Chapter – 1

INTRODUCTION TO ENGINEERING MATERIALS

(Topics: Engineering Materials, Mechanical Properties, Yielding, Elasticity, Plastic Properties, Fracture)

Assignment 1:

Question-1. Define the following terms:

a) Compressive Stress
b) Tensile Stress
c) Shear Stress
d) Strain
e) Shear Strain
f) Elasticity
g) Elastic Limit
h) Young's Modulus of Elasticity
i) Modulus of Rigidity
j) Poisson's Ratio
k) Plasticity
l) Malleability
m) Brittleness
n) Stiffness
o) Ductility
p) Toughness
q) Fatigue
r) Hardness
s) Resilience
t) Creep

Question- 2:

A 10 cm diameter and 20 cm height concrete cylinder was tested for evaluating its stress-strain curve, Young's modulus of elasticity, and ultimate strength. The test results are given in the attached sheet. Draw the stress-strain curves (use MPa unit and psi for stress units) and determine the other values.

SL	Load (kN)	Strain (in/in)	SL	Load (kN)	Strain (in/in)
1	5.33	0.00002	16	80.92	0.000285
2	10.32	0.0000425	17	86.25	0.0003025
3	15.65	0.00006	18	90.91	0.00032
4	20.65	0.00008	19	95.57	0.000335
5	25.64	0.0001	20	100.9	0.000355
6	31.3	0.00012	21	105.89	0.00037
7	36.63	0.00014	22	110.56	0.0003875
8	41.29	0.000155	23	115.88	0.000405
9	45.95	0.00017	24	120.55	0.0004225
10	51.28	0.0001875	25	126.21	0.0004425
11	55.61	0.0002025	26	130.87	0.0004575
12	60.61	0.00022	27	135.53	0.000475
13	65.93	0.000235	28	141.19	0.0004975
14	70.93	0.0002525	29	145.85	0.000515
15	75.59	0.00027	30	150.85	0.00053

SL	Load (kN)	Strain (in/in)	SL	Load (kN)	Strain (in/in)
31	155.18	0.00055	79	395.94	0.0016425
32	161.17	0.00057	80	400.93	0.0016775
33	165.83	0.0005875	81	405.59	0.0017075
34	170.83	0.000605	82	410.59	0.001745
35	175.49	0.0006225	83	415.58	0.0017825
36	181.15	0.0006425	84	420.58	0.0018225
37	185.81	0.000665	85	425.57	0.001865
38	190.81	0.0006825	86	430.57	0.00191
39	195.47	0.0006975	87	435.56	0.00196
40	201.13	0.00072	88	440.23	0.0020125
41	205.79	0.0007375	89	445.22	0.0020725
42	210.46	0.0007575	90	450.22	0.0021525
43	216.12	0.0007775	91	455.21	0.0022775
44	220.78	0.0007975	92	447.89	0.002525
45	226.11	0.0008175			
46	230.77	0.0008375			
47	236.10	0.00086			
48	240.76	0.0008775			
49	245.75	0.0009			
50	250.42	0.0009175			
51	255.41	0.0009375			
52	260.74	0.00096			
53	265.73	0.00098			
54	270.06	0.001			
55	275.39	0.0010225			
56	280.39	0.0010425			
57	285.38	0.0010675			
58	290.71	0.00109			
59	295.70	0.0011125			
60	300.37	0.001135			
61	305.03	0.001155			
62	310.69	0.00118			
63	315.35	0.0012025			
64	320.35	0.0012275			
65	325.67	0.0012525			
66	330.67	0.001275			
67	335.66	0.0013025			
68	340.66	0.001325			
69	345.65	0.0013525			
70	350.98	0.00138			
71	355.64	0.001405			
72	360.64	0.001435			
73	365.97	0.0014625			
74	370.96	0.0014925			
75	375.96	0.0015175			
76	380.62	0.0015475			
77	385.61	0.0015775			
78	390.94	0.00161			

Question-3:

The load and dial gauge reading of a rod tested for tensile strength is summarized below:

Gauge Length = 2 inch

1 Div of Dial Gauge = 0.001 mm

Bar Diameter = 0.5 inch

Load (kN)	Dial Gauge Reading
0	0
5	7
10	20
15	27
20	39
25	49
30	63
35	76
40	83
45	90
50	104
55	117
60	129
65	225
70	465
75	5080
70	10160

(i) Draw the stress-strain curve (Strain Axis – from 0 to 0.2)

(ii) Draw the stress-strain curve (Strain Axis – 0 to 0.02)

(iii) Determine the Yield Strength

(iv) Determine the Ultimate Strength

(v) Determine the ratio between Yield Strength and Ultimate Strength

(vi) Make Comments on the Results

Conversion of unit from *Psi* to *MPa*

1 psi = 1 lb/in^2

= 1×453.6/1000 kg/in^2 [∵ 1 lb = 453.6 gm]

= 1×453.6×100×100/(1000×2.54×2.54) kg/m^2 [∵ 1in = 2.54 cm]

= 9.81×1×453.6×100×100/(1000×2.54×2.54) N/m^2

= 6897.23 N/m^2

= 6897.23 Pa

= 6897.23/10^6 Mpa

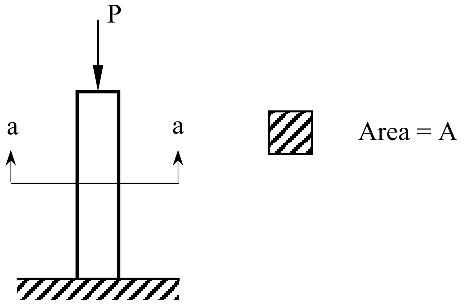
= 6.897 ×10^{-3} Mpa

∴ 1 Mpa = 145 psi

Stress

Intensity of force or force per unit area is called the stress.

Stress, □ = P/A

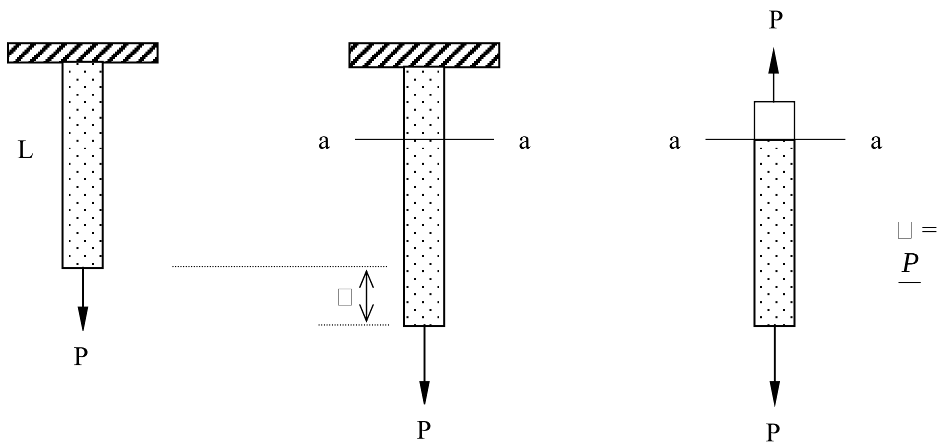


$$\text{Tensile Stress} = \frac{\text{Tensile force}}{\text{Area under tension}}$$

$$\text{Compressive Stress} = \frac{\text{Compressive force}}{\text{Area under compression}}$$

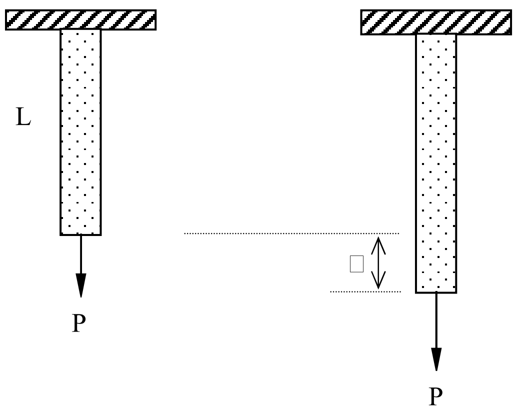
Normal Stress

The stress acting perpendicular to the cut surface, is referred to as a normal stress. The equation □ = P/A will give the average normal stress. *A* refers to the average area at the section which is perpendicular to the force *P*.



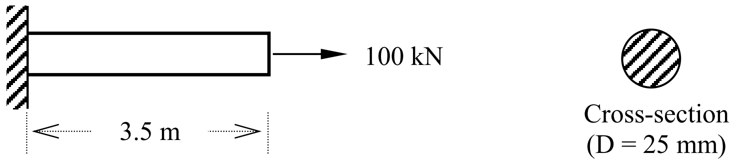
Strain

The ratio of the change in shape to the original shape is called strain. The change in length or deformation is denoted by □ (delta). The resulting state of stress and stain is called uniaxial stress and strain.



Strain, □ = □/L

Problem: A prismatic bar with a circular cross section is subjected to an axial tensile force of 100 kN. The measured elongation is □ = 1.5 mm . Calculate the tensile stress and strain in the bar.



Solution:

Tensile Stress, □ = P/A = 100×1000/{□$(25)^2$/4}= 203.72 N/mm^2 = 204 Mpa

Strain, □ = □/L = 1.5/(3.5×1000) = 4.3×10^{-4}

Problem: If the allowable stress at failure for the material is 35,000 psi and the applied load on the bar is P = 20,000 lb. What is the minimum area require to prevent failure?

Solution:

□ = P/A ⇒ A = P/ □ = 20,000/35,000 = 0.57 in^2

Problem: If the bar fails at strains greater than 0.15 and original length of the bar is L = 10 ft, what is the maximum allowable deformation before failure?

Solution:

□ = □/L ⇒ □ = □L = 0.15×10 = 1.5 ft

Strength

Maximum stress that can be withstand without failure.

Compressive Strength

The maximum compressive stress a material can withstand without failure.

Tensile Strength

The maximum tensile stress a material can withstand without failure.

Fatigue Strength

The maximum stress a material can endure for a given number of stress cycles without breaking (also known as *Endurance strength*)

Shear Strength

The maximum shear stress which a material can withstand without rupture.

Yield Strength

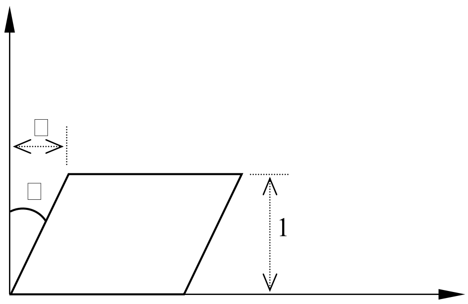
The stress at which a material exhibits a specified deviation from proportionality of stress and strain, that is, it indicates the end of elasticity and the beginning of plasticity.

Flexural Strength

Strength of a material in bending, that is, resistance to fracture.

Shearing Strain

It is defined as the angle of shear measured in radians.



$$\tan \square = \square_s/1$$

$$\therefore\ \square = \tan^{-1}(\square_s)$$

Longitudinal Strain

The ratio of change in length to original length is called longitudinal strain.

Poisson's Ratio

It is the ratio of lateral (transverse) strain to longitudinal strain.

$$\square = \frac{\text{Lateral Strain}}{\text{Longitudinal Strain}}$$

Hardness

It is the resistance to deformation and forced penetration

In materials science, hardness is the characteristic of a solid material expressing its resistance to permanent deformation. In other words, hardness is the resistance to wear.

Modulus of Rigidity or Shear Modulus

Modulus of rigidity, designated as *G*, is the shearing modulus of elasticity, which according to Hooke's law is the constant proportionality between shearing stress and shearing strain during elastic behavior.

$$G = \frac{\text{Shearing Stress}}{\text{Shearing Strain}}$$

$$= \frac{E}{2(1+\mu)}$$ Where, □ = Poison's Ratio

Stress-Strain curve for Steel

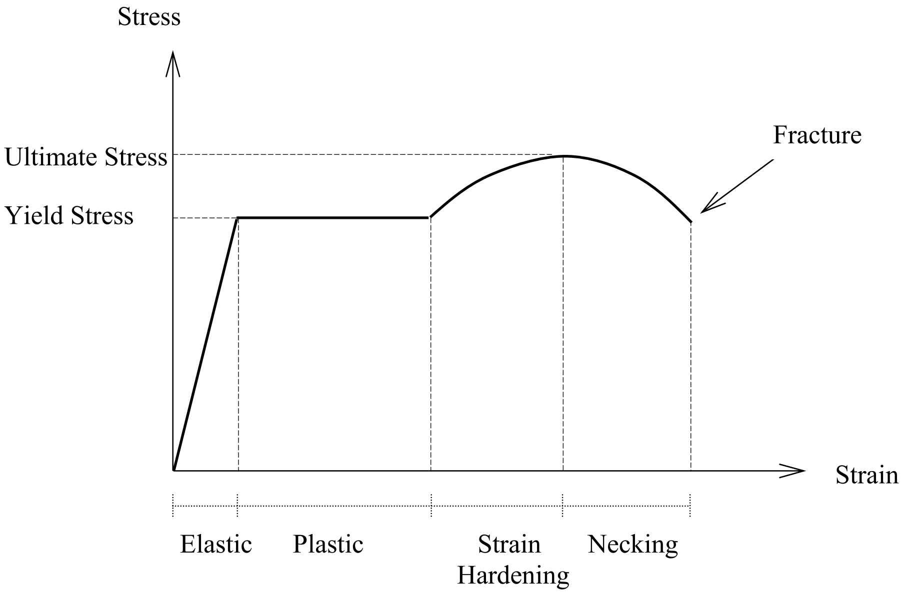


Fig: Typical Stress-Strain curve for Steel

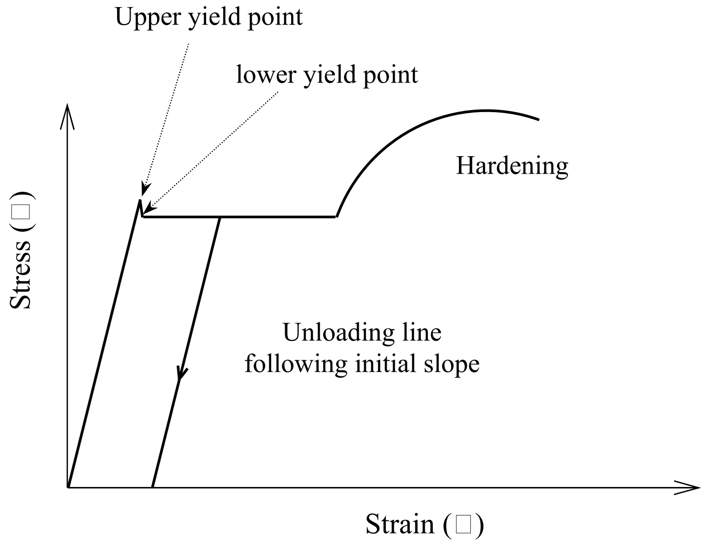


Fig: Typical Stress-Strain curve for Mild Steel

Yield Strength or the yield point

Yield strength or the yield point, is defined in engineering and materials science as the stress at which a material begins to plastically deform.

Elastic Limit

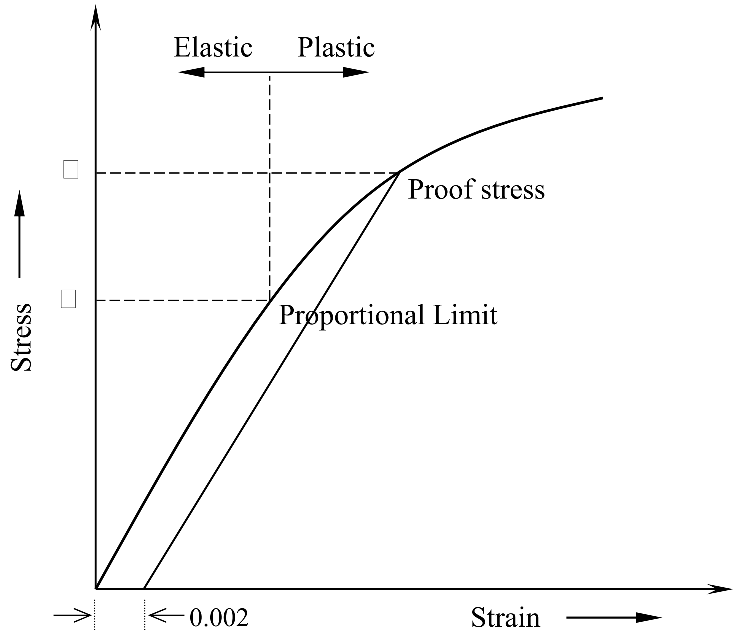
The lowest stress at which permanent deformation can be measured

Proportional Limit

The point at which the stress-strain curve becomes non-linear. In most metallic materials the elastic limit and proportional limit are essentially the same.

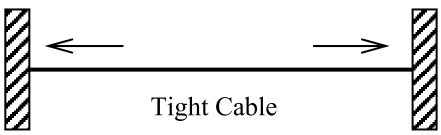
Offset Yield Point (Proof stress):

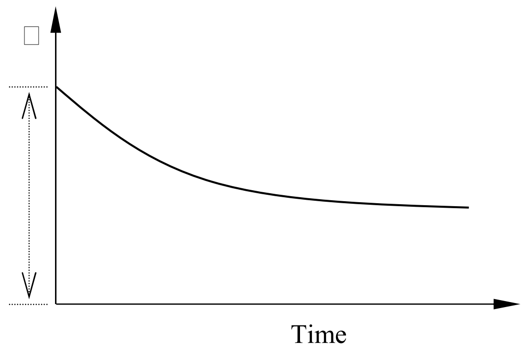
Due to the lack of a clear border between the elastic and plastic regions in many materials, the yield point is often defined as the stress at some arbitrary plastic strain (typically 0.2%, means 0.002 strain). This is determined by the intersection of a line offset from the linear region by the required strain.



Relaxation

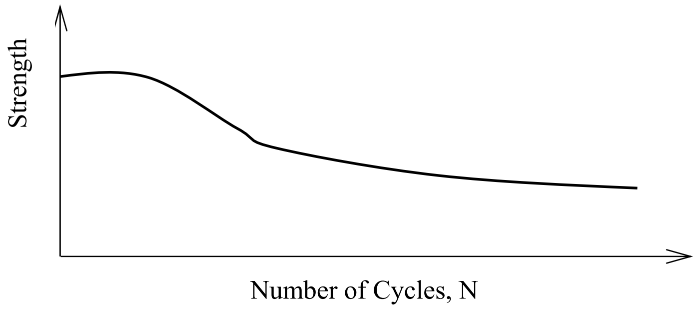
When a fixed strain is applied, the stress in the member will decrease with time. This phenomenon is called relaxation.





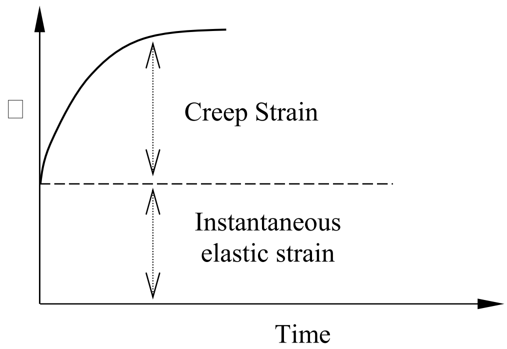
Fatigue

When cyclic loading is applied to a material, failure may occur at a stress much lower than the strength under static loading. This apparent weakening of the material is called fatigue.



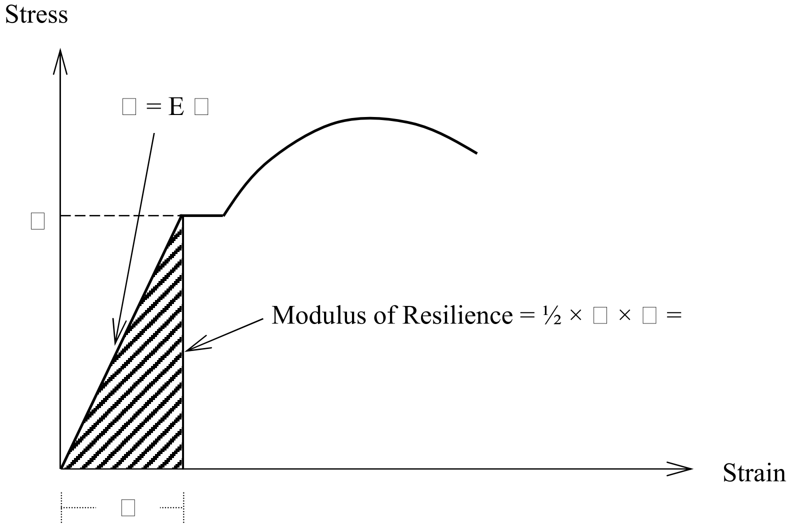
Creep

When a fixed stress is applied, after an instantaneous elastic response, the strain will continue to increase with time. This phenomenon is called creep. It is the term used to describe the tendency to relieve stressed.



Resilience

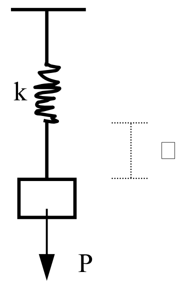
It is the ability to absorb energy in the elastic range. Resilience is defined as the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered.



Stiffness

It is the resistance to deform in the elastic range. Stiffness is the resistance of an elastic body to deflection or deformation by an applied force. It is an intensive material property. The stiffness *k* of a body that deflects a distance *d* under an applied force *P* is

$$k = \frac{P}{\Delta}$$



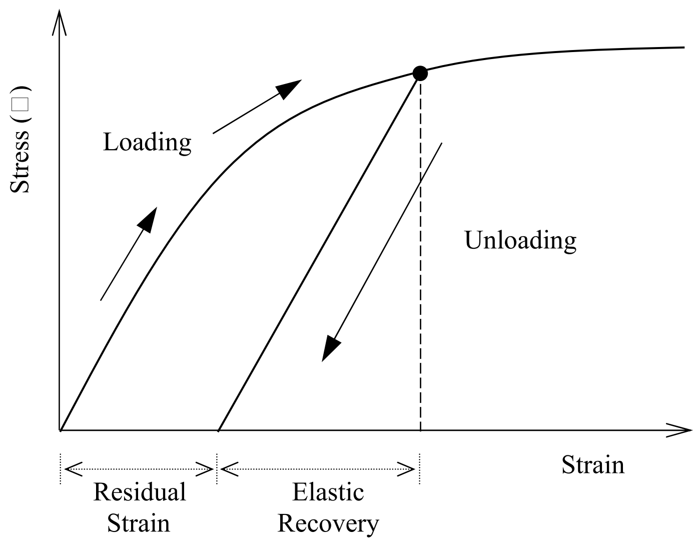
Toughness

The ability to withstand cracking, as opposed to brittleness. It is the ability to absorb or release energy in the plastic range. It is the resistance of a material to fracture when stressed.

Modulus of toughness = the area under the entire stress-strain curve

Plasticity

Plasticity is a property of a material to undergo a non-reversible change of shape in response to an applied force. If the loading is too great then a residual strain, or permanent strain, remains in the material. The corresponding residual elongation of the bar is called the permanent set (residual strain). The material is said to be partially elastic.



Brittleness

It is the tendency of a material to break before it undergoes plastic deformation. Materials that fail in tension at relatively low values of strain are classified as brittle materials.

Malleability

The ability of a material to take a new shape when hammered or rolled. It is the physical property of metals and metalloids, or generally of any kind of matter. A malleable metal can easily be deformed, especially by hammering or rolling.

Hysteresis Loop

For materials exhibiting creep behavior, when a stress is applied, the strain will increase with time. If stress is applied at a slower rate (i.e. over a longer period of time), the resulted strain will be more than that due to a stress applied at a rapid rate. For creeping materials, the loading and unloading curves do not overlap with one another. The area between the two curves (called the hysteresis loop) reflects the energy absorbed by the material over a loading/unloading cycle. This energy absorption varies with loading rate, and is highest at intermediate loading rate.

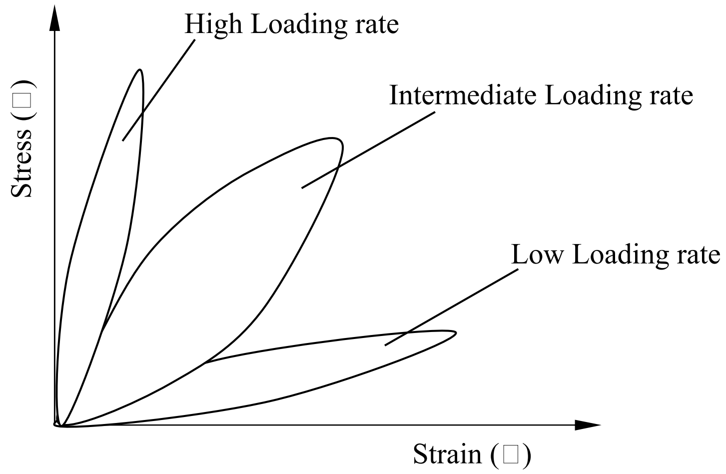


Fig: Hyteresis Behavior Under High and Low Loading Rates

Chapter- 2

BRICK

(Topics: Properties and Uses of Bricks, Efflorescence, Standard Tests of Bricks)

1. *What is brick*?

   Definition: The bricks are obtained by moulding clay (consisting of a suitable percentage of alumina, silica, lime, oxide of iron, and magnesia) in rectangular blocks of uniform size and then by drying and burning (at around 1150^oC) these blocks.

   The bricks seem to have been produced since the dawn of the civilization in the sun-dried form. The Great Wall of China (210 BC) was built with both, burned and sun-dried bricks. The other examples of use of bricks in early stage of civilization could be cited in Italy, Greece, India, Bangladesh and in other places around the globe.

2. *Advantages*:
   - The brick is popular in the places where stones are not easily available but where there is plenty of clay.
   - The brickwork is cheaper than the stonework.
   - The construction method of brickwork is simple.

3. *Disadvantages*:
   - The brickwork is less water tight than stonework
   - The bricks absorb moisture from the atmosphere and dampness can enter the building
   - The brickwork does not create a solid appearance in relation to the stonework, therefore for monumental structures, the stonework is found to be more useful.
   - The stonework is stronger than brickwork.
   - The stonework is cheaper in places where stones are easily available.

4. Constituents of Brick Clay and Their Function

   (i) Silica 55% (SiO_2)

   (ii) Alumina 30% (Aluminium Oxide):Al_2O_3

   (iii) Iron Oxide 8% (Fe_2O_3)

   (iv) Magnesia 5% (Magnesium Oxide): MgO

   (v) Lime 1% ($CaO + CO_2$)

   (vi) Organic Matters 1%

Silica

It exists in all clays either in free or combined. As free sand it is mechanically mixed with clay and in combined form, it exists in chemical composition with alumina. The presence of this constituents prevents cracking, shrinking, and warping of raw bricks. It thus imparts uniform shape to the bricks. The durability of bricks depends on the proper proportion of silica in brick earth. The excess of silica destroys the cohesion between particles and the bricks become brittle.

Alumina

This constitute imparts plasticity to the earth so that it can be molded. If alumina is present in excess, with inadequate quantity of sand, the raw bricks shrink and warp during drying and burning and become too hard when burnt.

Lime

A small quantity of lime is essential in brick earth. It should be present in a very finely powdered state because even small particles of the size of a pin-head cause flaking of the bricks. The lime prevents the shrinkage of the raw bricks. The sand alone is infusible. But it slightly fuses at kiln temperature in presence of lime. Such fuse sand works as hard cementing material for brick particles. The excess of lime causes the brick to melt and hence its shape is lost. The lumps of lime are converted into quick lime after burning and this quick lime slakes and expands in presence of moisture. Such an action results in splitting of bricks into pieces.

Iron Oxide

A small quantity of oxide of iron is desirable in good brick earth. It helps as lime to fuse sand. It also imparts red color to the bricks. The excess of oxide of iron makes the bricks dark blue or blackish. If, on the other hand, the quantity of iron oxide is comparatively less, the bricks will be yellowish in color.

Magnesia

A small quantity of magnesia in brick earth imparts yellow tint to the bricks and decreases shrinkage. But excess of magnesia leads to the decay of bricks.

Alkalies and Organic Matters

A small quantity of organic matter will assist burning bricks. But excess is bad, because if it is not completely burnt, the bricks will be porous. Small quantities of alkalies will lower the fusion point of clay.

5. Harmful Constituent of Bricks

- **Iron Pyrites:** If iron pyrites are present in brick earth (clay), the bricks are crystallized and disintegrated during burning because of the oxidation of the iron pyrites.
- **Alkalies:** They are mainly the chlorides and sulfates of calcium, magnesium, sodium, and potassium. They produce a dark greenish hue on the surface of bricks on drying. They cause the bricks to fuse twist and wrap during drying. Alkalies in bricks absorb moisture from atmosphere. Such moisture, when evaporated, leaves behind gray or white deposits on the wall surface. The appearance (aesthetic) of the building as a whole is then seriously spoiled.
- **Stone Particles:** Small particles of stones do not allow the clay to be mixed thoroughly and uniformly. These are harmful to the uniformity of brick-texture. These make bricks porous and weak.
- **Vegetation and Organic Matter:** They make the bricks porous and weak because vegetation and organic matter get burnt during the burning of bricks leaving small pores in them.
- **Lime:** Lime if present in excess causes the bricks to fuse too readily and the shape is lost. Lime in the form of limestone is very harmful and cause serious trouble to bricks. Because due to high heating, limestone ($CaCO_3$) is converted into CaO and CO_2. In contact with water, lime will hydrate and swell. It causes the bricks to split and crumble to pieces.

6. Manufacturing of Bricks

Following considerations govern the selection of a brick field for the manufacture of bricks:

- It should be linked up with the communicating roads so that the materials can be conveyed easily.
- It should be situated on a plain ground.
- It should be so selected that the earth for manufacturing good quality bricks is readily and easily available
- It should offer all the facilities to the workers employed in the manufacturing process.

In the process of manufacturing bricks, the following four distinct operations are involved:

(1) Preparation of Clay

(2) Moulding

(3) Drying

(4) Burning

Preparation of Clay

(a) Unsoiling: The top layer of soil about 200 mm in depth is taken out and thrown away. The clay in top layer is full of impurities and hence it is to be rejected for the purpose of preparing bricks.

(b) Digging: The clay is then dug out from the ground. It is spread on the level ground. The height of the heaps of clay is about 600 to 1200 mm.

(c) Cleaning: Vegetable matters, pebbles, stones are removed. Lumps of clay are converted into powder form. If impurities are in excess, screening and washing are necessary. These works are very troublesome and costly.

(d) Weathering: The clay is exposed to atmosphere for softening. The period of exposure varies from few weeks to full season.

(e) Blending: The clay is made loose and any ingredient to be added to it, is spread out at its top.

(f) Tempering: In the process of tempering, the clay is brought to a proper degree of hardness and it is made fit for the next operation of moulding. The tempering should be done sufficiently to obtain homogeneous mass of clay of uniform character.

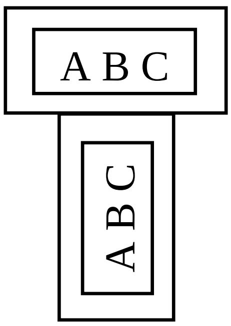
Your Reading: Please read text book for moulding, drying, and burning steps. I will try to cover these topics, if I have time.

7. **Qualities/Characteristics of Good Bricks**

- Bricks should be uniform in color, size, and shape.
- They should be sound and compact.
- They should be free from cracks and other flaws such as air bubbles, stone nodules, etc.
- They should not absorb more than 1/5 of their own weight of water when immerged in water for 24 hours (15 to 20% of dry weight)
- The compressive strength of bricks should be in the range of 5000 to 8000 psi
- The percentage of soluble salts (sulphates of calcium, magnesium, sodium, and potassium) should not exceed 2.5 % in burnt bricks, because the presence of excess soluble salts causes efflorescence.
- They should be neither over burnt or under burnt.
- They weight should be generally 6 lbs per brick and the weight per cft should not be less than 125 lbs.
- They should have low thermal conductivity.
- They should be non-inflammable and incombustible.
- Bricks should not change in volume when wetted.

