different sizes and blending them in right proportions. Water cement ratio shall be maintained at the correct value. The moisture content in the coarse and fine aggregates shall be frequently checked and necessary adjustments made for water to be added.

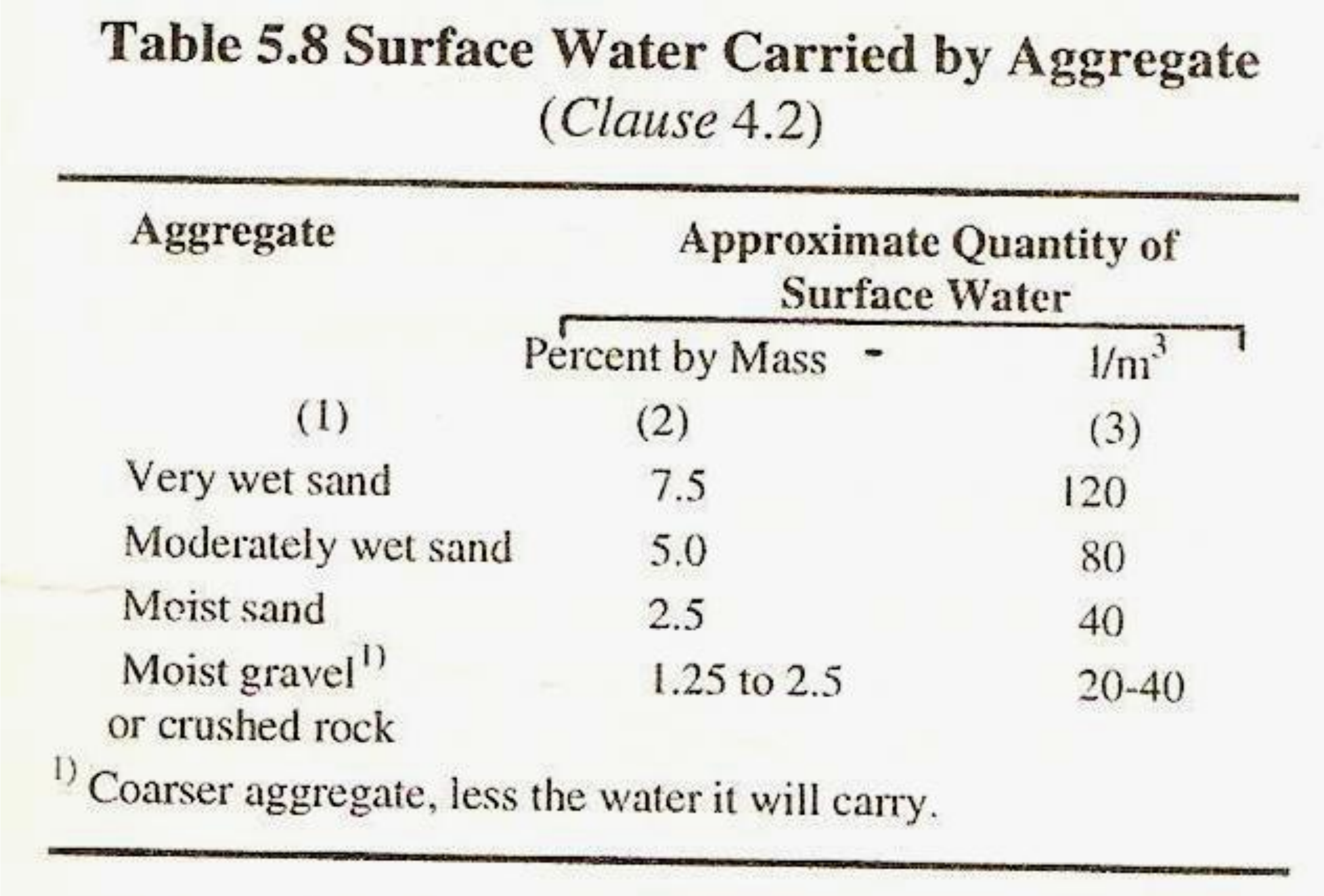


Table 5.8 Surface Water Carried by Aggregate

(*Clause* 4.2)

Aggregate	**Approximate Quantity of Surface Water**	
	Percent by Mass	l/m^3
(1)	(2)	(3)
Very wet sand	7.5	120
Moderately wet sand	5.0	80
Moist sand	2.5	40
Moist gravel[1)] or crushed rock	1.25 to 2.5	20-40

[1)] Coarser aggregate, less the water it will carry.

Mixing: Concrete shall be mixed in a mechanical mixer. Mixing time may be taken as 1 ½ to 2 minutes. Dry coarse aggregates shall be first placed followed by measured quantity of fine aggregates and then cement. The dry material shall be mixed at least for four turns of the drum, after which correct quantity of water shall be added. Total quantity of water shall be added before 25% of mixing time has elapsed.

Placing: Concrete shall be placed as nearly practicable in its final position to avoid rehandling. Concrete shall be compacted before setting commences. Care shall be taken to avoid segregation. Concreting shall not be done when the temperature falls below 4.5°C. Concrete placed shall be covered against frost. During hot weather, precautions shall be taken to see that temperature of wet concrete does not exceed 38°C.

Compaction: Mechanical vibrators shall be employed for compacting concrete. Over vibration of very wet mixes is harmful and should be avoided. Under vibration is harmful. The vibrator should penetrate to the bottom of the layer and at least 15 cm into the preceding layer. It should be held (generally 5 to 15 s) until the compaction is considered adequate.

Compaction, Finishing and Curing:

1. Adequate compaction without segregation to be ensured
2. Appropriate placing and compacting equipment and procedures
3. Full compaction in the vicinity of construction and expansion joints, embedded water bars and reinforcement
4. Good finishing practices without addition of cement and water

Compaction, Finishing and Curing:

5. Proper and adequate curing techniques to reduce permeability and enhance durability particularly in surface zone

Concreting in sea water:

- Concrete directly exposed along the sea coast shall be M 20 grade in case of plain concrete and M 30 in case of RCC
- Design mix to obtain densest possible concrete
- Slag, broken brick, soft lime stone or other porous or weak stone shall not be used

Concreting in sea water:

- As far as possible preference shall be given to pre-cast members unreinforced, well cured and hardened, without sharp corners, trowel finished surfaces free from crazing, cracks or other defects. Plastering shall be avoided
- No construction joints shall be allowed within 60mm below low water level or 600mm of upper/lower planes of wave action

Construction joints: Concreting shall be carried out continuously up to the construction joints, the position and arrangement shall be as indicated by the designer.

Curing: After the concrete has begun to harden, i.e. 1 to 2 hrs. after laying of concrete, curing shall be started. Exposed surfaces shall be continuously be kept in a damp or wet condition with layer of sacks, canvas, hessian or similar material and kept continuously wet at least for seven days

Joints in Concrete:

- **Construction joints:** joints must be so placed that the concrete is less vulnerable to maximum bending moment and shear force. The joint may be made at extreme position of middle third.
- **Expansion joints:** A long building longer than 45 M will undergo expansion of 2.5 Cm. position of expansion joints shall be decided taking into consideration temperature, exposure to weather and season of laying of concrete.

Joints in Concrete:

- Contraction joints: Concrete undergoes plastic shrinkage and drying shrinkage as a result of which concrete shrinks. When shrinkage is restrained, stresses are developed which result in the formation of cracks. To avoid these cracks, contraction joints are provided normally at intervals of 5 – 10 metres. Contraction joints are also called dummy joints. Contraction joints are not necessary if sufficient reinforcement is provided. Contraction joints are generally provided in unreinforced floors and pavements.

ENVIRONMENTAL EFFECTS ON CONCRTE

Table 9.6. Various Types and Causes of Cracks in Concrete

- Cracks in Concrete
  - Before Hardening
    - Drying
      - Plastic shrinkage
      - Settlement shrinkage
      - Bleeding
      - Delayed curing
    - Constructional
      - Formwork movement
      - Excess vibration
      - Sub grade settlement
      - Finishing
    - Early frost damage
  - After Hardening
    - Unsound Materials
      - Cement
      - Aggregates
      - Excess silt, mud and dust
    - Long-term drying shrinkage
    - Thermal
      - Heat of hydration
      - External temperature
      - Joints in Concrete
      - Elevated temperature
      - Freezing and thawing
    - Moisture movements
    - Transition zone
    - Biological
    - Structural design deficiencies
    - Chemical
      - Sulphate attack
      - Alkali-aggregate reaction
      - Acid attack
      - Sea water
      - Carbonation
      - Chloride attack
    - Corrosion of reinforcement

