LECTURE NOTES ON

CONCRETE TECHNOLOGY

UNIT- 1

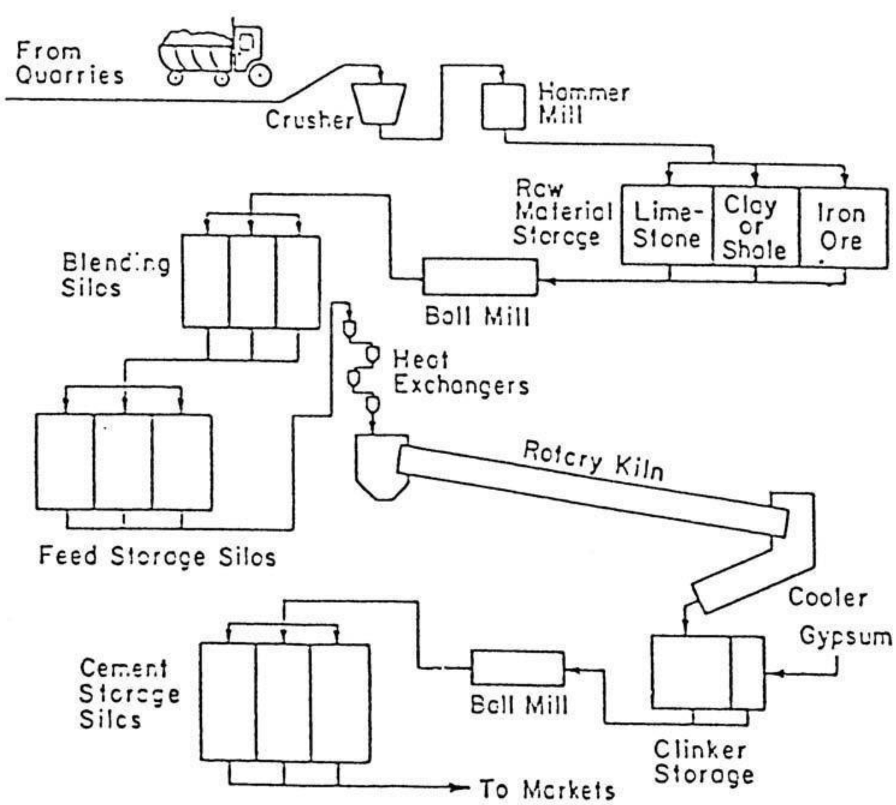
Cement, Admixtures

Portland Cement

Concrete is made by portland cement, water and aggregates. Portland cement is a hydraulic cement that hardens in water to form a water-resistant compound. The hydration products act as binder to hold the aggregates together to form concrete. The name portland cement comes from the fact that the colour and quality of the resulting concrete are similar to Portland stone, a kind of limestone found in England.

Manufacture of Portland cement

Portland cement is made by blending the appropriate mixture of limestone and clay or shale together and by heating them at 1450^{o}C in a rotary kiln. The sequence of operations is shown in following figure. The preliminary steps are a variety of blending and crushing operations. The raw feed must have a uniform composition and be a size fine enough so that reactions among the components can complete in the kiln. Subsequently, the burned clinker is ground with gypsum to form the familiar grey powder known as Portland cement.



The raw materials used for manufacturing Portland cement are limestone, clay and Iron ore.

a) Limestone (C_aCO_3) is mainly providing calcium in the form of calcium oxide (CaO)

$$C_aCO_3\ (1000^oC) \rightarrow CaO + CO_2$$

b) Clay is mainly providing silicates (SiO_2) together with small amounts of $Al_2O_3 + Fe_2O_3$

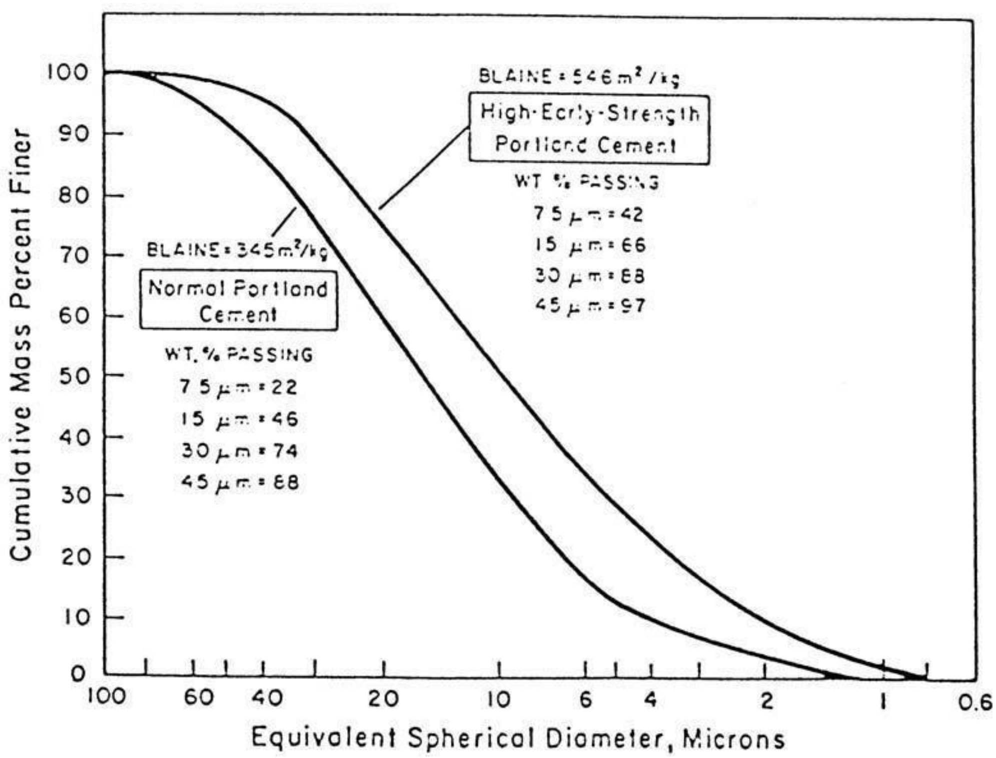
$$Clay\ (1450^oC) \rightarrow SiO_2 + Al_2O_3 + Fe_2O_3 + H_2O$$

c) Iron ore and Bauxite are providing additional aluminium and iron oxide (Fe_2O_3) which help the formation of calcium silicates at low temperature. They are incorporated into the raw mix.

Limestone		$3\ CaO^oSiO_2$
	High temperature	$2\ CaO^oSiO_2$
Clay	$\longrightarrow$	
	(1,450 ^oC)	$3\ CaO^oAl_2O_3$
Iron Ore, Bauxite		$4\ CaO^oAl_2O_3{}^oFe_2O_3$

d) The clinker is pulverized to small sizes (< 75 µm). 3-5% of gypsum (calcium sulphate) is added to control setting and hardening.

The majority particle size of cement is from 2 to 50 µm. A plot of typical particle size distribution is given below. (Note: "Blaine" refers to a test to measure particle size in terms of surface area/mass)



Chemical composition

a) Abbreviation:

$CaO = C$, $SiO_2 = S$, $Al_2O_3 = A$; $Fe_2O_3 = F$, $Ca(OH)_2 = CH$,

$H_2O = H$, $SO_3 = \bar{S}$ (sulphur trioxide)

Thus we can write 3 CaO = C_3 and 2 $CaO^{o}SiO_2 = C_2S$.

b) Major compounds:

Compound	Oxide composition	colour	Common name	Weight percentage
Tricalcium Silicate	C_3S	white	Alite	50%
Dicalcium Silicate	C_2S	white	Belite	25%
Tricalcium Aluminate	C_3A	white/grey	---	12%
Tetracalcium Aluminoferrite	C_4AF	black	Ferrite	8%

Since the primary constituents of Portland cement are calcium silicate, we can define Portland cement as a material which combine CaO SiO_2 in such a proportion that the resulting calcium silicate will react with water at room temperature and under normal pressure.

c) Minor components of Portland cement

The most important minor components are gypsum, MgO, and alkali sulphates.

Gypsum ($2CaSO_4^{o}2H_2O$) is an important component added to avoid flash set.

Alkalies (MgO, Na_2O, K_2O) can increase pH value up to 13.5 which is good for reinforcing steel protection. However, for some aggregates, such a high alkaline environment can cause alkali aggregate reaction problem.

Hydration

The setting and hardening of concrete are the result of chemical and physical processes that take place between Portland cement and water, i.e. hydration. To understand the properties and behaviour of cement and concrete some knowledge of the chemistry of hydration is necessary.

A) Hydration reactions of pure cement compounds

The chemical reactions describing the hydration of the cement are complex. One approach is to study the hydration of the individual compounds separately. This assumes that the hydration of each compound takes place independently of the others.

I. Calcium silicates

Hydration of the two calcium silicates gives similar chemical products, differing only in the amount of calcium hydroxide formed, the heat released, and reaction rate.

$2\ C_3S + 7\ H \rightarrow C_3S_2H_4 + 3\ CH$ $2\ C_2S + 5\ H \rightarrow C_3S_2H_4 + CH$

The principal hydration product is $C_3S_2H_4$, calcium silicate hydrate, or C-S-H (non-stoichiometric). This product is not a well-defined compound. The formula $C_3S_2H_4$ is only an approximate description. It has amorphous structure making up of poorly organized layers and is called glue gel binder. C-S-H is believed to be the material governing concrete strength. Another product is CH - $Ca(OH)_2$, calcium hydroxide. This product is a hexagonal crystal often forming stacks of plates. CH can bring the pH value to over 12 and it is good for corrosion protection of steel.

II. Tricalcium aluminate

Without gypsum, C_3A reacts very rapidly with water:

$C_3A + 6\ H \rightarrow C_3AH_6$

The reaction is so fast that it results in flash set, which is the immediate stiffening after mixing, making proper placing, compacting and finishing impossible.

With gypsum, the primary initial reaction of C_3A with water is :

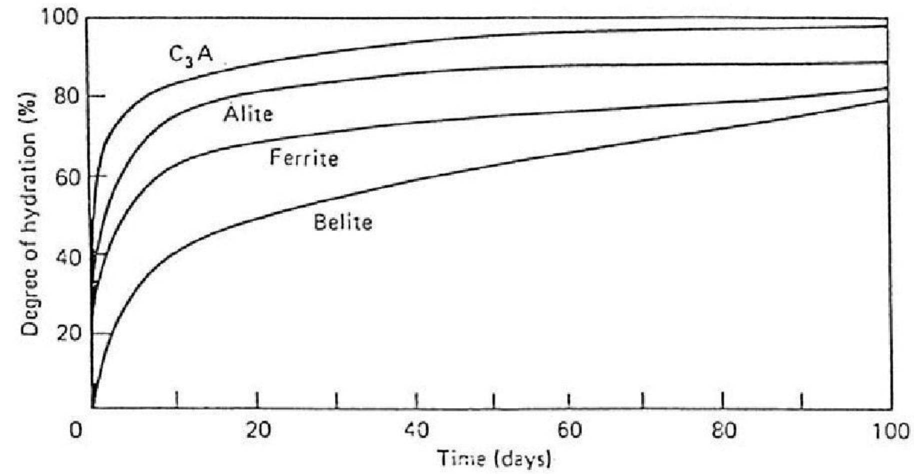
$C_3A + 3\ (C\ \bar{S}\ H_2) + 26\ H \rightarrow C_6A\ \bar{S}_3H_{32}$

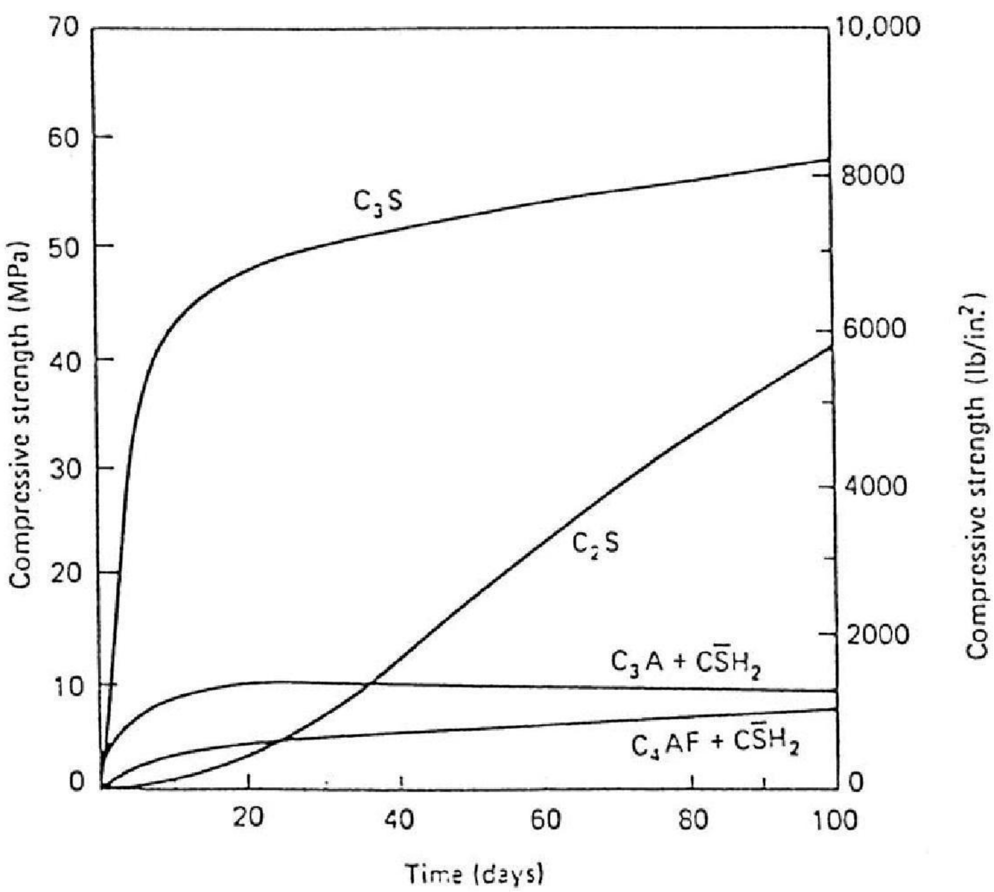
The 6-calcium aluminate trisulfate-32-hydrate is usually called ettringite. The formation of ettringite slows down the hydration of C_3A by creating a diffusion barrier around C_3A. Flash set is thus avoided. Even with gypsum, the formation of ettringite occurs faster than the hydration of the calcium silicates. It therefore contributes to the initial stiffening, setting and early strength development. In normal cement mixes, the ettringite is not stable and will further react to form monosulphate ($C_4A\ \bar{S}\ H_{18}$).

B) Kinetics and Reactivities

The rate of hydration during the first few days is in the order of $C_3A > C_3S > C_4AF > C_2S$.