8. **Field Tests of Bricks**

- Take a brick and try to make a mark on the surface by nail. If it is made easily, the quality of brick is not good. If not, it is very hard and compact.
- Take a brick and strike it with a hammer, if it gives clear metallic sound, it is a good brick
- Take two bricks and form a tee (T) and drop from a height of 6 ft on a more or less solid surface. If they break they are not good bricks.



- A brick is broken and its structure is examined. It should be homogeneous, compact and free from defects such as holes, lumps etc.
- *Presence of Soluble Salts*: The soluble salts, if present in bricks, will cause efflorescence on the surface of bricks. For finding out the presence of soluble salts in a brick, it is immersed in water for 24 hours. It is then taken out and allowed to dry in a shade. The presence of gray or white deposits on its surface indicate absence of soluble salts. If the white deposits cover 10 % surface, the efflorescence is said to be slight and it is considered as moderate, when the white deposits cover 50 % of the surface. If more than 50 % of the surface, the efflorescence is considered to be heavy, and it is treated as serious, when such deposits are converted into powdery mass.

9. Sizes of Bricks

In Bangladesh, the standard size of bricks is 9.5" × 4.5" × 2.75". With mortar, the final size becomes 10" × 5" × 3". The sizes of the walls which are constructed in Bangladesh are 3", 5", 10", 15", 20", 25" and 30". By using, standard size bricks, these sizes of walls can be built very easily without any breaking of the bricks.

10. Classification of Bricks

(i) *First Class Bricks*

- Uniform size and color
- Well and uniformly burnt
- Emit metallic sound when struck with a hammer or another brick
- No cracks, rain spots, or flaws on the surface
- Not absorb one sixth of their weight of water when kept under water for 24 hours

(i) *Second Class Bricks*

These bricks must possesses the hardness and color of first class bricks but are slightly irregular in shape, size or rough on the surface.

(ii) *Third Class Bricks*

- Not sufficient burnt
- Uniform shape and size
- Can be used for un-important construction

(iii) *First Class Bats*

Broken pieces of first and second class bricks

(iv) *Second Class Bats*

Broken pieces of the third class bricks

(v) *Picked Jhama Bricks*

- Uniform vitrified throushout
- Good shape, heavy, selected quality
- Not spongy

(vi) *Jhama Bricks*

(vii) *Jhama Bats*

(viii) *Special Bricks*

(a) Perforated Brick (for lightweight structure and multistoried framed structures, perforation may be rectangular, circular, square, or any other regular shape in cross-section)

(b) Hollow Bricks (also known as the cellular or cavity bricks. They are light in weight. They reduce the transmission of heat, sound, and dampness.)

(c) Checkered Bricks (less slippery, used for garden walks, street pavements, etc.)

(Please see Fig. 3.7 of book by M. A Aziz)

11. Uses of Bricks

- Construction of walls of any size
- Construction of floors
- Construction of arches
- Making khoa (broken bricks of required size to use as an aggregate in concrete)
- Manufacture of surki (powdered bricks) to be used in lime plaster and lime concrete

Note: For 100 cft of brickworks 1200 nos. of bricks and 45 cft of mortar are repaired. 830 bricks will make 100 cft of khoa for concrete.

5. Manufacturing (Remaining Steps: Moulding, Drying, and Burning)

For manufacturing good bricks on a large scale, the tempering is usually done in pug mill. The process of grinding clay with water and making it plastic is known as pugging bricks. If tempering is made properly, the good brick earth can then be rolled without breaking in small threads of 3 mm diameter.

Moulding

Two types of moulding:

1) Hand moulding (if labor is cheaper)
2) Machine moulding

The bricks shrink during drying and burning. Hence, the moulds are to be made larger than the size of the fully burnt bricks. The moulds are therefore made longer by about 8 to 12 % in all directions.

A brick moulder can mould 750 bricks per day with working period of 8 hours. When such bricks becomes sufficiently dry, they are transferred to drying sheds.

Hand moulding can be divided into the following two types:

- Ground moulded bricks (slop-moulded bricks, sand-moulded bricks)
- Table mouded bricks (less efficiency, costly)

Strike: Used to level the bricks

Frog Mark

A frog mark is a mark of depth of about 10 mm to 20 mm which is placed on raw brick during moulding. It has two purposes:

- It indicates the trade name of the manufacturer
- Acts as a key for mortar

Pallet/ Moulding Block/ Stock Boards: Used to make frog mark.

Drying

The damp bricks, if burnt, are likely to be cracked and distorted. All bricks are placed on edge. The moisture content at dry condition to be around 2 %.

- Natural Drying
- Artificial Drying
- Circulation of Air
- Drying Yard
- Period for Drying 3 to 10 days.
- Screens/ Sheds: Bricks are not directly exposed to wind or sun for drying.

Burning

It is very important operation in the manufacture of bricks. It imparts hardness and strength to the bricks and makes them dense and durable. The bricks should be burnt properly. If bricks are over burnt, they will be brittle and hence break easily. If they are under burnt, they will be soft and hence can not take load.

At 650^o C organic matter is crystallized. If cooling is applied at this temperature, it will absorb water from atmosphere and will rehydrate. The reactions of mineral constituents to give strength to brick are taken place at higher temperature, at around 1100^o C. Over burning causes to form a huge amount glassy mass and bricks are said to be vitrified. The bricks begin to loose their shape beyond a certain limit of vitrification.

Clamp Burning (Please read the book, I will only explain the main points verbally)
Kiln Burning (Please read the book, especially Hoffman's Kiln, I will only explain the main points verbally)

Comparison of Clamp Burning and Kiln Burning

	Clamp Burning	Kiln Burning
(1) Capacity	Low	High
(2) Cost of Fuel	Low	High
(3) Initial Cost	Very low	High
(4) Quantity of Bricks	60 % is good	90 % is good
(5) Regulation of Temperature	Not possible	Controlled
(6) Skilled Supervision	Not necessary	Necessary
(7) Structure	Temporary	Permanent
(8) Time of Burning and Cooling	2 to 6 months	Burning for chamber – 24 hours, cooling 12 days
(9) Wastage of Heat	High	The hot flue gas is used for drying and free heating

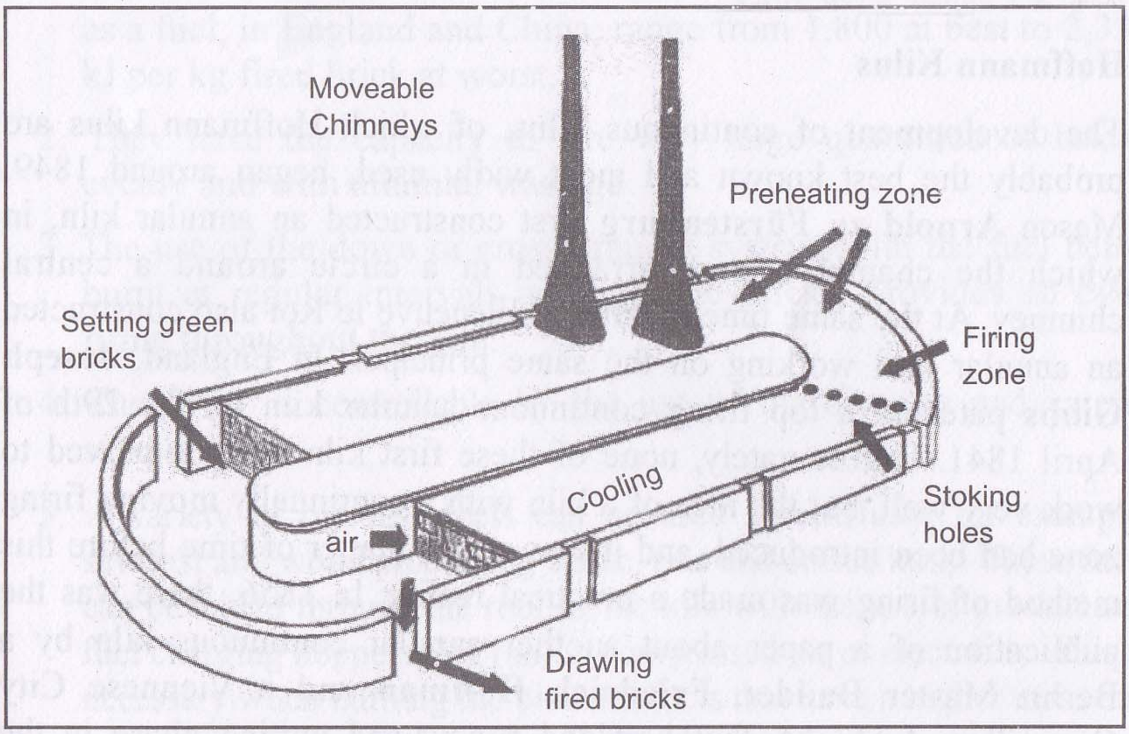


Fig. 7.4 Bull's Trench Klin

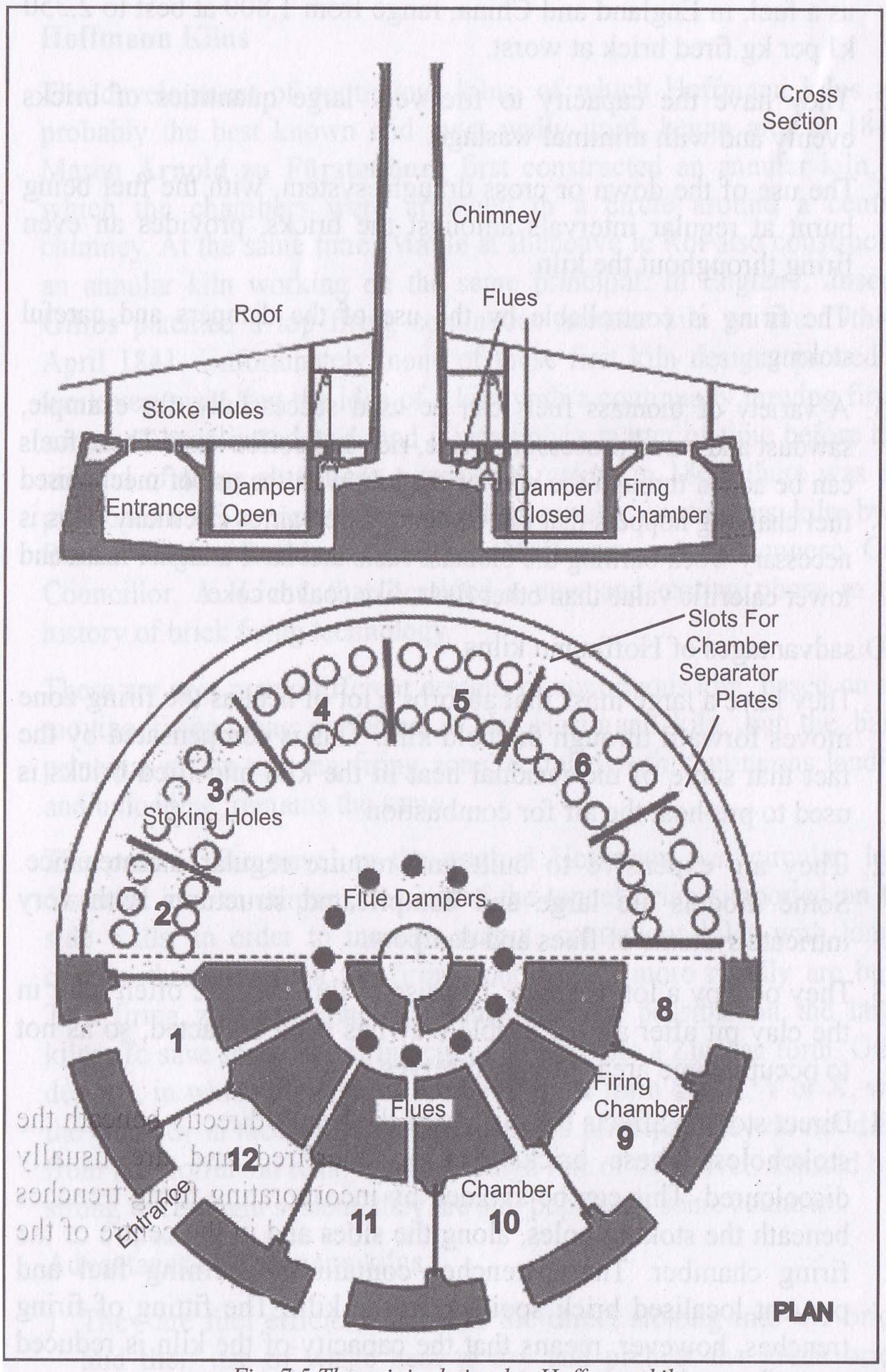


Fig. 7.5 The original circular Hoffmann kiln

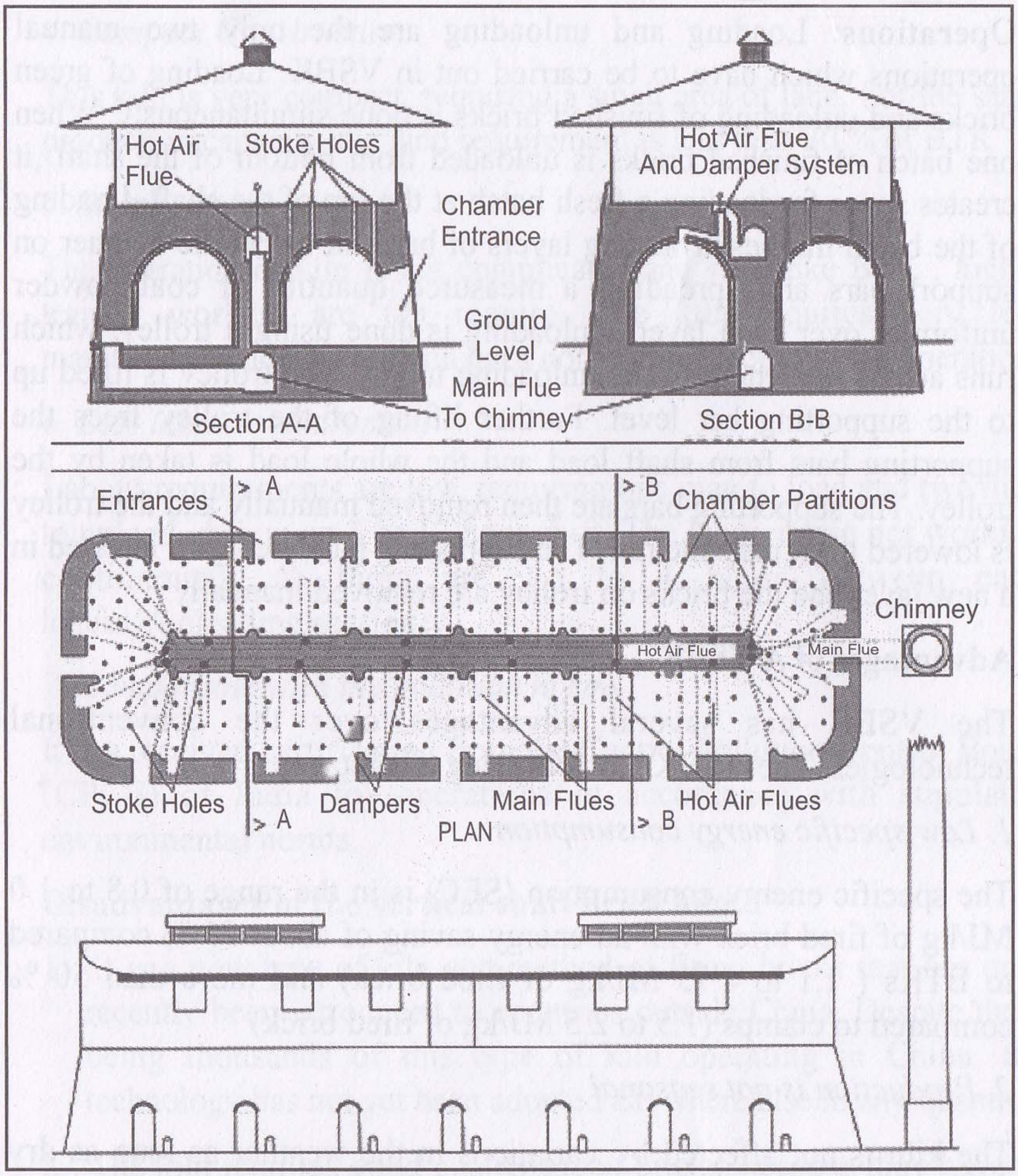


Fig.7.6 A modern 16 chamber Hoffmann kiln

Chapter – 3

CEMENT CHEMISTRY

Cement is a cementing or binding material used in engineering construction. It is mainly used in concrete work. It is manufactured from calcareous substance (compounds of calcium and magnesium) and is similar in many respects to the strongly hydraulic limes but possessing far greater hydraulic properties. It differs from lime in many respects.

- Particle size of cement : 10 ~ 20 μm
- 12 billion tons of concrete is newly placed in every year
- Normally cement concrete contains 15 % of cement
- It may be 20 % for a high strength concrete
- About 2 billion tons of cement is used in every year
- 1 ton CO_2 is emitted for 1 ton cement product
- Making long term durable structures is essential to reduce CO_2 emission from cement industries

How can we reduce the emission of CO_2? (cement industries)

We can not stop the cement production. We can reduce the consumption of cement.

- We can use blended cement to reduce cement clinker also to reduce CO_2
- Make durable concrete structure (service of structure to be increased)

Types of Cement

- Natural Cement
- Artificial Cement

Natural Cement

Manufactured by burning and crushing of natural stones containing 25 to 40 %. Clay and carbonate of lime ($CaCO_3$) remaining, sometimes magnesium carbonate is added. It is brown in color and sets quickly when mixed with water. The best variety of natural cement is known as 'Roman Cement' in England.

Artificial Cement

Artificial cement is known as ordinary cement/ordinary Portland cement/ Normal Portland cement/ Normal cement/Normal setting cement/ Ordinary Portland. Artificial cement is said to be Portland Cement due to its resemblance in color and quality to Portland stone which is found in Portland in England abandently.

Raw materials or composition of Portland Cement

1. Calcareous materials --- which are the compounds of calcium and magnesium. (lime stone)
2. Argillaceous materials ---- which are mainly silica, alumina and oxides of iron (clay or shale)

Mineral constituents of Portland Cement

Constituents	Oxide-composition	Abbreviation	Composition (%)
1. Tricalcium silicate	$3\ CaO.\ SiO_2$	C_3S	45 ~ 55
2. Dicalcium silicate	$2CaO.\ SiO_2$	C_2S	20 ~ 30
3. Tricalcium Aluminate	$3CaO.\ Al_2O_3$	C_3A	9 ~ 13
4. Tetra Calcium Alumino ferrite	$4CaO.\ Al_2O_3\ Fe_2O_3$	C_4AF	8 ~ 20
5. Calcium Sulphate (Gypsum)	$CaSO_4\ .\ 2H_2O$		2 ~ 6
6. Other Compounds			2 ~ 8

Oxide Components and their effects (acid & alkaline constituents)

- **Lime (CaO):** More than 60 % cement is lime. Hydration reaction occurs with the presence of lime. A deficiency in lime reduces the strength of cement and causes it to set quickly. Excess will make cement unsound and cause its to expand and disintegrate.
- **Silica (SiO_2):** It produces hydrates with lime and helps to create a dense structure.
- **Alumina (Al_2O_3):** It produces hydrate with lime. Excess will cause expansion. clinker temperature is lowered by the presence of requisite quantity of a alumina.
- **Magnesia (MgO):** It should not present more than 2 % in cement. Excess is harmful and reduce the strength of the cement.
- **Iron Oxide (Fe_2O_3):** It imparts color to cement. At very high temperature it reacts with calcium and aluminium to form C_4AF (it hydrates with lime and alumina) which imparts hardness and strength to cement.
- **Calcium Sulphate ($CaSO_4$. $2H_2O$):** It regards setting action of cement. Excess will cause expansion.
- **Sulphur Trioxide (SO_3):** Excess will cause unsoundness or expansion.
- **Alkalies:** Excess will cause expansion/efflorescence. Especially with the presence of reacting aggregates it will also reduce strength.

Oxide Compounds

Constituents	Composition (%)
1. Calcium Oxide (CaO)	60 ~ 67
2. Silica (SiO_2)	17 ~ 25
3. Magnesium Oxide (MgO)	0.1 ~ 4.0
4. Alumina (Al_2O_3)	3 ~ 8
5. Iron Oxide (Fe_2O_3)	0.5 ~ 6
6. Sulphur Trioxide (SO_3)	1 ~ 3
7. Potassium Oxide (k_2O)	0.3 ~ 1.0
8. Sodium Oxide (Na_2O)	0.4 ~ 1.3

Reactive Aggregates: Mainly used in Canada, Australia, USA

Ignition Loss & Insoluble Residue:

If we burn cement in 1100° C temperature, the measurement of loss amount is called ignition loss.

$$X \xrightarrow{1100^{o}\,C} Y$$

$$\therefore \ \%\ \text{loss} = \frac{X - Y}{X} \times 100\% \ \text{(Ignition loss)}$$

If we mixed cement with HNO_3, gel like solution is produced, and some amount of precipitation.

$$\text{Cement} + HNO_3 \rightarrow \text{gel (solution)} + \underset{(0.3 \sim 0.5\ \%)}{\text{Insoluble residue (ppt)}}$$

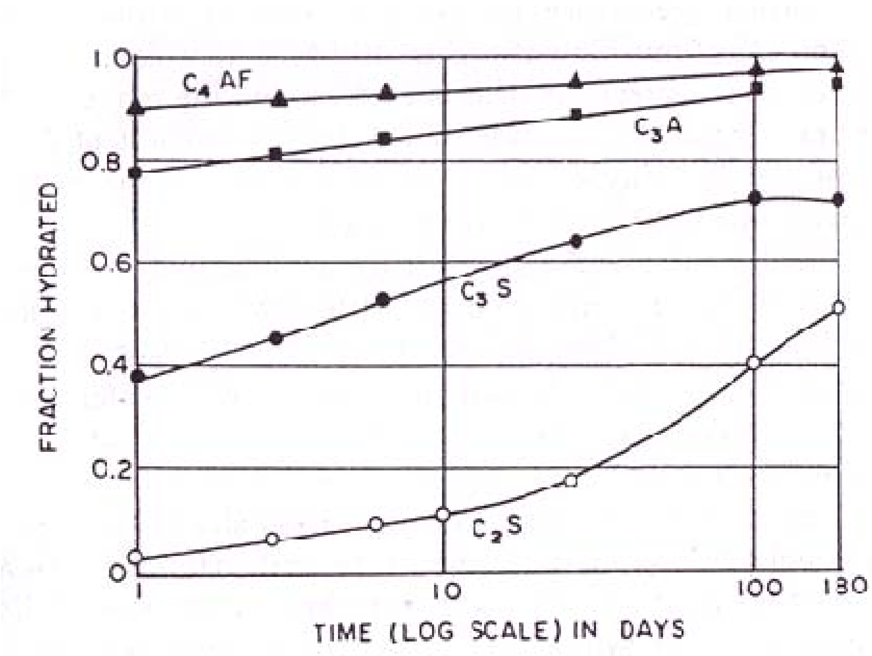
Hydration of Cement

Hydration: The term 'Hydration' is applied to all reactions of cement to water. All the cement constituent compounds are in a hydrous (dry) state. After addition of water in cement, C_3A & C_4AF react immediately with water and then C_3S is next to hydrate. C_2S is the slowest constituent component to hydrate and the process continuous for several days. The main strength is developed from the hydration of C_3S and C_2S. C_2S is responsible for the progressive strength of cement.

Hydration of Silicate

$C_3S + H_2O \rightarrow CSH + CH$

$C_2S + H_2O \rightarrow CSH + CH$



CSH: It is the amorphous compound. It is a gel like compound that gives strength to cement. Exactly it is the main compound to give strength (size 1 to 2 μm)

CH: It is a crystalline compound. It is like hexagonal sheet. It is more porous than CSH (size 10 to 20 μm)

Hydration of Aluminate

$C_3A + H_2O \rightarrow CAH$

$C_2AF + H_2O \rightarrow CAFH$

C_3A reacts very quickly. It causes immediate stiffening of the paste known as '*flash setting*'. To prevent it gypsum ($CaSO_4.2H_2O$) is added to cement clinker after grinding.

$C_3A + CaSO_4.2H_2O + H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31\ H_2O$ (insoluble calcium sulfoaluminate)

3CA. 3S . 32H is called ettringite. It is crystalline compound and needle like crystalline product (length 10 to 20 μm). It is an intermediate product which transformed into monosulfate hydrate.

3CA. S. 32H →3CA. S. 18H (plate like crystalline product)

The amount of gypsum added to the cement clinker has to be very carefully watched: in particular an excess of gypsum leads to an expansion and consequent disruption of the set cement paste and also the initial setting time is much delayed. The amount of gypsum added to cement clinker is usually expressed as the weight of SO_3 present. This is limited to a maximum of 2.5 % when the C_3A content is not more than 7 % and 3 % when the amount of C_3A exceeds 7 % but not more than 10 %.

Methods to determine the progress of hydration

The progress of hydration is measured by:

(1) The amount of CH [$Ca(OH)_2$] in the paste
(2) The heat evolved by hydration
(3) Microstructure of the paste
(4) The amount of chemically combined water
(5) The amount of undydrated cement paste
(6) From the strength of the hydrated paste
(7) The specific gravity of the paste

All hydration reactions are exothermic reactions.

Strength of Cement

The strength of cement is very important to design a structure. Cement can not tested alone because it is very fine material. Generally it is mixed with sand/ aggregates. It is tested for compressive strength. tensile strength and flexural strength. Cement is very weak in tension but very strong in compression. The tensile strength is generally $\frac{1}{10}$th of compressive strength. Test is carried out at 1, 3, 7, 14, 28 days. For fly ash slag cement, it is carried out at 51, 91 days.

Setting of Cement

The term '*setting*' is used to describe the stiffening of the cement paste. Setting refers to change of cement paste from a fluid to a rigid state. Setting differs from hardening of cement. The term hardening refers to the gain of strength of a set cement paste. Although during setting the paste acquires some strength.

Initial setting refers to a rapid rise in temperature. At initial setting, the cement paste gain certain degree of consistency. Final setting refers to the peak temperature. At final setting, the cement paste losses the workability. Setting time of cement is strongly effected by the temperature type of cement. fineness etc.

Type of Cement	Setting time
Ordinary cement	High
Fly ash cement	slow
Slag cement	slow

False Setting

False setting indicates abnormal premature stiffening of cement with in a few minutes of mixing with water. Remixing of the paste without addition of further amount of water restores plastic of the paste until it sets in the normal manner and without a loss of strength. Some causes of a false setting are:

- **Hydration of gypsum:** If gypsum ($CaSO_4$. $2H_2O$) is added with hot clinkers semi hydrate ($CaSO_4$. ½ H_2O) or anhydrate ($CaSO_4$) are formed and when the cement is mixed with water these hydrate to form gypsum again. Thus setting takes place with a resulting stiffening of the paste.
- **Excess amount of Alkalies in the paste:** During storage, they may carbonate, alkali carbonates react with CH to form $CaCO_3$. This precipitates and induces a rigidity of the paste.
- **Activation of C_3S by aeration:** Due to activation of C_3S with aeration during mixing a large amount of water may required. This may cause to the false setting of cement.

  [*** A good quality cement should be free from false setting]

Flash Setting

When water is added to a cement paste, C_3A hydrates very quickly and rigidity of the paste is developed. It is known as flash setting. To avoid flash setting, gypsum is added that controls the hydration of C_3A by forming ettringite which converted into monosulfate hydrate (3CASH or 3CaO. Al_2O_3. CaSO4.11H_2O)

Fineness of Cement

Fineness is the total surface area of cement that represent the material available for hydration. The rate of hydration is strongly influenced by the fineness of cement. The more the fineness the higher the hydration reactions. For a rapid development of strength., a higher fineness is necessary. Of course making finer cement costly, Finer cement gives stronger reactions and higher strength. Higher fineness improves the workability of the mix. During storage careful attention is necessary for a cement of higher fineness due to its high degree of activity moisture. Care attention should be given during mixing and curing for a cement with higher fineness. With the increase of fineness of cement durability decreases.

The unit of fineness of cement: Area/weight; cm^2/gm, m^2/kg etc. For Ordinary Portland Cement surface area $\geq$ 2250 cm^2/gm.

Fineness Graph of Cement

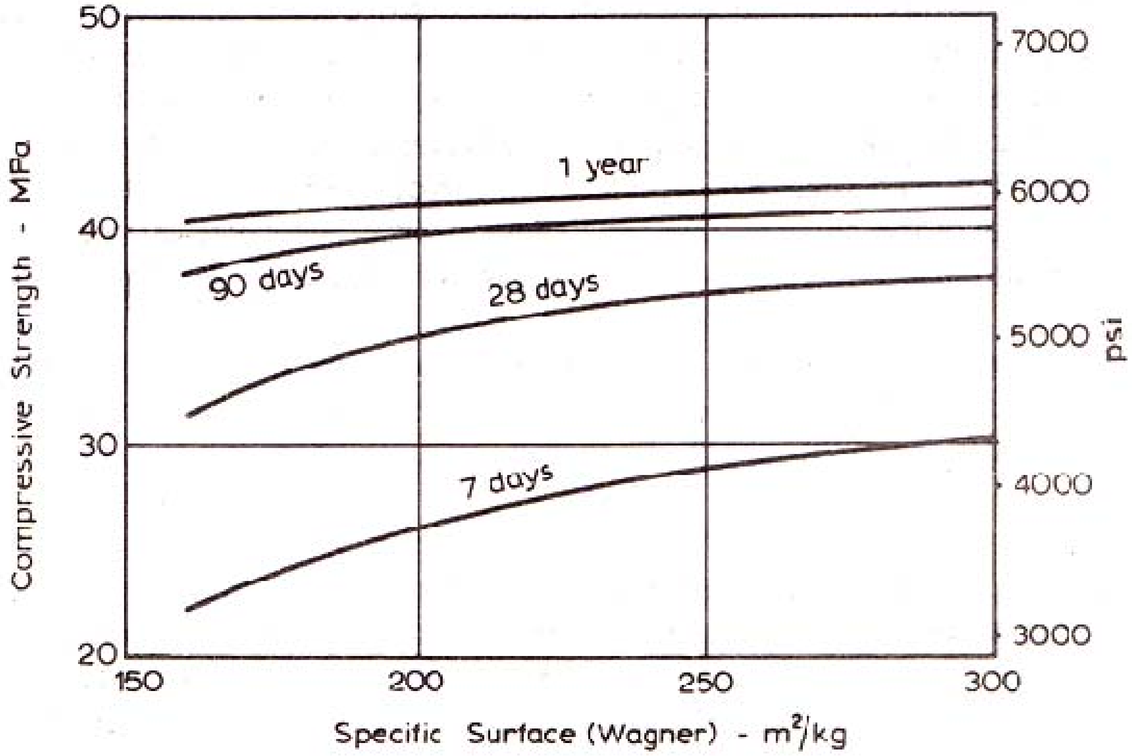


Fig. 1.5 Relation between strength of concrete at different ages and fineness of cement[1.43]

Soundness of Cement

It refers to the change in volume after setting. Excess amount of gypsum ($CaSO_4 . 2H_2O$), free lime (CaO), Magnesia (MgO) causes such kind of expansion. During burning, if excess lime is present in clinker, some lime remains in free condition. The free lime hydrates very slowly and the mortar or concrete prepare with such a cement is therefore liable to expand and crack after a few month on a year.

Cement with exhibit expansion are known as unsound. A sound cement will not show any expansion.

Test for Cement

To control the required quality of the cement, the following tests are carried out:

- Test for fineness
- Test for setting time (initial and final)
- Test for soundness
- Test for chemical composition
- Test for strength

Test for fineness

Fineness if a vital property of cement. BS (British Standard) sieve size: # 170 (90 μm). Maximum residue 10 % by weight for Ordinary Portland Cement. Maximum residue 5 % by weight for rapid hardening cement.

Test for setting time

By using Vicat's Apparatus, we can determined setting time of cement.