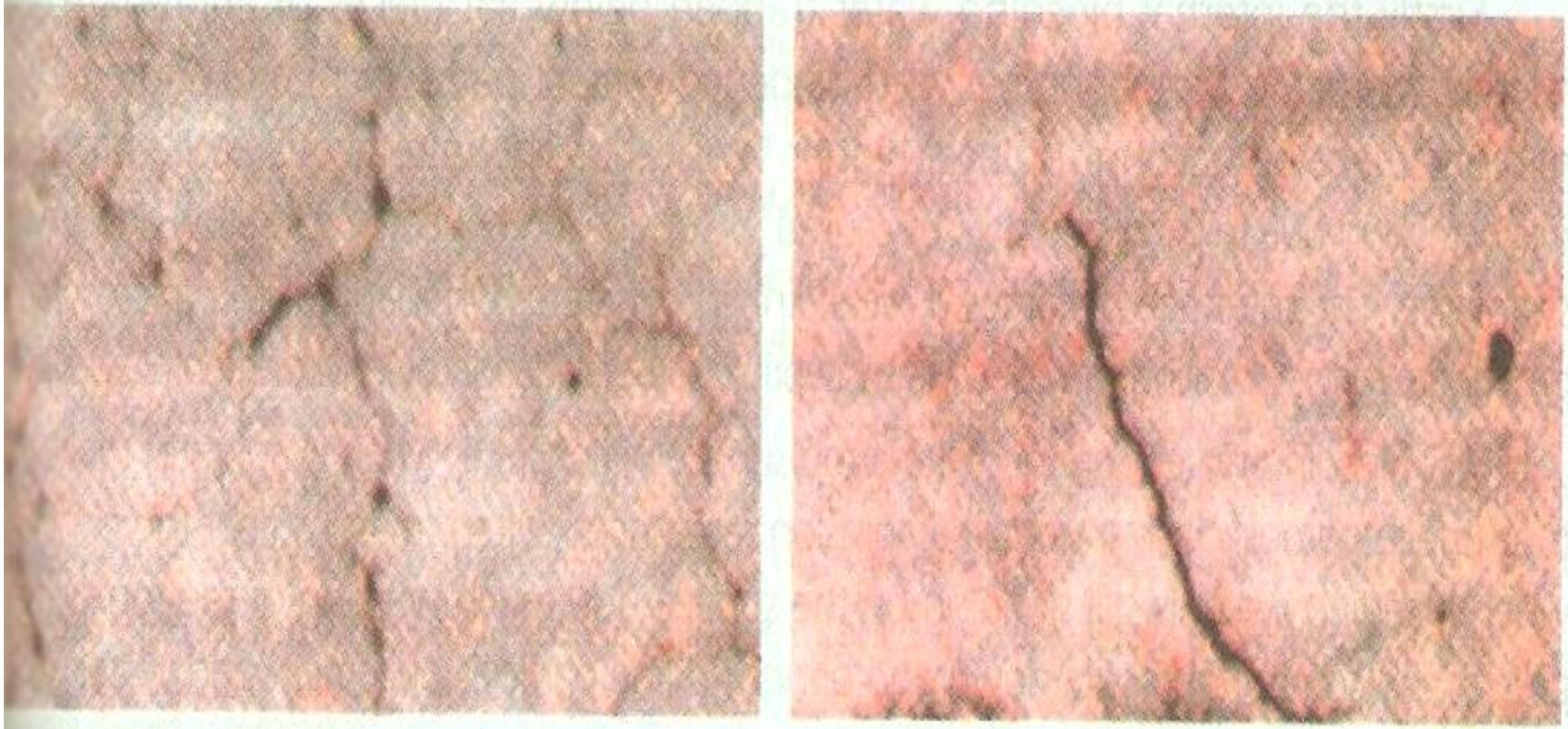


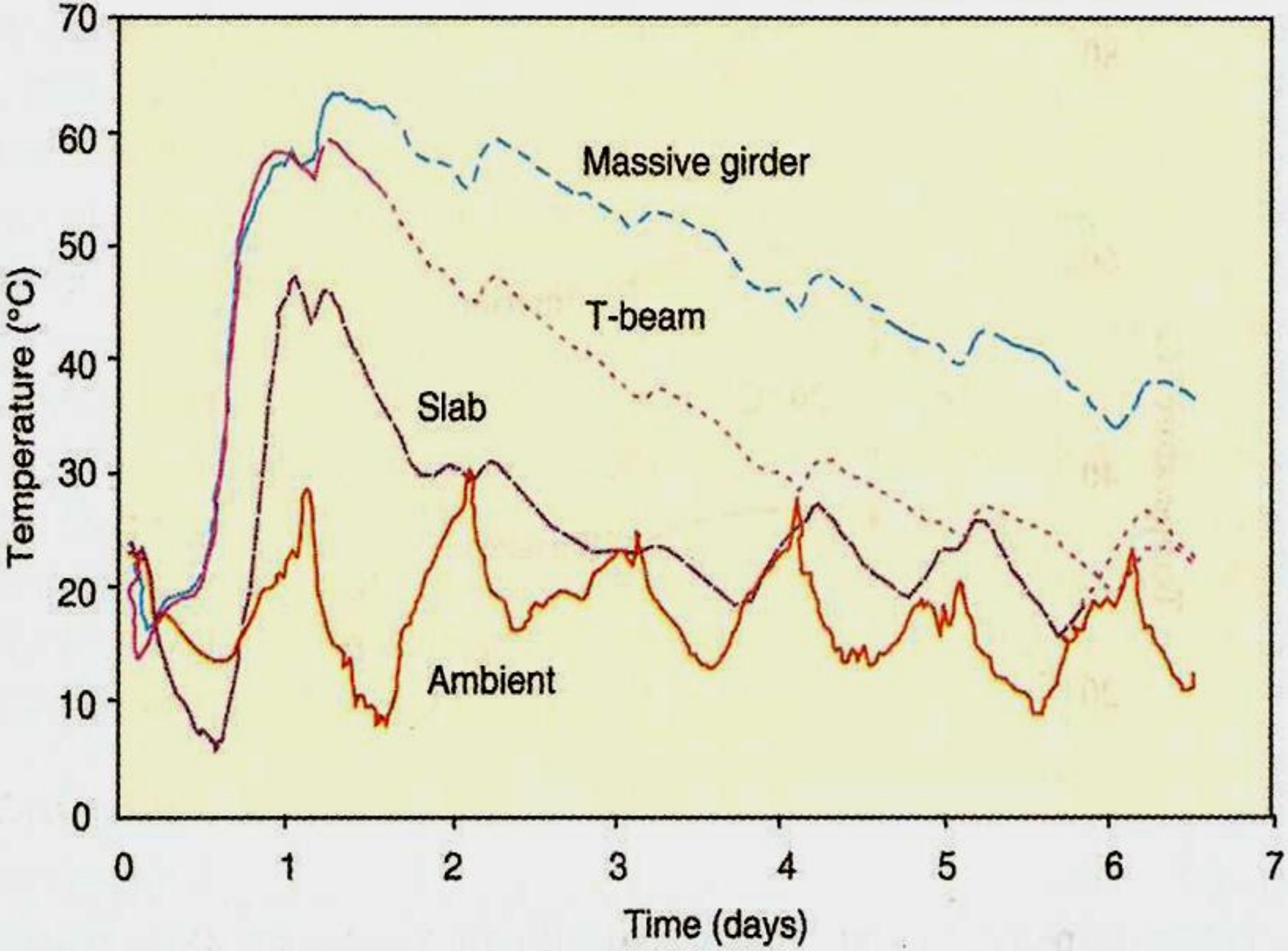
Fig. 9.3. Typical plastic shrinkage cracks.[9.5]

In Mumbai – Pune highway 100m long low tent erected on wheels to break the wind and also to protect green concrete from hot sun. In addition curing compound is sprayed immediately after finishing operation. Once the shrinkage cracks are formed in roof and floor slabs it is difficult to repair.

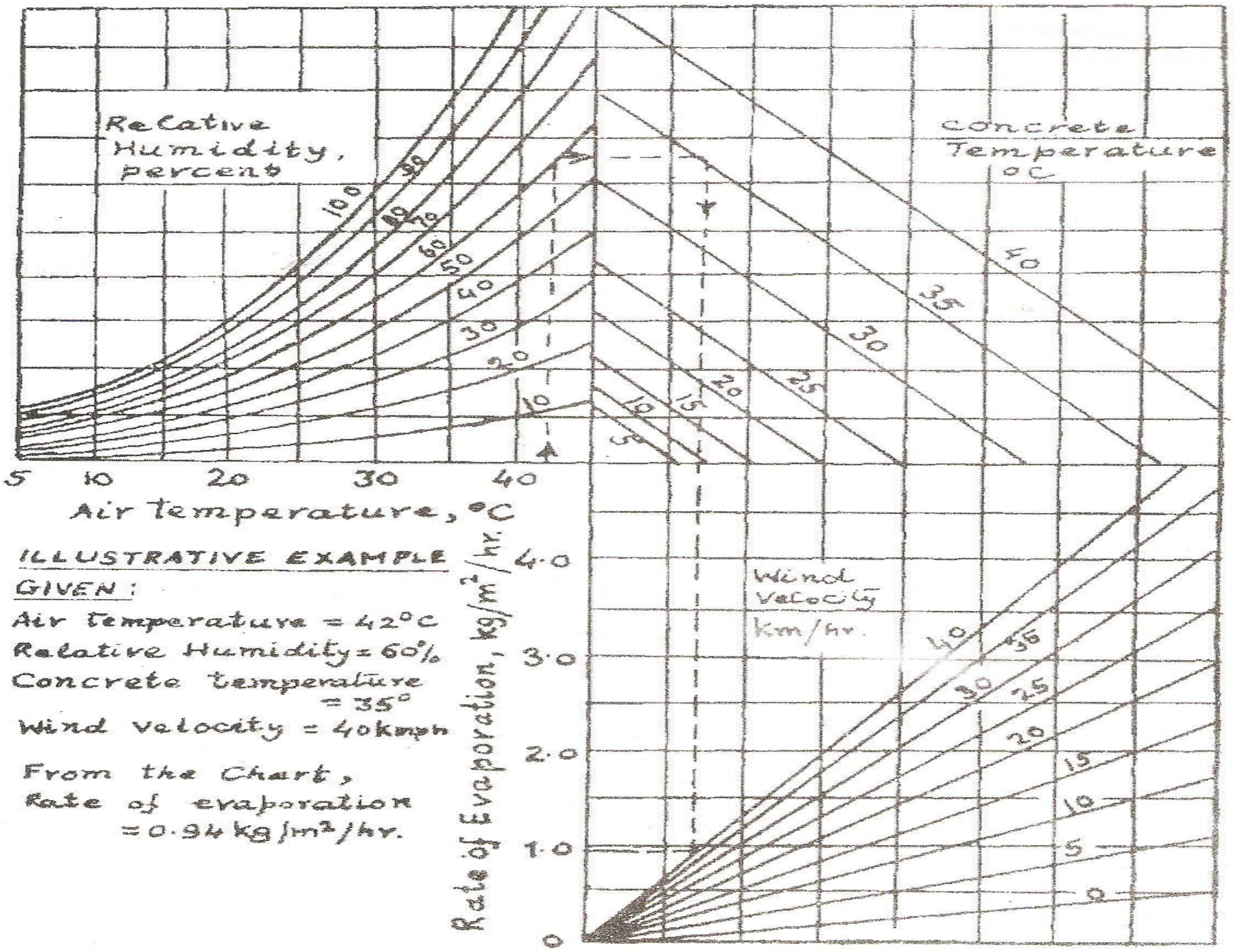
Impact of w/c ratio on durability: Higher w/c ratio-permeability-volume change-cracks-disintegration-failure are a sequential process. For durable concrete low w/c ratio is a fundamental requirement. Low water cement ratio concrete is less sensitive to carbonation and thus protects reinforcement from corrosion. If for any reasons, structural or environmental, concrete gets cracked, the unhydrated cement particles gets hydrated as soon as moisture or water penetrates through cracks.