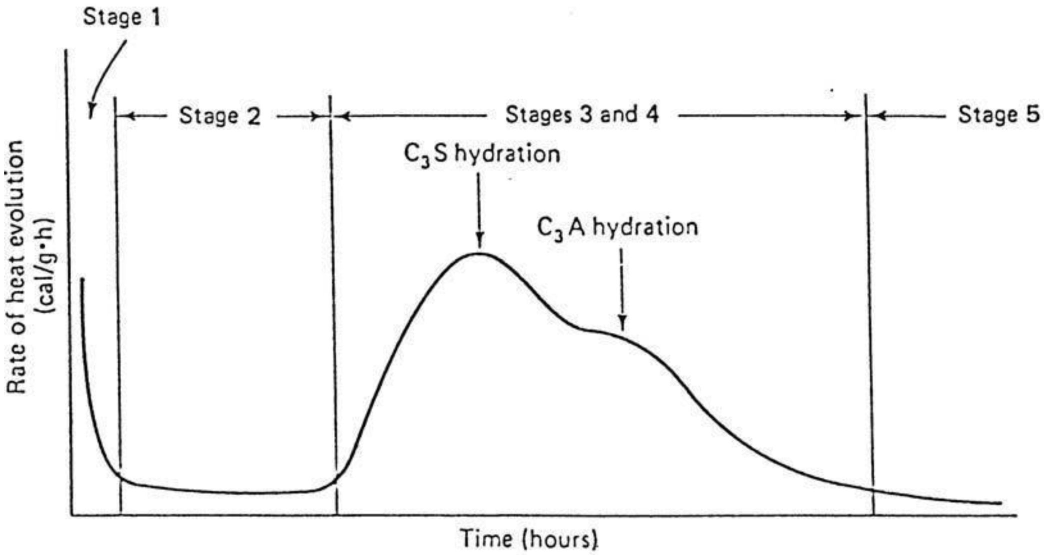
Their reactivities can be observed in the following figures.





C) Calorimetric curve of Portland cement

A typical calorimetric curve of Portland cement is shown in the following figure. The second heat peaks of both C_3S and C_3A can generally be distinguished, although their order of occurrence can be reversed.



From the figure, five stages can be easily identified. Since C_3S is a dominating component in cement, the five stages above can be explained using the reaction process of C_3S by the following table.

Reaction Stage	Kinetics of Reaction	Chemical Processes	Relevance to Concrete
1. Initial hydrolysis	Chemical control; rapid	Initial hydrolysis; dissolution of ions	-
2. Induction period	Nucleation control; slow	Continued dissolution of ions	Determines initial set
3. Acceleration	Chemical control: rapid	Initial formation of hydration products	Determines final set and rate of initial hardening
4. Deceleration	Chemical and diffusion control; slow	Continued formation of hydration products	Determines rate of early strength gain
5. Steady State	Diffusion control; slow	Slow formation of hydration products	Determines rate of later strength gain

On first contact with water, calcium ions and hydroxide ions are rapidly released from the surface of each C_3S grain; the pH values rises to over 12 within a few minutes. This hydrolysis slows down quickly but continues throughout the induction period. The induction (dormant) period is caused by the need to achieve a certain concentration of ions in solution before crystal nuclei are formed for the hydration products to grow from. At the end of dormant period, CH starts to crystallize from solution with the concomitant formation of C-S-H and the reaction of C_3S again proceeds rapidly (the third stage begin). CH crystallizes from solution, while C-S-H develops from the surface of C_3S and forms a coating covering the grain. As hydration continues, the thickness of the hydrate layer increases and forms a barrier through which water must flow to reach the unhydrated C_3S and through which ions must diffuse to reach the growing crystals. Eventually, movement through the C-S-H layer determines the rate of reaction. The process becomes diffusion controlled.

D) Setting and Hydration

Initial set of cement corresponds closely to the end of the induction period, 2-4 hours after mixing. Initial set indicates the beginning of forming of gel or beginning of solidification. It represents approximately the time at which fresh concrete can no longer be properly mixed, placed or compacted. The final set occurs 5-10 hours after mixing, within the acceleration period. It represents approximately the time after which strength develops at a significant rate.

In practice, initial and final set are determined in a rather arbitrary manner with the penetration test. While the determination of initial and the final set has engineering significance, there is no fundamental change in hydration process for these two different set conditions.

Types of Portland cements

According to ASTM standard, there are five basic types of Portland cement.

Type I Regular cement, general use, called OPC
Type II Moderate sulphate resistance, moderate heat of hydration, $C_3A < 7\%$
Type III With increased amount of C_3S, High early strength

Type IV Low heat

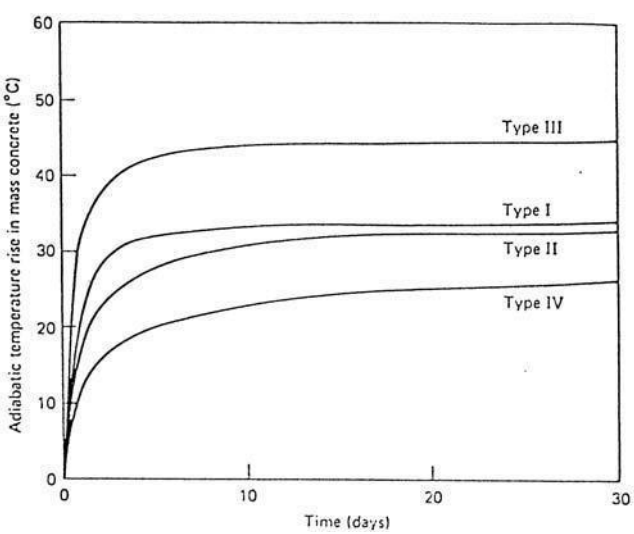
Type V High sulphate resistance

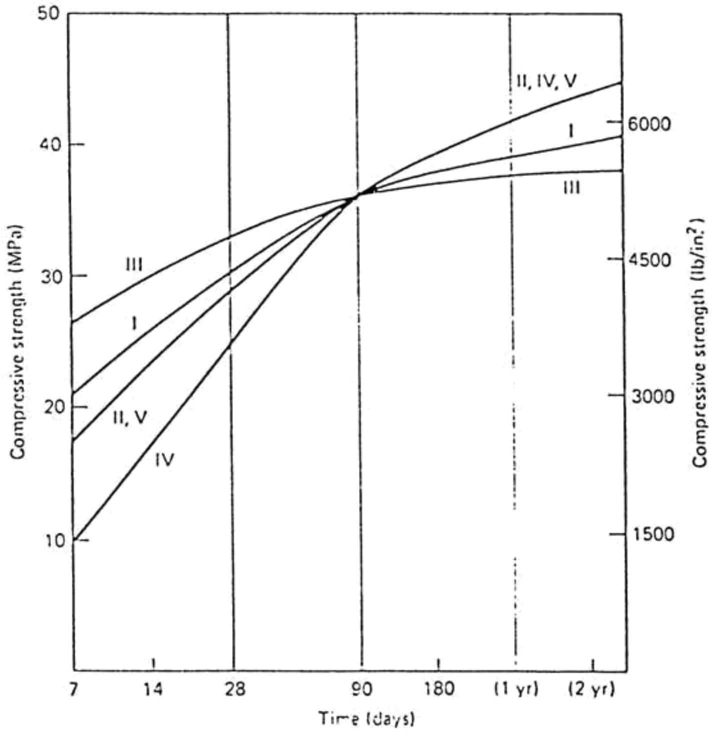
(Note: sulphates can react with $C_4A\ S\ H_{18}$ to from an expansive product. By reducing the C_3A content, there will be less $C_4A\ S\ H_{18}$ formed in the hardened paste)

Their typical chemical composition is given in the following table:

	I	II	III	IV	V
C_3S	50	45	60	25	40
C_2S	25	30	15	50	40
C_3A	12	7	10	5	4
C_4AF	8	12	8	12	10
$C\bar{S}H_2$	5	5	5	4	4
Fineness (Blaine, m^2/kg)	350	350	450	300	350
Compressive strength at 1 day, MPa (psi)	7 (1,000)	6 (900)	14 (2,000)	3 (450)	6 (900)
Heat of hydration (7 days, J/g)	330	250	500	210	250

From the above table, we can evaluate the behaviour of each type of cement and provide the standard in selecting different cement types. The following figures show the strength and temperature rise for the different types of cement.





These graphs provide the basic justification in selecting the cement for engineering application. For instance, for massive concrete structure, hydration heat is an important consideration because excessive temperature increase (to above 50-60°C) will cause expansion and cracking. Hence, type IV cement should be the first candidate and Type III should not be used. For a foundation exposed to groundwater with high concentration of sulphates, high sulphate resistance is needed. Thus, type V should be selected. If high early strength is needed, type III will be the best choice. But, generally, type I is the most popular cement used for civil engineering.

Porosity of hardened cement paste and the role of water

Knowledge of porosity is very useful since porosity has a strong influence on strength and durabilit y. In hardened cement paste, there are several types of porosity, trapped or entrained air (0.1 to several mm in size), capillary pores (0.01 to a few microns) existing in the space between hydration products, and gel pores (several nanometres or below) within the layered structure of the C-S-H. The capillary pores have a large effect on the strength and permeability of the hardened paste itself. Of course, the presence of air bubbles can also affect strength.

From experiments, the porosity within the gel for all normally hydrated cements is the same, with a value of 0.26. The total volume of hydration products (cement gel) is given by

$$V_g = 0.68\alpha \text{ cm}^3\text{/g of original cement}$$

Where, α represents the degree of hydration.

The capillary porosity can be calculated by

$$P_c = (w/c) - 0.36\alpha \qquad \text{cm}^3/\text{g of original cement}$$

Where, *w* is the original weight of water and *c* is the weight of cement and w/c is the water-cement ratio. It can be seen that with increase of w/c, the capillary pores increase.

The gel / space ratio (X) is defined as

$$X = \frac{\textit{volume of gel (including gel pores)}}{\textit{volume of gel + volume of capillary pores}}$$

$$= \frac{0.68\alpha}{0.32\alpha + w/c}$$

The minimum w/c ratio for complete hydration is usually assumed to be 0.36 to 0.42. It should be indicated that complete hydration is not essential to attain a high ultimate strength. For pastes of low w/c ratio, residual unhydrated cement will remain.

To satisfy workability requirements, the water added in the mix is usually more than that needed for the chemical reaction. Part of the water is used up in the chemical reaction. The remaining is either held by the C -S-H gel or stored in the capillary pore. Most capillary water is free water (far away from the pore surface). On drying, they will be removed, but the loss of free water has little effect on concrete. Loss of adsorbed water on surfaces and those in the gel will, however, lead to shrinkage. Movement of adsorbed and gel water under load is a cause of creeping in concrete

Basic tests of Portland cement

a) Fineness (= surface area / weight): This test determines the average size of cement grains. The typical value of fineness is 350 m^2 / kg.
Fineness controls the rate and completeness of hydration. The finer a cement, the more rapidly it reacts, the higher the rate of heat evolution and the higher the early strength.

	I	III	V
Fineness (m^2 / kg)	350	450	350
f'_c 1-day (MPa)	6.9	13.8	6.2

b) Normal consistency test: This test is to determine the water required to achieve a desired plasticity state (called normal consistency) of cement paste. It is obtained with the Vicat apparatus by measuring the penetration of a loaded needle.

c) Time of setting: This test is to determine the time required for cement paste to harden. Initial set cannot be too early due to the requirement of mixing, conveying, placing and casting. Final set cannot be too late owing to the requirement of strength development. Time of setting is measured by Vicat apparatus. Initial setting time is defined as the time at which the needle penetrates 25 mm into cement paste. Final setting time is the time at which the needle does not sink visibly into the cement paste.

d) Soundness: Unsoundness in cement paste refers to excessive volume change after setting. Unsoundness in cement is caused by the slow hydration of MgO or free lime.
Their reactions are $MgO + H_2O = Mg(OH)_2$ and $CaO + H_2O = Ca(OH)_2$. Another factor that can cause unsoundness is the delayed formation of ettringite after cement and concrete have hardened. The pressure from crystal growth will lead to cracking and damage. The soundness of the cement must be tested by accelerated methods. An example is the Le Chatelier test (BS 4550). This test is to measure the potential for volumetric change of cement paste. Another method is called Autoclave Expansion test (ASTM C151) which use an autoclave to increase the temperature to accelerate the process.

e) Strength: The strength of cement is measured on mortar specimens made of cement and standard sand (silica). Compression test is carried out on a 2" cube with S/C ratio of 2.75:1 and w/c ratio of 0.485 for Portland cements. The specimens are tested wet, using a loading rate at which the specimen will fail in 20 to 80 s. The direct tensile test is carried out on a specimen shaped like a dumbbell. The load is applied through specifically designed grips. Flexural strength is measured on a 40 x 40 x 160 mm prism beam test under a centre-point bending.

f) Heat of hydration test. (BS 4550: Part 3: Section 3.8 and ASTM C186). Cement hydration is a heat releasing process. The heat of hydration is usually defined as the amount of heat evolved during the setting and hardening at a given temperature measured in J/g. The experiment is called heat of solution method. Basically, the heat of solution of dry cement is compared to the heats of solution of separate portion of the cement that have been partially hydrated for 7 and 28 days. The heat of hydration is then the difference between the heats of solution of dry and partially hydrated cements for the appropriate hydration period. This test is usually done on Type II and IV cements only, because they are used when heat of hydration is an important concern.
Excessive heating may lead to cracking in massive concrete construction.

g) Other experiments. Including sulphate expansion and air content of mortar.

h) Cement S. G and U. W.: The S.G. for most types of cements is 3.15, and UW is 1000-1600 kg/m^3.

Admixtures

Admixtures are those ingredients in concrete other than portland cement, water, and aggregates that are added to the mixture immediately before or during mixing.

Admixtures can be classified by function as follows:

1. Air-entraining admixtures
2. Water-reducing admixtures
3. Plasticizers
4. Accelerating admixtures
5. Retarding admixtures
6. Hydration-control admixtures
7. Corrosion inhibitors
8. Shrinkage reducers
9. Alkali-silica reactivity inhibitors
10. Colouring admixtures
11. Miscellaneous admixtures such as workability, bonding, dampproofing, permeability reducing, grouting, gas forming, anti-washout, foaming, and pumping admixtures.

Concrete should be workable, finishable, strong, durable, watertight, and wear resistant. These qualities can often be obtained easily and economically by the selection of suitable materials rather than by resorting to admixtures (except air-entraining admixtures when needed).