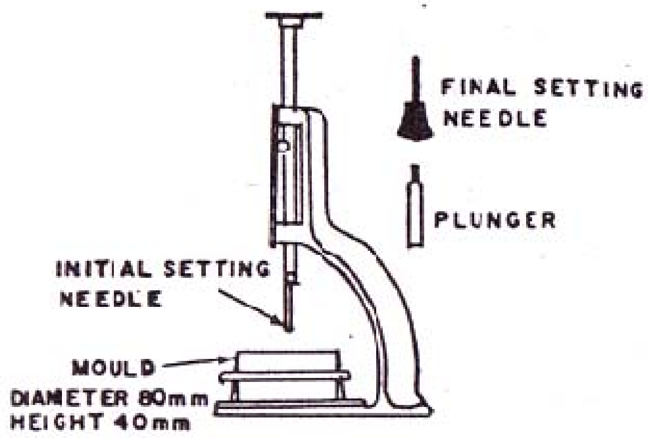


Fig: Vicat Apparatus

Normal consistency: measured by the Vicat's Apparatus →required water for mortar (10 mm penetration by 30 sec)

After determining normal consistency, tested for initial setting time and then for final setting time.

Initial setting time: Not less than 45 minutes (For OPC)
Not less than 60 minutes (For LHC)

Final Setting Time: 10 to 15 hr (OPC) (375 min)
Not more than 10 hr (Blast Furnace Portland Cement)

[*** Setting of cement is affected by the temperature and the humidity of the surrounding medium. These are specified as follows:

(i) Temperature between 58^{o} to 64^{o}F
(ii) Relative humidity of air not less than 90 %

Test for Soundness

The soundness of cement is tested by the *Le Chatellier Apparatus*. The expansion of the cement paste is measured after boiling the sample in water. The test indicates unsoundness due to free lime only.

Sometimes an excess amount of magnesia is present in cement. For this reason another test is needed named as Auto Clave Test. It is done at high temperature (420^{o}F) and high stream pressure (300 psi). The high stream pressure accelerates the hydration of both magnesia and lime

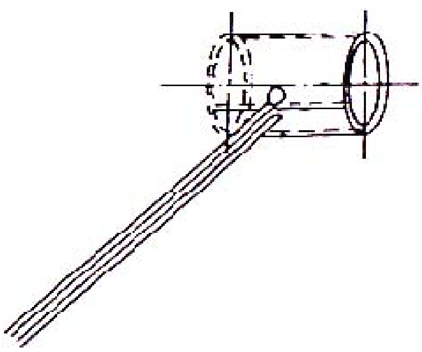


Fig: Le Chatler Apparatus

Chemical Composition test

Both ordinary and rapid hardening cement should give the following results:

(a) Net proportion of lime to silica, alumina and iron oxides shown below:

$$\frac{CaO}{2.8(SiO_2)+1.2(Al_2O_3)+0.065(Fe_2O_3)}$$

(b) Magnesia should not exceed 2 % by weight

(c) Loss of ignition should not exceed 2 % by weight

(d) Insoluble residues should not exceed 0.5 % by weight

(e) SO_3 should not exceed 2 % by weight

Test for Strength

Strength of cement is generally determined after making mortar or concrete. It is never tested alone for strength due to the difficulties in curing and evolution of high temperature. Normally standard sand is used. Standard sand can be uniformly graded sand.

Normal ratio of cement and sand = 1 : 3

Water cement ratio (w/c) = 0.4

(a) Tensile strength (roughly 1/10 of compressive strength)

(b) Compressive strength

(c) Flexural Strength

Tensile strength: Briquette test (Load/Area)

After making specimen it should be demoulded at 1 day age and further cured for 3, 7, 14, 28 days

For OPC ------------ after 3 days : not less than 300 psi
after 7 days: not less than 375 psi

For RHC ------------ not less than 300 psi (3 days); not less than 750 psi (7 days)

Compressive Strength

Mortar cube: Tested at 3, 7, 14, 28 days

For OPC -------------- 2200 psi --- 3 days
3400 psi – 7 days

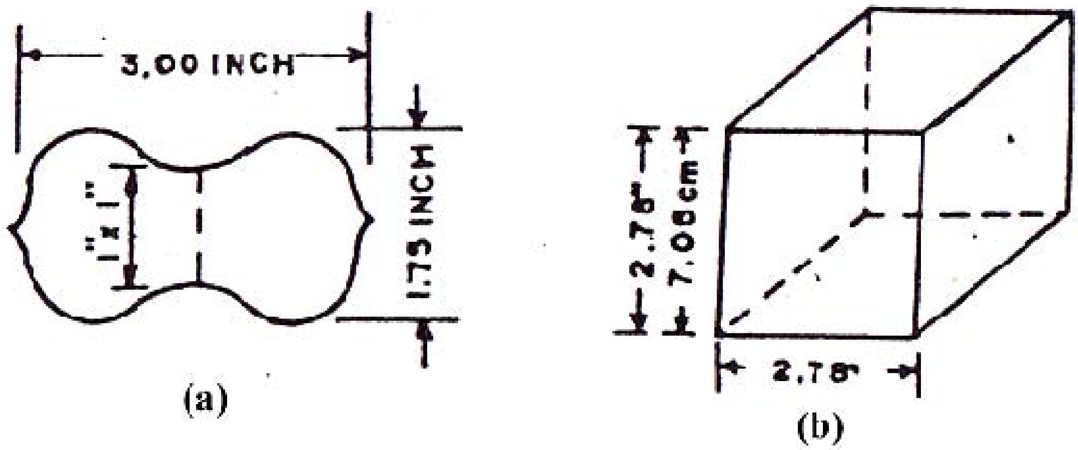


Fig: (a) Specimen for tensile test, (b) Mortar cube specimen

Field Testing of Cement

Field testing should be used only for preliminary investigation, and it does not replace the importance of laboratory tests. These tests are:

(1) **Visual Observation:** After opening the bags (packed with cement), there should be no visible lumps and the color should be greenish gray.

(2) **Feel Test:** In this test, the hand is plunged into a bag of cement. It should not feel warm but cool. The cement is then rubbed between the thumb and the forefinger. If it does not have a lumpy or gritty feeling but gives a smooth feeling, the cement is good.

(3) **Shrinkage Test:** The test requires making a thick paste of cement with water on a piece of thick glass. Ti is then immersed under water for 24 hours. If it does not crack, the cement is good.

(4) **Shape Test:** Take about 100 gm of cement with some water. Make a stiff paste. From the stiff paste, pat a cake with sharp edges. Put it on a glass plate and slowly take it under water in a bucket. See that the shape of the cake is not disturbed while taking it down to the bottom of bucket. After 24 hours, the cake should retain its original shape and at the same time it should also set and attain some strength.

(5) **Flexure Test:** The test requires making a 25 mm × 25 mm × 200 mm (1"× 1" × 8") block of cement with water. The block is then immersed under water for three days. After removing, it is supported 150 mm apart and weight of 15 kg uniformly placed over it. If it shows no signs of failure, the cement is good.

Main types of Portland Cement

English Description (B.SI)	American (ASTM) Description
1. Ordinary Portland	Type I
2. Modified Portland	Type II
a) Air Entraining Portland	
b) Expanding Portland	
3. Rapid Hardening Portland	Type III
4. Quick Setting Portland	---
5. Low Heat Portland	Type IV
6. Sulphate Resisting Portland	Type V
7. Blast Furnace	Type IS
8. Pozzolana Portland	Type IP
9. White Portland	---

Hydration (heat) of cement

Exothermic reactions are occurred. The rate of evolution of heat is an indication of the rate of hydration. The following shows a plot of the rate of evolution of heat against time:

three peak (I, II, III):

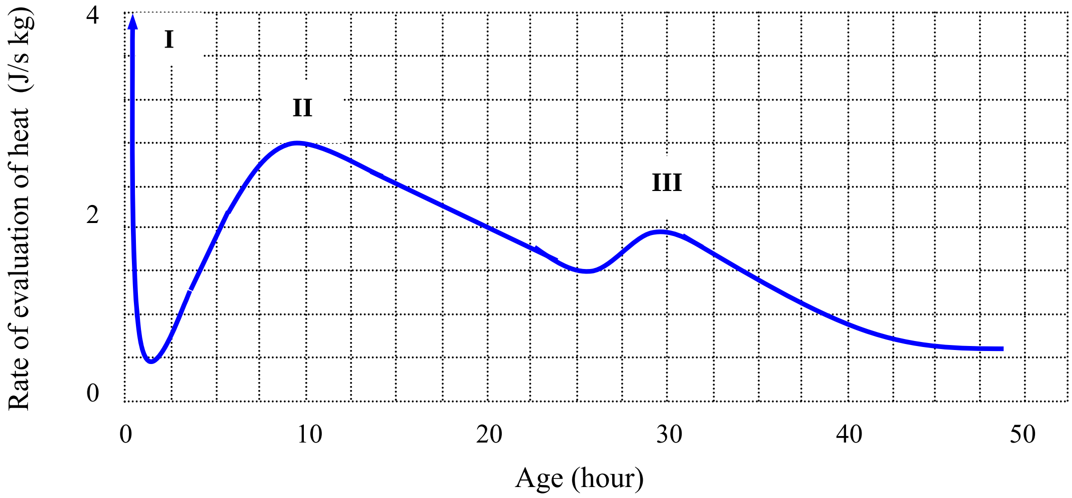


Fig: Rate of evaluation of heat of Portland cement with a water/cement ratio of 0.4.

(I) ⇒ Hydration at the surface of the cement particles largely involving C_3A. The duration of this rate of hydration is very short. A *dormant* period is observed immediately, sometimes also called induction period, during which the rate of evolution of heat is very low. This period lasts 1 to 2 hours during which the cement paste is workable.

Rate of hydration increases slowly and the products of hydration of individual grains come into contact with one another, setting then occurs. The rate of heat evolution reaches a second peak, typically at the age of about 10 hours, but sometimes as early as 4 hours.

(II) and (III) ⇒ During this peak, the rate of hydration slow down over long period. A third peak is occurred at the age of 18 to 30 hours. This peak is related to a renewed reaction of C_3A, following the exhaustion of gypsum. Second peak accelerated by the presence of alkalies, by a higher fineness, by an increases in temperature.

CH liberated by the hydrolysis of C_3S, C_2S forms thin hexagonal plates, often 10 μm long, but can be merge into a massive deposit.

Varieties of Cement

In addition to ordinary cement, the following are the other important varieties of cement:

(a) Acid-resistant Cement

(b) Blast Furnace Cement or Slag Cement

(c) Colored Cement

(d) Expanding Cement

(e) High Alumina Cement

(f) Hydrophobic Cement

(g) Low Heat Cement

(h) Pozzolana Cement

(i) Quick Setting Cement

(j) Rapid Hardening Cement

(k) Sulphate Resisting Cement

(l) White Cement

(m) Antibacterial Cement

(n) Blended Cement

Acid-resistant Cement

Some additives are used to increase resistance against acid attack. The acid-resistant cement is used for acid-resistant and heat-resistant coatings of installations of chemical industry.

Blast Furnace Cement or Slag Cement

Slag, a by-product of steel making industries is used in making blast furnace slag cement. Slag content in slag cement varies widely from 10 to 65 %. The higher amount of slag content is suitable for long-term durability in the marine environment. The hydration of slag cement is slower than the hydration of ordinary Portland Cement. The earlier strength of slag cement is low but in the long-term significant gain in strength is observed. Careful curing is necessary for its slow hydration process. It is environmentally friendly cement as it utilized by-product of steel making industries.

Colored Cement

Mineral pigments are added with ordinary Portland cement for making different colored cements. The amount of coloring material may vary from 5 to 10 %. More contents of coloring material may affect the strength of the cement. The chromium oxide gives green color. The cobalt imparts blue color. The iron oxides in different proportions gives brown, red, or yellow color. The manganese oxide is used to produce black or brown colored cement.

Expanding Cement

This type of cement is produced by adding an expanding agent like sulpho-aluminate and stabilizing agent to the ordinary cement. This cement expands at the early stage of hydration. whereas other cements shrink. The expanding cement is used to compensate drying shrinkage. This cement is used in construction of water retaining structures and also for repairing damaged concrete structures.

High Alumina Cement

Alumina content is high in this cement (more than 32 %). This cement is also known as Cement Fondu in England. It gives a high early strength due to the high alumina content. Unfortunately, strength loss of the cement is observed in the long-term due to some conversion of hydration process. Therefore, the use of this cement is officially restricted in the country like England. The cost of this cement is high.

Hydrophobic Cement

This type of cement contains admixtures which decrease the wetting ability of cement.

Low Heat Cement

A considerable amount of heat is released during the hydration of cement. To reduce the amount of heat this type of cement is used. It contains lower % of C_3A and higher % of C_2S. It is mainly used for mass concrete work. It posses less compressive strength at the early age.

Fly ash Cement

Fly ash is a by-product of thermal power plants. A certain % of cement is replaced with fly ash same as slag cement. The amount of replacement can be varied from 10 to 60 % of percent. It receives the heat of hydration, therefore it is good for mass concrete work. It gives low strength at the early age. The curing should be carefully performed due to the slow rate of hydration.

Quick Setting Cement

This cement is produced by adding a small % of aluminium sulfate and by finely grinding the cement. The hydration process quickly starts with the presence of water and gives significant strength 30 minutes after mixing with water. This cement is used to lay concrete under static water or running water.

Rapid Hardening Cement

The initial and final setting time of this cement is similar to the ordinary Portland cement. But, it gives a high at the early age. The C3S content of this cement is very high and also cement are grinded into very fine powder.

Sulphate Resisting Cement

In this cement, C_3A is kept below 5 %. The CAH is expanded with the presence of sulfate, therefore C_3A content of the cement is reduced.

White Cement

It is made from raw material containing very little amount of iron oxide, and manganese oxide. This cement is used for ornamental and architectural works.

Antibacterial Cement

In this cement, anti-bacterial agent is added to prevent the bacterial growth. This cement used in floors of food processing plants, swimming pools, etc.

Blended Cement

Fly ash cement and slag cement are known as blended cements. It is also possible to make cement with other combinations like OPC + FA + S + SF or OPC + FA + S. The blended cement produces a dense microstructure and therefore is very good for long-term durability. Careful curing is necessary for blended cements.

Manufacturing of Cement

There are two main processes, such as (i) Wet Process and (2) Dry Process

Wet Process

The main stages of this process are:

(a) Preparation of Cement Slurry.

(b) Making Cement Clinkers,

(c) Making Powder Cement.

(a) Preparation of Cement Slurry:

Three volumes of calcareous (CaO. MgO) materials are mixed with one volume of argillaceous materials. After mixing the materials are crushed in a crushing machine. Additional required materials are added accordingly. The grinding material should pass through No. 200 sieve. Water of about 45 % is added and complete homogenous suspension is made. The liquid is pumped into a silo and corrected for its composition.

(b) Making Cement Clinkers:

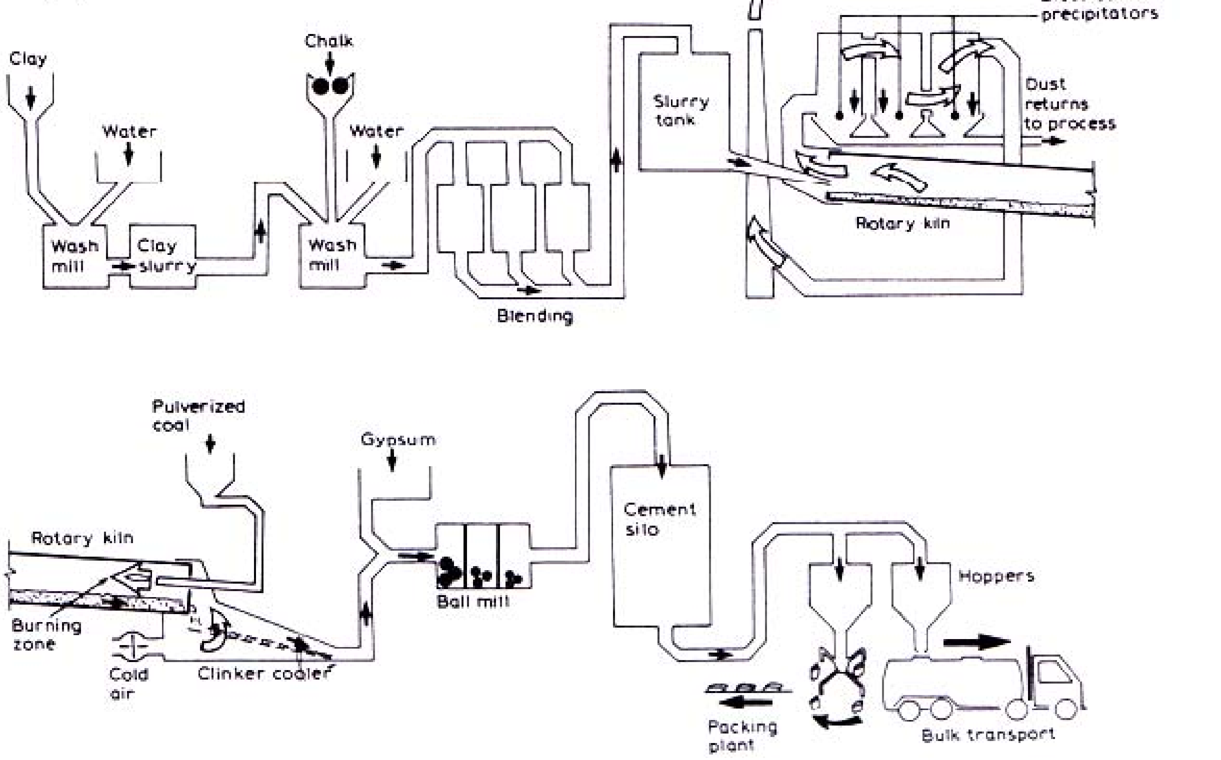
The slurry is fed into a rotary kiln at the top. It is inclined about 0.5 inch to a foot, and is about 8 to 12 ft in diameter and 200 to 400 ft in length. The fuel to be used for the purpose may be coal, oil, or gas. The kiln revolves at a speed of about 2 to 3 revolutions per minutes, depending upon the nature of the material and the time taken by the material to reach the lower end of the kiln. The kiln consists of drying zone, calcinated zone, clinker zone. (Refer to fig. 7.1 of reference by M. A Aziz). At drying zone, the temperature is about 400^o to 600^o F to remove water from the slurry. The next section is known as calcination zone. The temperature at calcination zone is about 1200^o to 1600^o F and the entire moisture from the flakes is removed. The next zone is clinker zone. The temperature at this zone is about 1600^o to 3000^o F. In this zone, the calcareous and argillaceous materials enters into chemical reactions and the composites of cement are formed. These compounds come out as vitrified glassy nodules of varying sizes from 3/8 to ¼ in downwards. This material is known as clinker.

(c) Making Powder Cement:

The hot clinkers have to be cooled and stored before grinding them into cement. Cooling cylinder is moulted at the lower end of the rotary kiln into which the hot clinkers fall and are cooled. The clinker is transferred to a clinker storage department.

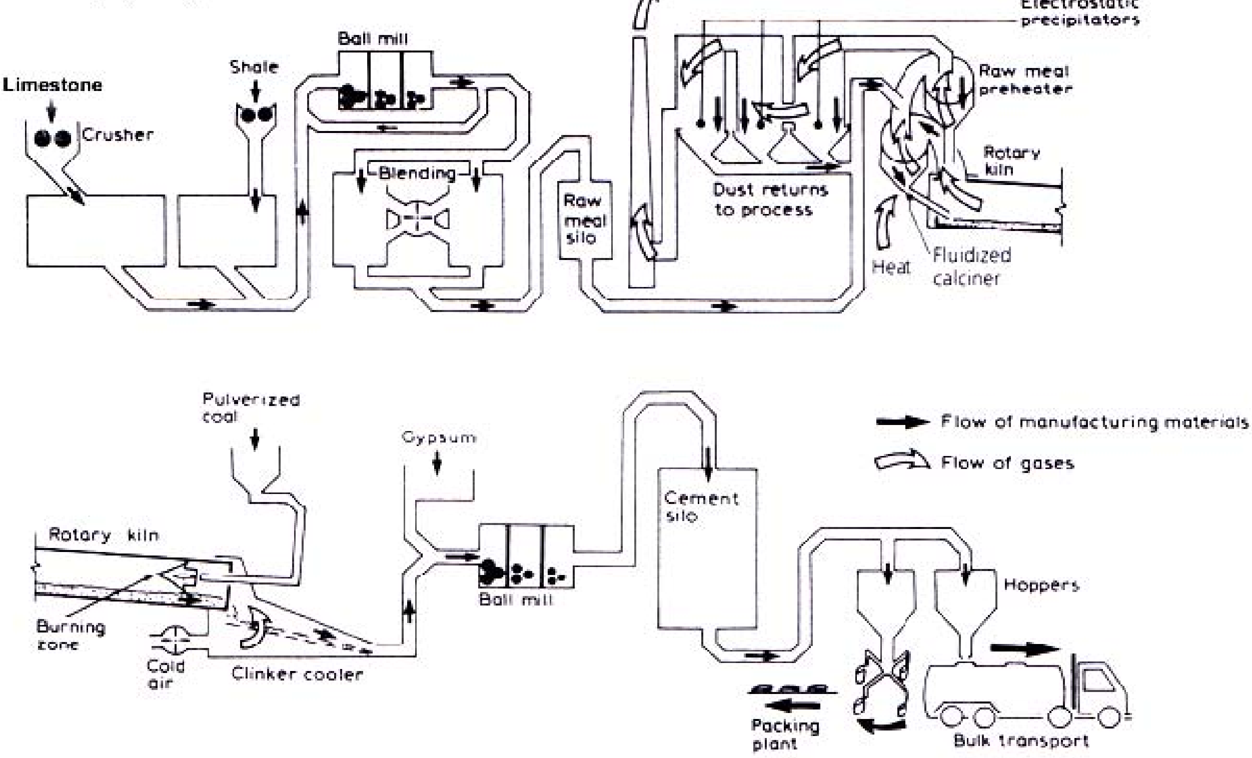
[*** Dry process is cheaper than wet process]

(a) Wet Process

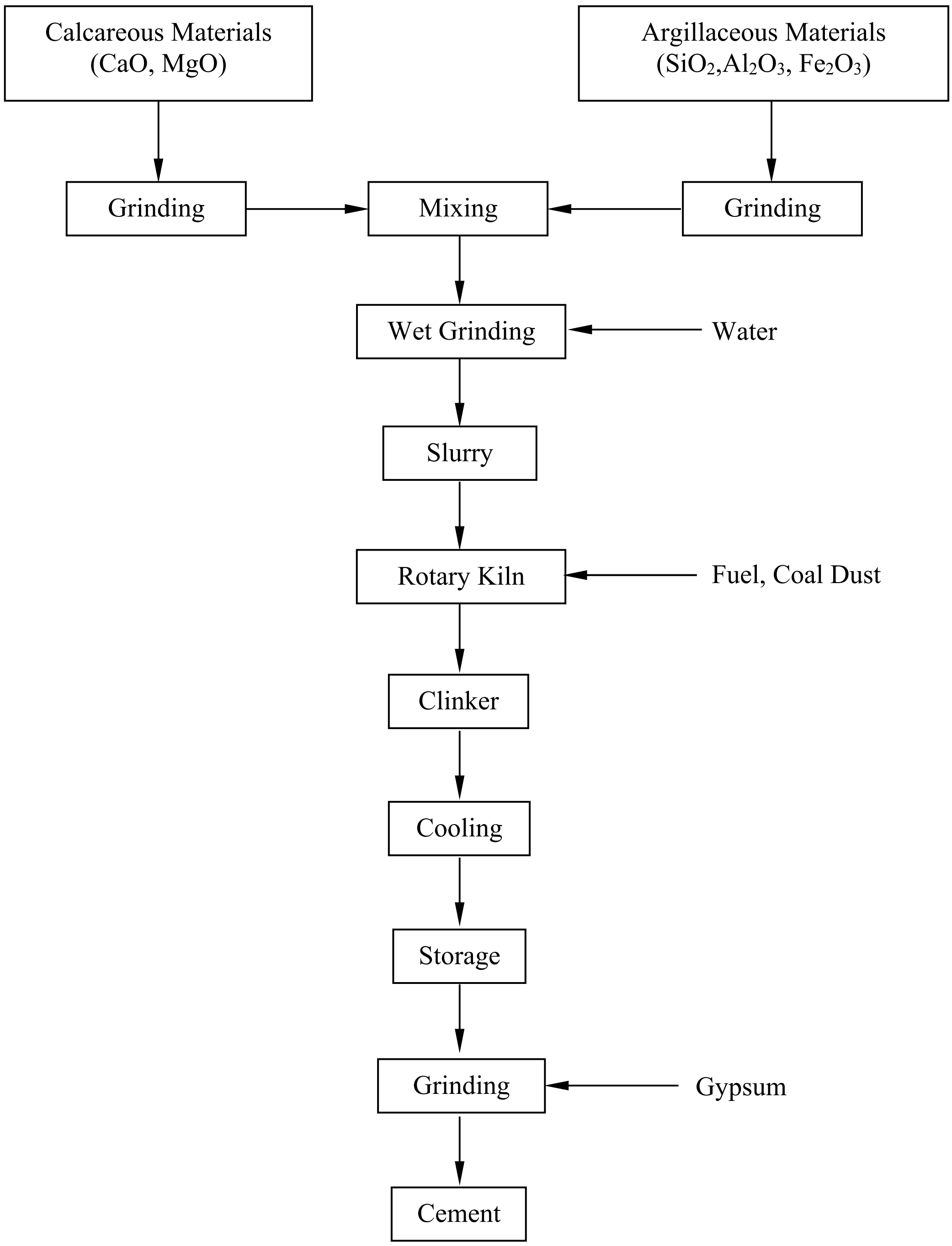


Need lots of energy

(b) Dry Process



Flow Diagram of Cement Manufacturing: Wet Process



Rotary Kiln

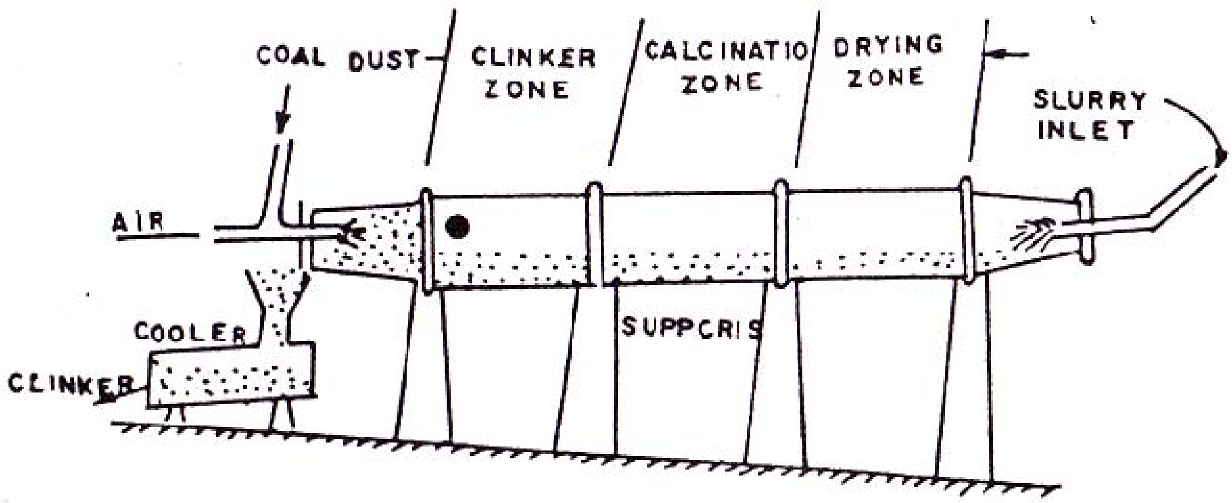


Fig: Rotary Kiln

Chapter – 4

AGGREGATES

What is Sand?

Sand is an engineering material in concrete work. It is usually termed as fine aggregate. Sand is a form of silica (quartz) and may be of argillaceous siliceous or calcareous according to its composition.

- More or less 75 % volume of concrete is aggregate. So good quality of aggregates should be used.
- Aggregates act as a filler material in concrete
- We need good quality aggregate for making good quality concrete.
- Sand should be free from dust (clay + silt) and sand
- Sand should be free from reactive silica or carbonate and organic matter
- Sand should be well graded

  If we have different sizes of particles, we will have less amount of voids. So, we need less amount of cement and get strength in concrete
- Washing of sand is necessary to remove dust
- Dust: which passes through the # 100 sieve. (Dust = Clay + Silt)

Density of different components of concrete: (Specific Gravity)

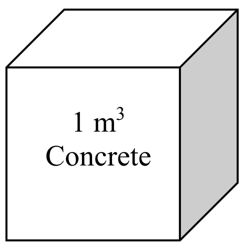
Components	Density (gm/cc)	Density (kg/m^3)	Density (lb/ft^3)
Cement	3.1	3100	
Coarse Aggregate (CA)			
Brick Chips	2.1 ~ 2.2	2100 ~ 2200	
Stone Chips	2.6	2600	
Shingle			
Fine Aggregate (Sand)	2.6	2600	
Water	1.0	1000	62.4
Concrete	2.3 ~ 2.1	2300	

Estimate the different components weight of unit weight of concrete:

1 m^3 concrete = 2300 kg concrete

Aggregates = 75 % of 2300 kg

□ 1780 kg



w/c ratio = 0.54

∴ Cement = 340 kg }
Water = 180 kg } 520 kg

1780 kg → { FA: 780 kg
CA: 1000 kg

Classification of Sand

According to Source:

- Pit Sand
- River Sand
- Sea Sand

According to Shape:

- Angular ( )
- Round ( )
- Flaky ( )

According to Size:

- Coarse Sand (3/8"), FM: 2.6
- Medium Sand (1/8"), FM: 2.2
- Fine Sand (1/16"), FM: 1.8 ~ 2.0

Test for Sand

(i) **Test for silt and clay:** Determined by the percentage loss in weight of a sample after washing the same with clean water.

$$\text{Silt} = \frac{M_{\text{before wash}} - M_{\text{after wash}}}{M_{\text{after wash}}}$$

(ii) **Organic Matter:** A sample of sand is mixed with NaOH in a closed bottle. The sample is left 24 hours. If any organic matter is exist. The solution will become brown. The amount organic matter is determined from the intensity of brown color.

Write down the uses of sand

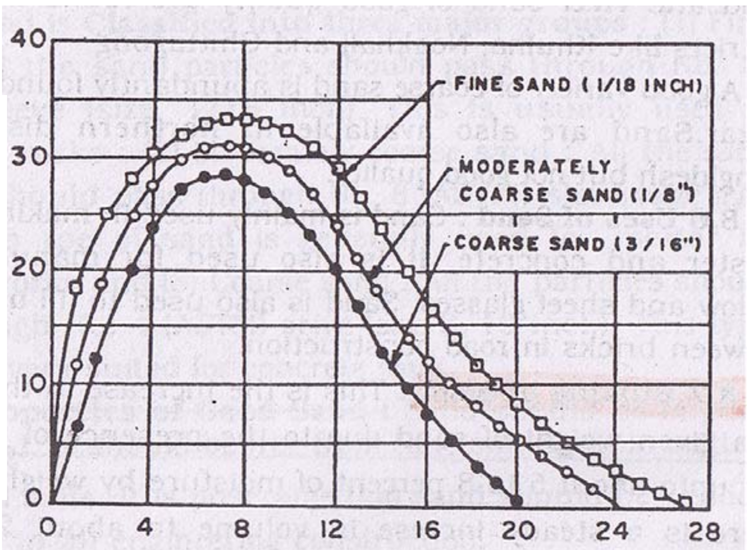
The uses of sand are follows:

- Making concrete and mortar
- Making glasses
- Filling gaps between brick in road construction

Bulking of Sand: This is the increase in the volume of a given weight of sand due to the presence of moisture, For up to about 5 ~ 8% of moisture by weight of sand there is a steady increase in volume to about 20 ~ 30 %.

The bulking of sand for small moisture content is due to the formation of thin film of water around the sand grains and interlocking the air in between the sand grains and the film of water.

Various Types of Pointing
BULKING-PERCENT
(By Volume)



Moisture Content – Percent (By Weight)

Fig: Bulking of Different Types of Sand

Bulking of moist sand is determined by the following expression:

$$b = \frac{\Delta V}{V} \times 100\ \%$$

Where,

ΔV = Change in volume

V = Volume of dry or saturated sand

b = % bulking of moist sand

With the increase of coarseness, bulking (%) decrease. So, bulking of coarse aggregate is less than fine aggregate.