Thermal expansion and shrinkage:

Due to diurnal variation of temperature tensile strain can occur in concrete. For a temperature variation of 20°C, the tensile stress can be of the order of 5N/mm^2 where as allowable tensile stress in concrete is only 3.5 N/mm^2 for M 25 concrete. This will cause micro cracks in concrete.



Temperature variations observed at the centre of the three structural elements



ILLUSTRATIVE EXAMPLE

GIVEN :

Air temperature = 42°C

Relative Humidity = 60%

Concrete temperature = 35°

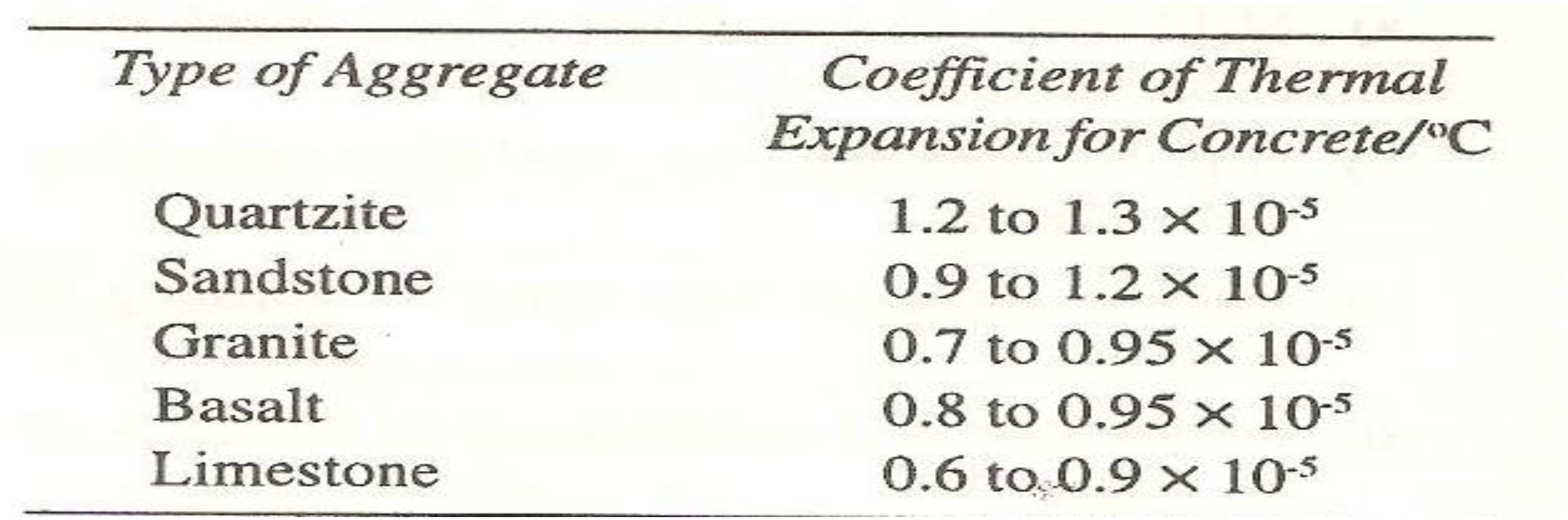
Wind velocity = 40kmph

From the Chart, Rate of evaporation = 0.94 kg/m²/hr.

Fig. 1 Chart for Calculation of Rate of Evaporation of Surface Moisture of Concrete from Air Temperature and Relative Humidity, Concrete Temperature and Wind Velocity. (Enter The Chart on The Temperature Scale and Proceed as Shown by Dotted Line, Till The Rate of Evaporation is Reached.

Shrinkage: Total shrinkage depends upon the constituents of concrete, size of member, and environmental conditions. For a given temperature and humidity, total shrinkage is influenced by amount of water present in concrete at the time of mixing, and to a lesser extent on cement content. The approximate value of total shrinkage strain may be taken as 0.0003 i.e. for 3m length it will be about 0.9mm.

Thermal Expansion: The coefficient of thermal expansion depends on nature of cement, aggregates, the cement content, relative humidity and the size of section. For different types of aggregates it may be taken as:



Type of Aggregate	*Coefficient of Thermal Expansion for Concrete/°C*
Quartzite	1.2 to 1.3×10^{-5}
Sandstone	0.9 to 1.2×10^{-5}
Granite	0.7 to 0.95×10^{-5}
Basalt	0.8 to 0.95×10^{-5}
Limestone	0.6 to 0.9×10^{-5}

CURING

Curing:

- Curing is the process of preventing loss of moisture from the concrete whilst maintaining a satisfactory temperature regime.
- Curing regime should prevent development of high temperature gradients. Supersulphated cement concrete is seriously affected by inadequate curing.

Curing:

- Exposed surfaces of concrete shall be continuously kept in damp or wet condition by ponding or wet Hessian cloth for at least 7 days from date of placing concrete in case OPC and at least 10 days where mineral admixtures or blended cements are used. For concrete containing PPC, PSC or mineral admixture, period of curing may be increased.

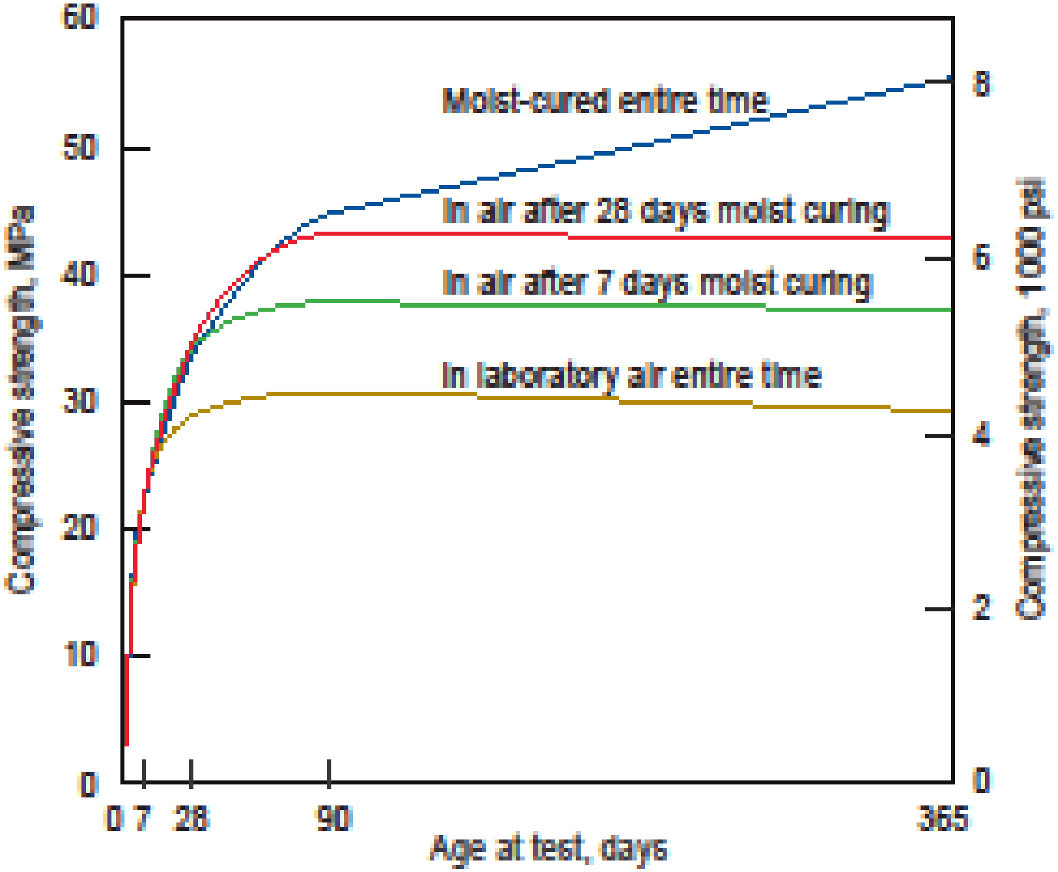


Fig. 12-2. Effect of moist curing time on strength gain of concrete (Gonnerman and Shuman 1928).