The major reasons for using admixtures

1. To reduce the cost of concrete construction
2. To achieve certain properties in concrete more effectively than by other means
3. To maintain the quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions
4. To overcome certain emergencies during concreting operations

Classification of admixtures

Type of admixture	Desired effect	Material
Accelerators (ASTM C 494 and AASHTO M 194, Type C)	Accelerate setting and early-strength development	Calcium chloride (ASTM D 98 and AASHTO M 144) Triethanolamine, sodium thiocyanate, calcium formate, calcium nitrite, calcium nitrate
Air detrainers	Decrease air content	Tributyl phosphate, dibutyl phthalate, octyl alcohol, water-insoluble esters of carbonic and boric acid, silicones
Air-entraining admixtures (ASTM C 260 and AASHTO M 154)	Improve durability in freeze-thaw, deicer, sulfate, and alkali-reactive environments Improve workability	Salts of wood resins (Vinsol resin), some synthetic detergents, salts of sulfonated lignin, salts of petroleum acids, salts of proteinaceous material, fatty and resinous acids and their salts, alkylbenzene sulfonates, salts of sulfonated hydrocarbons
Alkali-aggregate reactivity inhibitors	Reduce alkali-aggregate reactivity expansion	Barium salts, lithium nitrate, lithium carbonate, lithium hydroxide
Antiwashout admixtures	Cohesive concrete for underwater placements	Cellulose, acrylic polymer
Bonding admixtures	Increase bond strength	Polyvinyl chloride, polyvinyl acetate, acrylics, butadiene-styrene copolymers
Coloring admixtures (ASTM C 979)	Colored concrete	Modified carbon black, iron oxide, phthalocyanine, umber, chromium oxide, titanium oxide, cobalt blue
Corrosion inhibitors	Reduce steel corrosion activity in a chloride-laden environment	Calcium nitrite, sodium nitrite, sodium benzoate, certain phosphates or fluosilicates, fluoaluminates, ester amines
Dampproofing admixtures	Retard moisture penetration into dry concrete	Soaps of calcium or ammonium stearate or oleate Butyl stearate Petroleum products
Foaming agents	Produce lightweight, foamed concrete with low density	Cationic and anionic surfactants Hydrolized protein
Fungicides, germicides, and insecticides	Inhibit or control bacterial and fungal growth	Polyhalogenated phenols Dieldrin emulsions Copper compounds
Gas formers	Cause expansion before setting	Aluminum powder
Grouting admixtures	Adjust grout properties for specific applications	See Air-entraining admixtures, Accelerators, Retarders, and Water reducers
Hydration control admixtures	Suspend and reactivate cement hydration with stabilizer and activator	Carboxylic acids Phosphorus-containing organic acid salts
Permeability reducers	Decrease permeability	Latex Calcium stearate
Pumping aids	Improve pumpability	Organic and synthetic polymers Organic flocculents Organic emulsions of paraffin, coal tar, asphalt, acrylics Bentonite and pyrogenic silicas Hydrated lime (ASTM C 141)
Retarders (ASTM C 494 and AASHTO M 194, Type B)	Retard setting time	Lignin Borax Sugars Tartaric acid and salts
Shrinkage reducers	Reduce drying shrinkage	Polyoxyalkylene alkyl ether Propylene glycol
Superplasticizers* (ASTM C 1017, Type 1)	Increase flowability of concrete Reduce water-cement ratio	Sulfonated melamine formaldehyde condensates Sulfonated naphthalene formaldehyde condensates Lignosulfonates Polycarboxylates

Type of admixture	Desired effect	Material
Superplasticizer* and retarder (ASTM C 1017, Type 2)	Increase flowability with retarded set Reduce water–cement ratio	See superplasticizers and also water reducers
Water reducer (ASTM C 494 and AASHTO M 194, Type A)	Reduce water content at least 5%	Lignosulfonates Hydroxylated carboxylic acids Carbohydrates (Also tend to retard set so accelerator is often added)
Water reducer and accelerator (ASTM C 494 and AASHTO M 194, Type E)	Reduce water content (minimum 5%) and accelerate set	See water reducer, Type A (accelerator is added)
Water reducer and retarder (ASTM C 494 and AASHTO M 194, Type D)	Reduce water content (minimum 5%) and retard set	See water reducer, Type A (retarder is added)
Water reducer—high range (ASTM C 494 and AASHTO M 194, Type F)	Reduce water content (minimum 12%)	See superplasticizers
Water reducer—high range—and retarder (ASTM C 494 and AASHTO M 194, Type G)	Reduce water content (minimum 12%) and retard set	See superplasticizers and also water reducers
Water reducer—mid range	Reduce water content (between 6 and 12%) without retarding	Lignosulfonates Polycarboxylates

* Superplasticizers are also referred to as high-range water reducers or plasticizers. These admixtures often meet both ASTM C 494 (AASHTO M 194) and ASTM C 1017 specifications.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \end{bmatrix}$$

UNIT- 2

Aggregates, Fresh Concrete

Aggregates

Aggregates are defined as inert, granular, and inorganic materials that normally consist of stone or stone-like solids. Aggregates can be used alone (in road bases and various types of fill) or can be used with cementing materials (such as Portland cement or asphalt cement) to form composite materials or concrete. The most popular use of aggregates is to form Portland cement concrete. Approximately three-fourths of the volume of Portland cement concrete is occupied by aggregate. It is inevitable that a constituent occupying such a large percentage of the mass should have an important effect on the properties of both the fresh and hardened products. As another important application, aggregates are used in asphalt cement concrete in which they occupy 90% or more of the total volume. Once again, aggregates can largely influence the composite properties due to its large volume fraction.

Classification of Aggregate

Aggregates can be divided into several categories according to different criteria.

e) In accordance with size:

Coarse aggregate: Aggregates predominately retained on the No. 4 (4.75 mm) sieve. For mass concrete, the maximum size can be as large as 150 mm.

Fine aggregate (sand): Aggregates passing No.4 (4.75 mm) sieve and predominately retained on the No. 200 (75 µm) sieve.

f) In accordance with sources:

Natural aggregates: This kind of aggregate is taken from natural deposits without changing their nature during the process of production such as crushing and grinding. Some examples in this category are sand, crushed limestone, and gravel.

Manufactured (synthetic) aggregates: This is a kind of man-made materials produced as a main product or an industrial by-product. Some examples are blast furnace slag, lightweight aggregate (e.g. expanded perlite), and heavy weight aggregates (e.g. iron ore or crushed steel).

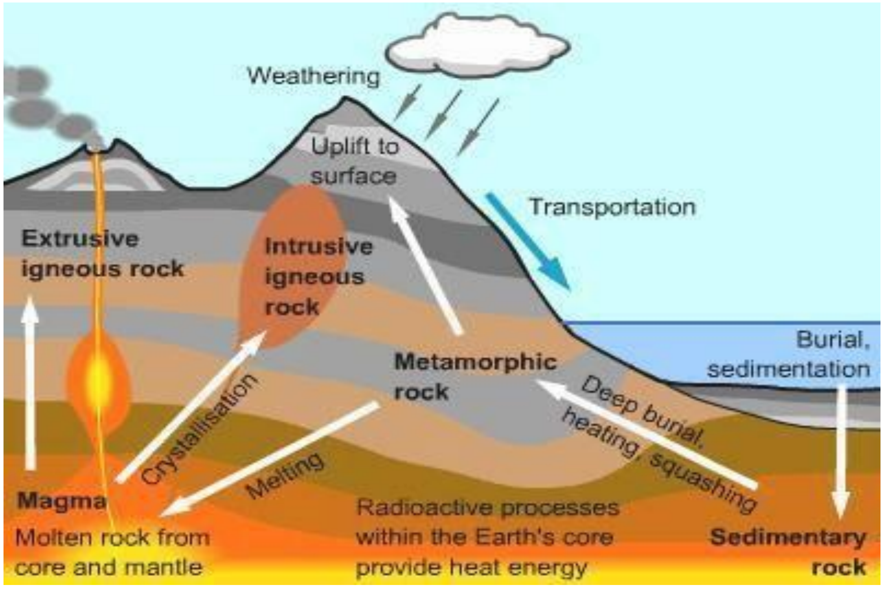
g) In accordance with unit weight:

Light weight aggregate: The unit weight of aggregate is less than 1120kg/m^3. The corresponding concrete has a bulk density less than 1800kg/m^3. (cinder, blast-furnace slag, volcanic pumice).

Normal weight aggregate: The aggregate has unit weight of 1520-1680kg/m^3. The concrete made with this type of aggregate has a bulk density of 2300-2400 kg/m^3.

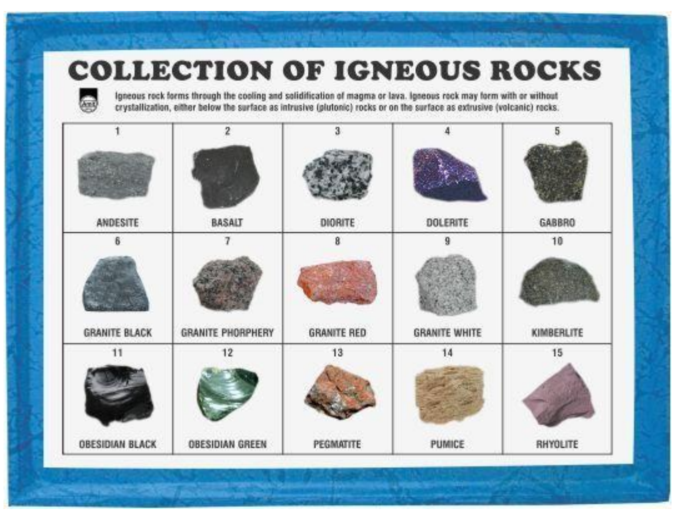
Heavy weight aggregate: The unit weight is greater than 2100 kg/m^3. The bulk density of the corresponding concrete is greater than 3200 kg/m^3. A typical example is magnesite limonite, a heavy iron ore. Heavy weight concrete is used in special structures such as radiation shields.

h) In accordance with origin:



Igneous rock Aggregate:

- Hard, tough and dense.
- Massive structures: crystalline, glassy or both depending on the rate at which they are cooled during formation.
- Acidic or basic: percentage of silica content.
- Light or dark coloured.
- Chemically active: react with alkalis.

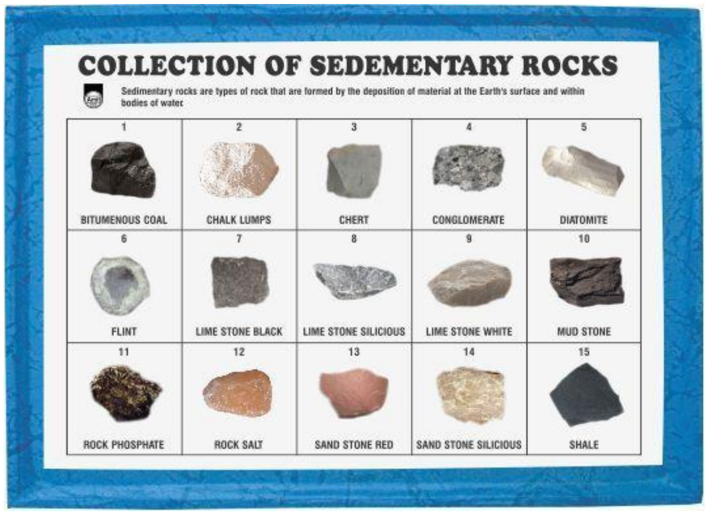


Sedimentary rock Aggregates:

- Igneous or metamorphic rocks subjected to weathering agencies

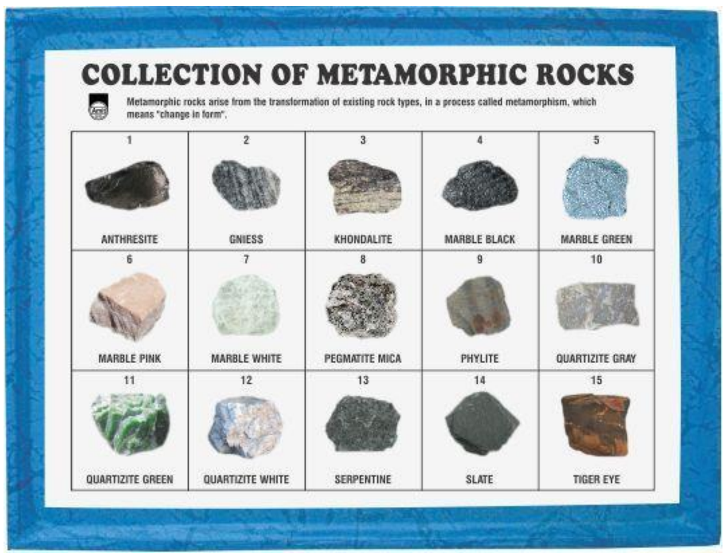
Decompose, fragmentise, transport and deposit deep beneath ocean bed are cemented together.

- Can be flaky.
- Range from soft-hard, porous-dense, light-heavy.
- Suitability decided by: degree of consolidation, type of cementation, thickness of layer and contamination.



Metamorphic rock Aggregate:

- Rocks subjected to high temperature and pressure.
- Economic factor into consideration.
- Least overall expense.



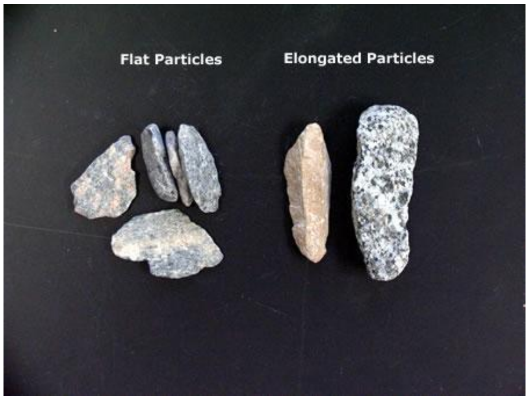
i) Particle shape:

- **Rounded Aggregate:** Good workability, low water demand, poor bond

- **Angular Aggregate:** Increased water demand, good bond

- **Flaky Aggregate:** Aggregate stacks give workability problems

- **Elongated Aggregate:** May lack cohesion and require increased fines



- **Irregular Aggregate:** Fair workability, low water demand. Irregular shape with rounded edges.

- **Angularity number (IS:2386-Part 1-1963):**
  - The concept of angularity number was suggested by Shergold.
  - It gives a qualitative representation of shape of aggregate.
  - In angularity number test, a quantity of single sized aggregate is filled into metal cylinder of 3 litres capacity. Then the aggregate is compacted in a standard manner and the percentage of void found out.
  - If the void content of the aggregate is 33% the angularity of such aggregate is considered 0.
  - If the void is 44%, the angularity number of such aggregate is considered 11.
- **Importance of Angularity Number:**

- The normal aggregate which are suitable for making concrete may have angularity number anything from 0 to 11.
- Angularity number 0 represents the most practicable rounded aggregate
- Angularity number 11 indicates the most angular aggregate that could be used for making concrete.