Bulking of Fine aggregate (1/16") = 33 %
Bulking of Coarse aggregate (1/2") = 11 %
} (For 8 % moisture content)

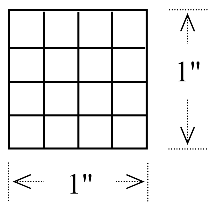
Gradation of Aggregates

- Gradation is the proportion of the different sizes of particles making up the aggregate
- Suitable gradation is required to ensure strength, workability and economy of concrete.
- Principle of Gradation: Smaller size particles fill up the voids left in large size particles
- Sieve analysis is the method to determine grading of aggregates
- For same size particles: void is more
- For different size particles: void is less

ASTM standard Sieve

Sieve Size	Opening (mm)
3"	76.2
$1\frac{1}{2}$"	38.1
3/4"	19.05
3/8"	9.5
# 4	4.75
# 8	2.36
# 16	1.19
# 30	0.59
# 50	0.30
# 100	0.15

4 ⇒



- # 100 ⇒ 1 in^2 ⇒ 100 × 100 (Opening)
- # 200 ⇒ 200 × 200 (Opening) in 1 in^2 area of sieve
- Smaller size sieves are defined by the number of opening per linear inch
- Sieves are used to screen the particles in the same sample

Fineness Modulus, Combined Grading and Grading Curve

Fineness Modulus: It is an index which gives an idea about fineness or coarseness of aggregate.

- FM is not an indication of grading of aggregates as an infinite number of grading can have same FM.
- Mathematically, FM is

$$FM = \frac{\sum \text{Cumulative \% retained on each standard sieve}}{100}$$

- For good concrete

  FM for FA is (2.25 ~ 3.25)

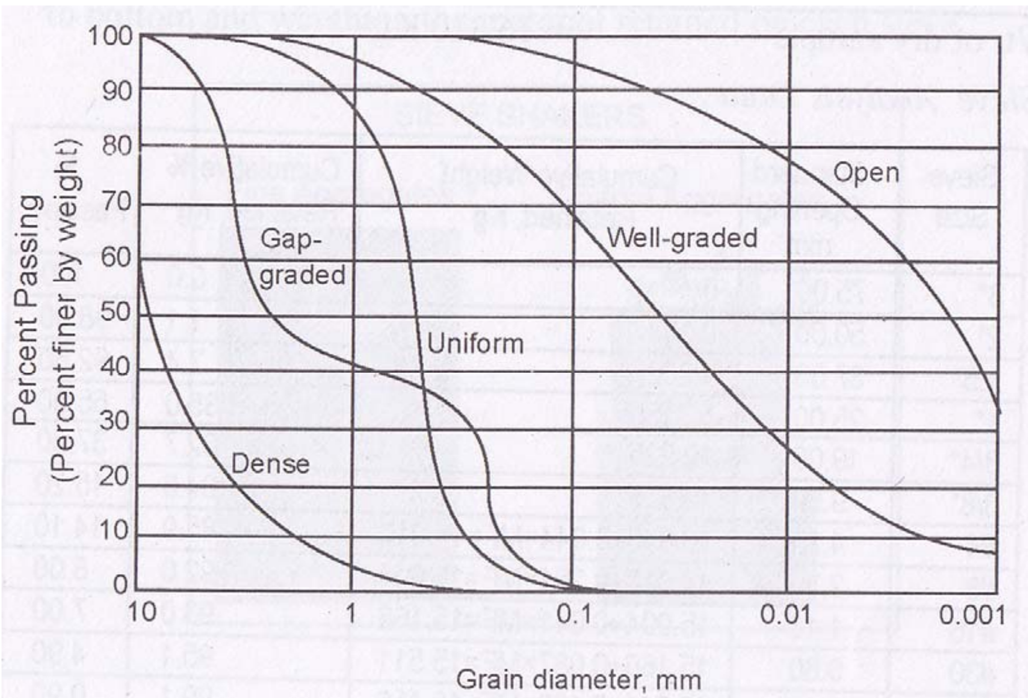
  FM for CA is (5.50 ~ 7.50)

- The smaller the value of FM, the more is smaller sizes in aggregate.

Grading Curve

The results of a sieve analysis can be grasped much more easily if represented graphically and for this reason, grading charts are very extensively used. By using a chart, it is possible to see at a glance whether the grading of a given sample conforms to that specified, or is too coarse or too fine, or deficient in a particular size.

- Gap grading caused uneconomical mix
- Uniformly grading --------- lot of voids
- More finely grading caused --- less workability, low strength concrete
- More coarsely grading caused segregation
- Uniformly grading caused segregation



Five Types of Gradation

Combined Grading: Mixed grading of CA and FA. FA fills up the voids left in CA.

Combined FM:

$$\text{FM}_{\text{comb}} = \frac{m_1 FM_1 + m_2 FM_2 + --------- + m_n FM_n}{m_1 + m_2 + -------- + m_n}$$

For two samples:

$$\text{FM}_{\text{comb}} = \frac{m_1 FM_1 + m_2 FM_2}{m_1 + m_2}$$

$$\Rightarrow \text{FM}_{\text{comb}} = \frac{m_1 / m_2 FM_1 + FM_2}{m_1 / m_2 + 1}$$

$$\Rightarrow m_1/m_2 = \frac{FM_2 - FM_{comb}}{FM_{comb} - FM_1}$$

$$\Rightarrow R = \frac{FM_2 - FM_{comb}}{FM_{comb} - FM_1}$$

$\therefore$ R : 1 = Sample -1(wt) : Sample -2 (wt)

m_1/m_2 = R

= Ratio of Sample–1 and Sample–2

FM_1 = Fineness modulus of Sample–1

m_1 = Mass of Sample–1

Problem: For a bridge construction project, the recommended FM for sand is 2.6. From a nearby market, two sand samples (sand-1 and sand-2) were collected. The samples were sent to the Concrete Laboratory of The University of Asia Pacific (UAP) for sieve analysis. The sieve analysis data are given below:

ASTM Sieve	**Amount Retained (gm)**	
	Sand – 1	**Sand – 2**
3□	0	0
1.5□	0	0
1.0□	0	0
3/4□	0	0
1/2□	0	0
3/8□	0	0
# 4	70	0
# 8	70	0
# 12	70	70
# 16	70	70
# 30	70	70
# 40	70	70
# 50	0	35
# 100	0	35
# 200	45	100
Pan	45	0

(i) Calculate FM of the sand samples (Note: It is necessary to screen the sand samples by # 4 sieve to calculate the FM)

(ii) Draw the grading curve of the sand samples

(iii) In what proportions, the sand samples are to be mixed to get the recommended FM?

(iv) Comment on the samples based on the sieve analysis data and grading curves

Solution:

Sieve Size	Sieve Opening (mm)	Sand – 1			Sand – 2		
		Materials Retained (gm)	**% Materials Retained**	**Cumulative % Retained**	**Materials Retained (gm)**	**Materials % Retained**	**Cumulative % Retained**
3□	304.8	0	0	0	0	0	0
1.5□	152.4	0	0	0	0	0	0
1.0□	76.2	0	0	0	0	0	0
3/4□	38.1	0	0	0	0	0	0
1/2□	19.05	0	0	0	0	0	0
3/8	9.5	0	0	0	0	0	0
# 4	4.75	70	13.73	13.73	0	0	0
# 8	2.36	70	13.73	27.46	0	0	0
# 12	1.70	70	13.73	41.19	70	15.56	15.56
# 16	1.19	70	13.73	54.92	70	15.56	31.12
# 30	0.59	70	13.73	68.65	70	15.56	46.68
# 40	0.425	70	13.73	82.38	70	15.56	62.24
# 50	0.30	0	0	82.38	35	7.78	70.02
# 100	0.15	0	0	82.38	35	7.78	77.8
# 200	0.075	45	8.82	91.20	100	22.22	100
Pan	–	45	8.82	100	0	0	100
Total		510			450		

$$\therefore \ FM_1 = \frac{\sum \text{Cumulative \% retained on each standard sieve}}{100}$$

$$= \frac{13.73 + 27.46 + 54.92 + 68.65 + 82.38 + 82.38}{100} = 329.52/100 = 3.29$$

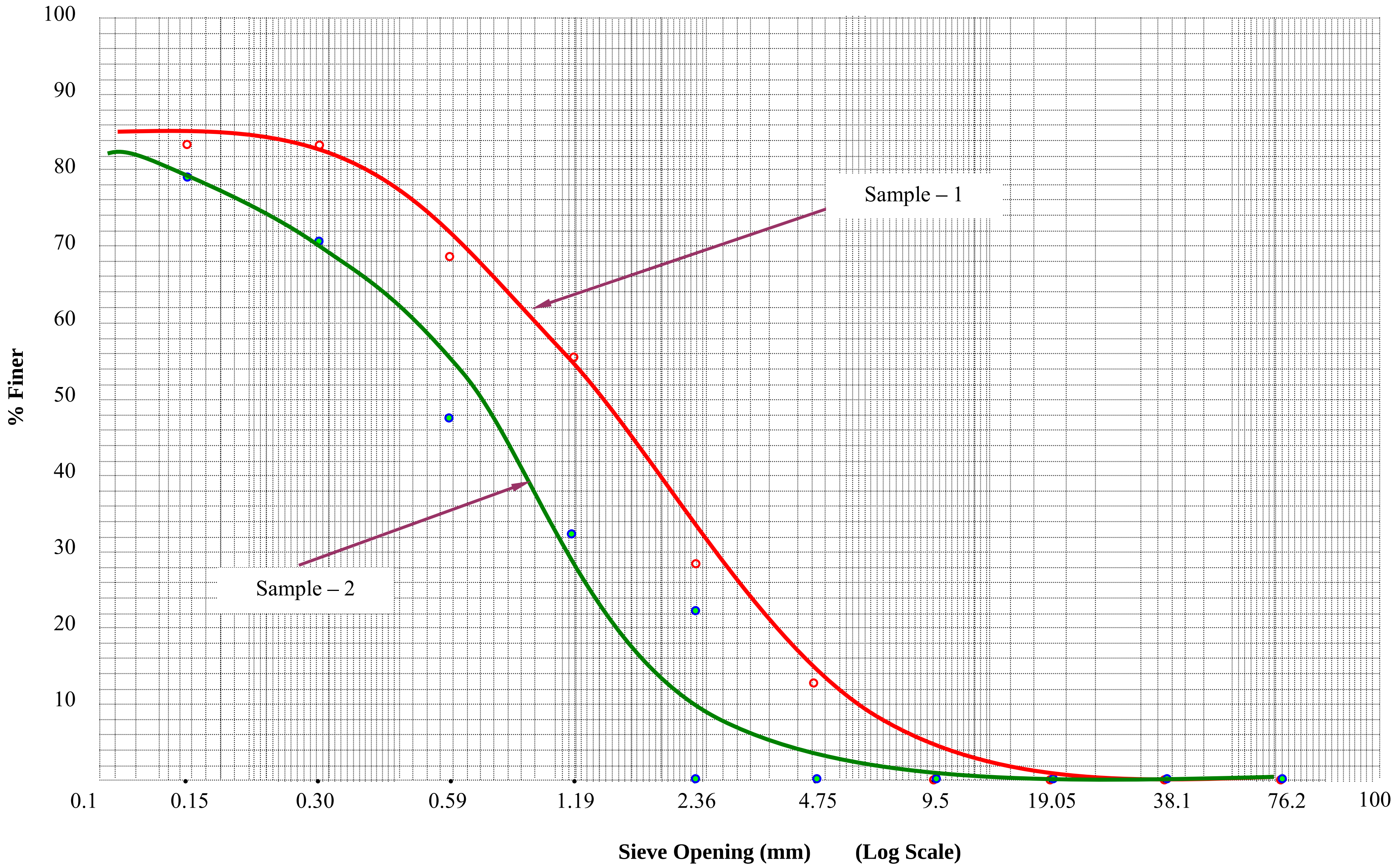
$$\therefore \ FM_2 = \frac{31.12 + 46.68 + 70.02 + 77.8}{100} = 225.62/100 = 2.26$$

$FM_{comb} = 2.60$

$$\therefore \ R = m_1/m_2 = \frac{2.26 - 2.60}{2.60 - 3.29} = 0.49 \ □ \ 0.5$$

$\therefore \ m_1 : m_2 = 1 : 2$

GRADATION CURVE



Explain the moisture States (different possible moisture conditions) of aggregates

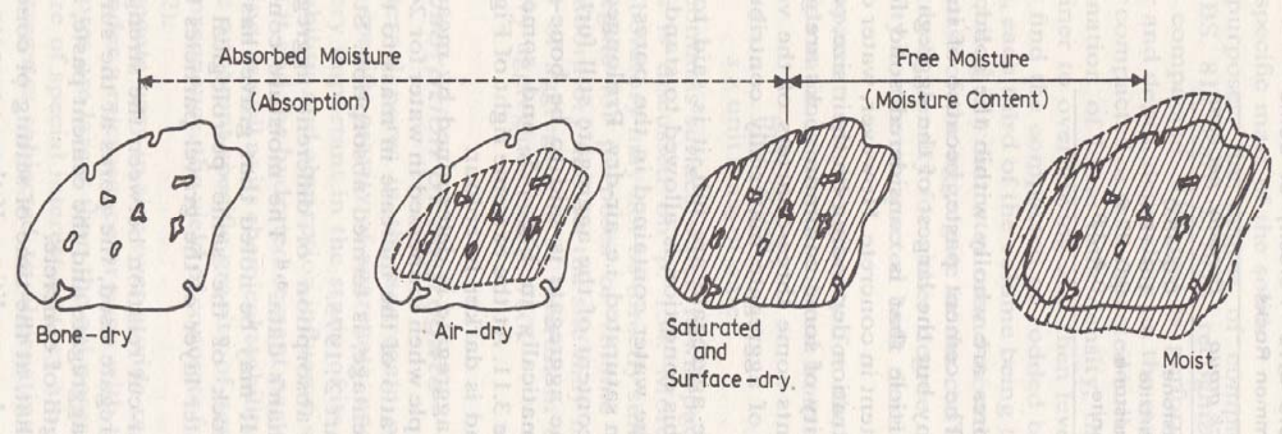


Fig: Diagrammatic representation of moisture in aggregate

- **Oven Dry Condition:** Permeable and impermeable pores are free from water. Oven dry condition is obtained by drying aggregate in a oven at a temperature of $110^{o} \pm 5^{o}$ C ($230^{o} \pm 9^{o}$ F) for 24 hours
- **Air Dry Condition:** Impermeable pores are saturated; permeable pores are free from water.
- **Saturated and Surface Dry Condition:** When all the pores (permeable, permeable pores) are full by water it is said to be saturated and surface dry.
- **Absorption Capacity:** Amount of water absorbed by the material with respect to its oven dry weight.

$$\% \text{ Absorption} = \frac{\text{SSD weight - OD weight}}{\text{OD weight}} \times 100\ \%$$

Brick = 15 ~ 20 %

Stone = 0.5 ~ 2.1 %

Define Bulk Specific Gravity and Apparent Specific Gravity

Bulk Specific Gravity: It is defined as the ratio of the weight of aggregate (OD or SSD) to the weight of water occupying a volume equal to that of the solid excluding the impermeable pores.

It is used :

- For calculation of the volume occupied by the aggregate in various mixtures containing aggregate on an absolute volume basis
- The computation of voids in aggregate
- The determination of moisture in aggregate

Apparent Specific Gravity: It is defined as the ratio of the weight of the aggregate dried in an oven at 100^{o} to 110^{o} for 24 hours to the weight of water occupying a volume equal to that of the solid including the impermeable pores.

Moisture Content of Aggregate:

Void Calculation:

T = Mass of measure (Cylinder)

V = Inner Volume of measure

G = Mass of measure with OD sample

M = Unit weight (OD condition)

M_{SSD} = Unit weight (SSD condition)

$$M = \frac{G-T}{V} \text{ -- (i)}$$

$$M_{SSD} = M\left(1+\frac{A}{100}\right) \left[A = \frac{M_{SSD}-M}{M}\times 100\right] \text{and } [M = M_{OD}]$$

$$\%\ \text{Void} = \left(1-\frac{M}{SW}\right)\times 100$$

S = Bulk Specific Gravity (OD basis)

Bulk Specific Gravity

$$\text{Bulk Specific Gravity (OD basis)} = \frac{\text{Weight of Sample (OD condition)}}{\text{Weight of same volume of water excluding impermeable pores}}$$

$$= \frac{A}{B-C}$$

$$\text{Bulk Specific Gravity (SSD basis)} = \frac{\text{Weight of Sample (SSD condition)}}{\text{Weight of same volume of water excluding impermeable pores}}$$

$$= \frac{B}{B-C}$$

Apparent Specific Gravity

$$G_{sa} = \frac{A}{A-C} = \frac{\text{Weight of Sample (OD condition)}}{\text{Weight of same volume of water including impermeable pores}}$$

Where,

A = Weight of sample (OD) in air

B = Weight of sample (SSD) in air

C = Weight of sample (SSD) in water

SPECIFIC GRAVITY OF COARSE AGGREGATE

ASSHTO T 85

GLOSSARY

Absorption: The increase in weight due to water contained in the pores of material.

Bulk Specific Gravity (also known as Bulk Dry Specific Gravity): The ratio of the weight in air of a unit volume of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at the stated temperature.

Bulk SSD Specific Gravity: The ratio of the weight in air of a unit volume of aggregate, including the weight of water within the voids filled to the extent achieved by submerging in water for approximately 15 hours, to the weight in air of an equal volume of gas-free distilled water at the stated temperature.

Apparent Specific Gravity: The ratio of the weight in air of a unit volume of the impermeable portion of aggregate (does not include the permeable pores in aggregate) to the weight in air of an equal volume of gas-free distilled water at the stated temperature.

SSD (Saturated Surface Dry): The condition in which the aggregate has been soaked in water and has absorbed water into its pore spaces. The excess free surface moisture has been removed so that the particles are still saturated, but the surface of the particle is essentially dry.

SCOPE

Specific Gravity is the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. Water, at a temperature of 73.4^{o}F (23^{o}C) has a specific gravity of 1 (one). Specific Gravity is important for several reasons. Some deleterious particles are lighter than the good aggregates. Tracking specific gravity can sometimes indicate a change of material or possible contamination. Differences in specific gravity can be used during production to separate the bad particles from the good during a heavy media liquid.

Specific gravity is critical information for Hot Mix Asphalt Design Engineer. It is used in calculating air voids, voids in mineral aggregate (VMA), and voids filled by asphalt (VFA). All are critical to a well performing and durable asphalt mix. Water absorption can also be an indicator of asphalt absorption. A highly absorptive aggregate could lead to a low durability asphalt mix.

In Portland Cement Concrete the specific gravity of the aggregate in employed in calculating the percentage of voids and the solid volume of aggregates in computations of yield. The absorption is important in determining the net water-cement ratio in the concrete mix. Knowing the specific gravity of aggregates is also critical to the construction of water filtration systems, slope stabilization projects, railway bedding and many other applications.

This test method determines the specific gravity of coarse aggregates that have been soaked for a period of 15 hours (Figure 1). There are four determinations that may be made from this procedure. They are as follows:

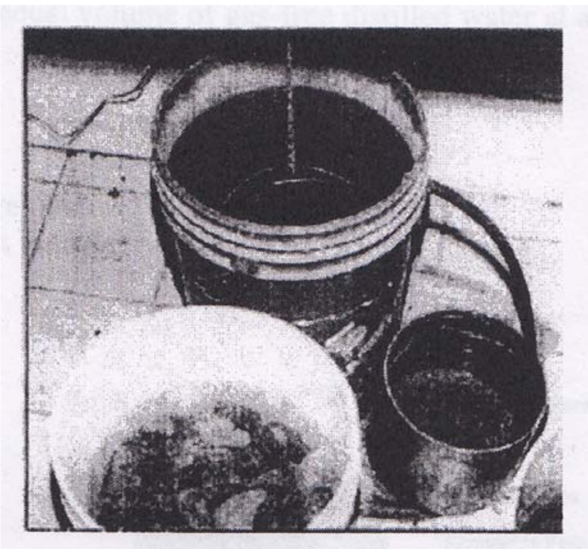


Figure: 1 (Coarse Aggregate Gravity Apparatus)

A. Bulk Specific Gravity (G_{sb}) (also known as Bulk Dry Specific Gravity)

The ratio of the weight in air of a unit volume of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature (Figure 2). This unit volume of aggregates is composed of the solid particle, permeable voids, and impermeable voids.

$$G_{sb} = \frac{A}{B - C}$$

Where,

A = Oven dry weight
B = SSD weight.
C = Weight in water.

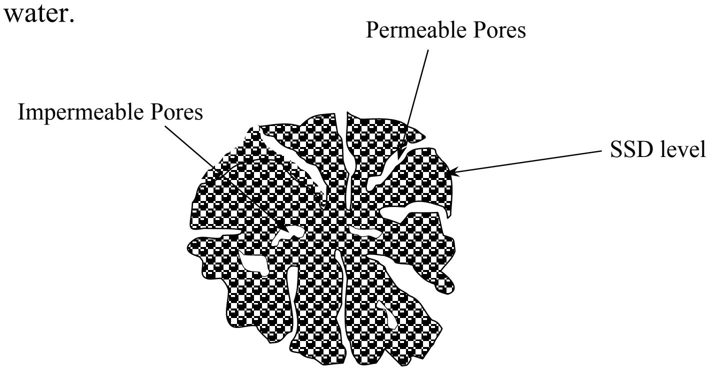


Figure: 2 (Diagram of Bulk Specific Gravity)

B. Bulk SSD Specific Gravity (Gsb SSD)

The ratio of the weight in air of a unit volume of aggregate, INCLUDING the weight of water within the voids filled to the extent achieved by submerging in water for approximately 15 hours, to the weight in air of an equal volume of gas-free distilled water at a stated temperature (Figure 3).

$$G_{sb} = \frac{B}{B - C}$$

Where,

B = SSD weight.
C = Weight in water.

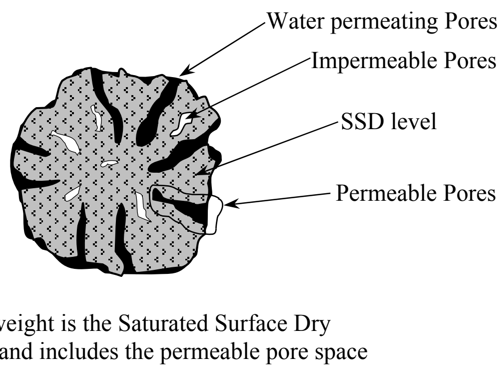


Figure:3 (Diagram of Bulk SSD Specific Gravity)

C. Apparent Specific Gravity (G_{sa})

The ratio of the weight in air of a unit volume of the IMPERMEABLE portion of aggregate (does not include the permeable pores in aggregate) to the weight in air of an equal volume of gas-free distilled water at a stated temperature (Figure 4)

$$G_{sa} = \frac{A}{A-C}$$

Where,
A = Oven Dry weight.
C = Weight in water.

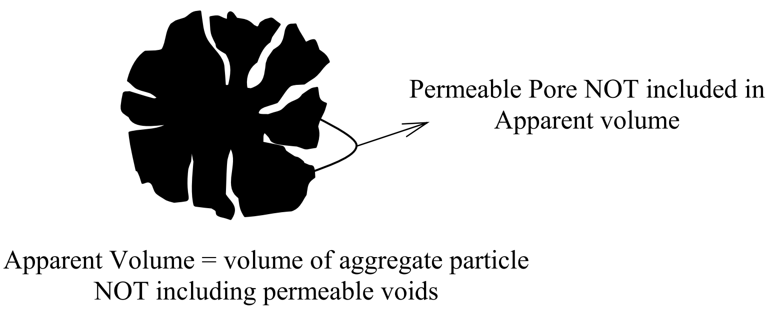


Figure: 4

D. Absorption (% Abs.)

The increase in weight of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles (Figure 5).

$$\%\ \text{Abs.} = \frac{B-A}{A} \times 100$$

Where,
A = Oven Dry weight.
B = SSD weight.

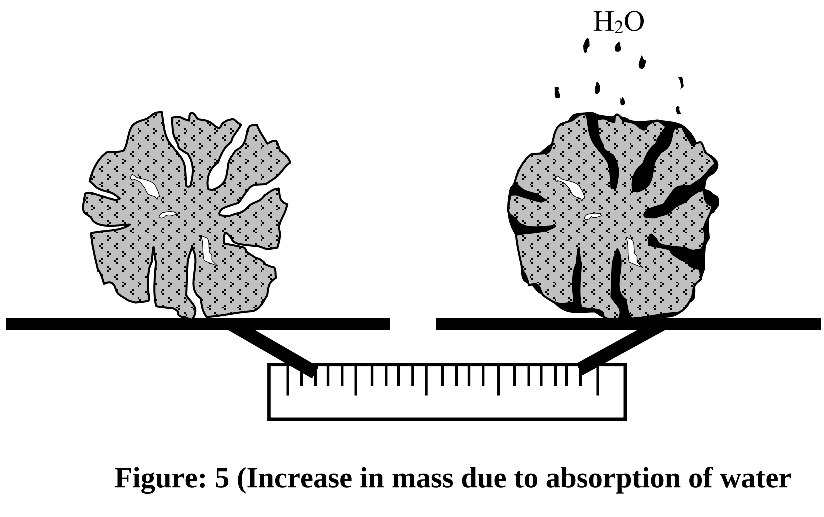


Figure: 5 (Increase in mass due to absorption of water

SUMMARY OF TEST

Apparatus

Apparatus, conforming with class G5 (AASHTO M231)

Sample container, wire basket of No. 6 (3.35 mm) or less mesh wire cloth, with a capacity of 1 to 1.75 gal (4 to 7 L) to contain aggregate with nominal maximum size of 1.5 in (37.5 mm) or smaller; larger basket for larger aggregates.

Water tank, watertight and large enough to completely immerse aggregate and basket, equipped with an overflow value to keep water at a constant level.

Suspended Apparatus, wire used to suspend apparatus with the smallest practical diameter. A hi-test fishing leader or other thin wire with utility hook can be used with a small hook attached to the handle of the basket or sample container.

Sieves, No. 4 (4.75 mm) or other size as needed, conforming to AASHTO M 92.

Chapter – 5

CEMENT AND LIME MORTAR

- **Definition of mortar and classification**

Mortar is a paste or mixture of binding material (cement or lime) and an inter material (sand or surki) with water. There are different types of mortar:

- **Cement Mortar:** Cement + Sand + Water
- **Lime Mortar:** Lime + Sand + Water
- **Surki Mortar:** Lime + Surki + Water
- **Lime-Surki Mortar:** Lime + Sand + Surki + Water
- **Mud Mortar:** Mud + Saw dust / Rice husk/ Cow dung + Water

- **Function of Sand in Mortar:**
  - Used mainly as an inter material to give volume for economy
  - Prevents shrinkage and cracking of mortar in setting
  - Improve workability
  - Light reaction between SiO_2 and cement

- **Uses of Mortar**
  - Plaster work
  - Making bond between bricks (1/4")
  - Filling gaps (wall,.....)
  - Hiding joints for improving appearance
  - Decoration purpose
  - In concrete as a matrix

- **Preparation of Mortar**

Hand Mixing (mainly)

- Select materials (cement, sand, water)
- Select appropriate proportion

  C : S = 1 : 3 or 1 : 4

  W/C = 0.5
- Spread the sand on a impervious bed
- Spread cement over sand
- Mix (cement and sand) [uniform color]
- Half of the water is sprinkled over the mixture
- Add another half and mix
- Use the mortar before the commencement of initial setting time
- Curing for hydration

[* * * Definition of curing: prevention of any water loss from concrete or mortar using water (screen)]

Pointing

Pointing is the finishing off (with the trowel) of the mortar in the rough brick joints of walls to give the surface a beautiful appearance.

- For cement pointing, the plaster should consist of cement and clean sand in the proportion 1:2.
- In lime and surki pointing, the plaster consists of lime and surki in the proportion 1:1
- All joints on walls are raked out to a depth not less than ½ inch and all dusts are brushed off

Pointing gives attractive appearance of walls. It protects joints from dampness, and makes then water proof. It is also applied on old walls when the joints become loose and defective

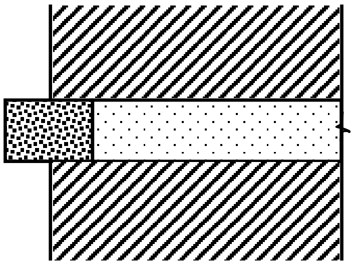


Fig: Tuck Pointing

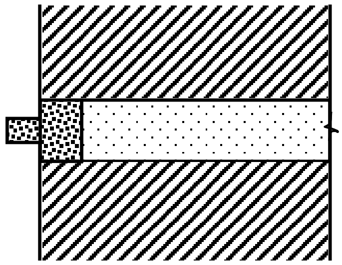


Fig: Bastard Pointing

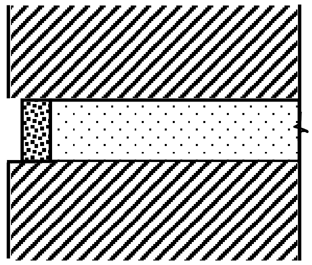


Fig: Cut Pointing

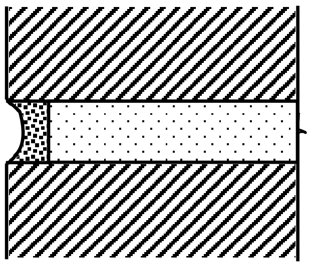


Fig: Rule Pointing

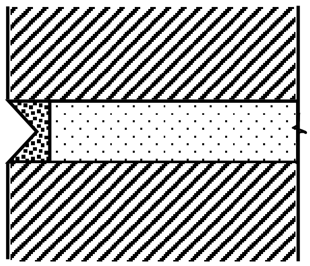


Fig: V- Pointing

Plaster

Definition: A thin coat of mortar on walls, columns, slab, beam etc.