Steam Curing

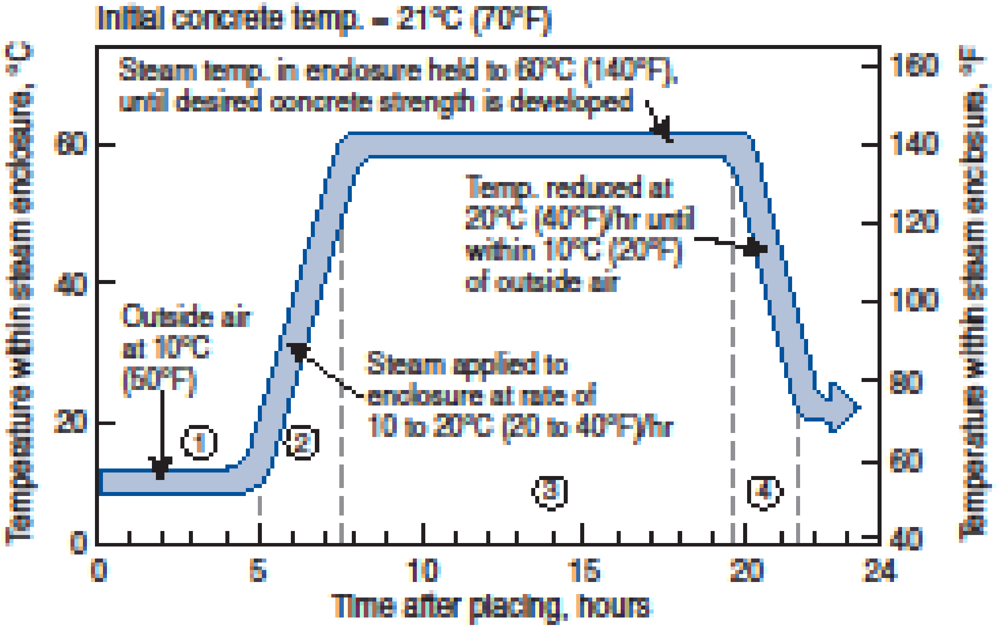
Steam curing is advantageous where early strength gain in concrete is important or where additional heat is required to accomplish hydration, as in cold weather.

Two methods of steam curing are used: live steam at atmospheric pressure (for enclosed cast-in-place structures and large precast concrete units) and high-pressure steam in autoclaves (for small manufactured units). Only live steam at atmospheric pressure will be discussed here.

A typical steam-curing cycle consists of (1) an initial delay prior to steaming, (2) a period for increasing the temperature, (3) a period for holding the maximum temperature constant, and (4) a period for decreasing the temperature. A typical atmospheric steam-curing cycle is shown in Fig. 12-9.

Steam curing at atmospheric pressure is generally done in an enclosure to minimize moisture and heat losses. Tarpaulins are frequently used to form the enclosure. Application of steam to the enclosure should be delayed until initial set occurs or delayed at least 3 hours after final placement of concrete to allow for some hardening of the concrete. However, a 3- to 5-hour delay period prior to steaming will achieve maximum early strength, as shown in Fig. 12-10.

Steam temperature in the enclosure should be kept at about 60°C (140°F) until the desired concrete strength has developed. Strength will not increase significantly if the maximum steam temperature is raised from 60°C to 70°C (140°F to 160°F). Steam-curing temperatures above 70°C (160°F) should be avoided; they are uneconomical and



①	Initial delay prior to steaming	3 to 5 hours
②	Temperature increase period	2½ hours
③	Constant temperature period	6 to 12 hours*
④	Temperature decrease period	2 hours

*Type III or high-early-strength cement, longer for other types

Fig. 12-9. A typical atmospheric steam-curing cycle.

Hydration process:

Immediately on adding water, some of the clinker sulphates and gypsum dissolve producing an alkali sulphate solution.

Stage I: C3A reacts with water to form an aluminate rich gel. This gel reacts with sulphate in solution to form small rod like crystals of ettringite. (Few minutes)

Stage II: Relatively low heat generated. (Dormant period)

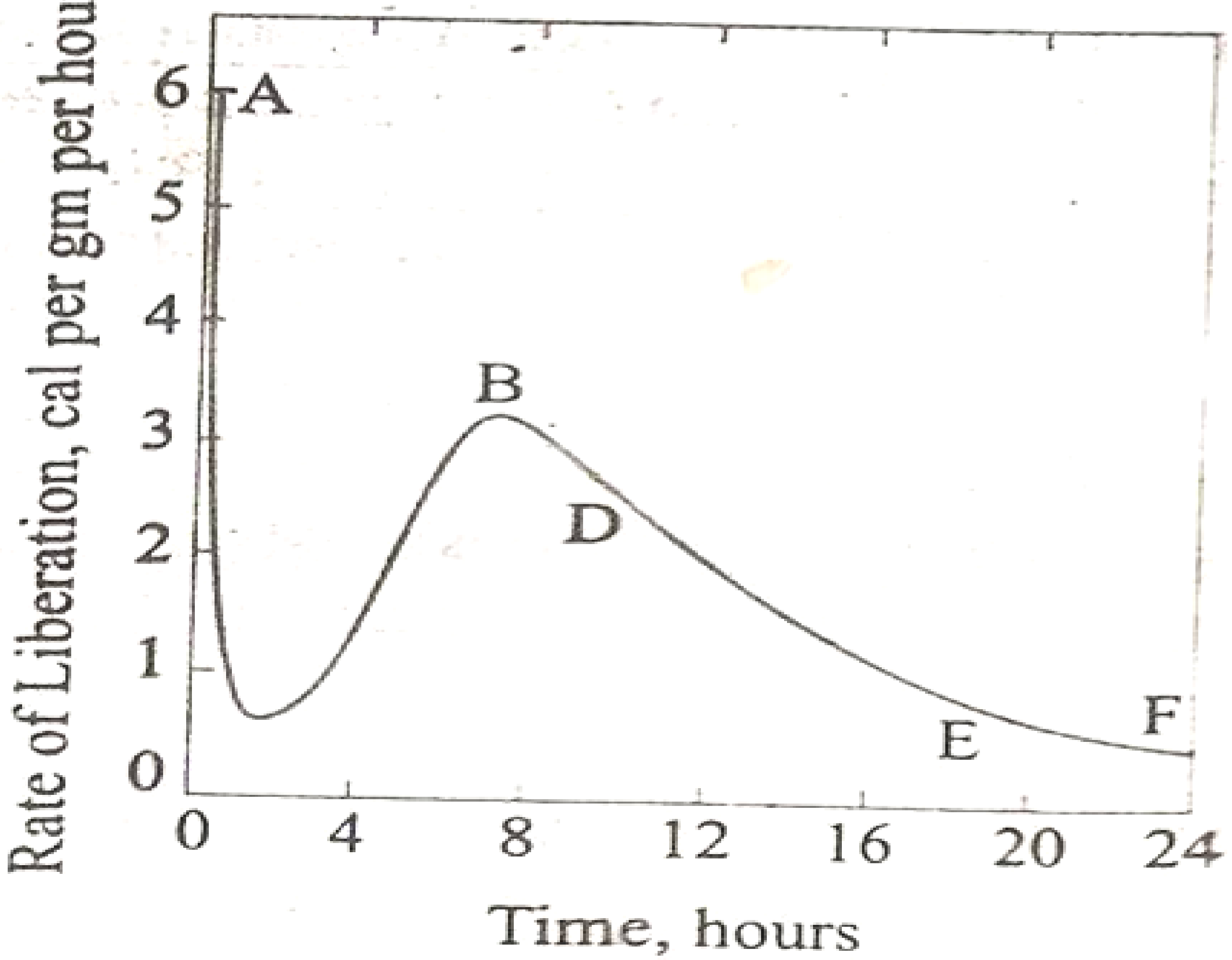


Fig. 1.2. Heat Liberation from a Setting Cement.[1]

Important Aspects of Construction

Stage III: Period of maximum heat evolution occurs typically about 10-20 hours after mixing till about a month and there after tapers off.