- **Angularity Index:**

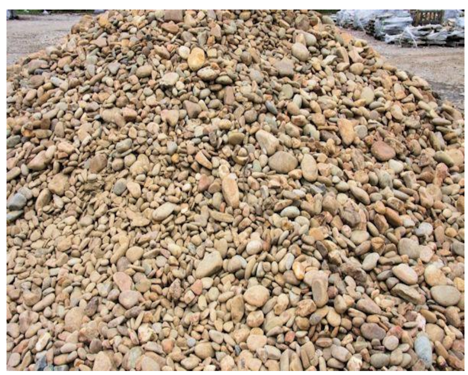
  - Suggested by Murdock for expressing shape of aggregate.
  - Angularity index = fA = $\frac{3\,fH}{20}$ + 1.0

    Where, fH is the angularity number.

j) Texture:

- It depends on hardness, grain size, pore structure, structure of the rock and degree to which forces acting on the particle surface have smoothened or roughened it.
- As surface smoothness increases, contact area decreases, hence a highly polished particle will have less bonding area with the matrix than a rough particle of the same volume.

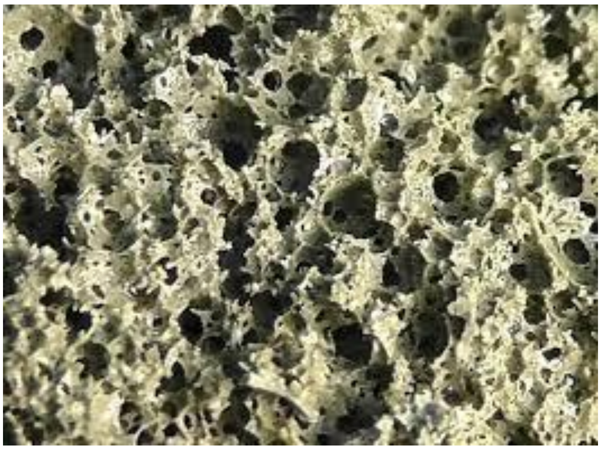
Glassy textured aggregate



Smooth textured aggregate

Granular textured aggregate

Crystalline textured aggregate



Porous textured aggregate

Strength of Aggregates

- When the cement paste is of good quality & its bond with the aggregate is satisfactory, then the mechanical properties of rock or aggregate will influence the strength of concrete.
- The test for strength of aggregate is required to be made in the following situations:
  i. For production of high strength & ultra -high strength concrete.
  ii. When contemplating to use aggregates manufacture from weathered rocks.
  iii. Aggregates manufactured by industrial process.

There are two sets of criteria that we must consider when making concrete;

1) Long-term requirements of hardened concrete, such as, strength, durability, and volume stability,

2) Short-term requirements, like workability. However, these two requirements are not necessarily complementary.

For fresh concrete to be acceptable, it should:

1. Be easily mixed and transported.
2. Be uniform throughout a given batch and between batches.
3. Be of a consistency so that it can fill completely the forms for which it was designed.
4. Have the ability to be compacted without excessive loss of energy.
5. Not segregate during placing and consolidation.
6. Have good finishing characteristics.

Workability

All the characteristics above describe many different aspects of concrete behavior. The term workability is used to represent all the qualities mentioned. Workability is often defined in terms of the amount of mechanical energy, or work, required to fully compact concrete without segregation. This is important since the final strength is a function of compaction.

The concept of viscosity is a measure of how a material behaves under stress. For a Newtonian fluid, the relationship may be written as:

$$\tau = \eta D$$

Where ***t*** is the shear stress, ***n*** is the viscosity, and ***D*** is the rate of shear or velocity gradient.

For a very dilute suspension of solids in liquids, this relationship holds true. However, for large volumes of suspended solids, like concrete, the Newtonian model does not work. Concrete has an initial shear strength that must be exceeded before it will flow. This type of behaviour is described by the Bingham model:

$$\tau - \tau_0 = \eta D$$

Where ***to*** is the yield shear stress, ***n*** is the plastic viscosity.

A third type of viscous behaviour is called thixotropic, where the apparent viscosity decreases with shear stress. Concrete will exhibit thixotropic characteristics.

Factors Affecting Workability

- **Water Content of the Mix** -- This is the single most important fact or governing workability of concrete. A group of particles requires a certain amount of water. Water is absorbed on the particle surface, in the volumes between particles, and provides "lubrication" to help the particles move past one another more easily. Therefore, finer particles, necessary for plastic behaviour, require more water. Some side-effects of increased water are loss of strength and possible segregation.

- **Influence of Aggregate Mix Proportions --** Increasing the proportion of aggregates relative to the cement will decrease the workability of the concrete. Also, any additional fines will require more cement in the mix. An "over sanded" mix will be permeable and less economical. A concrete deficient of fines will be difficult to finish and prone to segregation.

- **Aggregate Properties** -- The ratio of coarse/fine aggregate is not the only factor affecting workability. The gradation and particle size of sands are important. Shape and texture of aggregate will also affect workability. Spherical shaped particles will not have the interaction problems associated with more angular particles. Also, spherical shapes have a low surface/volume ratio, therefore, less cement will be required to coat each particle and more will be available to contribute to the workability of the concrete. Aggregate which is porous will absorb more water leaving less to provide workability. It is important to distinguish between total water content, which includes absorbed water, and free water which is available for improving workability.

- **Time and Temperature --** In general, increasing temperature will cause an increase in the rate of hydration and evaporation. Both of these effects lead to a loss of workability.

- **Loss of Workability** -- Workability will decrease with time due to several factors; continued slow hydration of C3S and C3A during dormant period, loss of water through evaporation and absorption, increased particle interaction due to the formation of hydration products on the particle surface. Loss of workability is measured as "slump loss" with time.

- **Cement Characteristics --** Cement characteristics are less important than aggregate properties in determining workability. However, the increased fineness of rapid-hardening cements will result in rapid hydration and increased water requirements, both of which reduce workability.

- **Admixtures** -- In general, air-entraining, water-reducing, and set-retarding admixtures will all improve workability. However, some chemical admixtures will react differently with cements and aggregates and may result in reduced workability.

Segregation and Bleeding

2.5.1 Segregation refers to a separation of the components of fresh concrete, resulting in a non-uniform mix. This can be seen as a separation of coarse aggregate from the mortar, caused from either the settling of heavy aggregate to the bottom or the separation of the aggregate from the mix due to improper placement.

Some factors that increase segregation are:

1. Larger maximum particle size (25mm) and proportion of the larger particles.

2. High specific gravity of coarse aggregate.
3. Decrease in the amount of fine particles.
4. Particle shape and texture.
5. Water/cement ratio.

Good handling and placement techniques are most important in prevention of segregation.

Bleeding is defined as the appearance of water on the surface of concrete after it has consolidated but before it is set. Since mixing water is the lightest component of the concrete, this is a special form of segregation. Bleeding is generally the result of aggregates settling into the mix and releasing their mixing water. Some bleeding is normal for good concrete.

However, if bleeding becomes too localized, channels will form resulting in "craters". The upper layers will become too rich in cement with a high w/c ratio causing a weak, porous structure. Salt may crystalize on the surface which will affect bonding with additional lifts of concrete. This formation should always be removed by brushing and washing the surface. Also, water pockets may form under large aggregates and reinforcing bars reducing the bond.

Bleeding may be reduced by:

1. Increasing cement fineness.
2. Increasing the rate of hydration.
3. Using air-entraining admixtures.
4. Reducing the water content.

Measurement of Workability

Workability, a term applied to many concrete properties, can be adequately measured by three characteristics:

1. Compatibility, the ease with which the concrete can be compacted and air void removed.
2. Mobility, ease with which concrete can flow into forms and around reinforcement.
3. Stability, ability for concrete to remain stable and homogeneous during handling and vibration without excessive segregation.

Different empirical measurements of workability have been developed over the years. None of these tests measure workability in terms of the fundamental properties of concrete. However, the following tests have been developed:

- **Subjective Assessment** -- The oldest way of measuring workability based on the judgement and experience of the engineer. Unfortunately, different people see things, in this case concrete, differently.

- **Slump Test** -- The oldest, most widely used test for determining workability. The device is a hollow cone-shaped mould. The mould is filled in three layers of each volume. Each layer is rodded with a 16mm steel rod 25 times. The mould is then lifted away and the change in the height of the concrete is measured against the mould. The slump test is a measure of the resistance of concrete to flow under its own weight.

  There are three classifications of slump; "true" slump, shear slump, and collapse slump. True slump is a general reduction in height of the mass without any breaking up. Shear slump indicates a lack of cohesion, tends to occur in harsh mixes. This type of result implies the concrete is not suitable for placement. Collapse slump generally indicates a very wet mix. With different aggregates or mix properties, the same slump can be measured for very different concretes.

- **Compaction Test** -- Concrete strength is proportional to its relative density. A test to determine the compaction factor was developed in 1947. It involves dropping a volume of concrete from one hopper to another and measuring the volume of concrete in the final hopper to that of a fully compacted volume. This test is difficult to run in the field and is not practical for large aggregates (over 1 in.).

- **Flow Test** -- Measures a concretes ability to flow under vibration and provides information on its tendency to segregate. There are a number of tests available but none are recognized by ASTM. However, the flow table test described for mortar flows is occasionally used.

- **Remoulding Test** -- Developed to measure the work required to cause concrete not only to flow but also to conform to a new shape.

    - **Vebe Test** - A standard slump cone is cast, the mould removed, and a transparent disk placed on top of the cone. The sample is then vibrated till the disk is completely covered with mortar. The time required for this is called the Vebe time.

    - **Thaulow Drop Table** - Similar to the Vebe test except a cylinder of concrete is remoulded on a drop table. The number of drops to achieve this remoulding is counted.

    - **Penetration Test** -- A measure of the penetration of some indenter into concrete. Only the Kelly ball penetration test is included in the ASTM Standards. The Kelly ball penetration test measures the penetration of a 30 lb. hemisphere into fresh concrete. This test can be performed on concrete in a buggy, open truck, or in form if they are not too narrow. It can be compared to the slump test for a measure of concrete consistency.

Setting of Concrete

Setting is defined as the onset of rigidity in fresh concrete. Hardening is the development of useable and measurable strength; setting precedes hardening. Both are gradual changes controlled by hydration. Fresh concrete will lose measurable slump before initial set and measurable strength will be achieved after final set.

Setting is controlled by the hydration of C_3S. The period of good workability is during the dormant period, (stage 2). Initial set corresponds to the beginning of stage 3, a period of rapid hydration. Final set is the midpoint of this acceleration phase. A rapid increase in temperature is associated with stage 3 hydration, with a maximum rate at final set.

If large amounts of ettringite rapidly form from C_3A hydration, the setting times will be reduced. Cements with high percentages of C_3A, such as expansive or set-regulated cements, are entirely controlled by ettringite formation.

Abnormal Setting Behavior

- **False Set** -- Early stiffening of concrete, fluidity may be restored by remixing. Basically, it is a result of hydration of dehydrated gypsum, which forms rigid crystals. Because there are few of these crystals and they are weak, the matrix can be destroyed by remixing. Accelerated hydration of C3A will cause rapid development of ettringite and false set.

- **Flash Set** -- Stiffening of concrete due to the rapid development of large quantities of C3A hydration products which cannot be returned to a fluid state with mixing. This is generally no longer a problem since the introduction of gypsum to control C3A hydration. However, some admixtures will increase C3A hydration and flash set may be a problem.

Tests of Fresh Concrete

1. They permit some estimation of the subsequent behaviour of the hardened concrete.
2. Changes in the properties of fresh concrete imply that the concrete mix is changing, so that some action can be taken if necessary.

Concrete is a composite material made from cement, aggregate, water, and admixtures. The variation of these components both in quality and quantity directly affects the resulting mix. When sampling fresh concrete for testing, it is important to take samples from various locations or several points during the discharge of the concrete. Samples should not have contacted forms or subgrade, and collection should be done in such a way that no segregation occurs.

- **Time of Setting** -- A penetration test, used to help regulate the times of mixing and transit, gauges the effectiveness of various set-controlling admixtures, and help plan finishing operations. The test is performed on the mortar faction, the amount of concrete passing a No. 4 sieve, of the concrete rodded into a container.

- **Air Content** -- These tests measure the total air content, entrained air plus entrapped air expressed in terms of the volume of concrete.
  - **Gravimetric Method** -- Compares the weight of a concrete containing air to that of a computed air-free concrete.
  - **Volumetric Method** -- Compares the volume of fresh concrete containing air with a volume of the same concrete after the air has be expelled by agitating the concrete under water. Difficult to measure in the field and required a large amount of physical effort.
  - **Pressure Method** -- The most common field measurement for air content. Compares the change in volume of a concrete under a given pressure. This change in volume is caused entirely by the compression of air in the concrete, both in the cement and the aggregate.

*** All these tests give no information about the spacing of the voids. They only measure the total air content of the concrete.

Unit Weight and Yield

The unit weight of fresh concrete can be determined by weighing a known volume. This is usually performed just before air content is determined since there is known volume concrete. The volume of a batch of concrete can be determined from the following relationship:

$$V = \frac{w}{Unit\ weight}(ft^3)$$

Where, **w** is the weight of the concrete components, including water.

The yield of a concrete mix can be determined from:

$$Y = \frac{V}{w_{cement}} \left(\frac{ft^3}{lb} \right)$$

Where, $\mathbf{w_{cement}}$ is the weight of the cement for a given mix.

Rapid Analysis of Fresh Concrete

There are a number of tests which separate the components of fresh concrete and test for a variety of mix properties; however, none are as yet accepted by ASTM. There are some tests that do not require separation of the components of the concrete:

- **Thermal Conductivity** -- Increase in water slows temperature rise.
- **Capacitance Test** -- Higher water content, increases dielectric constant.
- **Electrical Resistance** -- Electrical resistance of fresh concrete is inversely proportional to the water content.
- **Nuclear Methods** -- X-rays, gamma-rays, and neutron activation analysis can be used to measure the cement and water contents.

UNIT 3

Hardened Concrete

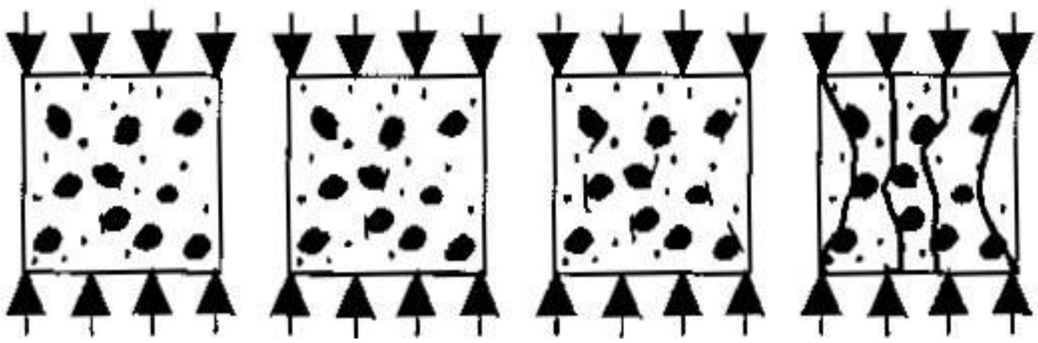
Strength of hardened concrete

Strength is defined as the ability of a material to resist stress without failure. The failure of concrete is due to cracking. Under direct tension, concrete failure is due to the propagation of a single major crack. In compression, failure involves the propagation of a large number of cracks, leading to a mode of disintegration commonly referred to as 'crushing'.
The strength is the property generally specified in construction design and quality control, for the following reasons:
(1) It is relatively easy to measure, and
(2) Other properties are related to the strength and can be deduced from strength data.