We need plaster to

- Improve appearance
- Increase durability of brick walls
- Improve water tightness

Apply plaster immediately after construction of walls

Before application of plaster, the surface should be cleaned and should be in wet condition

The plaster work is called plastering

- **Specification of good plaster:**
  - Adhere firmly on the surface
  - Not string or contract in volume
- **Cement Plaster**
  - Composed of cement, sand and water
  - Binder : cement
  - C : S = 1 : 3, 1 : 2, 1 : 4 (volume ratio)
  - W/C = 0.5 (weight ratio)

- **Before plastering we need to**
  - Smooth surface
  - Wet surface
  - Curing (at least for 14 days)

White Wash

- Need for better appearance

 # Composition:

- Hydrated / Slaked lime is used
- Cupper sulfate ($CuSO_4.5H_2O$) or Blue
- Gum

 # Process:

- 2 ~ 3 coats are needed
- One coat →Dry →Another →Dry →Another coat

Color Wash

- Need color ingredients
- Same as white wash

Distemper

- It is a coloring substance in solutions
- The process of coloring surfaces of walls with distempers is termed as distempering
- Readily available in the market in liquid state
- Different colors
- use for decorative purpose

Paints

- Example: Enamel, Plastic, Acrylic
- Costlier than white wash / distemper

Problem 1

A mortar is to be placed on a brick surface, sand to cement ratio (by weight) is 0.5. Calculate the proportion of each component (cement, sand, water) per unit cubic meter of mortar. What is the unit weight of mortar? Assume air content in mortar is 0 % and 3 %

You have to prepare on a wall of 20 ft long, 10 ft height and the mortar thickness is 1"

Estimate the amount of mortar necessary for the wall and the amount of each ingredient of mortar. Assume 5 % extra volume of mortar for loss during application. If bulking of sand is 15 %, calculate the volume of sand. [Sand unit weight = 1400 kg/m^3 with void (SSD)]

<u>Solution</u>:

Let, wt of water in 1 m^3 mortar = w

wt of cement in 1 m^3 mortar = c

wt of sand in 1 m^3 mortar = s

Volume of water in 1 m^3 mortar = V_w

Volume of cement in 1 m^3 mortar = V_c

Volume of sand in 1 m^3 mortar = V_s

Sp Gravity of Sand, $G_s = 2.6$

Sp Gravity of Cement, $G_c = 3.1$

Sp Gravity of Water, $G_w = 1.0$

Given, W/C = 0.5

$\Rightarrow$ W = 0.5 C -- (i)

Again, S/C = 2

$\Rightarrow$ S = 2 C --- (ii)

$\therefore$ $V_s + V_c + V_w$ + Air % = 1 (volume) ---------------------------------- (iii)

We know, unit weight of water = $\square_w$ = 1000 kg/m^3

From equation (iii) $\Rightarrow$

$$\frac{S}{G_s\gamma_w} + \frac{C}{G_c\gamma_w} + \frac{w}{G_w\gamma_w} + \text{Air} = 1$$

$$\Rightarrow \frac{S}{2600} + \frac{C}{3100} + \frac{W}{1000} + \text{Air} = 1$$

$$\Rightarrow \frac{2C}{2600} + \frac{C}{3100} + \frac{0.5C}{1000} + \text{Air} = 1 \text{ ---------------------- (iv)}$$ [From equation (i) and (ii)]

If air = 0 % then, from the equation (iv) $\Rightarrow$

$$\frac{2C}{2600} + \frac{C}{3100} + \frac{0.5C}{1000} = 1$$

$\Rightarrow$ C = 628.22 kg/m^3 mortar

$\therefore$ W = 314.11 kg/m^3 mortar

$\therefore$ S = 1256.43 kg/m^3 mortar

$\therefore$ Unit weight of mortar = 2198.76 kg/m^3

$\therefore$ Sp. Gravity of mortar = 2.198 $\approx$ 2.2

And Volume

$V_c = 0.2\ m^3$ mortar

$V_s = 0.48\ m^3$ mortar

$V_w = 0.314\ m^3$ mortar

Total = 1 m^3 of mortar

If air = 3 % then, from the equation (iv) $\Rightarrow$

$$\frac{2C}{2600} + \frac{C}{3100} + \frac{0.5C}{1000} + \frac{3}{100} = 1$$

$\therefore$ C = 609.37 kg/m^3 mortar

$\therefore$ W = 304.69 kg/m^3 mortar

$\therefore$ S = 1218.75 kg/m^3 mortar

And Volume

$$\left.\begin{array}{l} V_c = 0.1013\ m^3 \\ V_s = 0.2416\ m^3 \\ V_w = 0.1571\ m^3 \end{array}\right\}$$

Total = 0.5 m^3 of mortar

Volume of mortar in wall = 20 × 10 × 1/12 = 16.67 cft
= 0.47204 m^3

Considering 5 % loss, amount of mortar = 0.47204 × 105/100 m^3
= 0.496
$\approx$ 0.5 m^3

For 0.5 m^3 mortar, amount of materials necessary for plastering the wall are:

Cement = 628.22 × 0.5 = 314.11 kg = 7 bags

Sand = 1256.43 × 0.5 = 628.22 kg

Water = 314.11 × 0.5 = 157.10 kg

And Volume

$$\left.\begin{array}{l} V_c = 0.1013\ m^3 \\ V_s = 0.2416\ m^3 \\ V_w = 0.1571\ m^3 \end{array}\right\} = 0.5\ m^3 \text{ mortar}$$

Bulking of sand = 15 %

SSD sand = 1400 kg/m^3 with void

$\therefore$ SSD volume of sand = 628.22/1400 = 0.45 m^3 = 16.07 cft

$\therefore$ Actual volume of sand considering 15 % bulking = 16.07 × 1.15
= 18.481 cft
= 20 cft

Chapter – 6

CONCRETE

(Topics: Concrete, Salinity Problem in Concrete, Corrosion and its Prevention, Design of Concrete Mixes, Concrete for Special Purposes, Ferrocement)

- **Concrete**

Homogeneous mixture of binder (cement, lime), aggregate and water at a certain proportion and water cement ratio.

- o Concrete is one of the most useful of construction materials
- o It is used for economy as well as strength
- o CA and FA acts as a filler material, should be non reactive
- o Binding material (cement, lime) acts as a binder

- **Discuss the function of aggregate in concrete**
  - o Smaller size particles (FA's) fill up the voids left in large size particles (CA's)
  - o Aggregates are filler material acts as a filler of concrete which give volume to the concrete
  - o The properties of aggregate greatly affect the durability and strength, workability
  - o Aggregate size depend on (↑) structure size (cove concrete) (↑)

- **Qualities of aggregates for concrete**
  - o Fine aggregate (FA) and coarse aggregate (CA) should be non-reactive
  - o Should be clean, strong, durable and well graded
  - o Less absorption capacity

- **Advantages of aggregate**
  - o Aggregates are cheaper than cement
  - o It confers considerable technical advantage on concrete
  - o It has a high volume stability and better durability than the cement paste alone

- **Water Property**
  - o Water should be drinkable/potable, but some drinkable water may contain a large amount of chloride, sulphate, carbonate, bicarbonate which may lead to problems in concrete
  - o Water should be free from suspended solids
  - o Water is need for hydration and workability

- **Sea Water influence**
  - o Sea water contains 3.5 % of salt and a significant amount of sulphate (2000 ppm)
  - o .Sea water gives earlier strength to the OPC
  - o It accelerates hydration due to the presence of chlorides in sea water
  - o Sea water is dangerous for steel inside concrete. It make corrosion and volume increase upto six time of concrete
  - o Dampness, cracks, efflorescence

Classification of concrete

1. **Cement Concrete:** It consists of cement, aggregate and water. Mix proportion for slab – 1 : 2 : 4 : and column – 1 : 1.5 : 3

   Advantages of Fly Ash Cement Concrete:

   - Reduce cement consumption
   - More durable
   - Improve environment condition
   - Disposal the problem related to fly ash, slag

2. **Lime Concrete:**
   - Lime + Surki + Khoa + Water
   - Proportion – 1: 2 : 5
   - Mainly used in foundation and terrace roofing

3. **Porous Concrete**
   - The mixture of cement, CA, water and no or less amount of sand is called porous concrete
   - It makes lot of pores or voids in the concrete structure
   - It is not good for structure, used for roof, footpath
   - Environment of porous concrete is friendly concrete.

4. **High performance concrete**
   - It refers to the high strength, high workability, high durability of concrete
   - Low permeable concrete or less amount of voids, high dense
   - Rich mix concrete
   - High content of FA (FM: 2.8 to 3.2)

5. **Light weight concrete**
   - Light weight concrete made with natural aggregate originating from hard rock has a density with in a narrow range
   - It has a higher cement content than normal weight concrete
   - Gives better thermal insulation than ordinary concrete
   - Used for floating runway, mega float etc.
   - Narrow range means 20 to 120 lb/ft^3

6. **Under water concrete**
   - Need admixture to make this concrete
   - When concrete at rest, it's viscosity is high
   - It can improve those structure which are near to sea water

Problem Associated with concrete

1. **Segregation:** It can be defined as separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform.

   It is happened due to the difference in the sizes of particles and in the specific gravity of the mix constituents.

   Causes of segregation:

   - Over vibration (strength will be decreased)
   - Over compaction
   - Dropping from a considerable height
   - Use of less amount of binding materials (cement......)
   - Use of gap-graded aggregate
   - Mix concrete should not more than 5 ~ 6 minutes
   - Handling, transportation and placing

   How can we reduce segregation?

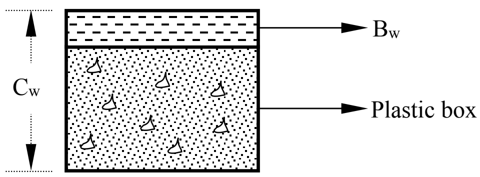
   - Entrained air reduces the danger of segregation
   - It can be controlled by choice of suitable grading and w/c ratio
   - By care handling, transporting and placing of concrete

2. **Bleeding:** Bleeding is one kind of segregation and also known as water gain in which some of the water in the mix tends to rise to the surface of freshly placed concrete. Water having the lowest specific gravity among constituents of concrete. Therefore it has a tendency to rise upward.

   Bleeding is generally expressed in terms of percentage of mixing water or quantitatively as the total settlement per unit weight of concrete.

$$\% \text{ Bleeding} = \frac{\text{Amount of bleed water in contain volume } (B_w)}{\text{Total amount of mixing water in the same volume } (C_w)} \times 100$$

   Causes of Bleeding:

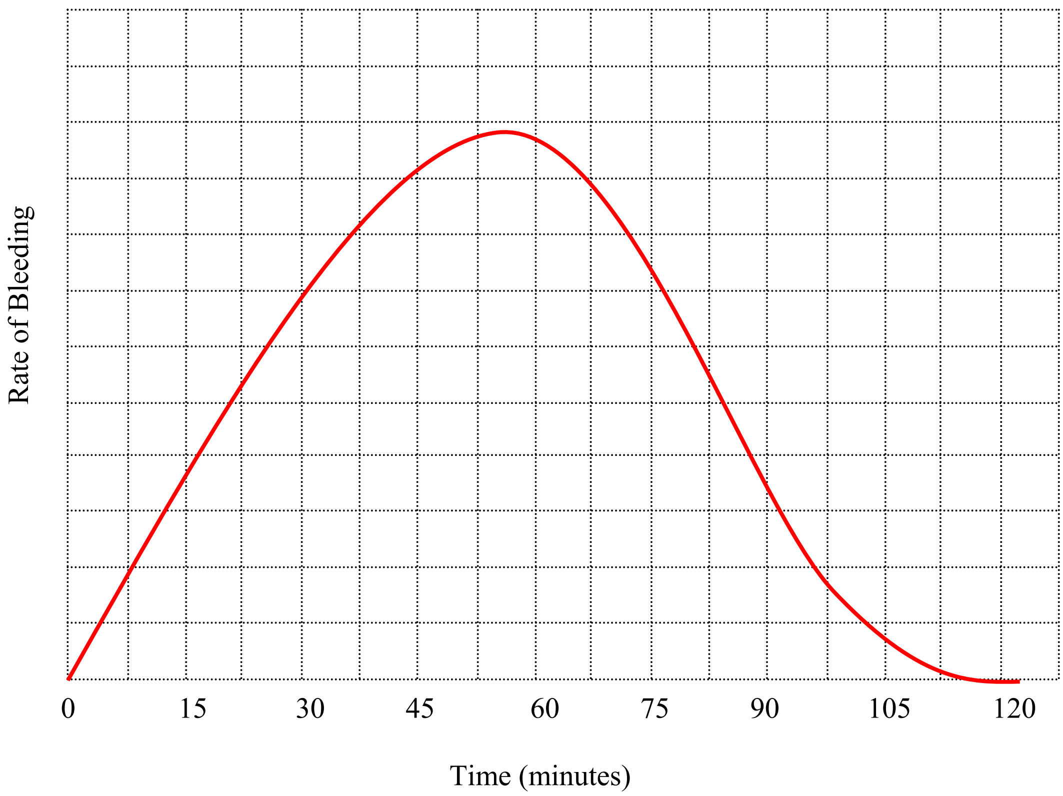


Fresh Concrete

   - Over vibration
   - Over compaction
   - Use of lots of water
   - Less amount of C3A content
   - Use of blended cement
   - High temperature, within the normal range increases the rate of bleeding, but total bleeding capacity probably unaffected.

How to control bleeding:

- By increasing the fineness of cement, bleeding is decreased
- High alkali content can control the bleeding
- Use of crushed FA, which contains excess very fine material (upto about 15 % passing the # 100 sieve)
- By the addition of pozzolands or other fine materials or aluminium powder.
- Air entrainment effectively reduces bleeding
- Less amount of water
- Proper compaction
- Control the grading of aggregate
- Proper bonding in top bar of concrete
- Rate of bleeding become increasing with the increasing of time, but rate of bleeding become decreasing with certain time



"Bond stress is less in top bar, high in bottom bar of concrete" why?

Bond stress is low in top bar because as a result of bleeding the top of concrete becomes too wet. If the water is trapped under the aggregate porous, weak and non-durable concrete will result. It can makes void and the strength of concrete become decreasing.

Distinguish between bleeding and segregation

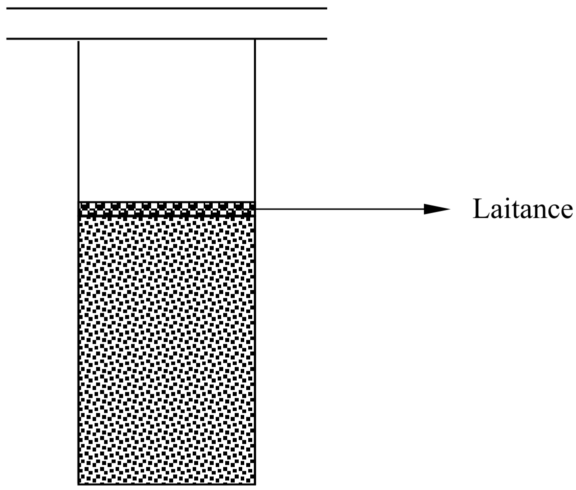
Bleeding is one kind of segregation, some of water in the mix tends to rise to the surface of freshly placed concrete. Water has a tendency to rise upward because of its lowest specific gravity among the constituents of concrete. It is happened if we use more water.

Segregation is a general form. The segregation of the constituents of a heterogeneous mixture, their distribution no longer forms. It is happened due to the different size of the particles and in the specific gravity of the mix constituents.

3. **Laitance:** Accumulation of fine particles on the surface of concrete due to an upward movement of water is called laitance.

Laitance produces a bad or weak concrete on the top of the placement. If we do not remove (2 ~ 3 % from joint) laitance before placing new concrete layer over it, it will result a weak joint. For good quality concrete segregation, bleeding and laitance should be carefully avoided.

In bleeding, laitance should always be removed by brushing and washing.



4. **Honey Comb:** Abundant interconnected large voids or cavities due to lack of fine particles or vibration. If formwork is not water tight, fine materials will come out with water. So large voids on the surface of concrete which is called honey comb.

Causes of honey comb:

- Water leakage through formwork, and make large void
- Lack of vibration
- Inadequate amount of FA in concrete mixture.

Honey comb can be reduced by replacing new concrete.

Why we need compaction?

To remove voids/entrapped air from freshly placed concrete. Otherwise strength decreases.

Properties of concrete

1. **Strength:** It requires to design concrete structure. Before steel structure were designed based on the strength requirement. But now-a-days considering the limitation of natural resources. It is realized that structure should be designed based on the strength and durability.

Two types: (i) Compressive strength
(ii) Tensile strength

Another types: (i) Flexural strength
(ii) Shearing strength

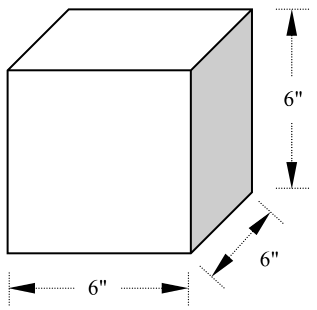
Compressive Strength

To measure compressive strength 6" cube or cylinder specimens are used. To get more obtained strength, curing is done for 28 days. After that strength increases slowly.

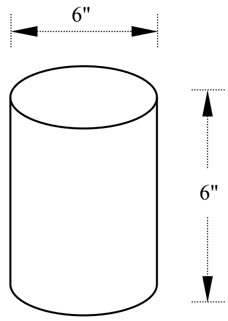
Cylinder Specimen: 6" × 6" × 6" or 4" × 4" × 4"

Cube Specimen: 6" × 12" or 4" × 8"

Test for OPC: 1, 3, 7, 14, 28 days



Cube Specimen

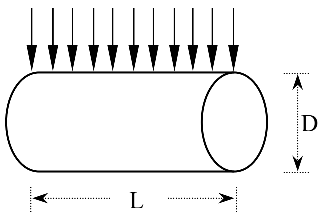


Cylinder Specimen

Tensile Strength

To measure tensile strength 6" × 12" cylinder specimens are splitted. Generally tensile strength of concrete is 1/10th of compressive strength.

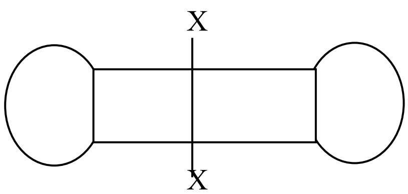
Indirect Test: $f_t = \dfrac{2P}{\pi DL}$



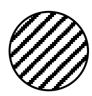
40 % sand of total aggregate

Indirect Test

Direct Test:



Briquette



Cross-section 1 in^2

Relation between compressive strength and tensile strength

$$f_t = 6 \sim 7 \sqrt{f'_c}$$

Where, f_t = Tensile Strength

f'_c = Compressive Strength

For example:

If $f'_c = 5000$ psi; $f_t = 6.5\sqrt{5000} = 460$ psi

Difference between cylinder and cube specimens

- The strength of cube is higher than the strength of cylinder. Cylinder strength = 0.8 ~ 0.85 × Cube strength
- L/D ratio is higher for cylinder because of the height of cylinder
- The direction of load parallel to the weak plane in case of cylinder test
- Capping is used in cylinder for making a level surface. But it may not make level 100 %
- Strength area more in cube than cylinder, because of less restrained surface for cylinder
- Small cylinder will take more load than large cylinder, (small cylinder × 0.9 = Large cylinder

Relation between Y and f'c

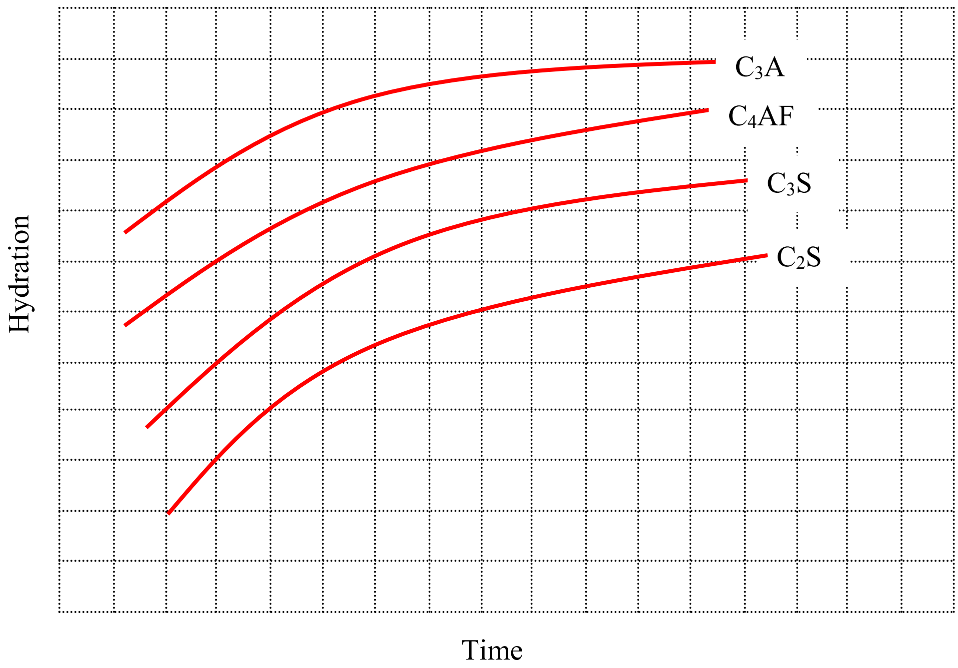
$E_c = 57000\sqrt{f'_c}$ [If $f'_c = 4000$ psi]

For Cube: $E_c = 57000\sqrt{4000} = 3.6\times10^6$ psi

For Cylinder: $E_c = 57000\sqrt{(4000\times0.8)} = 3.2\times10^6$ psi

Effect of age on strength of concrete

Mainly C_3S and C_2S give the strength to the concrete. Hydration of cement is continuous process. Therefore strength of concrete will increase with time.



Factors effecting the strength of concrete

- Fineness of cement
- w/c ratio
- Cement content
- Quality of cement and aggregate
- Curing
- Degree of compaction
- Grading, type, size of aggregate
- Temperature effect
- Water content
- Time

2. **Workability:** definition of workability by ACI "That property of freshly mixed concrete or mortar which determines the case and homogeneity with which it can be mixed, placed, consolidated and finished." It is vital property of freshly placed concrete.

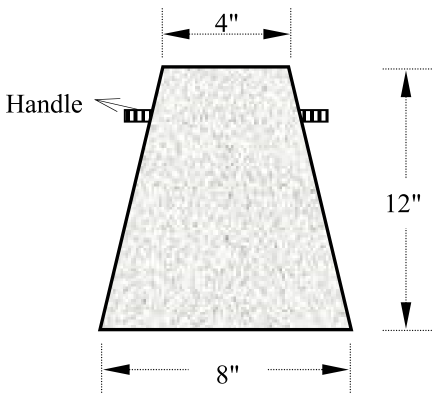
   Measurement of workability:

   Two methods: (i) Indirect method ----------- Slump test

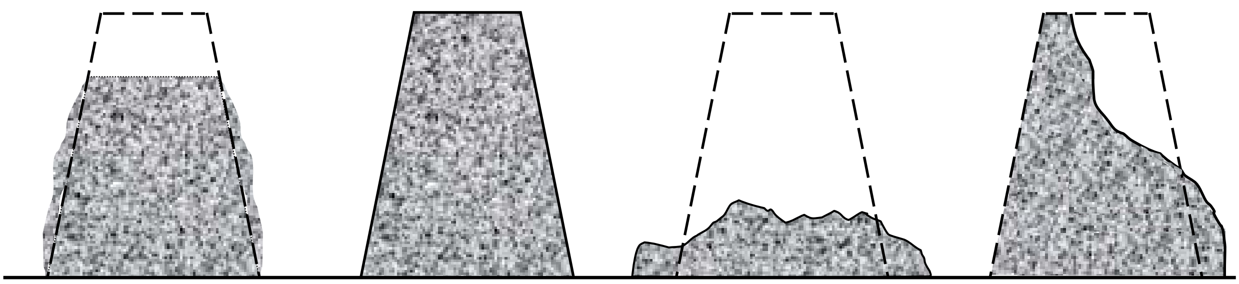
   (ii) Laboratory test ---------- Vebe test

Slump Test

Fill slump cone 3 layers with temping. Diameter of temping rod 5/8" and temping 25 times. So for 3 layers, total temping 75 times.



Slump Cone



Description of workability and magnitude of slump

Description of workability	Slump (in)
No slump	0
Very low	¼ to ½
Low	¾ to $1\frac{1}{4}$
Medium	$1\frac{1}{2}$ to 3
High	$3\frac{1}{4}$ to 6
Very high	$6\frac{1}{4}$ to collapse

Slump (cm)	Degree of workability
0	Very low
1 ~ 2	Low
2 ~ 4	Medium
4 ~ 7	High
7 ~ high	Very high

* For normal design standard value (8 ± 2) cm

Factors effecting workability

- Fineness, shape, size, gradation of aggregate
- w/c ratio
- Cement content
- Water content
- Temperature
- Mixture proportion
- Material used
- Fineness of cement
- Time after mixing
- Air entrainment
- Use of water reducing admixture (superplasticizer)

3. **Durability:** It follows that concrete must be able to withstand the processes of deterioration to which it can be expected to be exposed. Such concrete is said to be durable. Inadequate durability manifests itself by deterioration which can be due either to external factors or to internal causes with in the concrete itself.

Causes of earlier deterioration:

i. Internal causes:

1. Alkali silica reaction and alkali-carbonate reaction
2. Poor quality concrete (highly permeable concrete)
3. Excess free lime

ii. External causes:

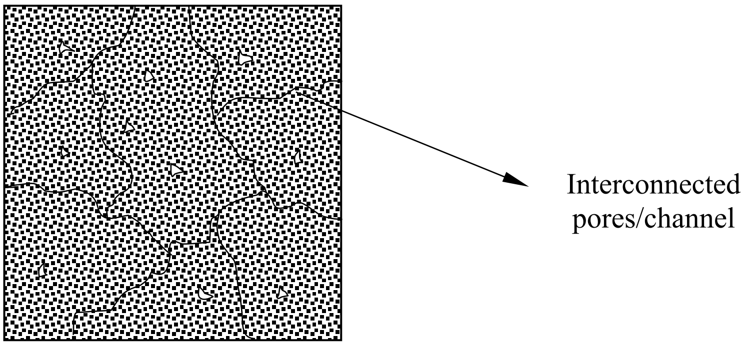
- Mechanical damage is caused by impact, abrasion, erosion or cavitations, earthquake, overloading etc,
- Physical causes (weathering, temperature, variation etc.)
- Chemical (Sea water, Sulfate bearing, Chlorides, CO_2)

Factors:

- Types of cement
- w/c ratio or voids

4. **Permeability:** Concrete is a porous material, it has a lot of interconnected pore channels. Harmful species like chloride, sulfate, CO_2, carbonate is strongly influenced by the permeability of concrete. A durable concrete should be less permeable. For liquid retaining structures, water tightness is also important.

   w/c ratio strongly influence the permeability of concrete. More permeable concrete is less durable. We should reduce w/c to make durable concrete.



[Question: "Permeability of concrete is a key factor related to durability of concrete" – why?]

Chemical Admixture

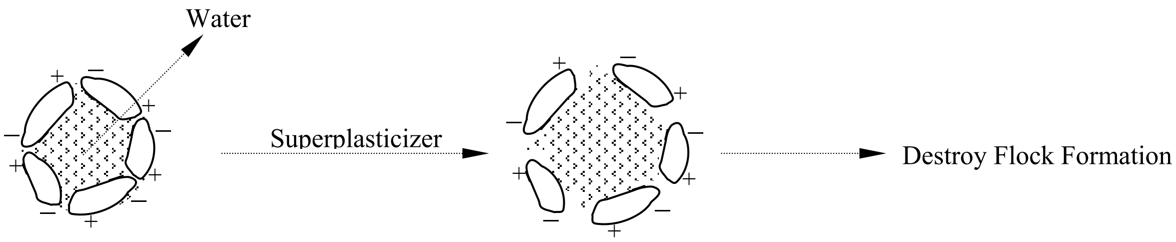
In concrete or mortar, a substance other than aggregate, cement or water added in small quantity, normally less than 5 % of the weight of the cement, to alter the properties of the mix or the hardened solid.

Types of Chemical Admixture:

- Water reducing
- Retarding
- Accelerating
- Water reducing and retarding
- Water reducing and accelerating
- High range water reducing or superplasticizing admixture
- High range water reducing and retarding or superplasticizing and retarding admixture
- Air entraining chemical admixture
- Air entraining and water reducing chemical admixture

Superplasticizer

When water is mixed with cement, some water entrapped between cement particles and therefore reduces the amount of water to give workability to concrete. Superplasticizer disperse the cement particles, unproper workability. It is possible to make a vibration free (flowing concrete) concrete with the use of superplasticizer. For a very congested layout of reinforcement, it is wise to use superplasticizer to make a flowable concrete.



Flock formation of cement particles

[* By using this, we can improve workability of concrete at a very low w/c ratio (0.40, 0.35 or 0.30)]

By using superplasticizer, we can get:

- Workable
- High strength
- Durable concrete

Superplasticizer is a chemical admixture (high range water reducing admixture). The dose of superplasticizer will depend on the cement content. Generally it is expressed as what (8 ~ 15 ml) of superplasticizer of per kg of cement.

Entrapped Air:

It is internal void of concrete. It should be removed from concrete. Diameter of this bubble (0.5 mm to 10 mm)

Entrained Air:

Entrained air in concrete is defined as air intentionally incorporated by means of a suitable agent. This air should be clearly distinguished from accidentally entrapped air. Diameter of bubble: 100 μm to < 0.5 mm

- Damaging action of freezing and thawing involves expansion of water will not occur.
- Improve workability of concrete

** Air entraining chemical admixture: vinsol (dose 3 ml/kg cement)

** Air entraining and water reducing chemical admixture. Example: Mighty 100

- Air entrainment effectively reduces bleeding.

Accelerators:

(i) Calcium chloride ($CaCl_2$): accelerate the hydration of C_3S. It has one serious defect: corrosion of steel

(j) NaCl, Barium chloride, Calcium nitrite, Calcium nitrate, Calcium formate, Triethanolamine.

Retarders:

(i) Suger, Soluble zinc, Salts, Soluble borate, Methanol.

(j) Carbohydrate derivatives

Water reducing and set-retarding admixture:

- Sodium salt of hydroxylic acid
- Lignin – based calcium salt
- Calcium – lignosulfonate based
- Phosphate based

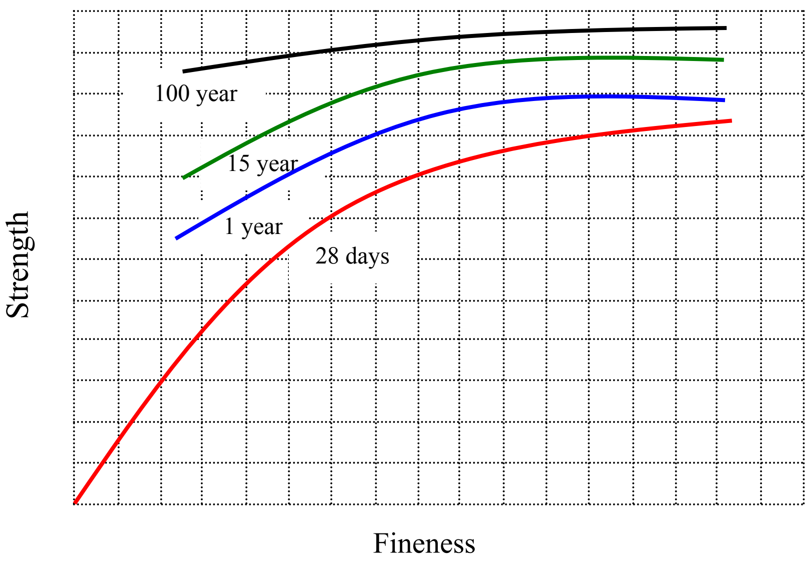
Other type of admixture:

(i) Water proofing admixtures

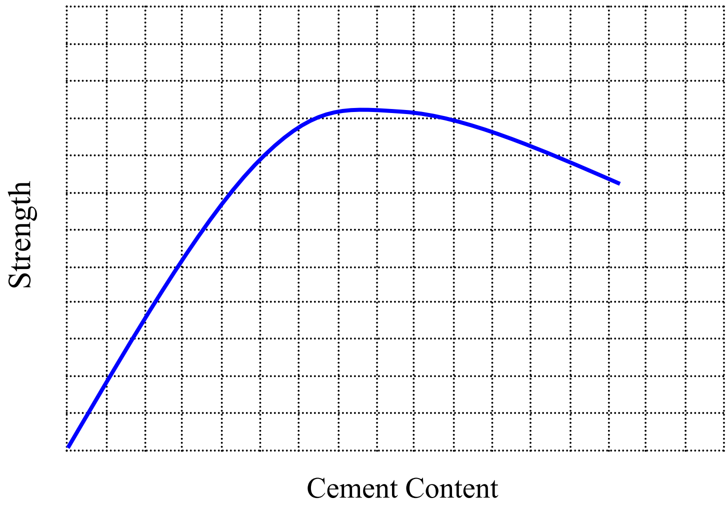
(j) Anti bacterial and similar admixtures

Factors controlling the properties of concrete

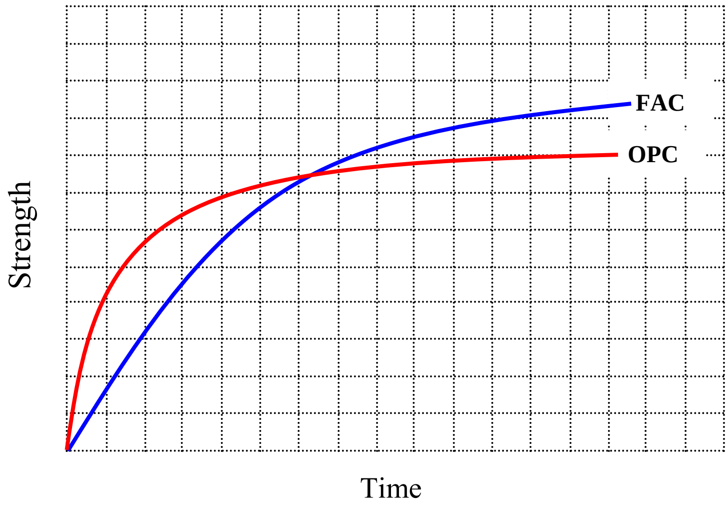
1. **Fineness of cement:** Fineness is the total surface area of cement that represent the material available for hydration. For more fine cement:
   - Rapid development of strength
   - Durability decreases
   - Slightly improves the workability of a cement concrete mix (w/c ratio increases)
   - Rapid hydration



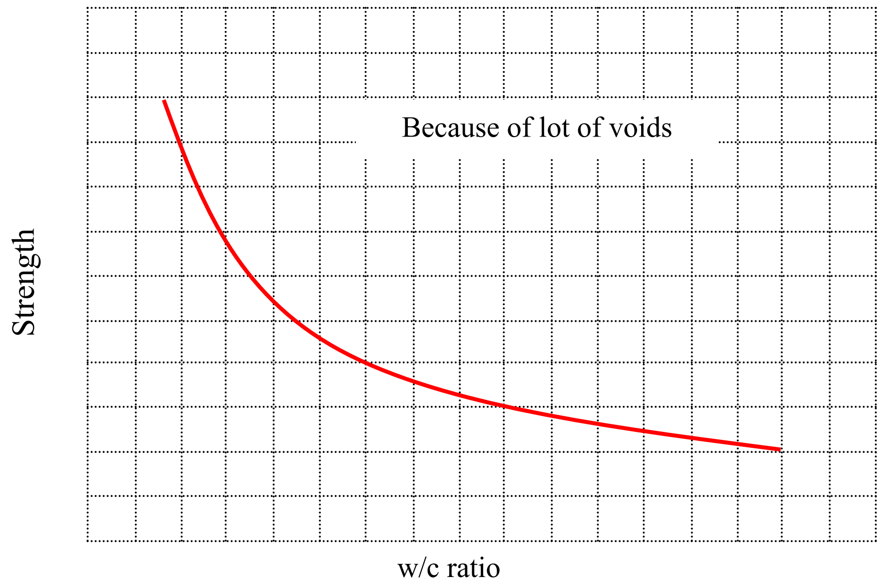
2. **Cement Content:** For more cement content, strength increases. For high strength concrete: Maximum cement content for 1 m^3 concrete: 350 kg ~ 440 kg. But a certain level, with the increase of cement content, strength decreases, concrete will be shrinked. With the increase of cement content, workability decreases.