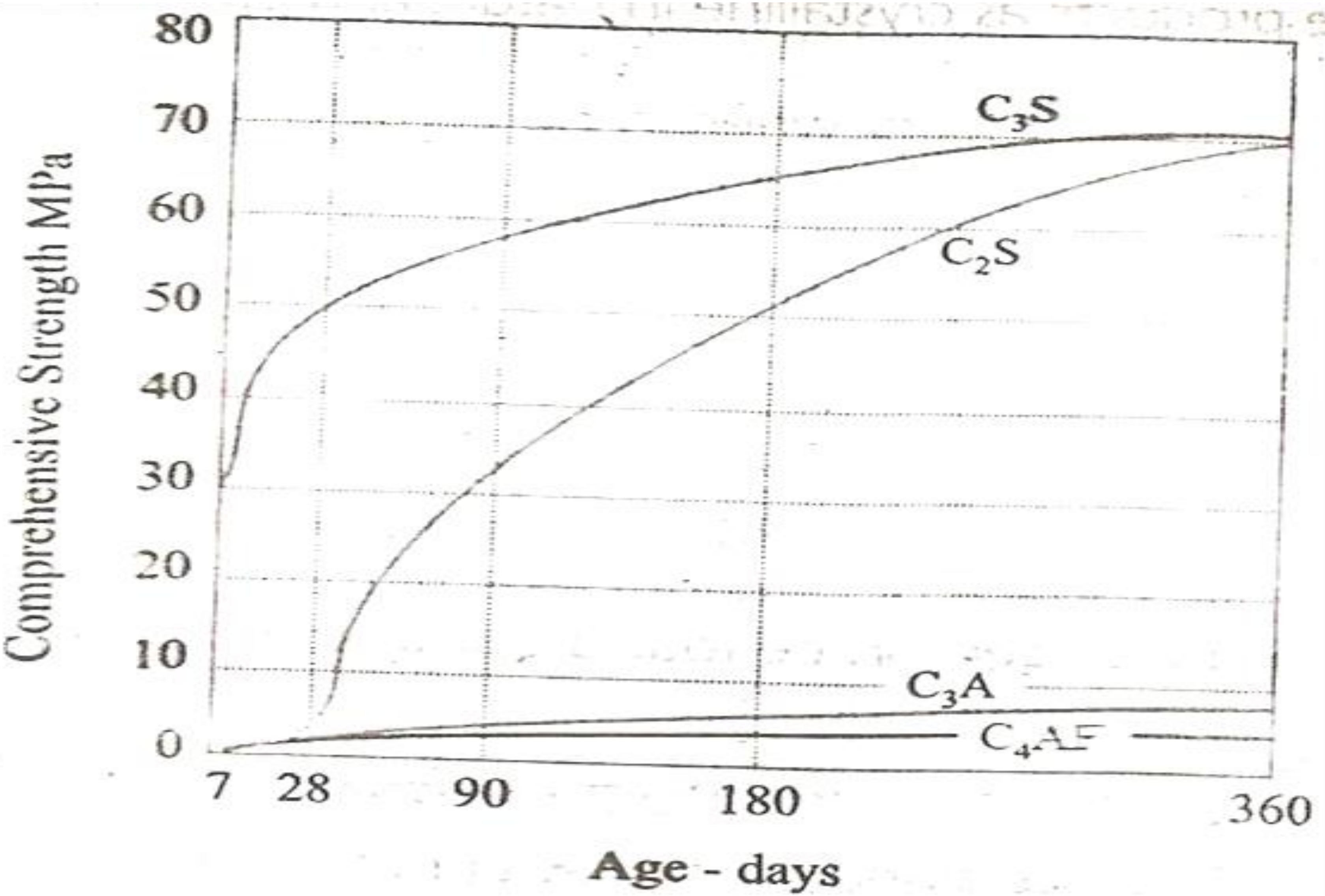


Fig. 1.4. Development of Strength of Pure Compounds

CARBONATION IN CONCRETE

Carbonation: It is a process by which carbon dioxide from air penetrates into concrete and reacts with calcium hydroxide to form carbonates. This will result in small shrinkage of concrete. In the presence of moisture, CO_2 changes into carbonic acid which attacks concrete and also reduces alkalinity of concrete. The pH value of pore water in concrete is generally between 12.5 to 13.5. The pH value will get reduced to around 9 when $Ca(OH)_2$ has become carbonated.

- Time

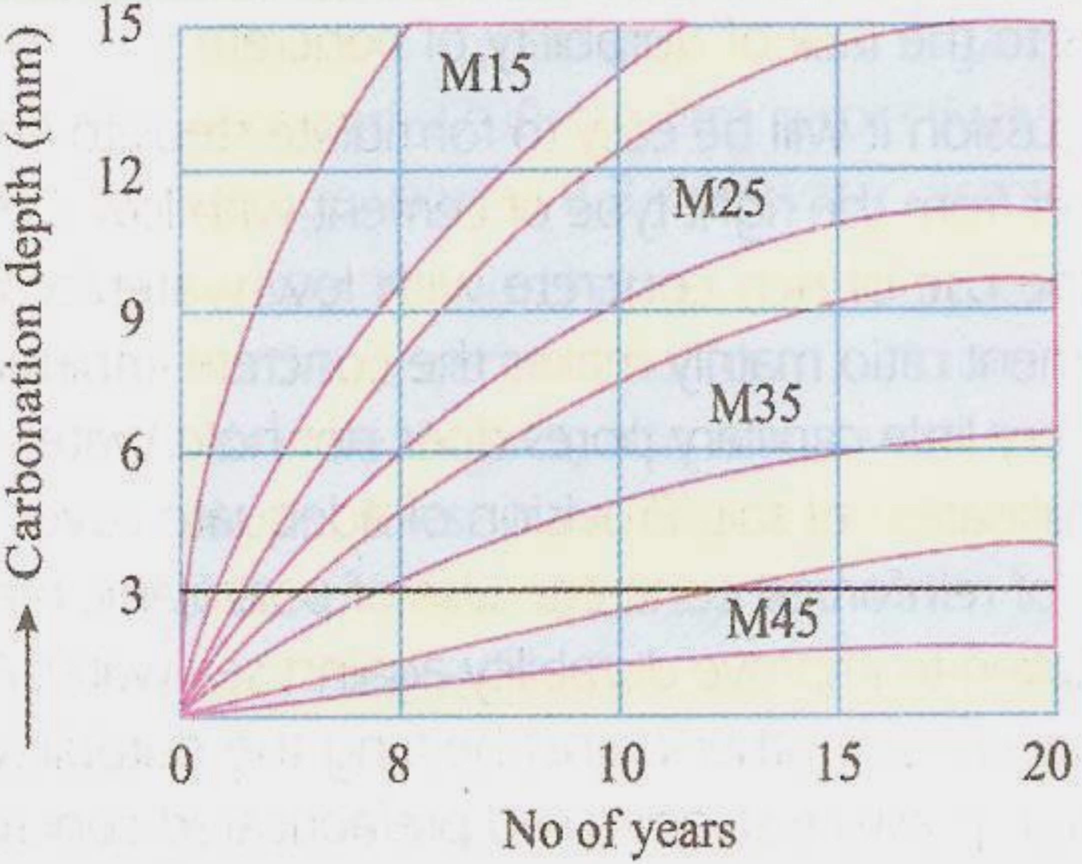
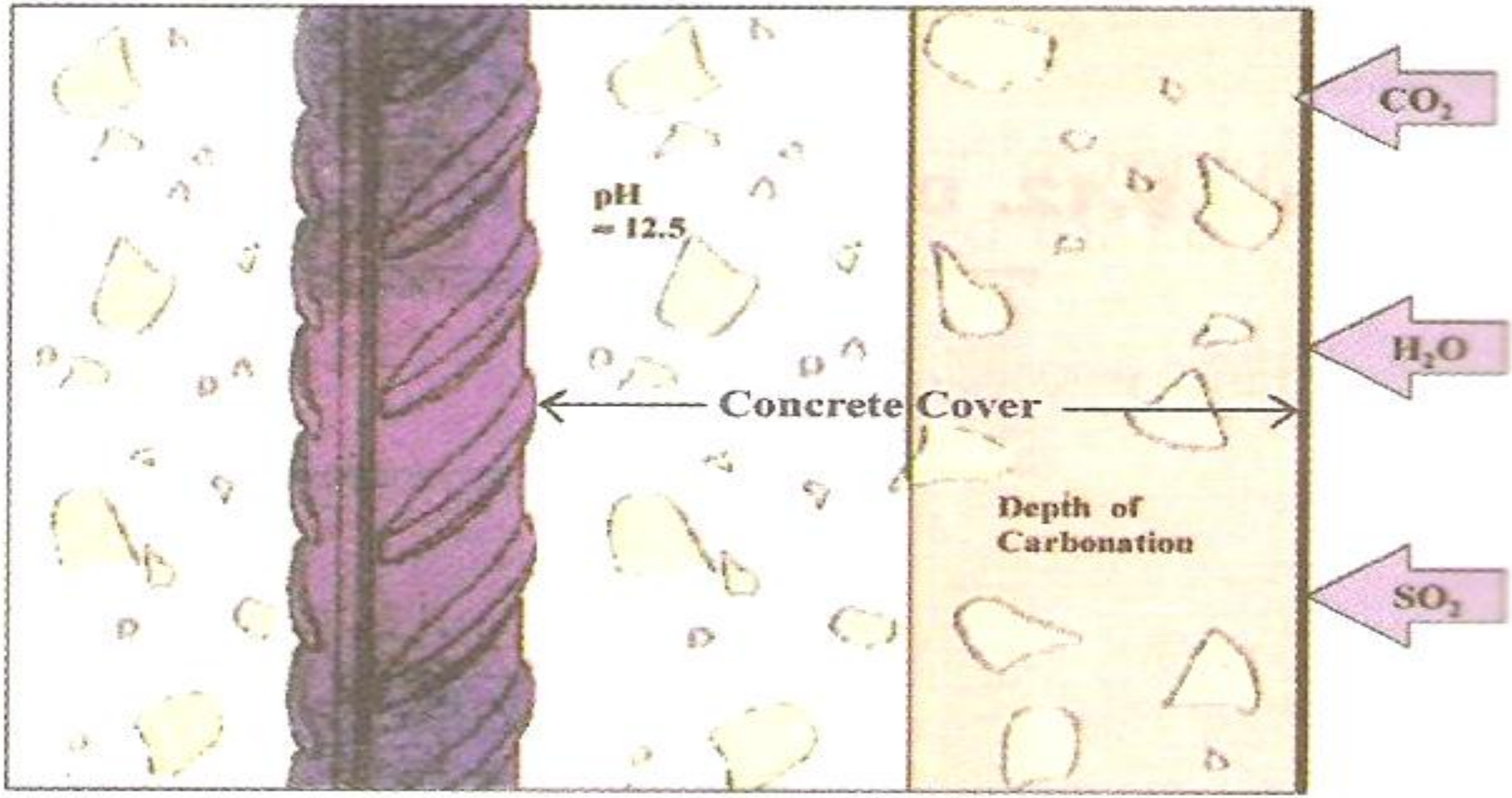


Fig. 9.21. Depth of carbonation with respect to strength (grade) of concrete

Steel in Passivative Condition



Concrete is under continuous attack by aggressive environmental agencies. Good concrete and suffecient cover is the answer for durability.