The 28-day compressive strength of concrete determined by a standard uniaxial compression test is accepted universally as a general index of concrete strength.

Compressive strength and corresponding tests

(a) Failure mechanism

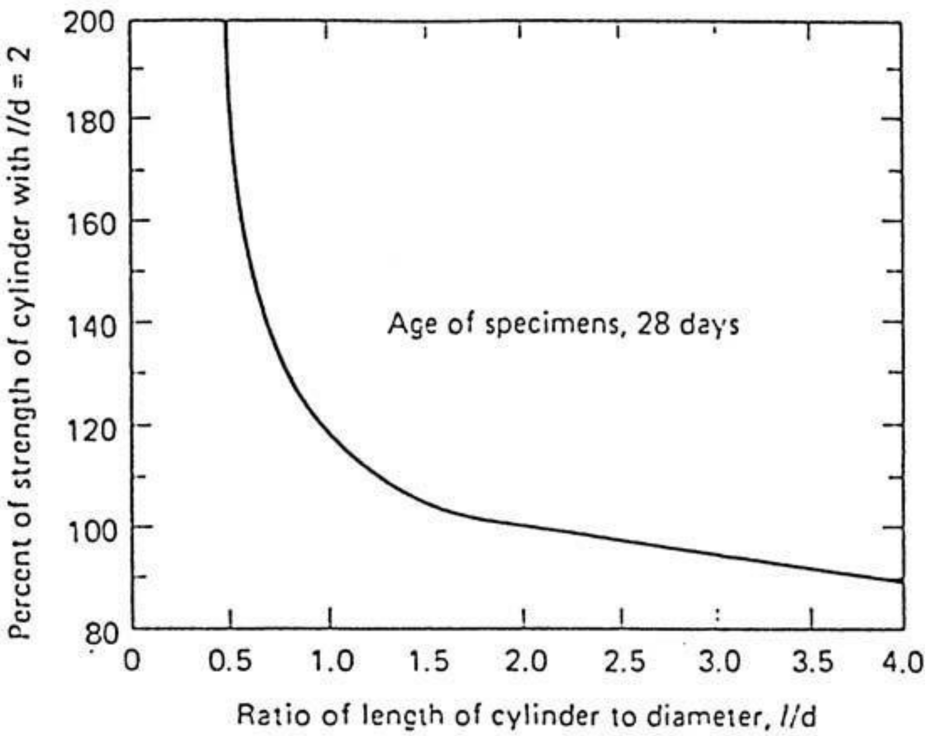


a. b. c. d.

a. At about 25-30% of the ultimate strength, random cracking (usually in transition zone around large aggregates) are observed
b. At about 50% of ultimate strength, cracks grow stably from transition zone into paste. Also, microcracks start to develop in the paste.
c. At about 75% of the ultimate strength, paste cracks and bond cracks start to join together, forming major cracks. The major cracks keep growing while smaller cracks tend to close.
d. At the ultimate load, failure occurs when the major cracks link up along the vertical direction and split the specimen

The development of the vertical cracks results in expansion of concrete in the lateral directions. If concrete is confined (i.e., it is not allow to expand freely in the lateral directions), growth of the vertical cracks will be resisted. The strength is hence increased, together with an increase in failure strain. In the design of concrete columns, steel stirrups are placed around the vertical reinforcing steel. They serve to prevent the lateral displacement of the interior concrete and hence increase the concrete strength. In composite construction (steel + reinforced concrete), steel tubes are often used to encase reinforced concrete columns. The tube is very effective in providing the confinement.

The above figure illustrates the case when the concrete member is under ideal uniaxial loading. In reality, when we are running a compressive test, friction exists at the top and bottom surfaces of a concrete specimen, to prevent the lateral movement of the specimen. As a result, confining stresses are generated around the two ends of the specimen. If the specimen has a low aspect ratio (in terms of height vs width), such as a cube (aspect ratio = 1.0), the confining stresses will increase the apparent strength of the material. For a cylinder with aspect ratio beyond 2.0, the confining effect is not too significant at the middle of the specimen (where failure occurs). The strength obtained from a cylinder is hence closer to the actual uniaxial strength of concrete. Note that in a cylinder test, the cracks propagate vertically in the middle of the specimen. When they get close to the ends, due to the confining stresses, they propagate in an inclined direction, leading to the formation of two cones at the ends.



(b) Specimen for compressive strength determination

The cube specimen is popular in U.K. and Europe while the cylinder specimen is commonly used in the U.S.

i. Cube specimen

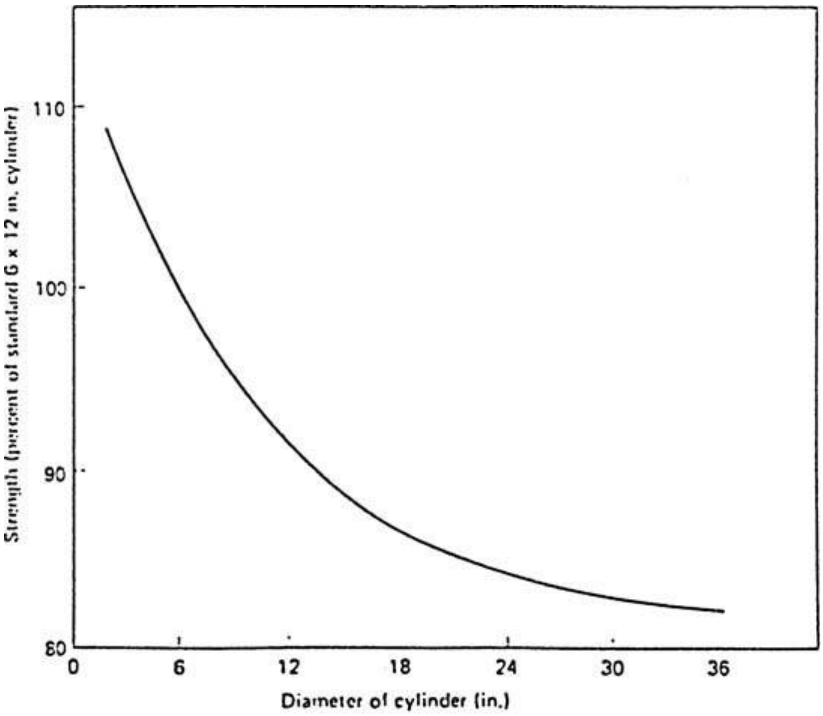
BS 1881: Part 108: 1983. Filling in 3 layers with 50 mm for each layer (2 layers for 100 mm cube). Strokes 35 times for 150 mm cube and 25 times for 100 mm cube. Curing at $20\pm5\,^{0}$C and 90% relative humility.

ii. Cylinder specimen

ASTM C470-81. Standard cylinder size is 150 x 300 mm. Curing condition is temperature of $23\pm1.7\,^{0}$C and moist condition. Grinding or capping is needed to provide level and smooth compression surface.

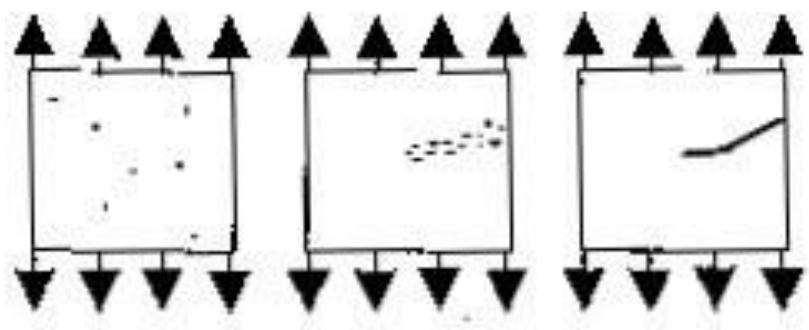
(c) Factors influencing experiment results

(i) End condition. Due to influence of platen restraint, cube's apparent strength is about 1.15 times of cylinders. In assessing report on concrete strength, it is IMPORTANT to know which type of specimen has been employed.
(ii) Loading rate. The faster the load rate, the higher the ultimate load obtained. The standard load rate is 0.15 -0.34 MPa / s for ASTM and 0.2-0.4 MPa/s for BS.
(iii) Size effect: The probability of having larger defects (such as voids and cracks) increases with size. Thus smaller size specimen will give higher apparent strength. Standard specimen size is mentioned above. Test results for small size specimen needs to be modified.



Tensile strength and corresponding tests

(d) Failure mechanism



a. b. c.

a. Random crack development (microcracks usually form at transition zone)
b. Localization of microcracks
c. Major crack propagation

It is important to notice that cracks form and propagate a lot easier in tension than in compression. The tensile strength is hence much lower than the compressive strength. An empirical relation between f_t and f_c is given by:

$f_t = 0.615 (f_c)^{0.5}$ (for 21 MPa < f_c < 83 MPa)

Substituting numerical values for f_c, f_t is found to be around 7 to 13% of the compressive strength, with a lower f_t/f_c ratio for higher concrete strength. In the above formula, f_c is obtained from the direct compression of cylinders while f_t is measured with the splitting tensile test, to be described below.

(e) Direct tension test methods

Direct tension tests of concrete are seldom carried out because it is very difficult to control. Also, perfect alignment is difficult to ensure and the specimen holding devices introduce secondary stress that cannot be ignored. In practice, it is common to carry out the splitting tensile test or flexural test.

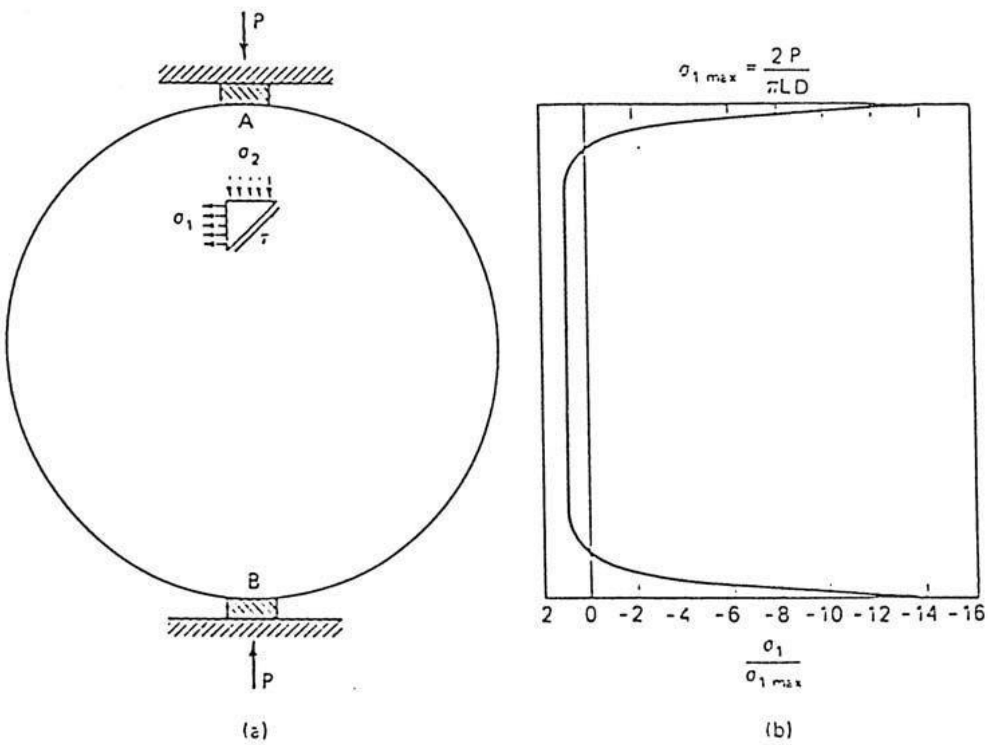
(f) Indirect tension test (split cylinder test or Brazilian test) BS 1881: Part 117:1983.

Specimen 150 x 300 mm cylinder. Loading rate 0.02 to 0.04 MPa/s

ASTM C496-71:

Specimen 150 x 300 mm cylinder. Loading rate 0.011 to 0.023 MPa/s

The splitting test is carried out by applying compression loads along two axial lines that are diametrically opposite. This test is based on the following observation from elastic analysis. Under vertical loading acting on the two ends of the vertical diametrical line, uniform tension is introduced along the central part of the specimen.

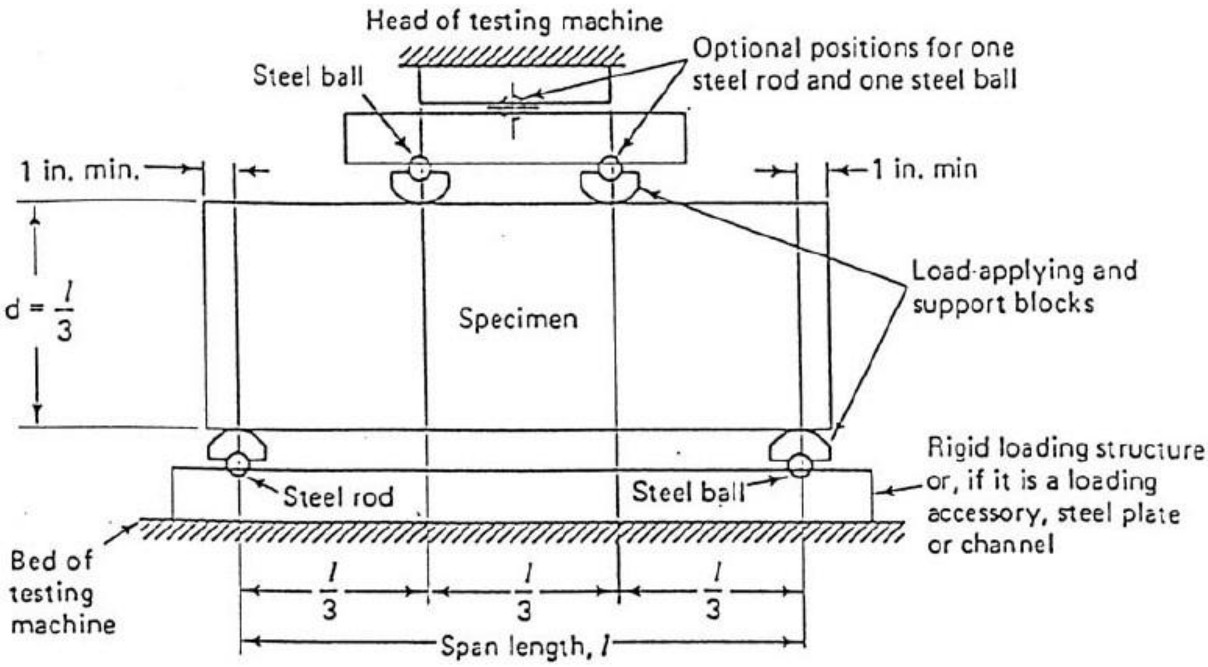


The splitting tensile strength can be obtained using the following formula:

$$f_{st} = \frac{2P}{\pi LD}$$

According to the comparison of test results on the same concrete, f_{st} is about 10-15% higher than direct tensile strength, f_t.