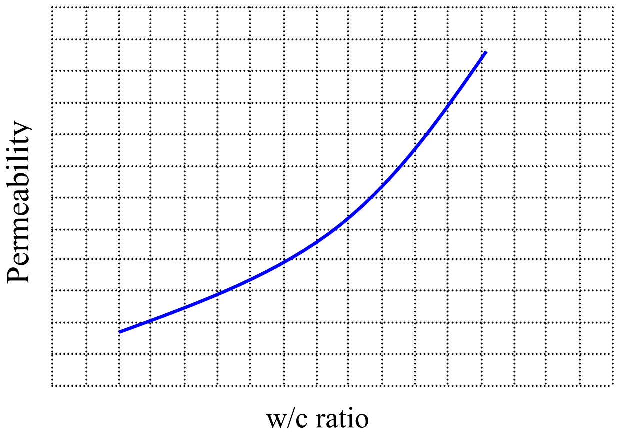


3. **Type of cement/ Different quality of cement**
   - For OPC strength increases rapidly but for Fly Ash Cement (FAC) strength increase slowly
   - Durability point of view, FAC is more good compared to OPC
   - For FAC, if we use lime mortar, strength increases. This is called pozzolanic property of cement/ concrete.



4. **w/c ratio**
   - Generally use in our country: 0.5 to 0.55
   - 16 % to 20 % water of cement is needed to hydrate cement
   - With the increase of w/c ratio, strength decreases due to pores or voids
   - With the increase of w/c ratio, workability increases.



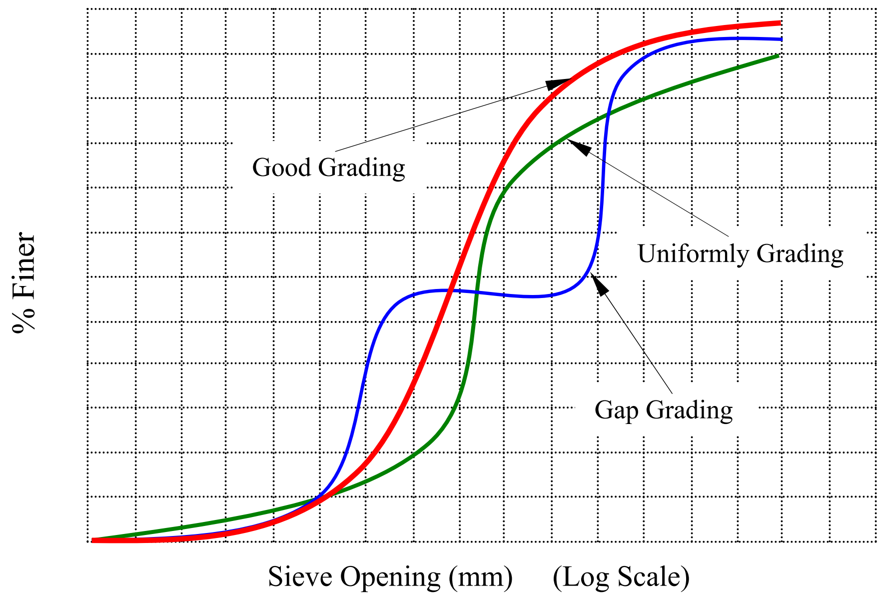


5. Water content

Water content increase the workability, strength and durability decreases.

6. Grading of aggregate

- Suitable gradation is required to ensure strength, workability and economy of concrete
- Principle of gradation: Small size particles fill up the voids left in large size particles
- Good grading aggregate →less voids →more strength and durability
- Gap grading aggregate →Segregation, uneconomical mix
- Uniformly grading →Lots of voids, segregation
- More coarsely grading →Segregation, Harsh concrete
- More finely grading →less workability (required more water), low strength concrete.



7. Fineness of Aggregate

- Fineness of aggregate can be measured by using sieve analysis and we can calculate FM.
- For fine aggregate FM: 2.25 ~ 3.25 and for CA, FM: 5.5 ~ 7.5
- More finer: less workability, low strength concrete

8. Type of Aggregate

- Brick Chips
- Stone Chips
- Shingle -------- more workable due to round shape
- Picked brick chips
- Recycling aggregate

9. Shape of Aggregate

- Angular
- Round
- Flaky

10. Absorption capacity of aggregate/ Moisture content

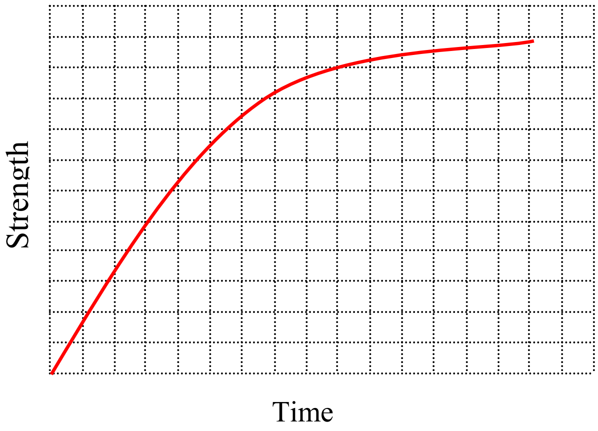
- More absorption capacity: Less workability
  : Less strength
  : Less durability

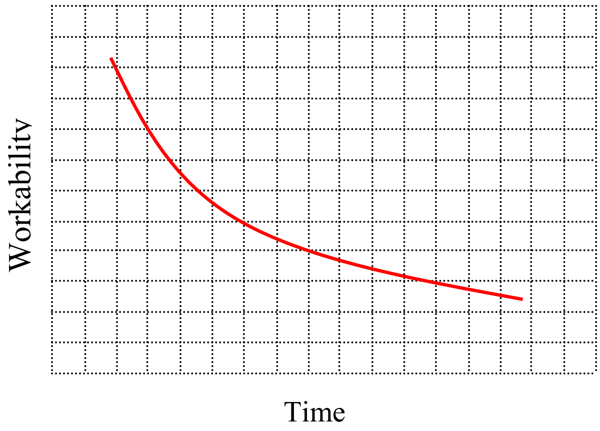
11. Temperature

- More temperature: less workability
- More temperature: rapid strength (hydration) of concrete
- More temperature: durability decreases

12. Time (after mixing)

- Strength increases
- Workability decreases





13. Compaction/ Vibration

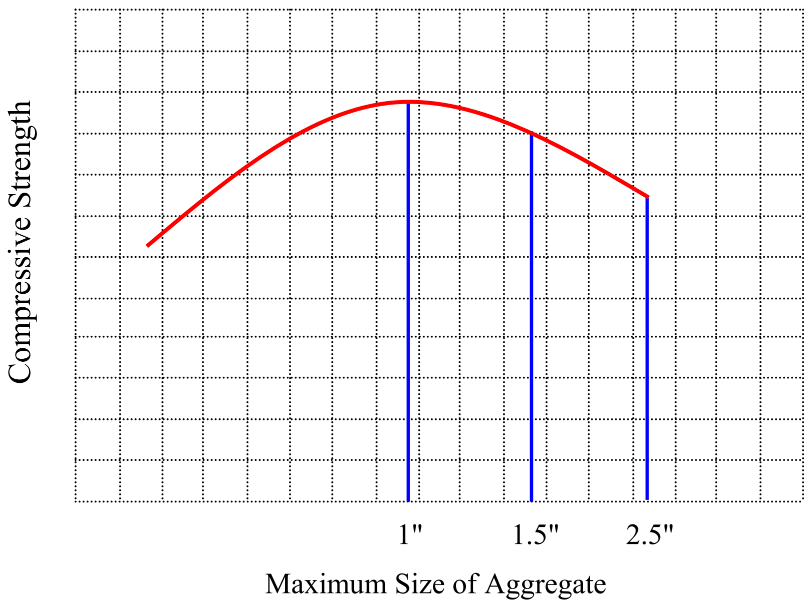
- Proper vibration/ compaction is required to give strength of concrete
- Voids of concrete are reduced for vibration/ compaction

14. Curing

- Curing is required to give strength to concrete (continuous curing)
- For FAC, more days curing is required
- Period of curing will depend largely on the type of cement

15. Maximum size of Aggregate

Compressive strength is gradually increased with the increase of size of aggregate (up to 1"). Then it reduces gradually with the increase of size of aggregate

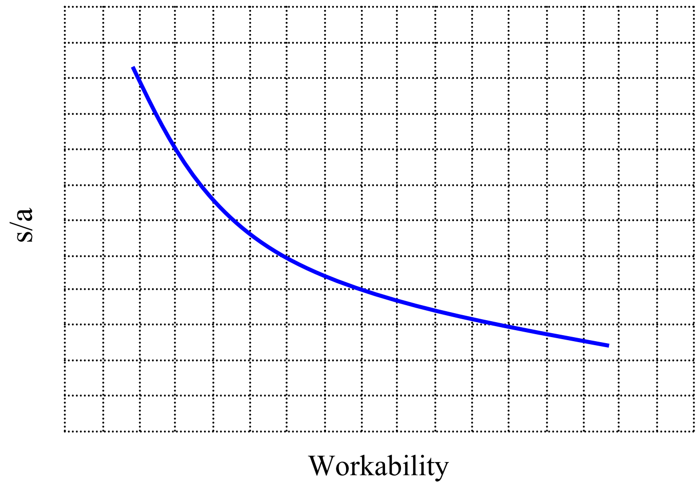


16. Air content

- Entrained air increases workability
- Entrapped air reduces strength of concrete

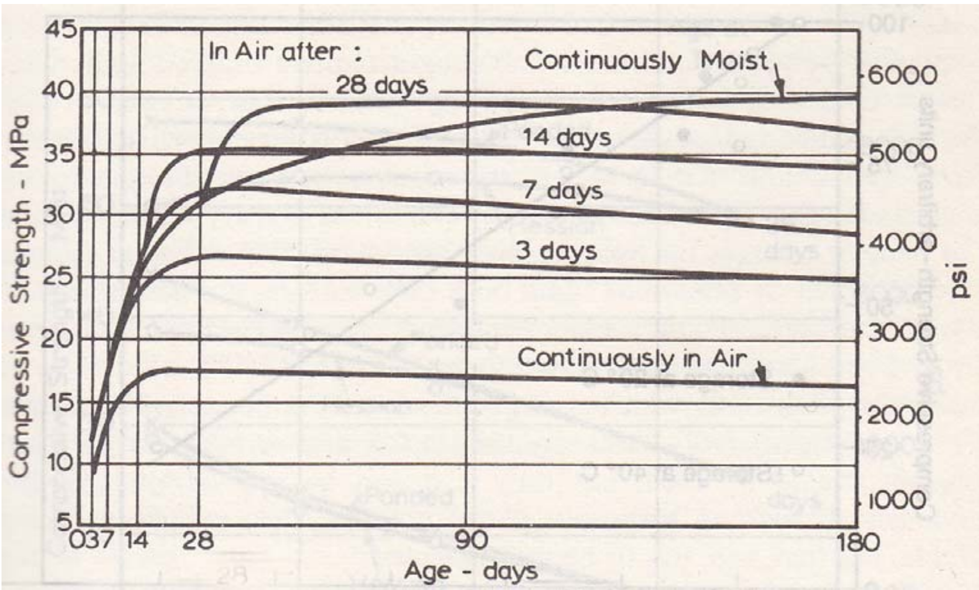
17. Sand to Aggregate (CA + FA) ratio:

- s/a ratio decrease the workability
- With the increase of volume of CA concrete strength increases



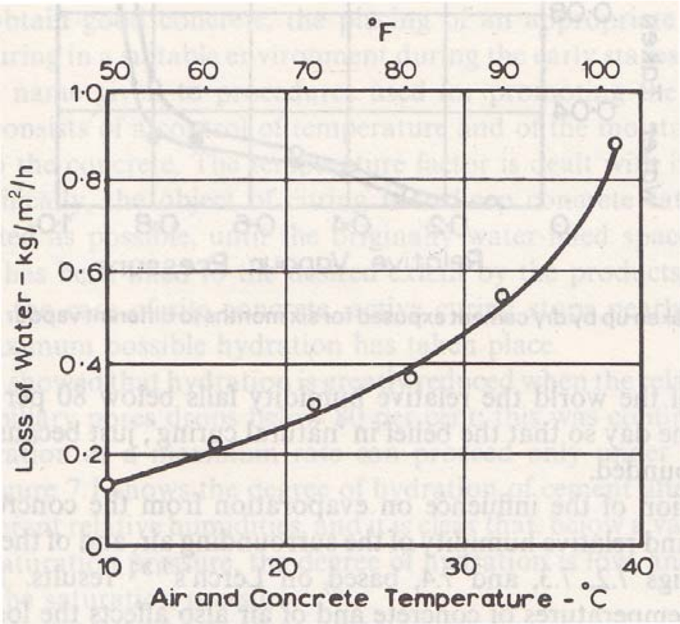
Curing

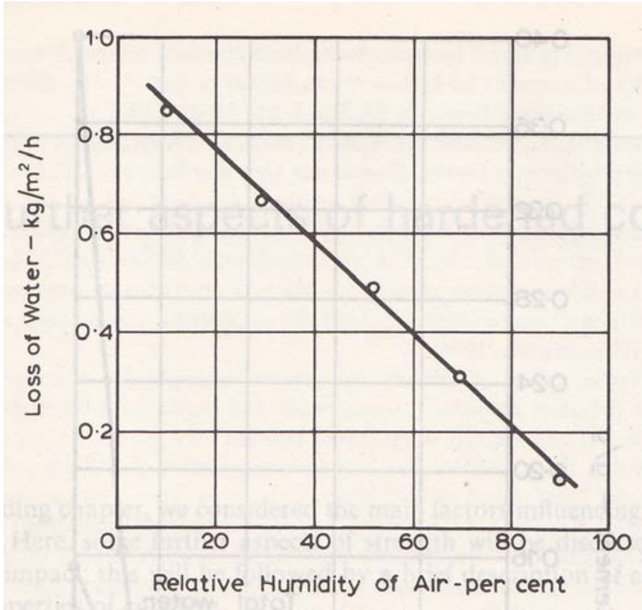
Curing promotes the hydration of cement by controlling temperature and moisture movement from and into the concrete. More specifically curing keeps concrete saturated so that hydration of cement can be take place in a suitable environment. Hydration at a maximum rate can proceed only under condition of saturation.



Evaporation of water from concrete surface will depend on

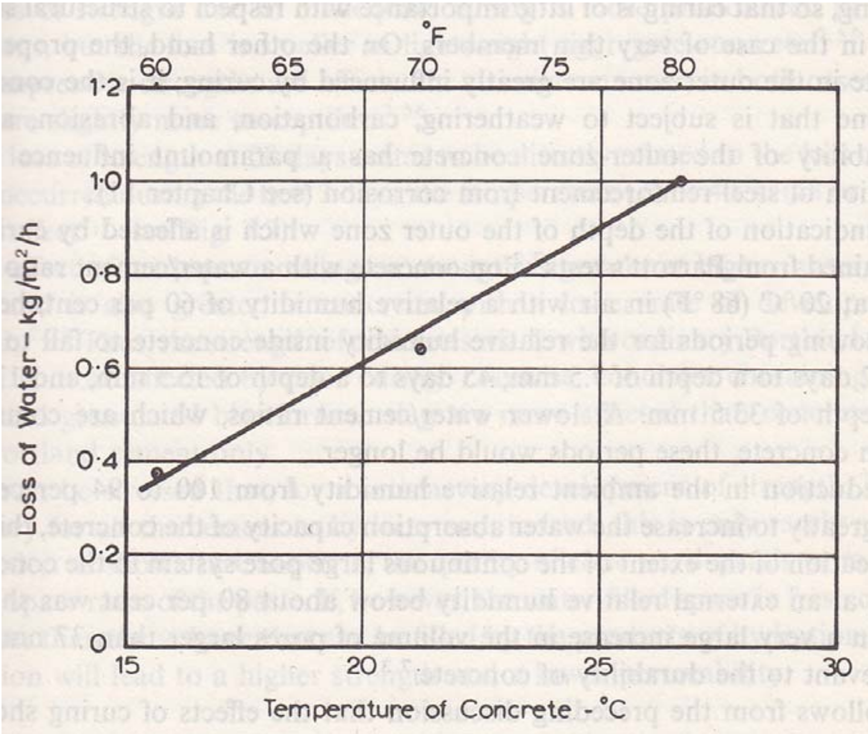
- Temperature
- Wind velocity
- Humidity



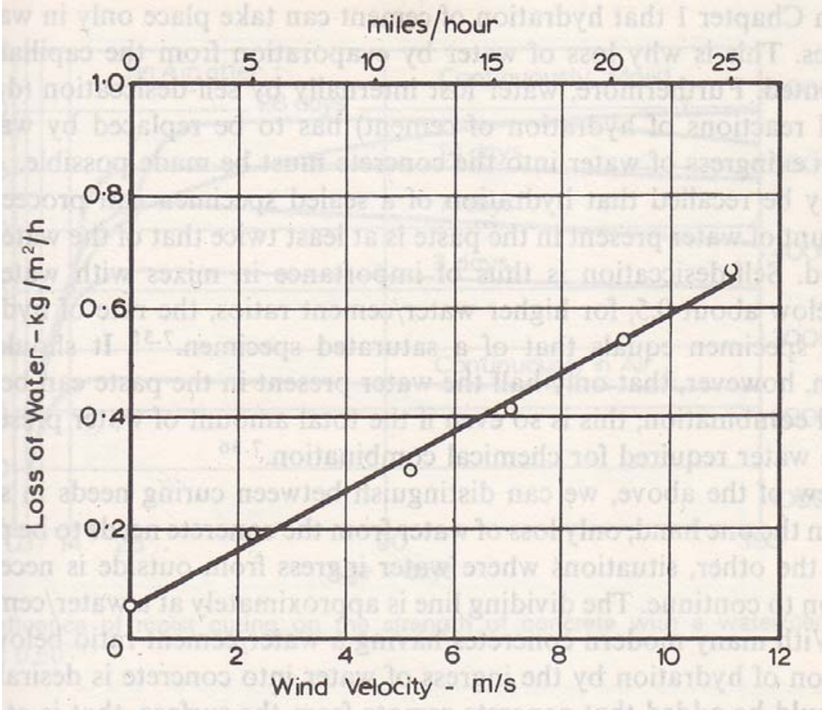


Methods of curing depend on the conditions on size, shape and position of the concrete member.

- If surface to volume ratio of concrete is small: $\frac{\text{Total surface area}}{\text{Volume}}$. Oiling or wetting the formworks before casting can be sufficient. Formworks any also be wetted during hardening and after removed of formworks. The concrete should be sprayed with water and wrapping with the polythene sheets or any other covering.



If surface to volume ratio large: (Road, slab) Loss of water should be prevented to avoid drying shrinkage, polythene sheets should be used to prevent quick water loss. This prevention is required for dry weather and it also protect the concrete from rain water. Wet curing can be provided by spraying or ponding (flooding) with water or by covering the concrete by wet sand, earth, saw dust, straw, cotton.



Continuous spraying of water is naturally more efficient,

Period of curing: It will depend largely on the types of cement

Influence of curing temperature on strength of concrete:

Arise in temperature speeds up the chemical reactions of hydration and help to develop earlier strength. It also be observed that a high temperature creates a porous micro structure and there by reduce the durability performance. A porous micro structure will allow the quick ingress of harmful ions such as Cl^-, SO_4^{2-}

Steam curing:

- Curing at a high temperature by steam.
- Used in precast industry (to accelerate the rate of hydration to get early strength)
- Less cost/economical

Effect: It may affects the long term strength and durability performance. It is very unfortunate we are giving enough attention to long term strength and durability.

Concreting in hot weather:

- Rapid hydration for high temperature
- Rapid setting
- Evaporation (plastic shrinkage, cracks)
- Air entrainment is difficult
- Curing should be done carefully

We need

- Blended cement
- Pre-cooling aggregate
- Cool water

How we cured

- Under water curing
- Covering sheet (Polythene)
- Wet jute bags
- Steam curing

Factors:

- Cement types: For FAC, SC →need long curing
- Surface to volume ratio

Concreting in cool weather

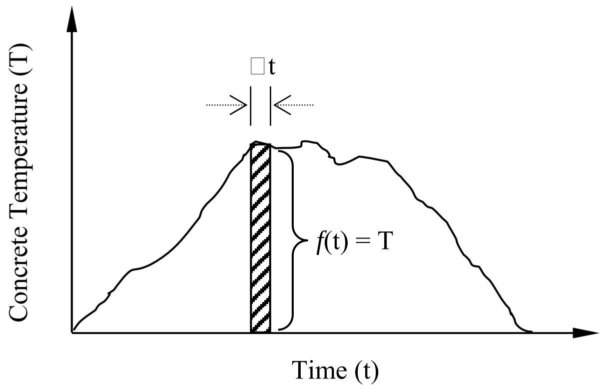
- Hot water
- Hot aggregate
- Steam curing

Maturity of concrete

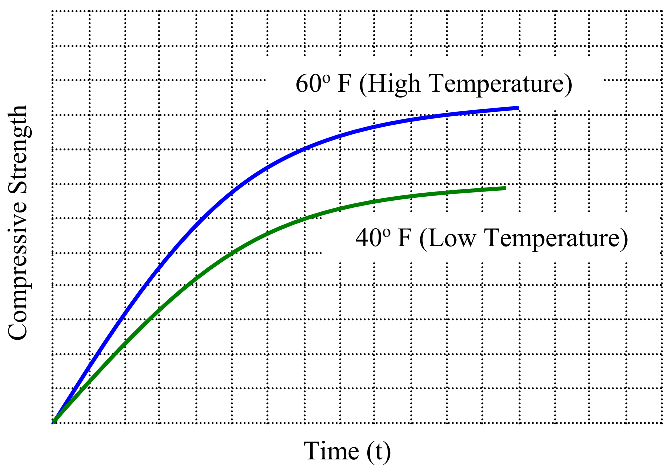
Concrete gains strength with time. It greatly influenced by the temperature. So the strength of concrete depends on both age and temperature. We can say that strength is a function of □ (time interval × temperature) and this summation is called maturity.

$$\text{Maturity} = \sum_{i=0}^{t}\left[\text{time (t)} \times \text{temperature (T)}\right]$$

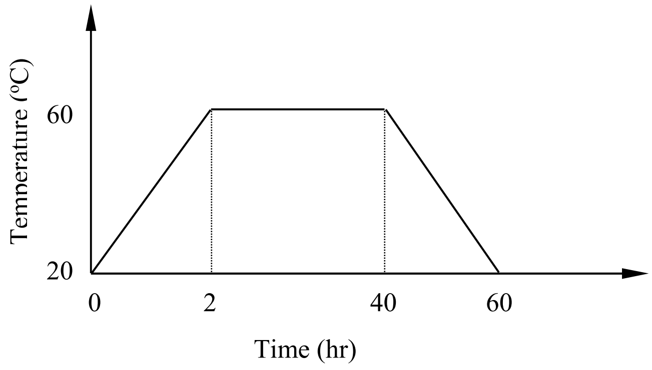
$$= \int_0^t (t)\,dt \qquad [T = f(t)]$$



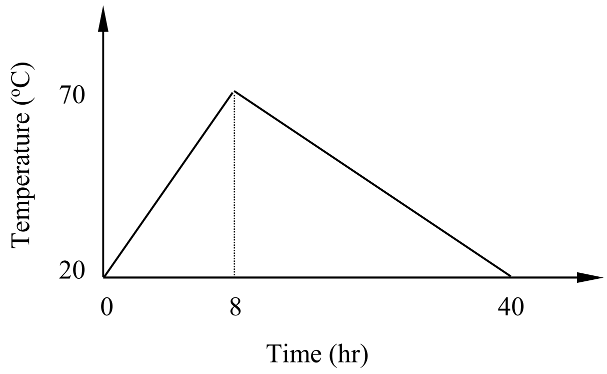
- Maturity is quantitatively expressed in terms of are under temperature vs time curve of concrete.
- Unit of maturity : ^{o}C–hr



Example:



Concrete A



Concrete B

Maturity of A = 1960° C–hr

Maturity of B = 1000° C–hr

$\therefore$ Maturity of A > Maturity of B

$\therefore$ Strength of A > strength of B

From maturity we get the effect of temperature

Shrinkage

Shrinkage is the contraction due to drying or chemical changes in concrete. Loading on the structure has no direct influence on shrinkage.

Types of shrinkage:

- Plastic shrinkage/ Autogenouus shrinkage
- Drying shrinkage
- Carbonate shrinkage
- Differential shrinkage

Plastic Shrinkage

During the progress of hydration, the cement paste (plastic) undergoes a volumetric contraction, which is about 1 % of the dry volume of cement. This construction is known as plastic shrinkage. Since it takes place when the concrete is in plastic states. Volume changes can occurs even after hardening of cement with the on-going hydration (even if there no moisture movement). This shrinkage is known as autogeneous shrinkage. It is generally observed in rich-mix design concrete (due to the large amount of cement content 450 kg/m^3)

Mostly due to the chemical change (no stress will develop)

Drying Shrinkage

Contraction of concrete due to evaporation of water from it. The loss of free water, which takes place first, causes little or no shrinkage.

Factors affecting drying shrinkage:

- Water content (increase) drying shrinkage increase
- Amount of aggregate
- Modulus of elasticity of concrete
- Rate of evaporation
- Atmosphere temperature
- Rate of hydration
- Wind velocity
- Condition of site
- Loss of water

Differential Shrinkage

It is special kind of drying shrinkage due to the loss of water from a thin layer around the structure.

Carbonation Shrinkage

The pH value of concrete is generally more than 13 i.e. concrete is a highly alkaline media. Unfortunately the atmospheric CO_2 reacts with $Ca(OH)_2$ of concrete and thereby produces $CaCO_3$. As a result the pH value of concrete drop to a level of around 8. This process is known as carbonation.

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

Due to the carbonation $Ca(OH)_2$ transforms into $CaCO_3$. For this chemical changes, concrete will shrink. This shrinkage is called carbonation shrinkage. Carbonation improves microstructure and mechanical properties of concrete.

Carbonation of concrete depends on:

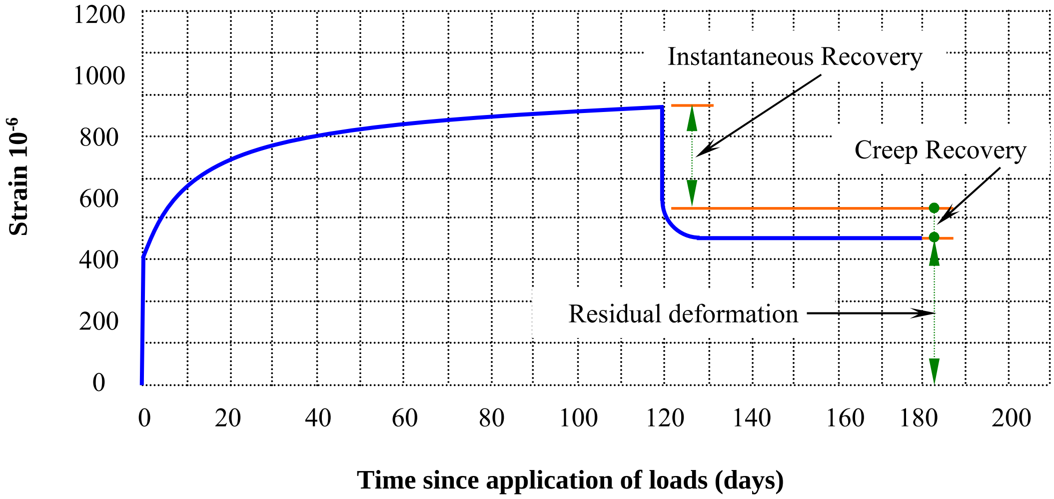
- Moisture content: less or no saturated concrete will not be subjected to concrete.
- Temperature: (carbonation increased with temperature)
- Quality of concrete (↑ ↑bad) (↓ ↓good)
- Cement type (OPC ↑)
- Cement content

Swelling of concrete

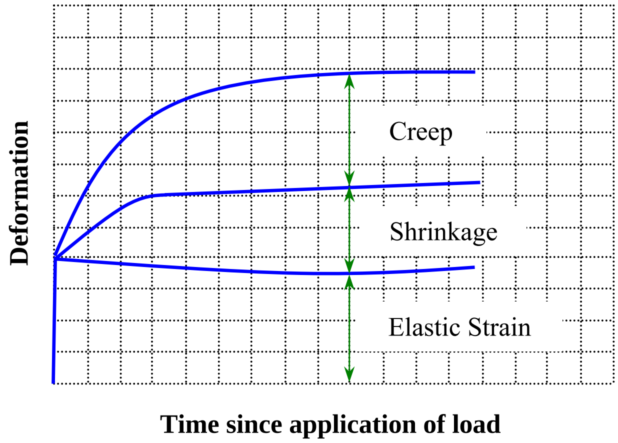
Due to moisture absorption, volume of concrete will increase. It is called swelling of concrete. Cement paste or concrete cured continuously in water from the time of placing exhibits a net increase in volume and an increase in mass. This is swelling.

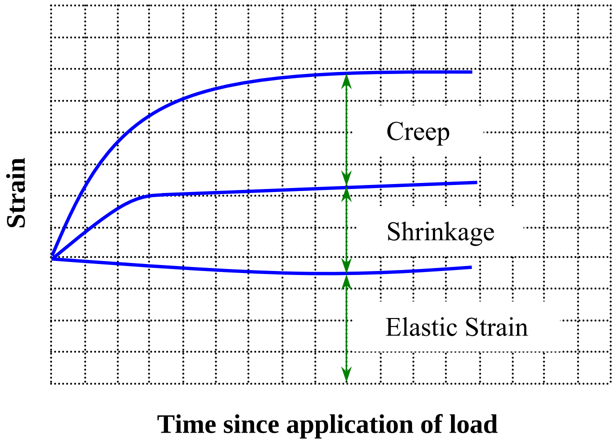
Creep of concrete:

Creep is the time dependent strain under sustained loading. When load is applied to a structure, instantaneously there is a deformation of the structure is called initial deformation. If the load is kept constant on the structure, there will be a time dependent deformation called "Creep".