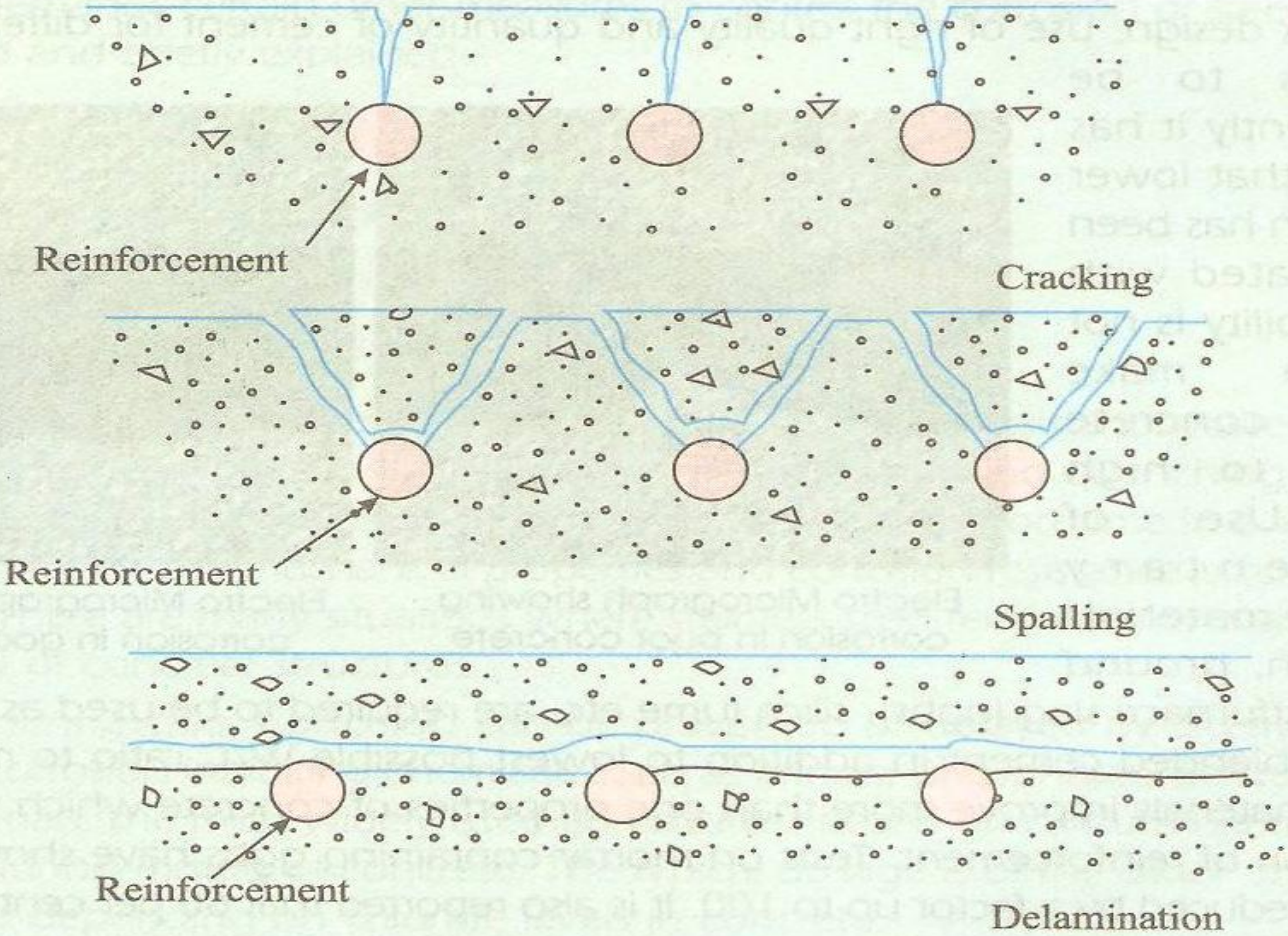
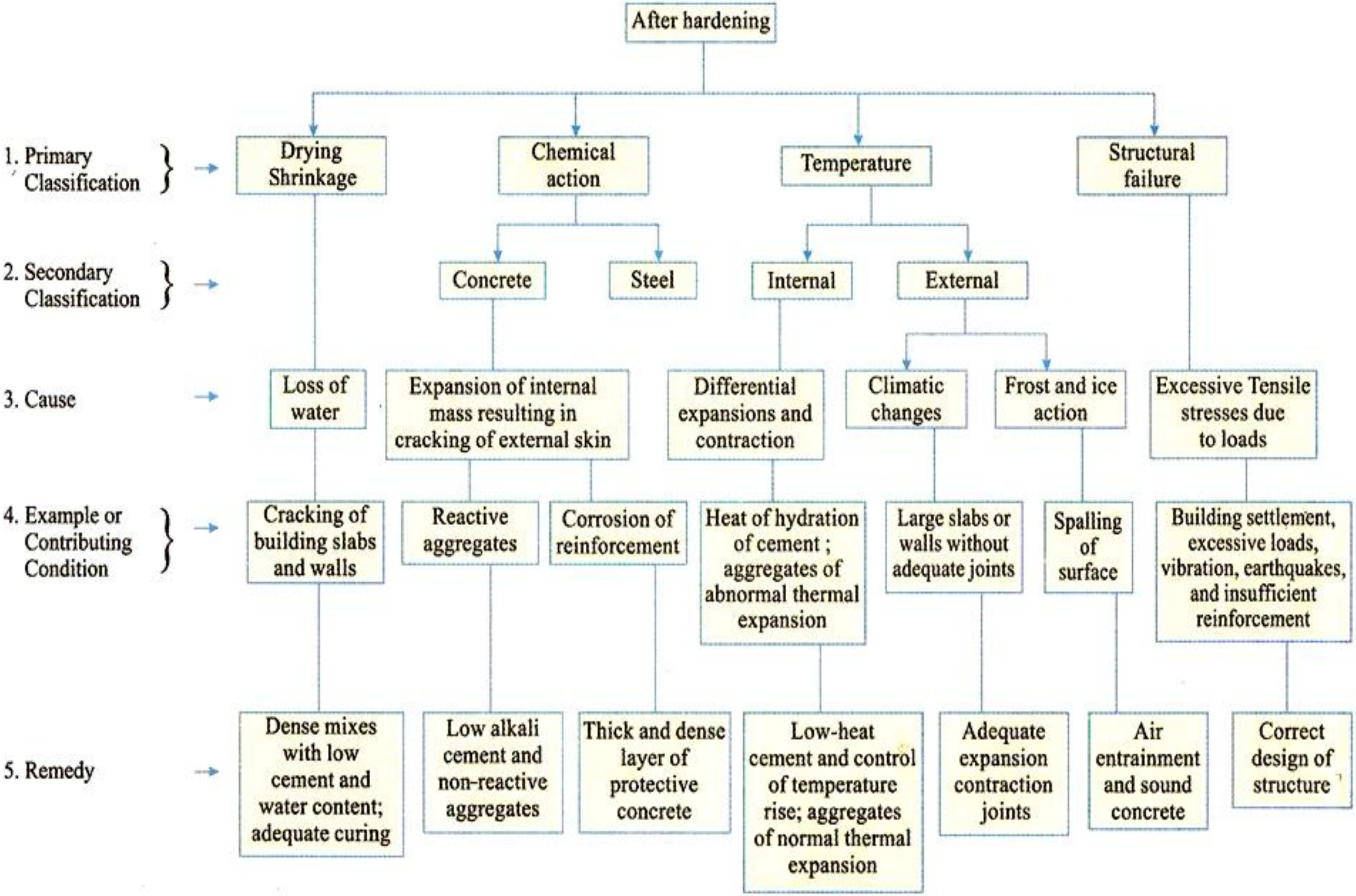


Fig. 9.25. Diagrammatic representation of damage induced by corrosion: cracking, spalling, and delamination