Flexural strength and corresponding tests



BS 1881: Part 118: 1983. Flexural test. 150 x 150 x 750 mm or 100 x 100 x 500 (Max. size of aggregate is less than 25 mm). The arrangement for modulus of rupture is shown in the above figure.

From Mechanics of Materials, we know that the maximum tension stress should occur at the bottom of the constant moment region. The modulus of rapture can be calculated as:

$$f_{bt} = \frac{Pl}{bd^2}$$

This formula is for the case of fracture taking place within the middle one third of the beam. If fracture occurs outside of the middle one-third (constant moment zone), the modulus of rupture can be computed from the moment at the crack location according to ASTM standard, with the following formula.

$$f_{bt} = \frac{3Pa}{bd^2}$$

However, according to British Standards, once fracture occurs outside of the constant moment zone, the test result should be discarded.

Although the modulus of rupture is a kind of tensile strength, it is much higher than the results obtained from a direct tension test. This is because concrete can still carry stress after a crack is formed. The maximum load in a bending test does not correspond to the start of cracking, but correspond to a situation when the crack has propagated. The stress distribution along the vertical section through the crack is no longer varying in a linear manner. The above equations are therefore not exact.

Dimensional stability--Shrinkage and creep

Dimensional stability of a construction material refers to its dimensional change over a long period of time. If the change is so small that it will not cause any structural problems, the material is dimensionally stable. For concrete, drying shrinkage and creep are two phenomena that compromise its dimensional stability.

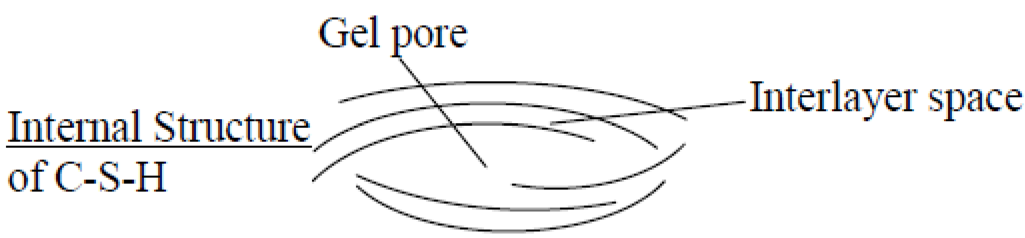
Shrinkage and creep are often discussed together because they are both governed by the deformation of hydrated cement paste within concrete. The aggregate in concrete does not shrink or creep, and they serve to restrain the deformation.

Drying shrinkage

After concrete has been cured and begins to dry, the excessive water that has not reacted with the cement will begin to migrate from the interior of the concrete mass to the surface. As the moisture evaporates, the concrete volume shrinks. The loss of moisture from the concrete varies with distance from the surface. The shortening per unit length associated with the reduction in volume due to moisture loss is termed the shrinkage. Shrinkage is sensitive to the relative humidity. For higher relative humidity, there is less evaporation and hence reduced shrinkage. When concrete is exposed to 100% relative humidity or submerged in water, it will actually swell slightly.

Shrinkage can create stress inside concrete. Because concrete adjacent to the surface of a member dries more rapidly than the interior, shrinkage strains are initially larger near the surface than in the interior. As a result of the differential shrinkage, a set of internal self-balancing forces, i.e. compression in the interior and tension on the outside, is set up.

In additional to the self-balancing stresses set up by differential shrinkage, the overall shrinkage creates stresses if members are restrained in the direction along which shrinkage occurs. If the tensile stress induced by restrained shrinkage exceeds the tensile strength of concrete, cracking will take place in the restrained structural element. If shrinkage cracks are not properly controlled, they permit the passage of water, expose steel reinforcements to the atmosphere, reduce shear strength of the member and are bad for appearance of the structure. Shrinkage cracking is often controlled with the incorporation of sufficient reinforcing steel, or the provision of joints to allow movement. After drying shrinkage occurs, if the concrete member is allowed to absorb water, only part of the shrinkage is reversible. This is because water is lost from the capillary pores, the gel pores (i.e., the pore within the C-S-H), as well as the space between the C-S-H layers. The water lost from the capillary and gel pores can be easily replenished. However, once water is lost from the interlayer space, the bond between the layers becomes stronger as they get closer to one another. On wetting, it is more difficult for water to re-enter. As a result, part of the shrinkage is irreversible.



The magnitude of the ultimate shrinkage is primarily a function of initial water content of the concrete and the relative humidity of the surrounding environment. For the same w/c ratio, with

increasing aggregate content, shrinkage is reduced. For concrete with fixed aggregate/cement ratio, as the w/c ratio increases, the cement becomes more porous and can hold more water. Its ultimate shrinkage is hence also higher. If a stiffer aggregate is used, shrinkage is reduced.
The shrinkage strain, ε_{sh}, is time dependent. Approximately 90% of the ultimate shrinkage occurs during the first year.

Both the rate at which shrinkage occurs and the magnitude of the total shrinkage increase as the ratio of surface to volume increases. This is because the larger the surface area, the more rapidly moisture can evaporate.

Based on a number of local investigations in Hong Kong, the value of shrinkage strain (after one year) for plain concrete members appears to lie between 0.0004 and 0.0007 (although value as high as 0.0009 has been reported). For reinforced concrete members, the shrinkage strain values are reduced, as reinforcement is helpful in reducing shrinkage.

Creep

Creep is defined as the time-dependent deformation under a constant load. Water movement under stress is a major mechanism leading to creeping of concrete. As a result, factors affecting shrinkage also affect creep in a similar way. Besides moisture movement, there is evidence that creep may also be due to time-dependent formation and propagation of microcracks, as well as microstructural adjustment under high stresses (where stress concentration exists). These mechanisms, together with water loss from the gel interlayer, lead to irreversible creep. Creeping develops rapidly at the beginning and gradually decreases with time. Approximately 75% of ultimate creep occurs during the first year. The ultimate creep strain (after 20 years) can be 3-6 times the elastic strain.

Creep can influence reinforced concrete in the following aspects.

i). Due to the delayed effects of creep, the long-term deflection of a beam can be 2-3 times larger than the initial deflection.

ii). Creeping results in the reduction of stress in pre-stressed concrete which can lead to increased cracking and deflection under service load.

iii). In a R.C column supporting a constant load, creep can cause the initial stress in the steel to double or triple with time because steel is non-creeping and thus take over the force reduced in concrete due to creep.

Creep is significantly influenced by the stress level. For concrete stress less than 50% of its strength, creep is linear with stress. In this case, the burger's body, which is a combination of Maxwell and Kelvin models, is a reasonable representation of creep behaviour. For stress more than 50% of the strength, the creep is a nonlinear function of stress, and linear viscoelastic models are no longer applicable. For stress level higher than 75-80% of strength, creep rupture can occur. It is therefore very important to keep in mind that in the design of concrete column, 0.8 f_c is taken to be the strength limit.

Factors affecting Creep of concrete

a) w/c ratio: The higher the w/c ratio, the higher is the creep.
b) Aggregate stiffness (elastic modulus): The stiffer the aggregate, the smaller the creep.

c) Aggregate fraction: higher aggregate fraction leads to reduced creep.

d) Theoretical thickness: The theoretical thickness is defined as the ratio of section area to the semi- perimeter in contact with the atmosphere. Higher the theoretical thickness, smaller the creep and shrinkage.

e) Temperature: with increasing temperature, both the rate of creep and the ultimate creep increase. This is due to the increase in diffusion rate with temperature, as well as the removal of more water at a higher temperature.

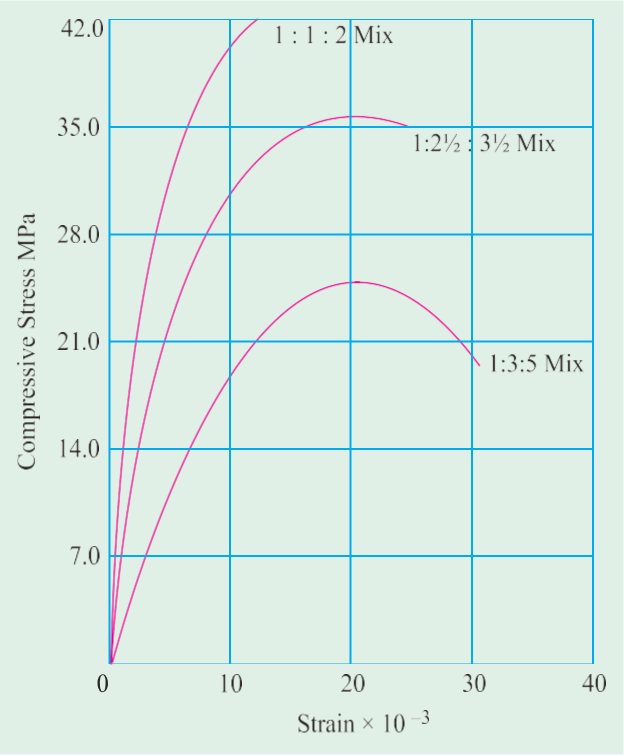
f) Humidity: with higher humidity in the air, there is less exchange of moisture between the concrete and the surrounding environment. The amount of creep is hence reduced.

g) Age of concrete at loading: The creep strain at a given time after the application of loading is lower if loading is applied to concrete at a higher age. For example, if the same loading is applied to 14 day and 56 day concrete (of the same mix), and creep strain is measured at 28 and 70 days respectively (i.e., 14 days after load application), the 56 day concrete is found to creep less. This is because the hydration reaction has progressed to a greater extent in the 56 day concrete. With less capillary pores to hold water, creep is reduced.

UNIT – IV

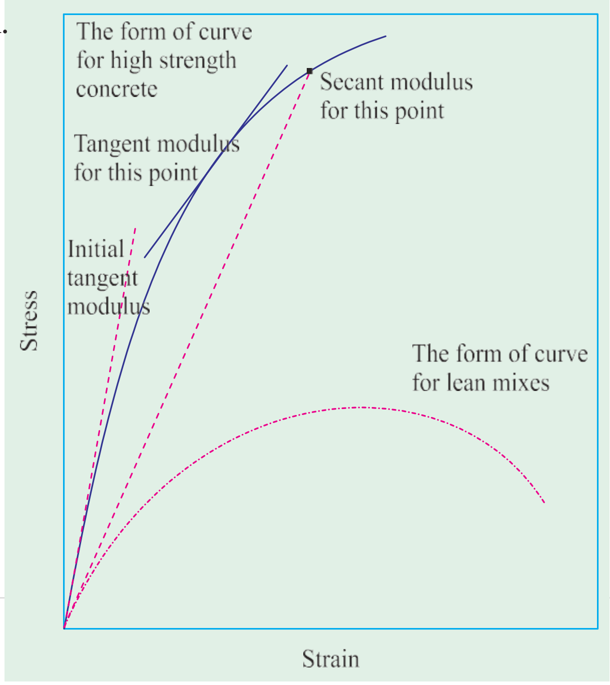
ELASTICITY, SHRINKAGE AND CREEP: ELASTICITY, SHRINKAGE AND CREEP

In the theory of reinforced concrete, it is assumed that concrete is elastic, isotropic, homogenous and that it conforms to Hooke's law. Actually none of these assumptions are strictly true and concrete is not a prefectly elastic material. Concrete deforms when load is applied but this deformation does not follow any simple set rule. The deformation depends upon the magnitude of the load, the rate at which the load is applied and the elapsed time after which the observation is made. In other words, the rheological behaviour of concrete *i.e.*, the response of concrete to applied load is quite complex.The knowledge of rheological properties of concrete is necessary to calculate deflection of structures, and design of concrete members with respect to their section, quantity of steel and stress analysis. When reinforced concrete is designed by elastic theory it is assumed that a perfect bond exists between concrete and steel. The stress in steel is "*m*" times the stress in concrete where "*m*" is the ratio between modulus of elasticity of steel and concrete, known as modular ratio. The accuracy of design will naturally be dependent upon the value of the modulus of elasticity of concrete, because the modulus of elasticity of steel is more or less a definite quantity.

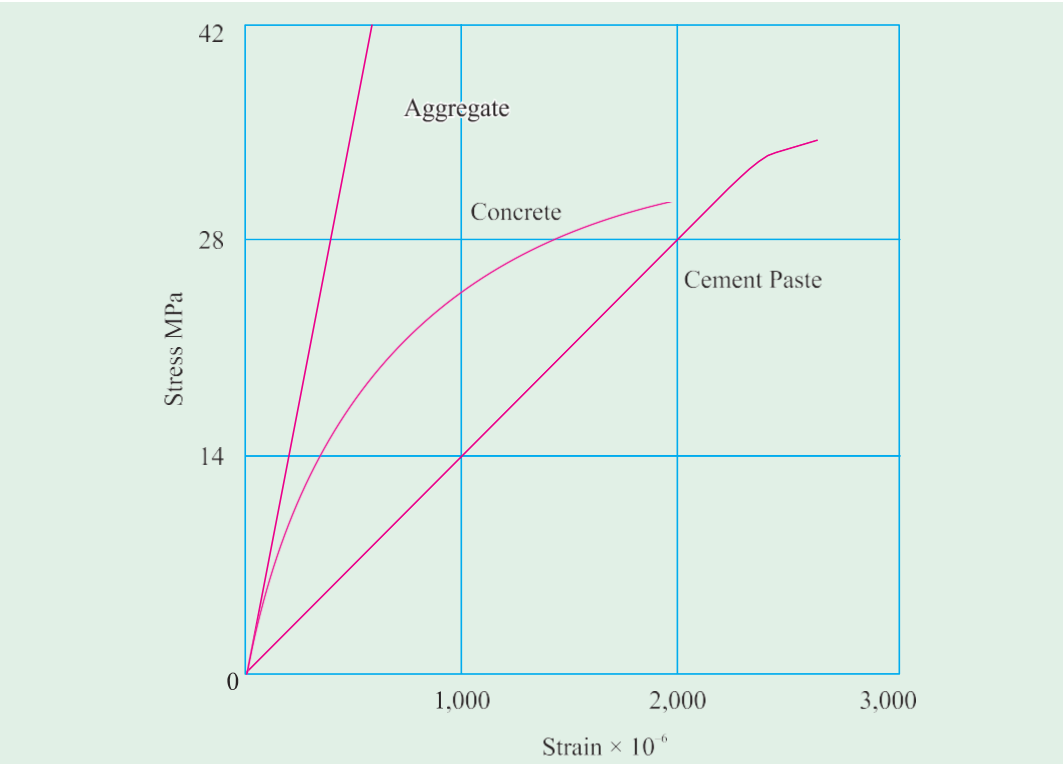


It is to be further noted that concrete exhibits very peculiar rheological behaviour because of its being a heterogeneous, multi-phase material w hose behaviour is influenced by the elastic properties and morphology of gel structures. The modulus of elasticity of concrete being so important and at the same time so complicated, we shall see this aspect in little more detail.