Due to drying of concrete, concrete is also subjected to drying shrinkage. Creep is thus calculated as the difference between the total time deformation of the loaded specimen and the shrinkage A similar unloaded specimen stored under same condition through out the time period.





- Elastic deformation reduces with development of strength and we have true elastic deformation
- Creep $\propto \dfrac{1}{\text{strength}}$

Mechanism of creep

The exact mechanism of creep is still unknown. Perhaps, it depends on sizes and orientation of hydration products.

Effect of creep

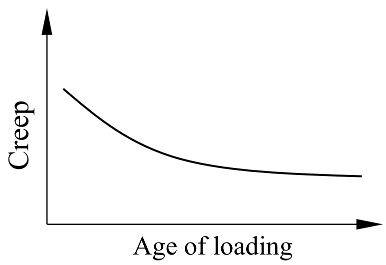
- Gradual increase in strain or deformation
- Loss of prestress

Creep coefficient

$$\text{Creep coefficient} = \frac{\text{Creep deformation}}{\text{Elastic deformation}}$$

Factors influencing creep

- Relative humidity (low humidity→high creep)
- Shrinkage: (higher shrinkage →high creep)
- Strength: creep $\propto \dfrac{1}{\text{strength}}$
- Aggregate: If modulus of elasticity of aggregate is high, creep will be lower.
- Temperature: (high temperature →high creep)
- Maturity and age:



- Type of cement: (BF cement →higher creep than OPC)
- Fineness of cement: (Finer cement →high creep)

Joints:

Joints are formed in concrete between old and new placements of construction. Joints are break out (interface between new and old placement) in concrete. Therefore minimum number of joints should be provided in a concrete structure.

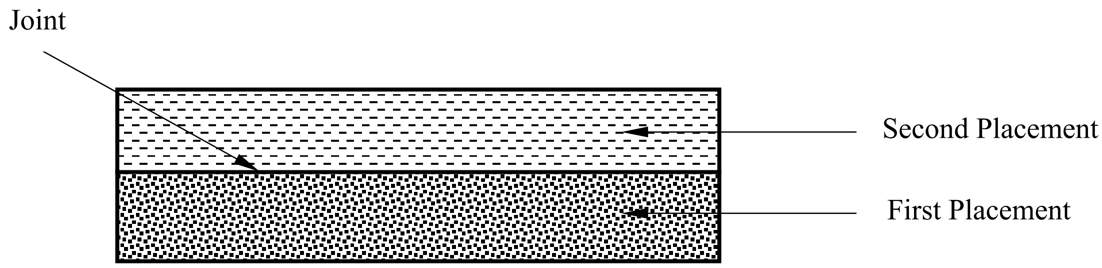


Fig: Joint in a beam

Type of joints:

- Cold joint
- Construction joint
- Contraction joint
- Expansion joint
- Isolation joint

Cold joint

A weak and leaky joint between two lifts of concrete, caused by delay between them.

Construction joint

Joints formed in concrete due to the placement limitation is called construction joint. Construction joints should be located at minimum bending moment. Laitance on the cast face may have to removed by scabbling, brushing.

Expansion joint

Expansion joints are intentionally provided to prevent the development of stress with the thermal expansion of the structure or structure members. Necessary for more than 100 ft long structure.

Contraction joint

A break in a structure made to allow for the drying and temperature shrinkages (of concrete or masonry) and thus to prevent cracks forming at undesirable place.

Isolation joints

When one portion of a building is higher than the other, the soil below the higher portion will be subjected to greater pressure than the soil below the lower portion of the building. In such cases complete separation joint of the two parts of the structures are provided.

Shuttering/ Formwork

A temporary structure used as a mold to cast the members of the structure to required shape and size by laying concrete in it.

Formwork should be:

- Smooth, uniform
- Concrete is correct dimensions
- Water tight
- Cheap, easily available, reusable

Timber is commonly used in Bangladesh for shuttering because it is cheap, light, available and has sufficient strength. However, steel shuttering are recently used in urban areas. Shuttering are removed after sufficient time so that concrete can take its own load and dry other load coming on it.

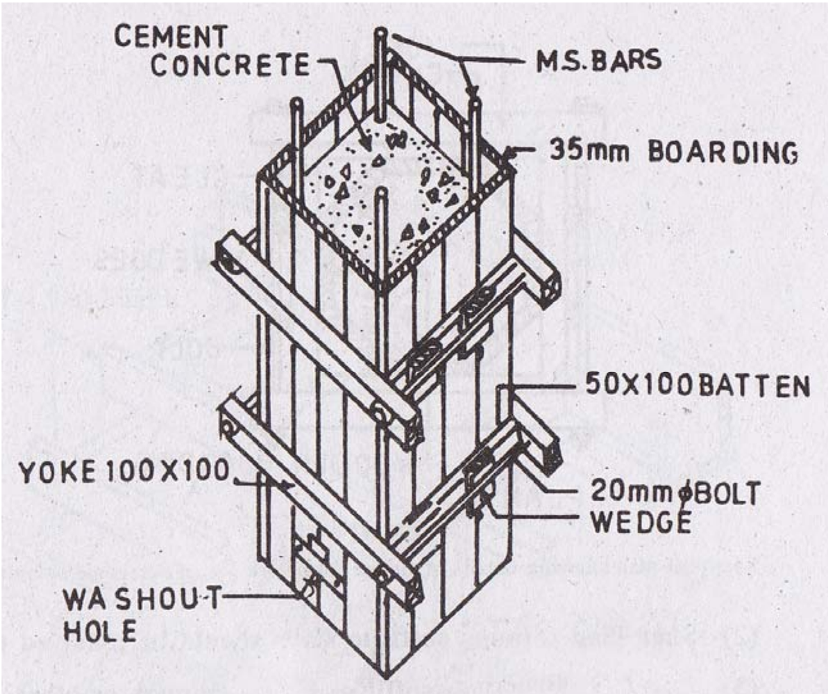


Fig: Timber Formwork of Rectangular RCC Column

Approximate time to remove formworks:

Length	OPC	Rapid Hardening PC
Short beams, walls, column, Roof	10 ~ 14 days	6 ~ 9 days
Long beam	14 ~ 22 days	10 ~ 16 days

Order of Removing Formwork

- Shuttering forming vertical faces of walls, beams and columns sides (which bear no load but are used only to retain the concrete) should be removed first.
- Shuttering forming soffit to slabs should be removed next.
- Shuttering forming soffit of beams, girders or other heavily loaded shuttering should be removed in the end.

Chemical attack in concrete:

- **Leaching out of concrete (efflorescence):** $Ca(OH)_2$ will come out from concrete with water. This is called leaching.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
$$CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2 \text{ (soluble in water)}$$
$$\downarrow$$
White deposit in concrete surface

Due to the leaching of CH from concrete porosity of concrete will be increased but strength will be reduced

***Ways to reduce efflorescence*:**

- Make quality concrete which will have a dense microstructure
- Prevent moisture movement (pointing)

- **Sulfate attack**

Source of sulfate:

- Sewerage facilities
- Sea water
- Soil (sulfate contaminated soil)
- Industrial waste

Reaction:

$$\underset{\text{(monosulfate)}}{3CaO.Al_2O_3.CaSO_4.18H_2O} + \text{Sulfate} \rightarrow \underset{\text{(Ettringite)}}{3CaO.\ Al_2O_3.\ 3CaSO_4.32H_2O}$$

- Due to this reaction, volume expansion, concrete will be cracked hence strength reduction of structure.
- If concentration of sulfate is high, the sulfate will consume CSH of concrete and will reduce the strength of concrete significantly.
- Sulfate attack is very dangerous for concrete
- We need less amount of C_3A content to use sulfate resisting cement.

- **Sea water attack**
  - Salt (NaCl, $MgCl_2$, $CaCl_2$)
  - Sulfate ($MgSO_4$, $CaSO_4$, ...)
  - CO_2 (# due to aeration of atmosphere, # decay of leaves or other organic materials, # pH (6 to 8)

Sulfate

(i) $MgSO_4 + Ca(OH)_2 + 3CaO.Al_2O_3.CaSO_4.\ 18\ H_2O \rightarrow \underset{\text{(Ettringite)}}{3CaO.Al_2O_3.\ 3CaSO_4.32H_2O} + \underset{\text{(Brucite)}}{Mg(OH)_2}$

$$\downarrow$$

we will have volume expansion and hence crack and strength reduction

(ii) $MgSO_4 + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaSO_4.\ 2H_2O$

(Brucite) Gypsum (soluble)

↓

Concrete will be porous

(iii) $MgSO_4 + Ca(OH)_2 + CSH \rightarrow MgO.SiO_2.x\ H_2O + CaSO_4.2H_2O$

Magnesium silicate hydrate (MSH) Gypsum (soluble)

↓

Brittle material

↓

Porous and less strength of concrete

CO_2

(i) $CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2$

(Carbonation reaction) (soluble)

↓

porous, loss strength

(ii) $CO_2 + Ca(OH)_2 + 3CaO.\ Al_2O_3.\ CaSO_4.\ 18\ H_2O \rightarrow 3CaO.\ Al_2O_3.\ CaCO_3.\ x\ H_2O + CaSO_4.\ 2H_2O$

↓ Gypsum (soluble)

Loss strength, porous concrete

- CO_2 attack is dangerous for concrete as sulfate attack
- Fortunately the level of CO_2 in sea water is very low

Chloride Attack

(i) $MgCl_2 + Ca(OH)_2 \rightarrow Mg(OH)_2 + CaCl_2$ (soluble)

(ii) $3CaO.Al_2O_3.CaSO_4.18H_2O$ + Chloride $\rightarrow 3CaO.Al_2O_3.CaCl_2.12H_2O$ (*Friedel's salt*)

↓

Not bed for concrete

Friedel's salt

- Fill the voids in concrete and therefore will improve microstructure of concrete
- Gain in strength

Chloride effect

- Chloride is an accelerator (Example: $CaCl_2$)
- Chloride is not so harmful for concrete
- Steel bar corrosion
- Chloride helps to destroy the passivation (protection) film over the steel bar that prevent it from corrosion.
- If chloride level over the steel bar reach the threshold level (0.4 % of cement or 1.2 kg/m^3) the protection film will be broken.
- After broken down the passivation film, corrosion over steel bar will start →Rust Formation (6 ~ 7 times volume increase) →cracking →Spalling of concrete

Steel bar Corrosion

Chloride Attack

$3CaO.Al_2O_3.CaSO_4.18H_2O$ + Chloride →$3CaO.Al_2O_3.CaCl_2.12H_2O$ (Friedel's salt)

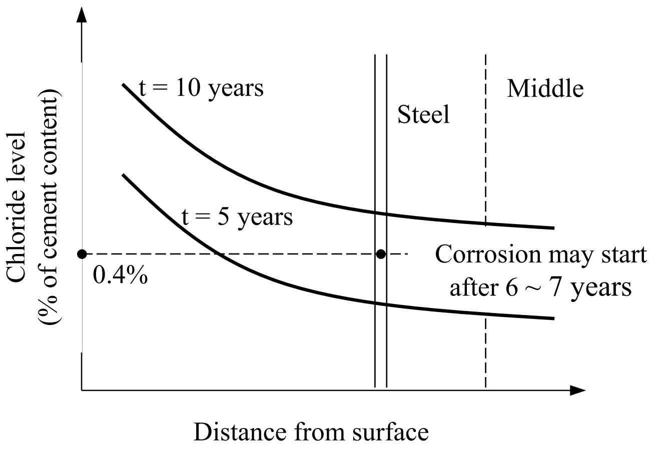
- Chloride is an accelerator
- Chloride is not so harmful for concrete
- Steel bar corrosion
- Chloride helps to destroy the passivation/ protection film over the steel bar that prevent if from corrosion
- If chloride level over the steel bar reach the threshold level (0.4 % of cement or 1.2 kg/m3) the protection film will be broken.

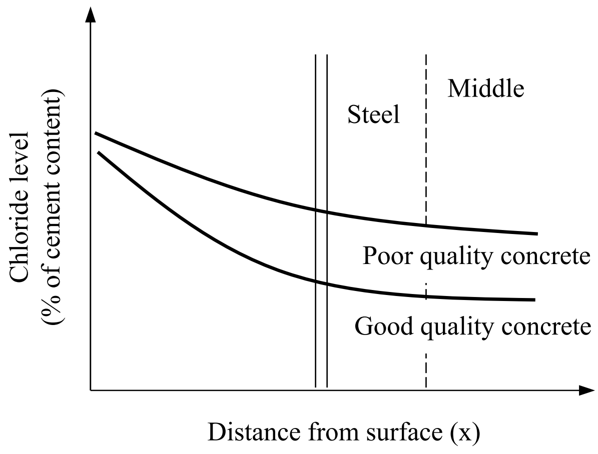
[due to the high alkalinity (pH > 13) of concrete, a protection film (passivation) is formed over the steel bar. This film protects steel from corrosion]

Corrosion Process (by Chloride)

In sea water 2 ~ 3 % chloride or 20,000 ppm of chloride is present. Concrete is a porous material. Chloride from sea water will enter gradually into concrete and after a certain time it will reach over the steel bar. The level of chloride over the steel bar be increased with time due to the further ingress of chloride into concrete. When the level of chloride crosses the threshold level of chloride the passivation film will be broken.

Corrosion will start (rust formation) →continue →Cracking →Spalling





[** Good quality concrete is essential in marine environment to protect steel bar corrosion]

Corrosion reaction:

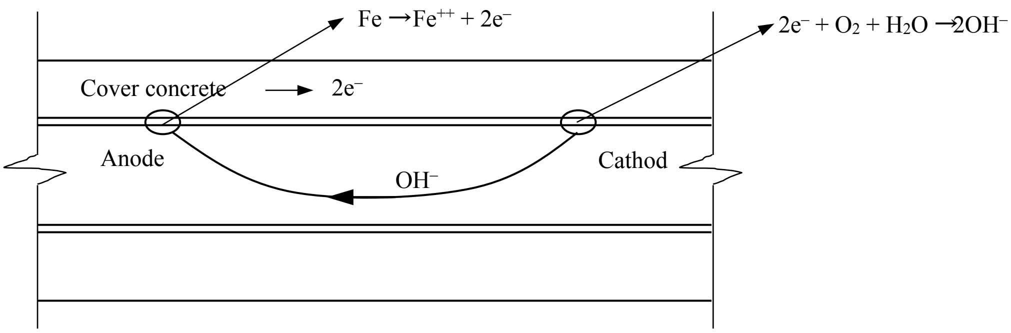
- It is electrochemical reaction
- we need anode and cathode
- Anode generate electron by anodic reaction
- Cathode consume electron by cathodic reaction

$Fe \rightarrow Fe^{++} + 2e^{-}$ (Anodic reaction)

$2e^{-} + O_2 + H_2O \rightarrow OH^{-}$

$Fe^{++} + OH^{-} \rightarrow Fe(OH)_2$ (Rust)

Volume increase → Stress → cracks → spalling



- OH^{-} ion will move with the concrete
- Crack will move along steel bar

Corrosion by Carbonation:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2$

By this reaction, pH of concrete will drop. If pH < 11 then corrosion will start to break down of protection film

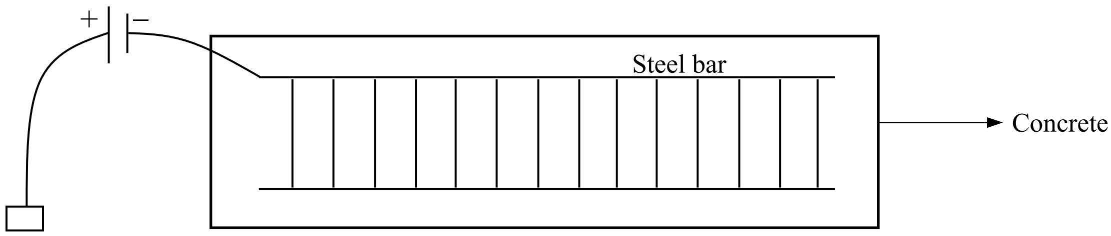
Acid Attack:

Prevention of corrosion

1. **Quality concrete:** More strength, less porous, more durable, reduce w/c ratio upto 0.4 ~ 0.45 by using superplasticizer

2. **Concrete cover:**

3. **Cathode protection:**



By this system steel will always (-) ve

Steel →Cathodic reaction (no rust)

----- Due to cathodic reaction over steel (Rare case)

↓

Hydrogen formation

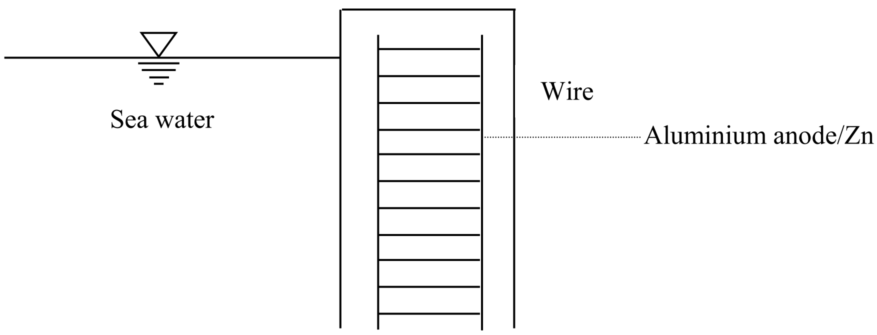
↓

Hydrogen embrittlement

↓

Failure of steel

- Cathodic protection by discrete anode:



Ferrocement:

Special type of concrete made of cement, sand, water and wear mesh of diameter 8 mm, 10 mm, 12 mm

- Generally Coarse Aggregate (CA) are not used
- We have more cement
- Thickness of ferrocement concrete ranges from 20 to 30 mm

Uses of Ferrocement:

- Water tank
- Shed
- Boat,
- Repair/ Rehabilitation
- Sculpture

Advantages of Ferrocement:

- Light in weight
- Economical
- Durable
- Better appearance

Disadvantages of Ferrocement:

- Need careful curing
- Labour intensive
- Slow progress in work

We have to curing carefully because of small thickness of ferrocement and small diameter of steel

Chapter-7

PAINTS, VARNISHES AND METALLIC COATING

Paint:

Construction materials need to be protected from deterioration caused by atmospheric influence or any other harmful species. A large number of organic compositions are available to coat the surface of the structures to prevent the deterioration.

Purpose/Why paints are used?

- To prevent materials from atmospheric influence or actions of other liquids
- Produce a pleasing appearance
- Prevents decay of wood or corrosion of steel
- The surface become hygienically good, clean and attractive
- Smooth surface for cleaning
- Improve sanitary condition
- Obtain better distribution of light

Characteristics of an ideal paint

- Should possess a good spreading power
- Should adhere firmly on the surface applied
- Should be economical
- Should be easily applied
- Should be dried in a reasonable time
- Color is maintained for a long time
- Form a hard and durable surface
- Should not affect the health of worker
- Should not show cracks after drying
- Should possess good moisture resistance
- Produce a thin uniform film when applied
- Should not affect by the atmospheric action
- Should make

Constituents of Paint

(i) **Base:** Chief ingredient of paint. Generally a metallic oxide and it is used in the form of powder. Example: Lead, zinc oxide, iron oxide, graphite, titanium oxide, antimony white, red lead etc.

(ii) **Vehicles:** a liquid which acts as a binder. Example: linseed oil. It is quickly react with atmospheric O_2 and hardened by forming a thin film.

(iii) **Pigment:** A coloring agent which gives desired color to the paints. Generally available in the form of powder.

(iv) **Drier:** The function of drier is to absorb O_2 from atmosphere and supply to the vehicles to dry and harden through the process of oxidation.

(v) **Thinner/Solvent:** A thinner is a solvent added to paints to obtain a product of desired consistency. It helps the paints to be spread uniformly on the surface. The thinner evaporates and drier the paint consequently. Turpentine, petroleum spirit, highly solvent naptha are commonly used solvent or thinner

Types of Paints:

- Oil Paints
- Water Paints
- Aluminum paints
- Cellulose paints
- Water repellent cement paints
- Distempers (one kind of water paint)
- Cement based paints
- Bituminous paints

Painting Plastered surface:

Preparation of the surface before painting is extremely important. Plastered surface should not ordinarily be painted until it has dried completely. Allow time to dry the plaster for 12 months (better), at least 1 month. Wash with Na_2SO_4 or $ZnSO_4$ to neutralize free lime on the walls. Before application of primer, the holes should be filled with plaster of Paris ($CaSO_4$, ½ H_2O) and surface rubbed smooth. After the primed surface has dried, two or more coats of the desired paint may be applied in the usual way.

Paints on steel

- Remove rust and mill scale
- Remove oil, grease and dust from surface by using petrol, benzene, or lime water
- Apply a priming coat consisting of red lead
- Apply two or more coat of the desired paint with brush or spray.
- Apply a coat after drying of the previous coat.

Varnish:

The term varnish is used to indicate the solution of resins or resinous substances dissolved in either alcohol, oil or turpentine.

Types of Varnish:

- Oil varnish
- Spar varnish
- Flat varnish
- Asphalt varnish
- Spirit varnish
- Turpentine varnish

Objectives of Varnish:

- To decorate the surface with out hiding the beautiful grains of wood.
- To protect the surface against the adverse influence of the atmosphere
- Painted surfaces are varnished to enhance the appearance of the paint and to increase the durability of the paint film

Ingredients:

- **Resins:** Copal is commonly used
- **Driers:** Accelerate the process of drying
- **Solvents:** dissolve the resins

Characteristic of the ideal varnish:

- Make the surface glossy
- Dry rapidly and gives a finished surface which is uniform in nature and pleasing in appearance
- Should not fade away under the action of atmosphere
- The film should be hard and durable
- Not shrink or show cracks after hardening

Metallic coating

Processes:

(i) Hot dipping

(ii) Electroplating

Hot dipping:

- Zinc plating (also called Galvanizing)
- Tin plating
- Al, Gld, Nicle plating

Metallic Coating

- Refers to the application a metal coating on a metal.
- Apply to stop deterioration of the materials

Chapter- 8

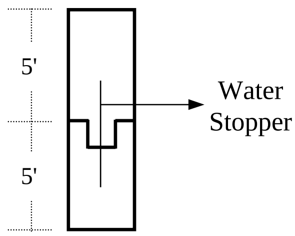
RUBBER, TIMBER AND PLASTIC

Rubber:

- It is an important engineering material
- Polymer
- Elastomer [can take lot of strain, without permanent deformation]
- Use in manufacturing of tubes, types of vehicles or belt, toys.

Civil Engineering uses:

- Base isolation material (earthquake design to isolation use rubber pad)
- Water stopper
- Joint scaler



Types of Rubber:

(i) Natural Rubber

(ii) Artificial Rubber (Synthetic)

Natural Rubber:

This is the main source of rubber (from rubber tree). The latex (milky juice of rubber) is obtained from rubber trees. To get it 2 feet long groves are made in the cambium layer of the rubber trees. Latex (water + rubber) come out through the groves and collected in container/pot.

Artificial Rubber:

Rubber is separated from the latex coagulation. Alcohol or acetic acid is used for coagulation. During coagulation rubber is settled down, like- card, water is liberated at top and drained off. The coagulation rubber is cut into small pieces. Filler materials-like: tar, sulfate etc. are used sometimes.

Properties of Rubber:

- Very strong in tension
- Weak in shear (for this reason we use it for base isolation)
- Insoluble in water
- If placed in boiling water, loss the elasticity
- Deteriorate easily by oil, grease, fat
- An elastomer (large elastic deformation)

Valcanization:

Sometimes *sulfur* is added with rubber to improve its property. The process is known as valcanization.

- Increase in tensile strength
- Increase weathering resistance
- Become more elastic
- Good dimensional stability

(iii) Manufactured it from acetylene gas.

Properties:

- Resistance to acid, grease, oil etc
- High resistance to sunlight and heat

Types

(i) Butadines

(ii) Poly acerletes

(iii) SBR

Timber

Any wood which is used in engineering construction is termed as timber

Tress:

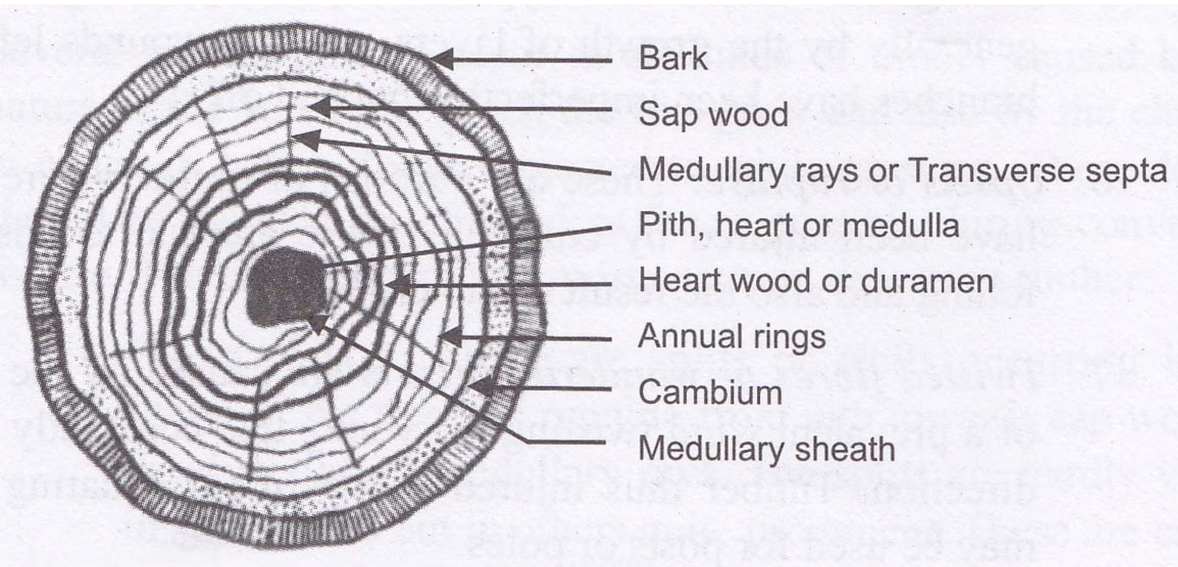
According to the manner of growth, two types:

- **Exogenous:** Expand or growth in both laterally and longitudinally. Example: Teak, Sal etc.
- **Endogenous:** Expand or growth mainly in longitudinally. Example: Bamboo, Cone etc.

Advantages of timber over other materials:

- Easily worked with load
- Relatively stronger in strength in comparison to weight
- Can be used as load bearing and non-load bearing purposes.
- Can be economical
- Used as furniture, decorative purpose
- Has low thermal conductivity
- Durable if properly treated and carefully protected
- Mostly used as plywood, veneers, laminated boards, batten boards as industrial timber.

Typical Cross-section of a timber:



Distinguish between Sap and Heart wood

Sap wood	Heart wood
Mostly newly formed cells	Mostly old and dead cells
Light in color	Dark in color
Decomposable easily (due to the presence of a lot of sap)	Less decomposable (due to the presence of resin)
More moisture content	Less moisture content
Light	Dense

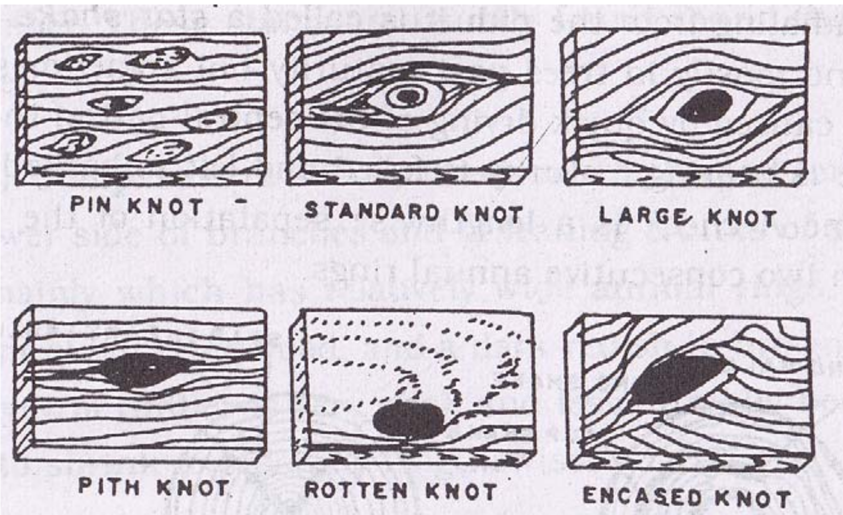
Annual Ring formation

Trees growths rapidly in spring due to the available food. But in summer season the growth of the trees is reduced. For this reason, the trees growth in spring has light color and the trees growth in summer season has dark color. Due to this variation of color an annual ring is formed in one year.

Defects of timber:

Natural defects:

(i) Knots (*at the base of branches*).



(ii) Twisted Fibers: (due to the compressive stress)

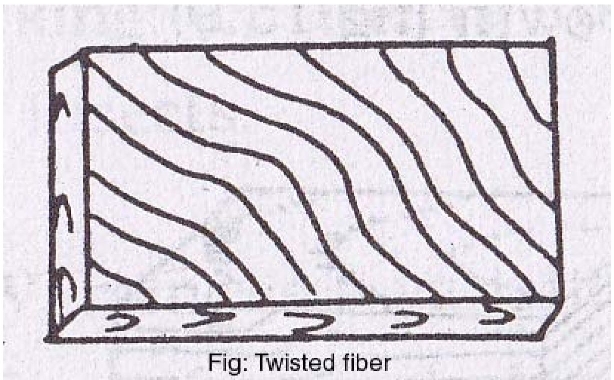


Fig: Twisted fiber

(iii) Shakes:

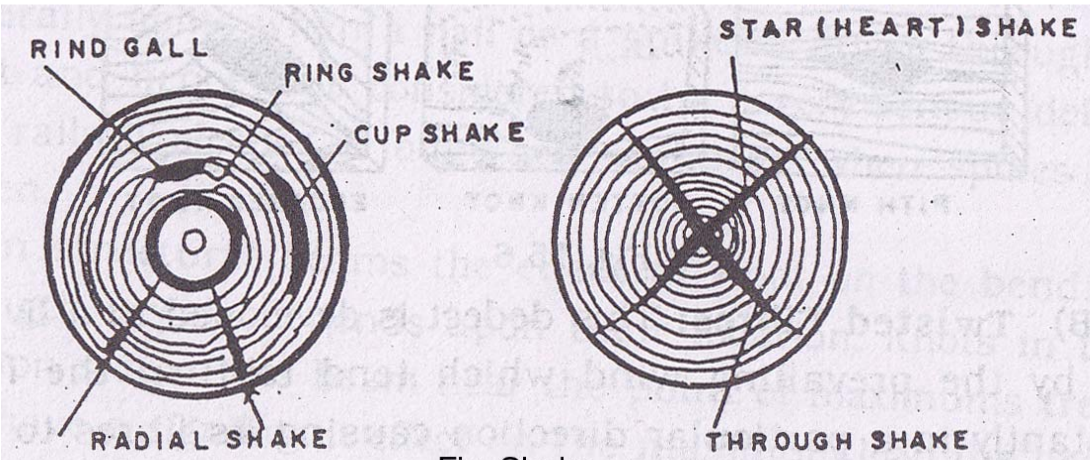
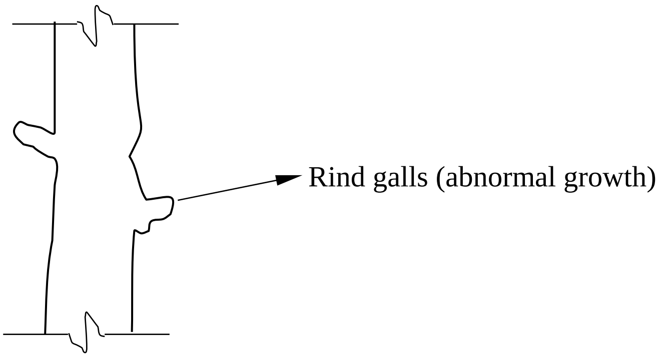


Fig: Shake

(iv) Rind Galls



(v) Upsets

(vi) Foxiness

(vii) Compression

(viii) Pitch pockets

Artificial defects:

(i) Warping

(ii) Splitting and Cracking

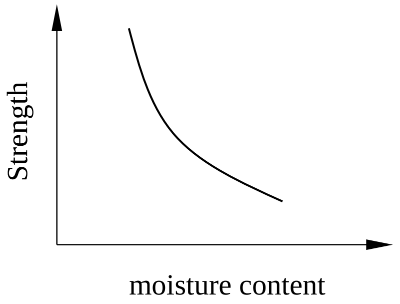
(iii) Defect due to fungal action

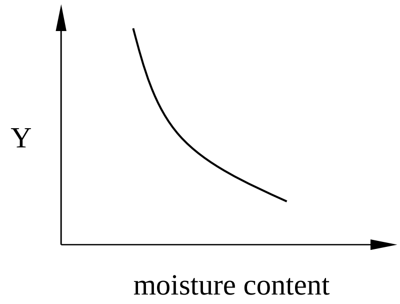
(iv) Defect due to insects and worms

- **Moisture content:**

Amount of water (%) absorbed by timber = $\frac{W_{AD} - W_{OD}}{W_{OD}} \times 100$ %

Here, W_{AD} = weight (air dry) of timber
W_{OD} = weight (oven dry) of timber





- **Marketable form of timber or conversion of timber:**

The preparation of timber from felled trees by strimming of ... , removing the bark, cutting and sawing to convert it into marketable forms is called conversion.