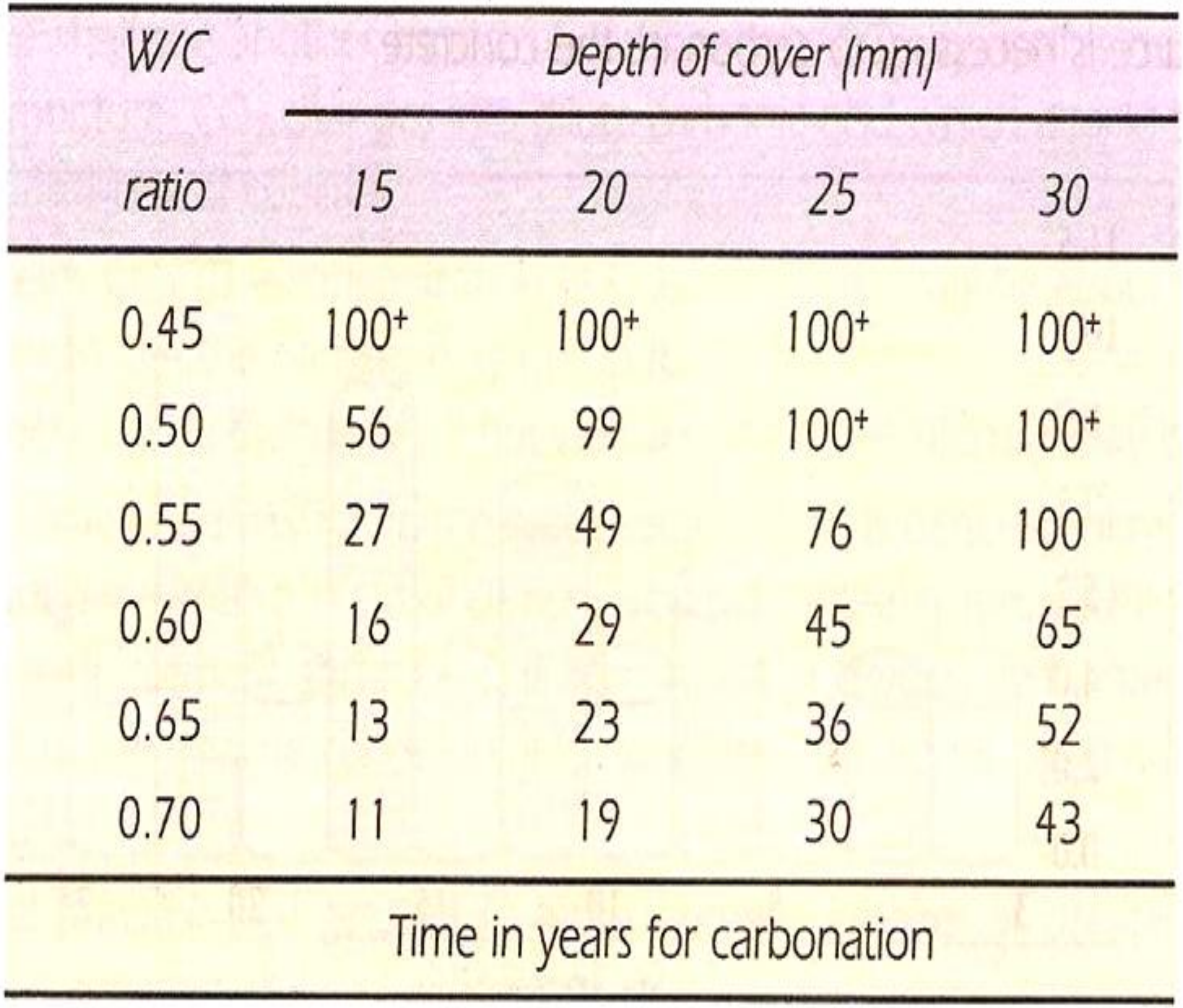
Table 9.5. Other Properties, Types and Causes of Concrete Cracking[9.4]



After hardening

1. Primary Classification	2. Secondary Classification	3. Cause	4. Example or Contributing Condition	5. Remedy
Drying Shrinkage		Loss of water	Cracking of building slabs and walls	Dense mixes with low cement and water content; adequate curing
Chemical action	Concrete	Expansion of internal mass resulting in cracking of external skin	Reactive aggregates	Low alkali cement and non-reactive aggregates
			Corrosion of reinforcement	Thick and dense layer of protective concrete
	Steel			
Temperature	Internal	Differential expansions and contraction	Heat of hydration of cement ; aggregates of abnormal thermal expansion	Low-heat cement and control of temperature rise; aggregates of normal thermal expansion
	External	Climatic changes	Large slabs or walls without adequate joints	Adequate expansion contraction joints
		Frost and ice action	Spalling of surface	Air entrainment and sound concrete
Structural failure		Excessive Tensile stresses due to loads	Building settlement, excessive loads, vibration, earthquakes, and insufficient reinforcement	Correct design of structure

Table 9.13. Approximate relations between W/C, depth of cover and time in years for carbonation depth to reach the reinforcement.



W/C	Depth of cover (mm)			
ratio	15	20	25	30
0.45	100^+	100^+	100^+	100^+
0.50	56	99	100^+	100^+
0.55	27	49	76	100
0.60	16	29	45	65
0.65	13	23	36	52
0.70	11	19	30	43

Time in years for carbonation

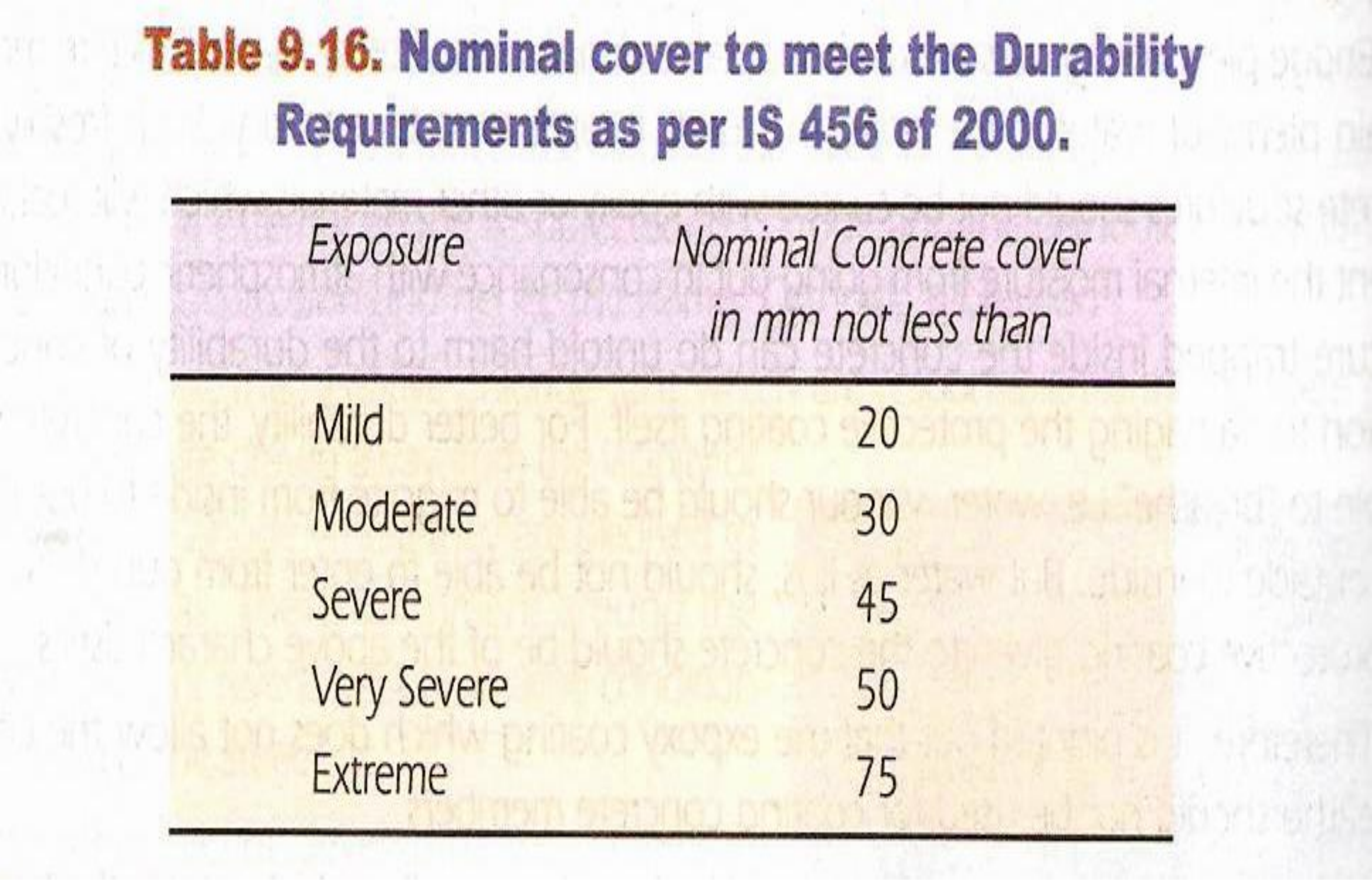


Table 9.16. Nominal cover to meet the Durability Requirements as per IS 456 of 2000.

Exposure	Nominal Concrete cover in mm not less than
Mild	20
Moderate	30
Severe	45
Very Severe	50
Extreme	75

Note: For main reinforcement up to 12mm for mild exposure conditions, cover may be reduced by 5mm.

Cover for fire resistance:

HrS	Beams simply supported mm	Beams continuous mm	Slabs simply supported mm	Slabs continuous mm	Columns mm
0.5	20	20	20	20	40
1.0	20	20	20	20	40
1.5	20	20	25	20	40
2.0	40	30	35	25	40
3.0	60	40	45	35	40
4.0	70	50	55	45	40

Deflection:

The structure should be tested to 1.25 times imposed load for 24 hours. If the structure does not recover 75% of deflection, test should be repeated after 24 hours. If the recovery is < 80%, the structure shall be deemed to be accepted.

Maximum deflection in = 40 L^2/D (Overall depth), L- Effective span

If the deflection is less during 24 hrs., recovery need not be measured.

CORROSION OF STEEL REINFORCEMENT

The corrosion of steel in the presence of oxygen but without chlorides, takes place in several steps.

1. At the anode iron is oxidized to the ferrous state and releases electrons.
2. The electrons migrate to the cathode where they continue with water and oxygen to form hydroxyl ions.
3. The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide
4. In the presence of water oxygen the ferrous hydroxide is further oxidized to form Fe_2O_3

Causes for Corrosion of Reinforcement

The corrosion of steel in concrete in the presence of chlorides, but with no oxygen (at the anode) takes place in several steps.

1. At the anode, iron reacts with chloride ions to form an intermediate soluble iron-chloride complex.
2. When the iron-chloride complex diffuses away from the bar to an area with higher pH and concentration of oxygen, it reacts with hydroxyl ions to form $Fe(OH_2)$. The complex reacts with water form ferrous hydroxide.

Causes for Corrosion of Reinforcement

The corrosion of steel in concrete in the presence of chlorides, but with no oxygen (at the anode) takes place in several steps.