The modulus of elasticity is determined by subjecting a cube or cylinder specimen to uniaxial compression and measuring the deformations by means of dial gauges fixed between certain gauge length. Dial gauge reading divided by gauge length will give the strain and load applied divided by area of cross- section will give the stress. A series of readings are taken and the stress-strain relationship is established.



The modulus of elasticity can also be determined by subjecting a concrete beam to bending and then using the formulae for deflection and substituting other parameters. The modulus of elasticity so found out from actual loading is called static modulus of elasticity. It is seen that even under short term loading concrete does not behave as an elastic material. However, up to about 10-15% of the ultimate strength of concrete, the stress-strain graph is not very much curved and hence can give more accurate value. For higher stresses the stress-strain relationship will be greatly curved and as such it will be inaccurate. Figure 8.1 shows stress- strain relationship for various concrete mixes.



In view of the peculiar and complex behaviour of stress-strain relationship, the modulus of elasticity of concrete is defined in somewhat arbitrary manner. The modulus of elasticity of concrete is designated in various ways and they have been illustrated on the stress-strain curve in Figure 8.2. The term Young's modulus of elasticity can strictly be applied only to the straight part of stress-strain curve. In the case of concrete, since no part of the graph is straight, the modulus of elasticity is found out with reference to the tangent drawn to the curve at the origin. The modulus found from this tangent is referred as initial tangent modulus. This gives satisfactory results only at low stress value. For higher stress value it gives a misleading picture.

Tangent can also be drawn at any other point on the stress-strain curve. The modulus of elasticity calculated with reference to this tangent is then called tangent modulus. The tangent modulus also does not give a realistic value of modulus of elasticity for the stress level much above or much below the point at which the tangent is drawn. The value of modulus of elasticity will be satisfactory only for stress level in the vicinity of the point considered.

A line can be drawn connecting a specified point on the stress-strain curve to the origin of the curve. If the modulus of elasticity is calculated with reference to the slope of this line, the modulus of elasticity is referred as secant modulus. If the modulus of elasticity is found out with reference to the chord drawn between two specified points on the stress-strain curve then such value of the modulus of elasticity is known as chord modulus.

The modulus of elasticity most commonly used in practice is secant modulus.

There is no standard method of determining the secant modulus. Sometime it is measured at stresses ranging from 3 to 14 MPa and sometime the secant is drawn to point representing a stress level of 15, 25, 33, or 50 per cent of ultimate strength. Since the value of secant modulus decreases with increase in stress, the stress at which the secant modulus has been found out should always be stated.

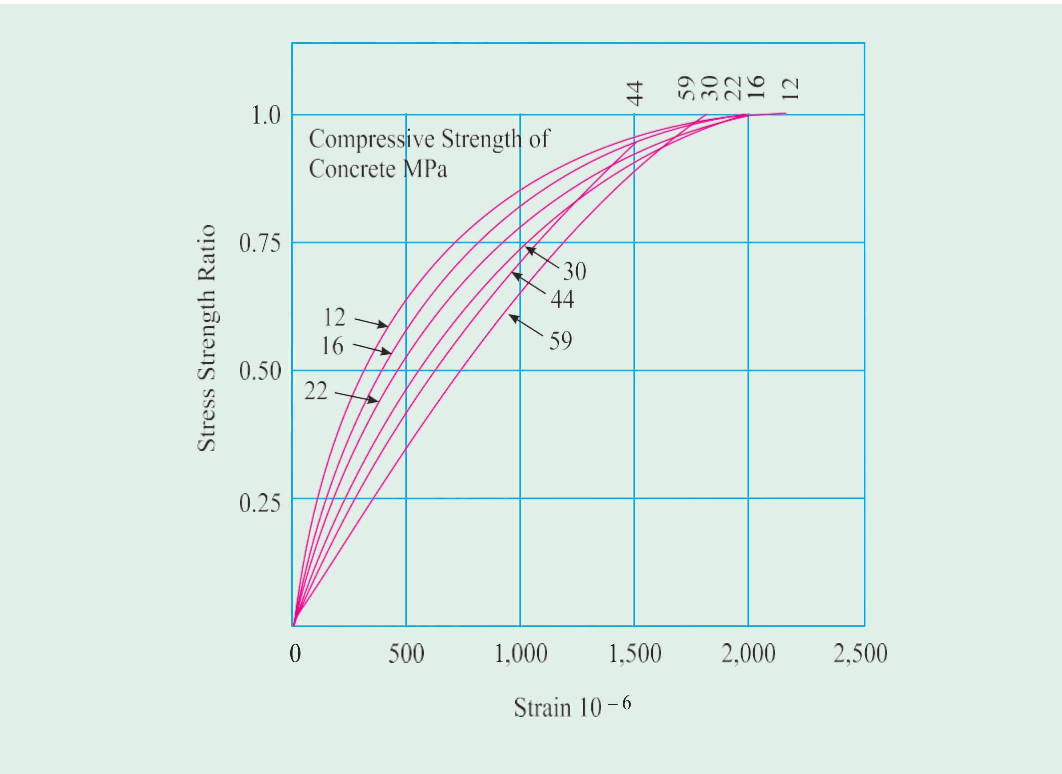
Modulus of elasticity may be measured in tension, compression or shear. The modulus in tension is usually equal to the modulus in compression.

It is interesting to note that the stress-strain relationship of aggregate alone shows a fairly good straight line. Similarly, stress-strain relationship of cement paste alone also shows a fairly good straight line. But the stress-strain relationship of concrete which is combination of aggregate and paste together shows a curved relationship. Perhaps this is due to the development of micro cracks at the interface of the aggregate and paste. Because of the failure of bond at the interface increases at a faster rate than that of the applied stress, the stress-strain curve continues to bend faster than increase of stress. Figure 8.3 shows the stress-strain relationship for cement paste, aggregate and concrete.

Relation between Modulus of Elasticity and Strength

Figure 8.4 shows the strain in concrete of different strengths plotted against the stress- strain ratio. At the same stress-strength ratio, stronger concrete has higher strain. On the contrary, stronger the concrete higher the modulus of elasticity. This can be explained that stronger the concrete the stronger is the gel and hence less is the strain for a given load. Because of lower strain, higher is the modulus of elasticity. The Table 8.1 gives the values of modulus of elasticity for various strengths of concrete.

Modulus of elasticity of concrete increases approximately with the square root of the strength. The IS 456 of 2000 gives the Modulus of elasticity as $E_C = 5000\sqrt{f_{ck}}$ where E_C is the short term static modulus of elasticity in N/mm ^{2}.



Modulus of Elasticity of Concrete of Different strengths

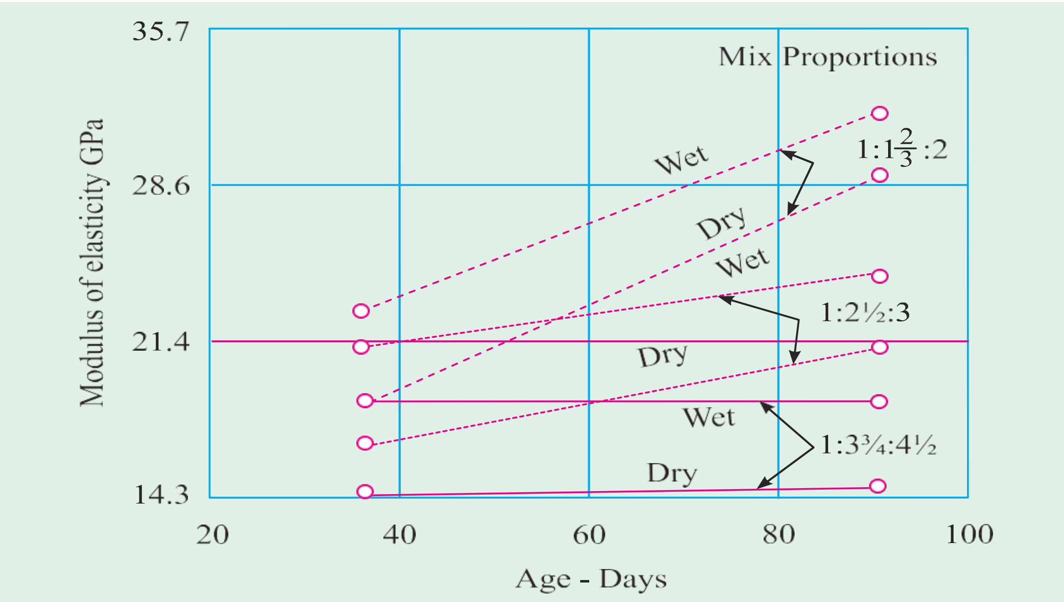
Average compressive strength of works cubes MPa	*Modulus of Elasticity GPa*
21	21.4
28	28.5
35	32.1
42	35.7
56	42.9
70	46.4

Actual measured values may differ by ± 20 per cent from the values obtained from the above expression.

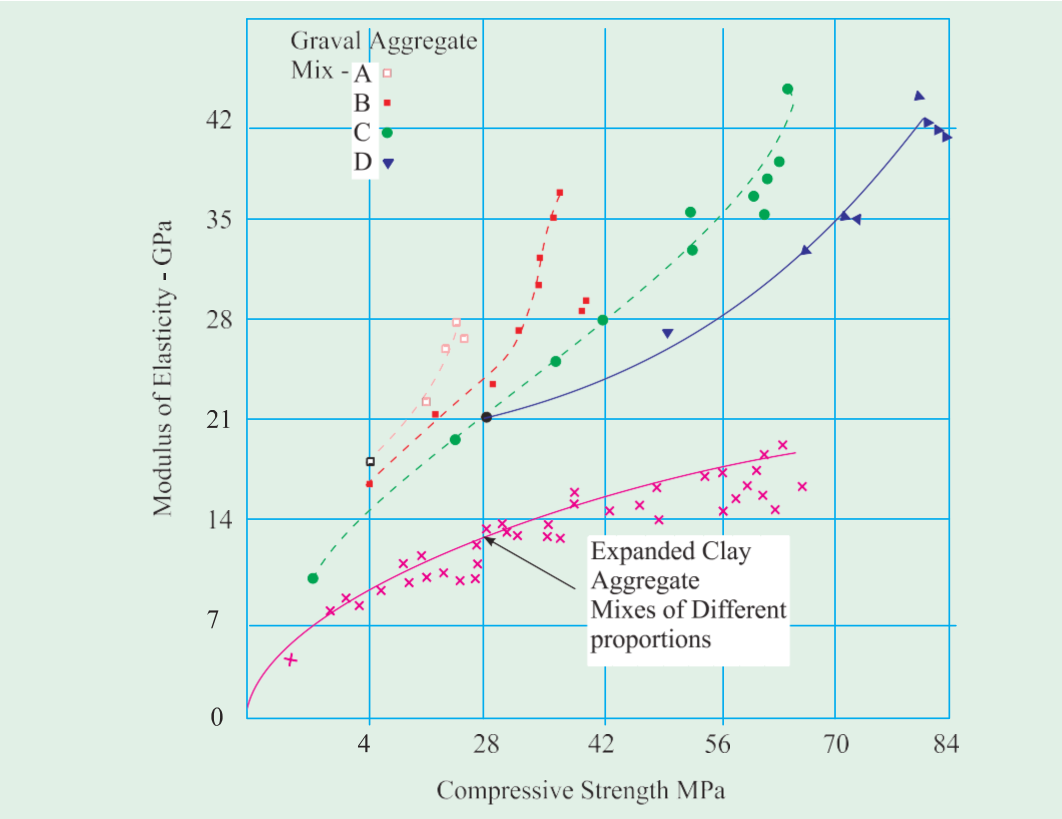
Factors Affecting Modulus of Elasticity

As explained earlier, one of the important factors affecting the modulus of elasticity of concrete is the strength of concrete. This can be represented in many ways such as the relationship between ratio of mix or water/cement ratio. The modulus of elasticity also depends upon the state of wetness of concrete when other conditions being the same. Wet concrete will show higher modulus of elasticity than dry concrete. This is in contrast to the strength property that dry concrete has higher strength than wet concrete. The possible reason is that wet concrete being saturated with water, experiences less strain for a given stress and, therefore, gives higher modulus of elasticity, whereas dry concrete shows higher strain for given stress on account of less gel water and inter-crystal adsorbed water. Figure 8.5 shows the influence of moisture content on the modulus of elasticity.

Figure 8.5 also shows the relationship between the modulus of elasticity, mix proportions and age of concrete. It can be seen that richer mixes show higher



modulus of elasticity. Similarly older the concrete which again is supposed to have become stronger shows higher



modulus of elasticity, thereby confirming that the stronger the concrete higher is the modulus of elasticity.

The quality and quantity of aggregate will have a significant effect on the modulus of elasticity. It is to be remembered that the strength of aggregate will not have significant effect on the strength of concrete, whereas, the modulus of elasticity of aggregate influences the modulus of elasticity of concrete. Figure 8.6 shows the modulus of elasticity of concrete with gravel aggregates and expanded clay aggregates. It has been seen that if the modulus of elasticity of aggregate is E_a and that of the paste E_p then the modulus of elasticity of concrete E is found out to be

$$\frac{1}{E} = \frac{V_p}{E_p} + \frac{V_a}{E_a}$$

where V_p and V_a are volume of paste and aggregate respectively in the concrete.

The modulus of elasticity of light weight concrete is usually between 40 to 80 per cent of the modulus of elasticity of ordinary concrete of the same strength. Since there is little difference between the modulus of elasticities of paste and light weight aggregate the mix proportions will have very little effect on the modulus of elasticity of light weight concrete.[8.1]

The relation between the modulus of elasticity and strength is not much effected by temperature upto about 230°C since both the properties vary with temperature in approximately the same manner. Steam-curved concrete shows a slightly lower modulus than water-curved concrete of the same strength.

Experiments have shown that the modulus in tension does not appear to differ much from modulus in compression. As the experimental set-up presents some difficulties, only limited work has been done to determine the modulus of elasticity in tension.

Since the principal use of reinforced concrete is in flexural members, considerable amount of work has been conducted to find out the modulus of elasticity in flexure on specimens of beam. The approach was to load the beam, measure deflection caused by known loads and to calculate the modulus of elasticity from well-known beam deflection formulae. It has been seen that the stress-strain curves in flexure agreed well with the stress-strain curve obtained in companion cylinders concentrically loaded in compression.