<u>Some principle marketable forms are as follow</u>:

(i) **Log:** It is trunk of trees obtained after removal of branches

(ii) **Pole:** Long round, logs of wood (diameter > 200 mm)

(iii) **Plank:** A parallel sided pieces of timber (thickness < 50 mm, width > 50 mm)

(iv) **Board:** A plank (thickness < 50 mm, width > 150 mm)

(v) **Batten:** A plank (Breadth and thickness > 50 mm)

(vi) **Deal:** A plank (1.5 to 2 inches thickness, width < 9 inches)

- **Seasoning of timber:**
  - Before use timber, we need seasoning
  - Seasoning is the process of drying sap and moisture of timber

Main objectives of seasoning:

- To bring timber to state of equilibrium moisture content which is essential for all subsequent conversion and use
- To reduce weight of timber to facilitate transportation and handling
- To make timber durable and more resistant to decay due to fungal action
- To make timber strong, hard and stiff
- To dry sap and to reduce moisture
- To make timber more suitable for polishing and pointing

Method of seasoning

(1) Natural seasoning

(2) Artificial seasoning

(3) Water seasoning

Artificial Seasoning:

- Kiln Seasoning
- Chemical Seasoning
- Electrical Seasoning
- Streaming Seasoning
- Boiling Seasoning
- Smoke Seasoning

Industrial form of timber

(1) Veneers:
- Thin sheets of timber
- Thickness 0.4 ~ 0.6 mm or more
- Can be used on inferior wood surface
- Used in decorative purpose

(2) Plywoods
- Made by several veneers
- Used in ceilings, doors, furniture, partition, formwork

(3) Laminated Boards
- Made by several reneers
- It consists of a core of thick strips about 1/8"
- Total thickness: 0.5" ~ 2"
- Used as partitions, decorative works, furniture etc

(4) Batten Boards
- Like laminated boards except the middle thick panel is replaced by cut wood battens of 0.5" ~ 1" thick
- Used as decorative purpose, furniture, partitions etc.

(5) Reconstructed wood
- Insulating board (fiber)
- Soft board
- Hard board

- Super-hard boards
- Laminated fiber building boards

Fiber boards are used as:

- Partition walls
- Interior finish furniture
- Flush doors
- Table tops
- Railway coaches
- Notice boards
- Ship building
- Packing industries

<u>Plastic:</u>

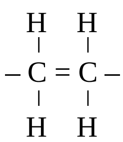
The plastic is an organic substance. It consists of natural or synthetic binders/resin with or without molding

- Mostly use in repair material
- The finished product of plastic is rigid and stable at natural work

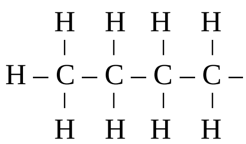
<u>Polymerization:</u>

Plastic consists of one basic chemical unit called monomer or monolith. A long chain of this basic unit is formed by polymerization. Example:

<u>Ethylene (C_2H_4);</u>



<u>Polythelyne $(C_2H_4)_n$</u>



[High molecular wt.]

Types of plastic:

There are two types of plastic based on heat treatment.

(i) Thermo-plastic
(ii) Thermo-setting plastic

Thermo-Plastic:

- Heat non-convertible group
- Can be recycled
- For example: Shopping bags (Polythene)

Thermo-Setting Plastic

- Heat convertible group
- Used in many engineering applications
- More hard
- For example: Poly-vinyl chloride (P.V.C)

Properties of Plastic:

- Appearance:→transparent (pigments are added to make it different color)
- Ductility: →Lack of ductility
- Dimensional Stability: →Good
- Durability: →Good
- Maintenance: →Need less maintenance
- Strength: →Can be improved by using fibers.

Fibers:

Types of Fiber:

(i) Carbon Fiber
(ii) Glass Fiber
(iii) Aramid Fiber

Fiber Reinforce Plastic (FRP) = Plastic + Fiber

Plastic ↓ Acts as binder; Fiber ↘ Acts as reinforce

- Use Carbon ---------------- CFRP
- Use Glass ------------------ GFRP
- Use Aramid --------------- AFRP

Purposes:

- FRP generally used for repair and strengthening or rehabilitation of concrete structure
- Direction of firer is important for structure

Causes of Repair:

- Error in design
- Earthquake
- Natural causes

PVC Pipe:

One kind of thermo-setting plastic (heat convertible group). Commonly used in Bangladesh for plumbing

Properties of Fiber:

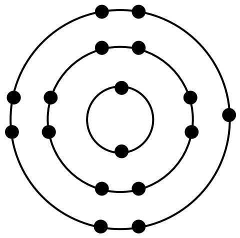
- Good thermal insulation
- Rigid structure
- Less friction
- Durable
- Chloride is added in carbon chain of polymer

Chapter – 10

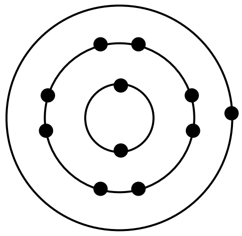
ATOMIC STRUCTURES AND BONDING

The atoms in a solid are hold together by inter atomic forces. This process is known as bonding. The physical, chemical and other properties of a metal depend on the nature of the bonding.

Atomic Structure:



Cl (17)



Na (11)

Rule-1: $n \leq 2n^2$ [n = No. of cells; 1, 2, 3 -------------]

Rule -2:

- The outer most shell can not have more than 8 electrons. The penultimate shell can not have more than 18 electrons.
- If outer shell has less than 8 electrons, It will try to give or take electrons
- If outer most shell has 8 electrons called saturated shell or saturated condition
- If more than 4 – take electrons ----- electronegative
- If less than 4 – give electrons ----- electropositive
- The elements which have the tendency to give (lend) electrons are called metals
- The elements which have the tendency to take (receive/borrow) electrons are called non-metals

Ex: $N^+ + Cl^-$ ---------- NaCl

Bonds:

- Primary Bonds
  - Ionic Bond
  - Covalent Bond
  - Metallic Bond
- Secondary Bonds -------- Hydrogen Bond
- Mixed Bonds

Ionic Bond

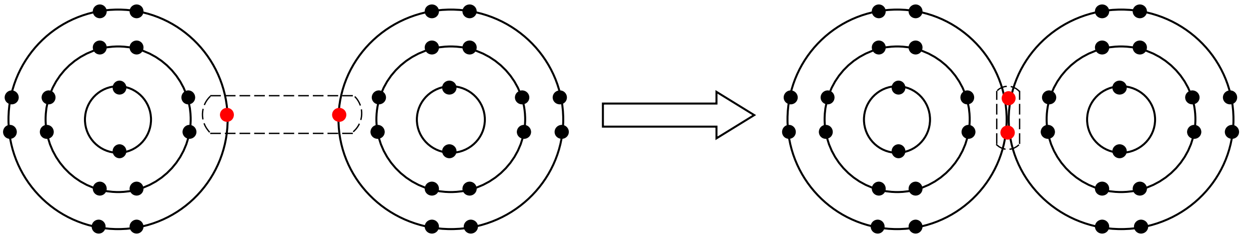
Give and take electrons between elements. Example: NaCl

Properties of Ionic Bond:

- Crystal structure
- Soluble in water
- Non conductor of electricity
- High melting and boiling points due to strong electrostatic force

Covalent Bond:

This bond is formed by shearing of electrons between two atoms.



Properties of Covalent Bond:

- Non soluble in water
- Electric insulator
- Soft
- Low boiling and melting point due to weak electrostatic force

Metallic Bond:

All commercial metals have one, two or three valency electrons in their outer most shell of the atoms. These electrons can be easily released to a common pool of electrons and it results in the formation of an electron cloud which surrounds the solid metal.

- They are bound to different atoms at different times for a short period.
- These bonds are weaker than ionic bonds

Properties of Metallic Bond:

- Good conductor of heat and electricity
- Crystal structure
- high melting point

Hydrogen Bond

These bonds are formed between atomic groups with no electrons to share. They occur frequently in organic materials in which hydrogen often play a major role. This bond is formed due to Vander Wall's force of attraction arising form electrical dipoles.

Mixed Bond:

Combination of pure bonds

Chapter- 10

CRYSTAL STRUCTURES

Crystal Structures:

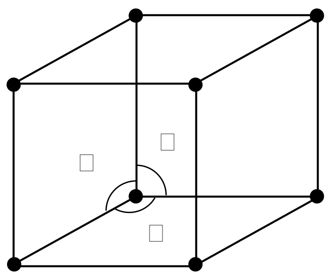
For solids ------------------------------- → Crystal / → Non-crystal (Amorphous)
(with respect to arrangement of atoms)

- In crystal structures, the atoms are arranged in a particular manner/way.
- For non-crystal structure, there is no particular arrangement of atoms

Space Lattice and Unit Cell

A space lattice is a three dimensional geometric construction which indicates the arrangement of atoms in a crystal solid.

The smallest component of the lattice structure is known as unit cell.



- a, b, c, □, □, □ = Lattice parameters
- Brick wall = Space lattice

The study of the space lattice is important:

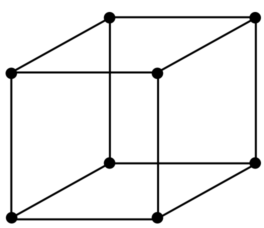
- To describe the arrangement of atoms in a crystal
- To compare the arrangement of atoms in different crystals

Types of unit cell:

1) Plain cubic unit cell
2) Body centered cubic unit cell
3) Face centered cubic unit cell
4) Hexagonal close packed unit cell

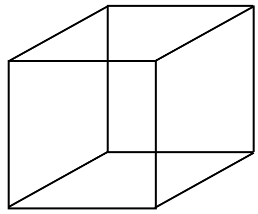
Plain Cubic Unit Cell

Smallest possible unit cells. Eight atoms at the corners which are shared by eight adjoining cubic.



Shear of atoms for each cube = $8 \times \frac{1}{8}$

Body centered cubic unit cell

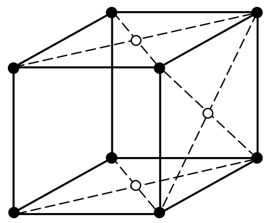


- Eight atoms are at corners
- One atom at corner
- Corner atoms are shared by eight unit cells
- Share of atoms for each unit cell = 1+8 ×1/8 = 2

Face Centered Cubic Unit Cell

Corner atoms ---------- 8 (shared by 8 cubes)
Face atoms ------------- 6 (shared by 2 cubes)

14

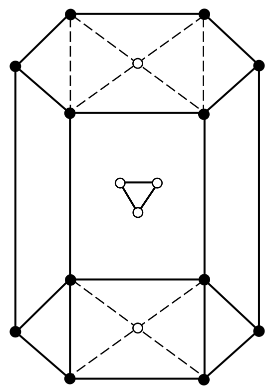


- Unit cell = cubes
- Share of each cell = $8\times\frac{1}{8}+\frac{1}{2}\times 6$

$= 1 + 3$

$= 4$

Hexagonal close packed unit cell



- One atom at each corner = 12 atoms (shared by 6 cubes)
- One atom at the face = 2
- Inside = 3

= 17 atoms

- Share of atoms of each unit cell = 3 + 12 × 1/6 + 2 × ½
  = 6 atoms

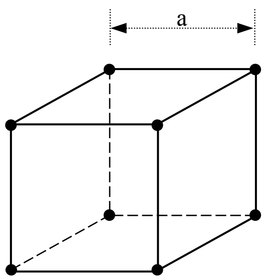
Atomic Radius

1. Plain Cubic Unit Cell

Atoms touch each other along the lattice parameter

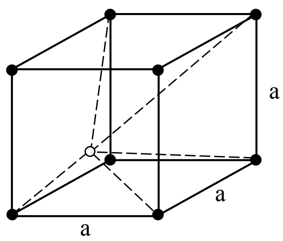
$a = 2\,r$

$r = a/2$



2. Body Centered Cubic Unit Cell

Atoms touch each other along the diagonal of two cubes



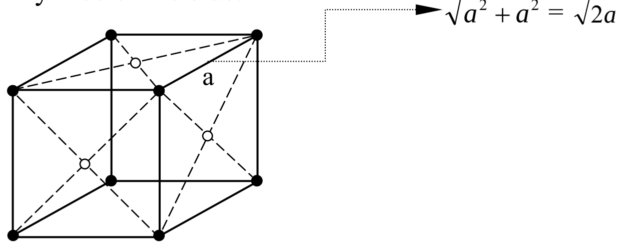
Diagonal = 4r

$$\therefore 4r = \sqrt{\left(\sqrt{2}a\right)^2 + (a)^2} = \sqrt{3}\,a$$

$$\therefore r = \sqrt{3}/4 \times a = 0.433\,a$$

3. Face Centered Unit Cell

Atoms touch each other along the diagonal of any face of the side.



Diagonal of the face = 4r

$\therefore$ 4r = $\sqrt{2}$ a

$\therefore$ r = $\sqrt{2}$ /4 × a = 0.353 a

Atomic Packing Factor (APF):

It is defined as the fraction of volume occupied by spherical atoms as compared to the total volume of the structure. It is also termed as the relative density of packing.

Say, v = Volume of the atoms

V = Volume of the unit cell

$$\therefore \text{APF} = \frac{v}{V}$$

1. Plain Cubic Unit Cell

$$\therefore \text{APF} = \frac{v}{V} = \frac{(4/3)\times\pi\times(a^3/8)}{a^3} = \frac{\pi}{6}$$

$\therefore$ APF = 0.524

52.4 % volume is occupied by the atoms

r = a/2

No. of atom = 1

V = a × a × a = a^3

v = (4/3)×□×r^3

= (4/3)× □ × $(a/2)^3$

2. Body Centered Cubic Unit Cell

No. of atoms for each unit cell = 2

r = 0.433 a

$$\therefore \text{APF} = \frac{(4/3)\times\pi\times(0.433a)^2\times 2}{a^3}$$

$\therefore$ APF = 0.68

68 % volume is occupied by the atoms

3. Face Centered Cubic Unit Cell

No. of atoms shared by an unit cell,

n = 4

r = 0.353 a

v = (4/3)×□×$(0.353a)^3$×4

V = a^3

$$\therefore \text{APF} = \frac{(4/3)\times\pi\times(0.353a)^2\times 4}{a^3}$$

$\therefore$ APF = 0.74

74 % volume is occupied by the atoms

Electroplating

- **What is Electroplating?**

Electroplating is a plating process that uses electrical current to reduce cations of a desired material from a solution and coat a conductive object with a thin layer of the material, such as a metal.

- **Why Electroplating is used?**

  - It is primarily used for depositing a layer of material to bestow a desired property (e.g., abrasion and wear resistance, corrosion protection, lubricity, aesthetic qualities, etc.) to a surface that otherwise lacks that property.
  - To build up thickness on undersized parts.

The process used in electroplating is called **electro-deposition**. It is analogous to a galvanic cell acting in reverse. The part to be plated is the cathode of the circuit. In one technique, the anode is made of the metal to be plated on the part. Both components are immersed in a solution called an electrolyte containing one or more dissolved metal salts as well as other ions that permit the flow of electricity. A power supply supplies a direct current to the anode, oxidizing the metal atoms that comprise it and allowing them to dissolve in the solution. At the cathode, the dissolved metal ions in the electrolyte solution are reduced at the interface between the solution and the cathode, such that they "plate out" onto the cathode. The rate at which the anode is dissolved is equal to the rate at which the cathode is plated, vis-à-vis the current flowing through the circuit. In this manner, the ions in the electrolyte bath are continuously replenished by the anode.

Other electroplating processes may use a non consumable anode such as lead. In these techniques, ions of the metal to be plated must be periodically replenished in the bath as they are drawn out of the solution.

Contents

Process

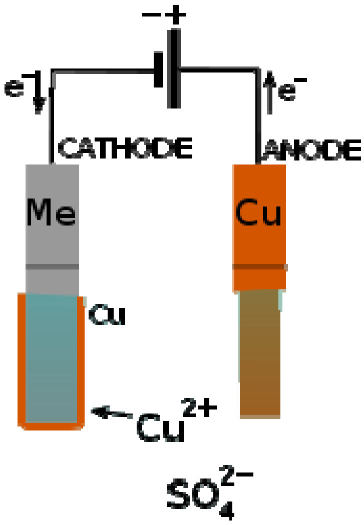


Fig: Electroplating of a metal (Me) with copper in a copper sulfate bath

The anode and cathode in the electroplating cell are both connected to an external supply of direct current - a battery or, more commonly, a rectifier. The anode is connected to the positive terminal of the supply, and the cathode (article to be plated) is connected to the negative terminal. When the external power supply is switched on, the metal at the anode is oxidized from the zero valence state to form cations with a positive charge. These cations associate with the anions in the solution. The cations are reduced at the cathode to deposit in the metallic, zero valence state. For example, in an acid solution, copper is oxidized at the anode to Cu^{2+} by losing two electrons. The Cu^{2+} associates with the anion SO_4^{2-} in the solution to form copper sulfate. At the cathode, the Cu^{2+} is reduced to metallic copper by gaining two electrons. The result is the effective transfer of copper from the anode source to a plate covering the cathode.

The plating is most commonly a single metallic element, not an alloy. However, some alloys can be electrodeposited, notably brass and solder.

Many plating baths include cyanides of other metals (e.g., potassium cyanide) in addition to cyanides of the metal to be deposited. These free cyanides facilitate anode corrosion, help to maintain a constant metal ion level and contribute to conductivity. Additionally, non-metal chemicals such as carbonates and phosphates may be added to increase conductivity.

When plating is not desired on certain areas of the substrate, stop-offs are applied to prevent the bath from coming in contact with the substrate. Typical stop-offs include tape, foil, lacquers, and waxes.

Strike

Initially, a special plating deposit called a "strike" or "flash" may be used to form a very thin (typically less than 0.1 micrometer thick) plating with high quality and good adherence to the substrate. This serves as a foundation for subsequent plating processes. A strike uses a high current density and a bath with a low ion concentration. The process is slow, so more efficient plating processes are used once the desired strike thickness is obtained.

The striking method is also used in combination with the plating of different metals. If it is desirable to plate one type of deposit onto a metal to improve corrosion resistance but this metal has inherently poor adhesion to the substrate, a strike can be first deposited that is compatible with both. One example of this situation is the poor adhesion of electrolytic nickel on zinc alloys, in which case a copper strike is used, which has good adherence to both

Current density

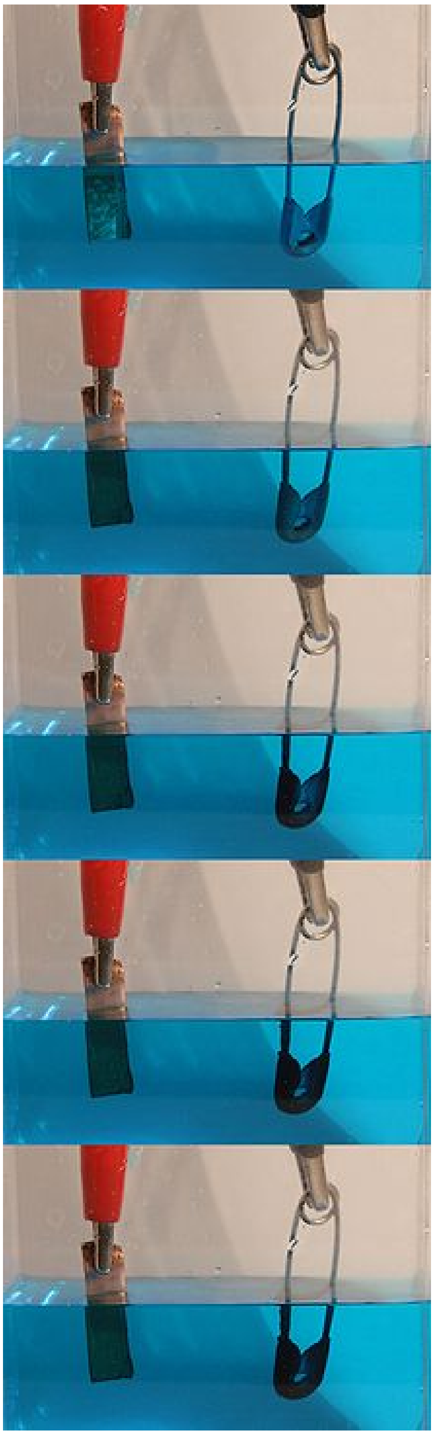


Fig: A time course of electroplating with copper

The anode on the left is pure copper, the safety pin on the right is the target for plating. The first image is before the electrical supply has been connected, the second image shows plating with a thin layer of copper and the later images show the buildup of "fluffy" structurally weak deposits

The current density (amperage of the electroplating current divided by the surface area of the part) in this process strongly influences the deposition rate, plating adherence, and plating quality. This density can vary over the surface of a part, as outside surfaces will tend to have a higher current density than inside surfaces (e.g., holes, bores, etc.). The higher the current density, the faster the deposition rate will be, although there is a practical limit enforced by poor adhesion and plating quality when the deposition rate is too high.

While most plating cells use a continuous direct current, some employ a cycle of 8–15 seconds on followed by 1–3 seconds off. This technique is commonly referred to as "pulse plating" and allows high current densities to be used while still producing a quality deposit. In order to deal with the uneven plating rates that result from high current densities, the current is even sometimes reversed in a method known as "pulse-reverse plating", causing some of the plating from the thicker sections to re-enter the solution. In effect, this allows the "valleys" to be filled without over-plating the "peaks". This is common on rough parts or when a bright finish is required. In a typical pulse reverse operation, the reverse current density is three times greater than the forward current density and the reverse pulse width is less than one-quarter the forward pulse width. Pulse-reverse processes can be operated at a wide range of frequencies from several hundred hertz up to the order of megahertz.

Brush electroplating

A closely-related process is brush electroplating, in which localized areas or entire items are plated using a brush saturated with plating solution. The brush, typically a stainless steel body wrapped with a cloth material that both holds the plating solution and prevents direct contact with the item being plated, is connected to the positive side of a low voltage direct-current power source, and the item to be plated connected to the negative. The operator dips the brush in plating solution then applies it to the item, moving the brush continually to get an even distribution of the plating material. The brush acts as the anode, but typically does not contribute any plating material, although sometimes the brush is made from or contains the plating material in order to extend the life of the plating solution.

Brush electroplating has several advantages over tank plating, including portability, ability to plate items that for some reason cannot be tank plated (one application was the plating of portions of very large decorative support columns in a building restoration), low or no masking requirements, and comparatively low plating solution volume requirements. Disadvantages compared to tank plating can include greater operator involvement (tank plating can frequently be done with minimal attention), and inability to achieve as great a plate thickness.

Electroless deposition

Usually an electrolytic cell (consisting of two electrodes, electrolyte, and external source of current) is used for electro-deposition. In contrast, an electroless deposition process uses only one electrode and no external source of electrical current. However, the solution for the electroless process needs to contain a reducing agent so that the electrode reaction has the form:

$$M^{z+} + Red_{solution} \xrightarrow{\text{catalytic surface}} M_{solid} + Oxy_{solution}$$

For example, an electroless process is used for electroless nickel plating.

Cleanliness

Cleanliness is essential to successful electroplating, since molecular layers of oil can prevent adhesion of the coating. ASTM B322 is a standard guide for cleaning metals prior to electroplating. Cleaning processes include solvent cleaning, hot alkaline detergent cleaning, electrocleaning, and acid etc. The most common industrial test for cleanliness is the water-break test, in which the surface is thoroughly rinsed and held vertical. Hydrophobic contaminants such as oils cause the water to bead and break up, allowing the water to drain rapidly. Perfectly clean metal surfaces are hydrophilic and will retain an unbroken sheet of water that does not bead up or drain off. ASTM F22 describes a version of this test. This test does not detect hydrophilic contaminants, but the electroplating process can displace these easily since the solutions are water-based. Surfactants such as soap reduce the sensitivity of the test and must be thoroughly rinsed off.

Effects of Electroplating

Electroplating changes the chemical, physical, and mechanical properties of the workpiece. An example of a chemical change is when nickel plating improves corrosion resistance. An example of a physical change is a change in the outward appearance. An example of a mechanical change is a change in tensile strength or surface hardness

Limitations of Electroplating

Obtaining a uniform thickness with electroplating can be difficult depending on the geometry of the object being plated. The plating metal is preferentially attracted to external corners and protrusions, but unattracted to internal corners and recesses. These difficulties can be overcome with multiple anodes or a specially shaped anode that mimics the object geometry; however both of these solutions increase cost.

Galvanic Corrosion

What is Galvanic Corrosion?

Galvanic corrosion (also called ' dissimilar metal corrosion' or wrongly 'electrolysis') refers to corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte.

When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes faster than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone.

Conditions to form Galvanic Corrosion

For galvanic corrosion to occur, **three conditions** must be present:

- Electrochemically dissimilar metals must be present
- These metals must be in electrical contact, and
- The metals must be exposed to an electrolyte

The relative nobility of a material can be predicted by measuring its corrosion potential. The well known ***galvanic series*** lists the relative nobility of certain materials in sea water. A small anode/cathode area ratio is highly undesirable. In this case, the galvanic current is concentrated onto a small anodic area. Rapid thickness loss of the dissolving anode tends to occur under these conditions. Galvanic corrosion problems should be solved by designing to avoid these problems in the first place. Galvanic corrosion cells can be set up on the macroscopic level or on the microscopic level. On the micro-structural level, different phases or other micro-structural features can be subject to galvanic currents.

Galvanic Table

The following galvanic table lists metals in the order of their relative activity in seawater environment. The list begins with the more active (anodic) metal and proceeds down the least active (cathodic) metal of the galvanic series.

- A "galvanic series" applies to a particular electrolyte solution
- In a galvanic couple, the metal higher in the series (or the smaller) represents the anode, and will corrode preferentially in the environment.
- Listed below is the latest galvanic table from MIL-STD-889 where the materials have been numbered for discussion of characteristics.
- For any combination of dissimilar metals, the metal with the lower number will act as an anode and will corrode preferentially.
- The table is the galvanic series of metals in sea water from Army Missile Command Report RS-TR-67-11, "Practical Galvanic Series." (Reference)

Active (Anodic)

1. Magnesium
2. Mg alloy AZ-31B
3. Mg alloy HK-31A
4. Zinc (hot-dip, die cast, or plated)
5. Beryllium (hot pressed)
6. Al 7072 clad on 7075
7. Al 2014-T3
8. Al 1160-H14
9. Al 7079-T6
10. Cadmium (plated)
11. Uranium
12. Al 218 (die cast)
13. Al 5052-0
14. Al 5052-H12
15. Al 5456-0, H353
16. Al 5052-H32
17. Al 1100-0
18. Al 3003-H25
19. Al 6061-T6
20. Al A360 (die cast)
21. Al 7075-T6
22. Al 6061-0
23. Indium
24. Al 2014-0
25. Al 2024-T4

26. Al 5052-H16
27. Tin (plated)
28. Stainless steel 430 (active)
29. Lead
30. Steel 1010
31. Iron (cast)
32. Stainless steel 410 (active)
33. Copper (plated, cast, or wrought)
34. Nickel (plated)
35. Chromium (Plated)
36. Tantalum
37. AM350 (active)
38. Stainless steel 310 (active)
39. Stainless steel 301 (active)
40. Stainless steel 304 (active)
41. Stainless steel 430 (active)
42. Stainless steel 410 (active)
43. Stainless steel 17-7PH (active)
44. Tungsten
45. Niobium (columbium) 1% Zr
46. Brass, Yellow, 268
47. Uranium 8% Mo
48. Brass, Naval, 464
49. Yellow Brass
50. Muntz Metal 280
51. Brass (plated)
52. Nickel-silver (18% Ni)
53. Stainless steel 316L (active)
54. Bronze 220
55. Copper 110
56. Red Brass
57. Stainless steel 347 (active)
58. Molybdenum, Commercial pure
59. Copper-nickel 715
60. Admiralty brass
61. Stainless steel 202 (active)
62. Bronze, Phosphor 534 (B-1)
63. Monel 400
64. Stainless steel 201 (active)
65. Carpenter 20 (active)
66. Stainless steel 321 (active)
67. Stainless steel 316 (active)
68. Stainless steel 309 (active)
69. Stainless steel 17-7PH (passive)
70. Silicone Bronze 655
71. Stainless steel 304 (passive)
72. Stainless steel 301 (passive)
73. Stainless steel 321 (passive)
74. Stainless steel 201 (passive)
75. Stainless steel 286 (passive)
76. Stainless steel 316L (passive)

77. AM355 (active)
78. Stainless steel 202 (passive)
79. Carpenter 20 (passive)
80. AM355 (passive)
81. A286 (passive)
82. Titanium 5A1, 2.5 Sn
83. Titanium 13V, 11Cr, 3Al (annealed)
84. Titanium 6Al, 4V (solution treated and aged)
85. Titanium 6Al, 4V (anneal)
86. Titanium 8Mn
87. Titanium 13V, 11Cr 3Al (solution heat treated and aged)
88. Titanium 75A
89. AM350 (passive)
90. Silver
91. Gold
92. Graphite

Galvanic Compatibility

Often when design requires that dissimilar metals come in contact, the galvanic compatibility is managed by finishes and plating. The finishing and plating selected facilitate the dissimilar materials being in contact and protect the base materials from corrosion.

- For ***harsh environments***, such as outdoors, high humidity, and salt environments fall into this category. Typically there should be not more than 0.15 V difference in the "Anodic Index". For example; gold - silver would have a difference of 0.15V being acceptable.
- For ***normal environments***, such as storage in warehouses or non-temperature and humidity controlled environments. Typically there should not be more than 0.25 V difference in the "Anodic Index".
- For ***controlled environments***, such that are temperature and humidity controlled, 0.50 V can be tolerated. Caution should be maintained when deciding for this application as humidity and temperature do vary from regions.

Galvanic Series in Seawater

A galvanic series **has been drawn up for metals and alloys in seawater**, which shows their relative nobility. The series is based on corrosion potential measurements in seawater. The relative position of the materials can change in other environments. The further apart the materials are in this series, the higher the risk of galvanic corrosion.

Most cathodic, noble, or resistant to corrosion

Platinum
Gold
Graphite
Titanium
Silver
/ Chlorimet 3
\ Hastelloy C
/ 18-8 Mo stainless steel (passive)
| 18-8 stainless steel (passive)
\ Chromium steel >11 % Cr (passive)
/ Inconel (passive)
\ Nickel (passive)
/ Silver solder
| Monel
| Bronzes
| Copper
\ Brasses
/ Chlorimet 2
\ Hastelloy B
/ Inconel (active)
\ Nickel (active)
Tin
Lead
Lead-tin solders
/ 18-8 Mo stainless steel (active)
\ 18-8 stainless steel (active)
Ni-resist
Chromium steel >11 % Cr (active)
/ Cast iron
\ Steel or iron
2024 aluminum
Cadmium
Commercially pure aluminium
Zinc
Magnesium and its alloys