3. The hydrogen ions then combine with electrons to form hydrogen
4. As in the case of corrosion of steel without chlorides, the ferrous hydroxide, in the presence of water and oxygen, is further oxidized to form Fe_2O_3 (Rust)

Corrosion of Steel (Chloride induced)

Corrosion of steel in concrete is an electrochemical process. When there is a difference in electrical potential along the steel reinforcement in concrete, an electrochemical cell is set up. In the steel, one part becomes anode and other part becomes cathode connected by electrolyte in the form of pore water in the hardened cement paste. The positively charged ferrous ions Fe^{++} at the anode pass into solution while the negatively charged free electrons e^- pass through the steel into cathode where they are absorbed by the constituents of the electrolyte and combine with water and oxygen to form hydroxyl ions $(OH)^-$. These travel through electrolyte and combine with the ferrous ions to form ferric hydroxide which is converted by further oxidation to rust.

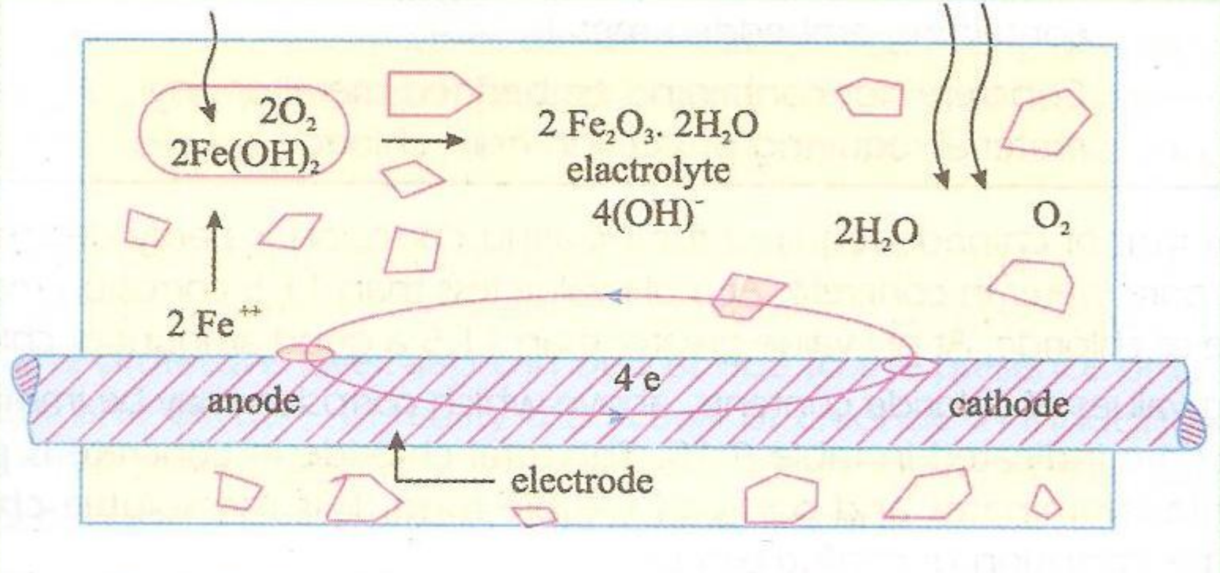
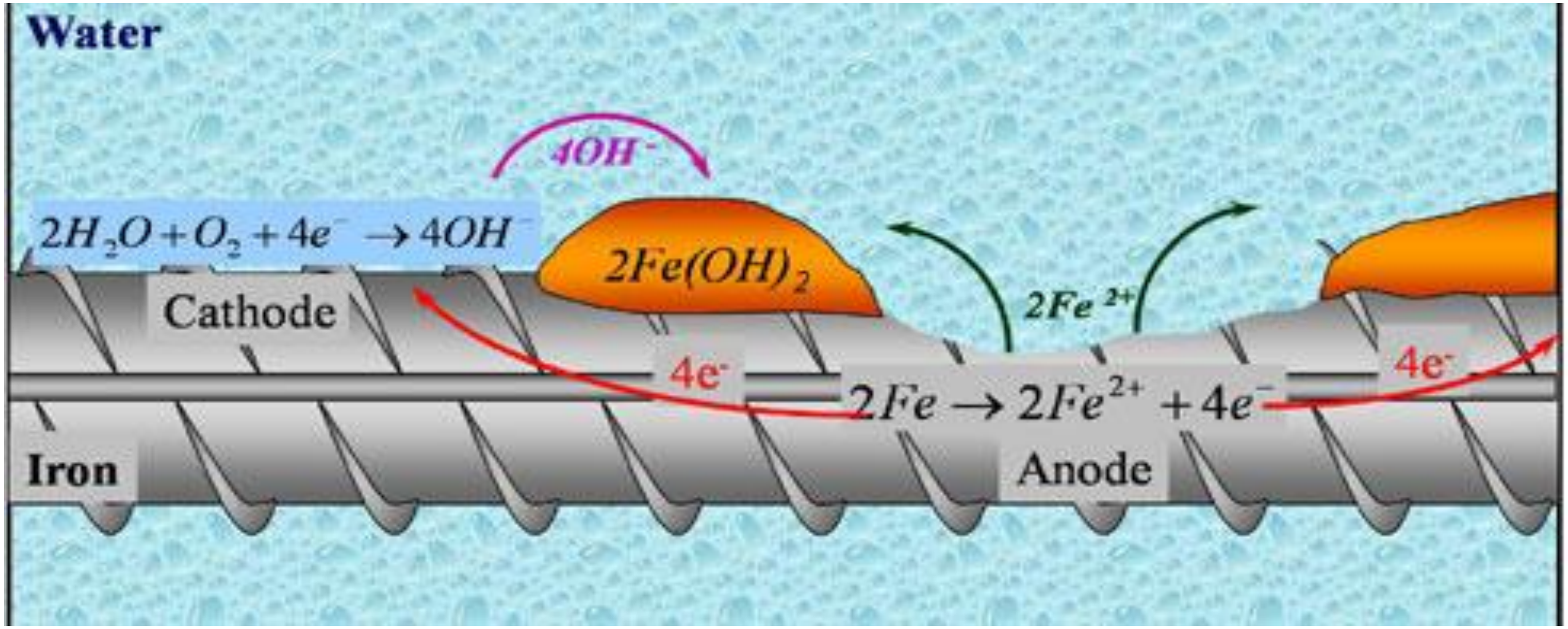
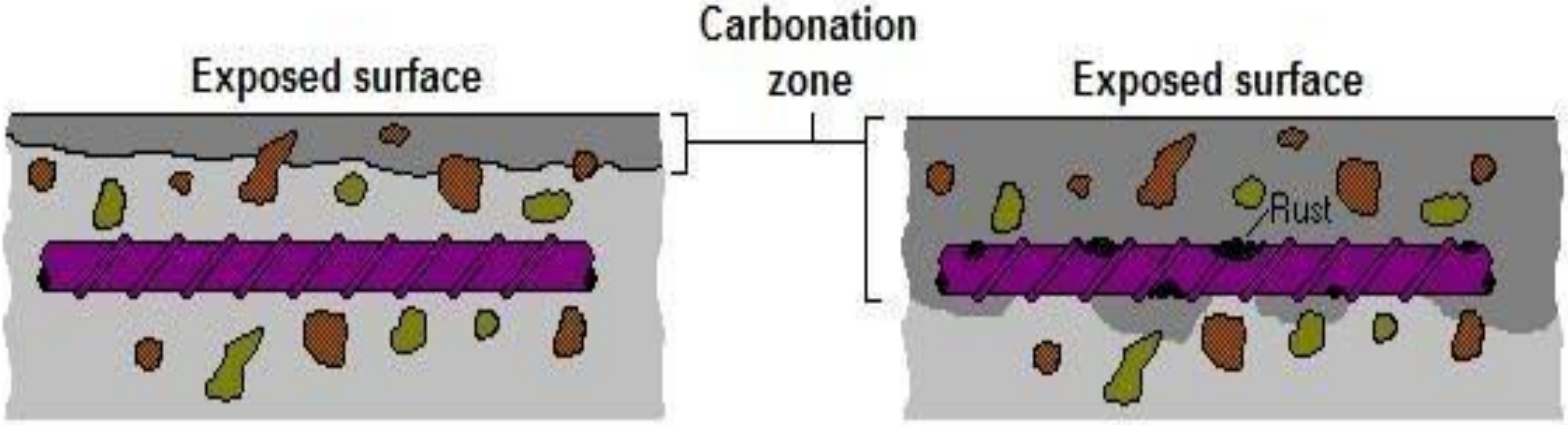


Fig. 9.23. Simplified model representing corrosion mechanism 9.21



PROCESS OF CORROSION OF STEEL



Early stages

Carbonation progression

EFFECT OF SOME MATERIALS ON CONCRETE

Effects of some materials on concrete:

1. Mineral oils – Petrol do not attack hardened concrete. Creosotes have some affect on concrete. Lubricating oils do not attack concrete.
2. Organic Acids – Acetic acid, formic acid, tannic acid and phenols are mildly corrosive. Fresh milk does not harm concrete

Effects of some materials on concrete:

3. Vegetable oils - have slow corrosive effect. Animal oils are corrosive.
4. Sugar – It may gradually corrode concrete. However storage of molasses has been done with satisfactory results
5. Sewage – Domestic sewage is not detrimental on good concrete. Septic sewage in sewage sludge digestion tanks/ industrial wastes may promote formation of sulphuric acid which can attack concrete.

Surface treatment to concrete:

- Aqueous solution of sodium silicate
- Magnesium or zinc silico fluoride
- Drying oils like linseed oil or tung oil
- Chlorinated rubber paint
- Neoprene paint
- Epoxy paint or coal tar epoxy paint
- Silicon fluoride treatment

AIM
SHOULD BE
TO MAKE
OUR
CONCRETE
AS
DURABLE
AS
THESE
MONUMENTS!

Thank You