Dynamic Modulus of Elasticity

It has been explained earlier that the stress-strain relationship of concrete exhibits complexity particularly due to the peculiar behaviour of gel structure and the manner in which the water is held in hardened concrete. The value of E is found out by actual loading of concrete *i.e.*, the static modulus of elasticity does not truly represent the elastic behaviour of concrete due to the phenomenon of creep. The elastic modulus of elasticity will get affected more seriously at higher stresses when the effect of creep is more pronounced.

Attempts have been made to find out the modulus of elasticity from the data obtained by non-destructive testing of concrete. The modulus of elasticity can be determined by subjecting the concrete member to longitudinal vibration at their natural frequency. This method involves the determination of either resonant frequency through a specimen of concrete or pulse velocity travelling through the concrete. (More detail on this aspect is given under the chapter ('Testing of concrete'). By making use of the above parameters modulus of elasticity can be calculated from the following relationship.

$$E_d = Kn^2L^2\rho$$

where E_d is the dynamic modulus of elasticity; K is a constant, n is the resonant frequency; L is the length of specimen; and ρ is the density of concrete.

If L is measured in millimetres and ρ in kg/m^3 then $E_d = 4 \times 10^{-15} n^2L^2\rho$ GPa

The value of E found out in this method by the velocity of sound or frequency of sound is referred as dynamic modulus of elasticity, in contrast to the value of E found out by actual loading of the specimen and from stress-strain relationship which is known as static modulus of elasticity.

The value of dynamic modulus of elasticity computed from ultrasonic pulse velocity method is somewhat higher than those determined by static method. This is because the modulus of elasticity as determined by dynamic modulus is unaffected by creep. The creep also does not

Ultra Sonic Pulse Velocity Equipment is used for finding dynamic modulus of elasticity.

significantly effect the initial tangent modulus in the static method. Therefore, the value of dynamic modulus and the value of initial tangent modulus are found to be more or less agree with each other. Approximate relationship between the two modulai expressed in GN/m^2 is given by

$$E_c = 1.25\, E_d - 19$$

where E_c and E_d are the static and dynamic modulus of elasticity.

The relationship does not apply to light weight concrete or for very rich concrete with cement content more than 500 kg/m^3. For light weight concrete the relationship can be as follows

$$E_c = 1.04\, E_d - 4.1$$

Poisson's Ratio

Sometimes in design and analysis of structures, the knowledge of poisson's ratio is required. Poisson's ratio is the ratio between lateral strain to the longitudinal strain. It is generally denoted by the letter μ. For normal concrete the value of poisson's ratio lies in the range of 0.15 to 0.20 when actually determined from strain measurements.

As an alternative method, poisson's ratio can be determined from ultrasonic pulse velocity method and by finding out the fundamental resonant frequency of longitudinal vibration of concrete beam. The poisson's ratio μ can be calculated from the following equation.

$$\left(\frac{V}{2nL}\right)^2 = \frac{1-\mu}{(1+\mu)(1-2\mu)}$$

where V is the pulse velocity (mm/s),

n is the resonant frequency (Hz) and L is the length of the beam (in mm). The value of the poisson's ratio found out dynamically is little higher than the value of static method. The value ranges from 0.2 to 0.24.

Dynamic modulus of elasticity can also be found out from the following equation.

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

where V is the pulse velocity

ρ is the density and

μ is the Poisson's ratio

Creep

Creep can be defined as "the time-dependent" part of the strain resulting from stress. We have discussed earlier that the stress-strain relationship of concrete is not a straight line relationship but a curved one. The degree of curvature of the stress-strain relationship depends upon many factors amongst which the intensity of stress and time for which the load is acting are of significant interest. Therefore, it clearly shows that the relation between stress and strain for concrete is a function of time. The gradual increase in strain, without increase in stress, with the time is due to creep. From this explanation creep can also be defined as the increase in strain under sustained stress.

All materials undergo creep under some conditions of loading to a greater or smaller extent. But concrete creeps significantly at all stresses and for a long time. Furthermore, creep

of concrete is approximately linear function of stress upto 30 to 40 per cent of its strength. The order of magnitude of creep of concrete is much greater than that of other crystalline material except for metals in the final stage of yielding prior to failure. Therefore, creep in concrete is considered to be an isolated rheological phenomenon and this is associated with the gel structure of cement paste. Cement paste plays a dominant role in the deformation of concrete. The aggregates, depending upon the type and proportions modify the deformation characteristics to a greater or lesser extent. Therefore, it is logical initially to examine the structure of cement paste and how it influences creep behaviour and then to consider how the presence of aggregate modifies the creep behaviour

Cement paste essentially consists of unhydrated cement grains surrounded by the product of hydration mostly in the form of gel. These gels are interpenetrated by gel pores and interspersed by capillary cavities. The process of hydration generates more and more of gel and subsequently there will be reduction of unhydrated cement and capillary cavities. In young concrete, gel pores are filled with gel water and capillary cavities may or may not be filled with water. The movement of water held in gel and paste structure takes place under the influence of internal and external water vapour pressure. The movement of water may also take place due to the sustained load on concrete.

The formation of gel and the state of existence of water are the significant factors on the deformative characteristics of concrete. The gel provides the rigidity both by the formation of chemical bonds and by the surface force of attraction while the water can be existing in three categories namely combined water, gel water and capillary water.

It is interesting to find how such a conglomeration of very fine colloidal particles with enclosed water-filled viods behave under the action of external forces. One of the explanations given to the mechanics of creeps is based on the theory that the colloidal particles slide against each other to re-adjust their position displacing the water held in gel pores and capillary cavities. This flow of gel and the consequent displacement of water is responsible for complex deformation behaviour and creep of concrete.

Creep takes place only under stress. Under sustained stress, with time, the gel, the adsorbed water layer, the water held in the gel pores and capillary pores yields, flows and readjust themselves, which behaviour is termed as creep in concrete.

Rheological Representation of Creep

Analysis of the mechanical behaviour of a material like hardened cement paste which exhibits both elastic and inelastic components of deformation under load, can be expressed in rheological terms. The rheological approach illustrates the mechanical behaviour of an ideal elastic, viscous and plastic components.

Macroscopic Rheological Approach

At the macroscopic level, the structure of cement paste can be represented as a continuous solid phase containing saturated voids having a wide ranges of sizes. Figure 8.7 (*a*) shows macroscopic representation of deformational behaviour of hardened cement paste. This model can show the time-dependent volume changes, as long as the isotropic stresses are applied through the solid phase and the drainage of the liquid can take place.[8.2]

The corresponding rheological model consists of a spring device representing the elastic mass around a central viscous dash-pot representing the confined liquid. Refer Figure 8.7 (*b*). With the help of this model it is possible to have an idea about the deformational behaviour of cement paste.

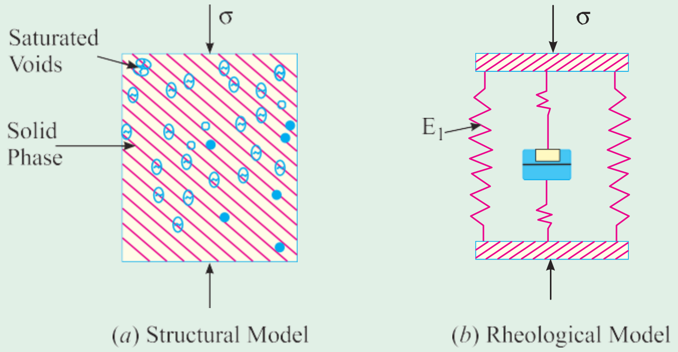
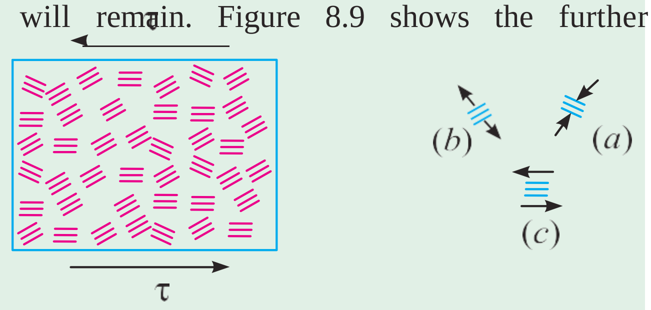


Fig. 8.7. Macroscopic representation of the deformational behaviour of hardened cement paste.

Microscopic Rheological Approach

At the microscopic level, the structure of cement of gel can be represented as an anisotropic crystal clusters randomly oriented in a solid matrix (Figure 8.8). The application of a macroscopic shear stress to the anisotropic system results in an irrecoverable volumetric contraction of the spaces in some of the clusters [Figure 8.8 (*a*)] and a separation in other clusters [Figure 8.8 (*b*)]. Only. a fraction of the elements is subjected to pure shear [Figure 8.8 (*c*)]. On removal of the load there is a visco-elastic recovery, but due to some deviatory stress component, certain local irrecoverable volume changes will remain. Figure 8.9 shows the further submicroscopic models.



They represented metastable crystalline gel consisting of two sheet like crystals separated by a layer of water. Three basically different mechanisms of deformation are possible. They are compressive stresses normal to contact layer [Figure 8.9 (*a*)] tensile stresses normal to the contact layer [Figure 8.9 (*b*)] sheer stresses parallel to the contant layer [Figure 8.9 (*c*)]

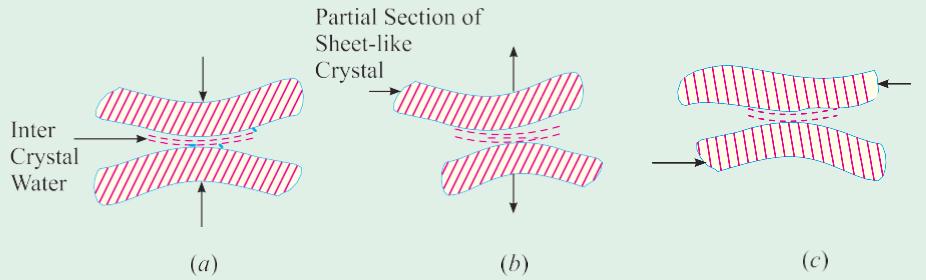


Fig. 8.9. Sub-microscopic models representing the three basic intercrystal mechanical states.

In mechanism (*a*), the liquid is compressed and squeezed out laterally. This is accompanied by a reduction of the intercrystalline space. The rate of liquid movement is slow and will decrease with narrowing of space which tends towards a limit equal to a monomolecular compressed water layer (about 3 Å). This squeezing away of liquid against strong frictional forces is the principal cause of the time dependent, irrecoverable changes in the cement gel.

In mechanism (*b*), visco-elastic elongation may be expected, at a faster rate than in the case of compression. This elongation is restrained, however, by the solid matrix and delayed, although complete recovery may be expected long after unloading.

In mechanism (*c*), the shear stress results in the water layers.[8.3]

Under the complex systems of applied loading, below the elastic limit of the material, various combinations of these basic mechanisms of deformation may be expected. On the basis of the available experimental evidence, it may be assumed that the long term deformation mechanism in cement gel is that involving narrowing of the intercrystalline spaces. This is reflected in the slow and decreasing rate of time-dependent of deformation, as well as in the irrecoverable component of the deformations which increase with loading time.

The time dependent deformation behaviour of loaded and unloaded hardened cement paste shows a distinct similarity between creep (and its recovery) and shrinkage (and swelling). All these processes are governed by movement or migration of the various types of water held. It can be further explained as follows:

Application of uniaxial compression which is the most usual type of loading, results in as instantaneous elastic response of both solid and liquid systems. The external load is distributed between these two phases. Under sustained load, the compressed liquid begins to diffuse and migrate from high to lower stressed areas. Under uniform pressure, migration takes place outwards from the body. This mechanism is accompanied by a transfer of load from the liquid phase to the surrounding solid, so that stress acting on the solid matrix increases gradually, resulting in an increased elastic deformation.

There is reason to believe that, after several days under sustained load, the pressure on the capillary water gradually disappears, being transferred to the surrounding gel. Similarly, the pressure on the gel pore water disappears after some weeks. The pressure on the inter and intracrystalline adsorbed water continues to act during the entire period of loading, although the magnitude decreases gradually. It can be said that the ultimate deformation of the hardened cement paste, in fact, is the elastic response of its solid matrix, which behaves as if the spaces within it (which are filled with unstable gel) were quite empty.

Hydration under Sustained Load

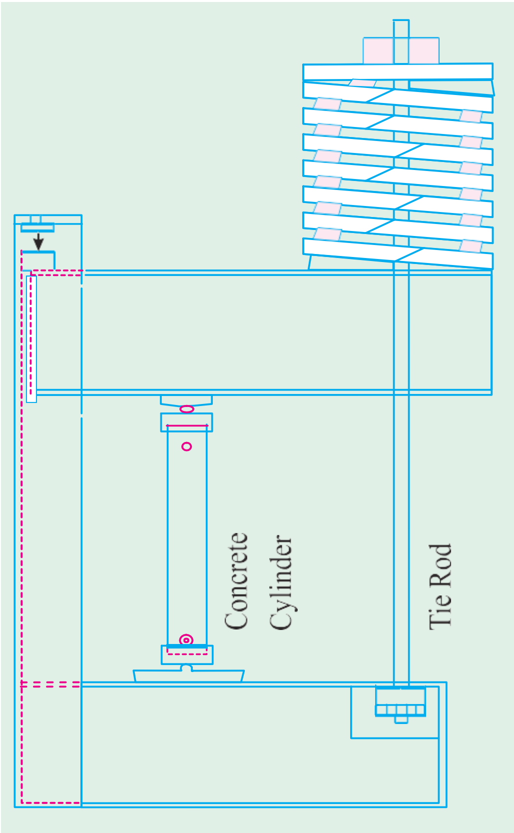
Under sustained load the cement paste continues to undergo creep deformation. If the member is subjected to a drying condition this member will also undergo continuous shrinkage. The migration of liquid from the gel pore due to creep may promote the shrinkage to small extent. It can be viewed that the creep, the shrinkage and the slip deformations at the discontinuities cause deformations and micro cracks. It should be remembered that the process of hydration is also simultaneously progressing due to which more gel is formed which will naturally heal-up the microcracks produced by the creep and shrinkage. This healing up micro cracks by the delayed hydration process is also responsible for increasing the irrecoverable componentofthedeformation

Increased rigidity and strength development with age are additional contribution of hydration to time dependent deformation. Moreover, it is likely that, with continuing hydration the growth of the solid phase at the expense of the liquid phase gradually changes the parameter governing the extent and rate of the total creep.

Concrete structures in practice are subjected to loading and drying. At the same time certain amount of delayed hydration also takes place. Under such a complex situation, the structure creeps, undergoes drying shrinkage, experiences micro cracks and also due to progressive hydration, heals up the micro cracks that are formed due to any reason.

Measurement of Creep

Creep is usually determined by measuring the change with time in the strain of specimen subjected to constant stress and stored under appropriate condition. A typical testing device is shown in Figure 8.10. The spring ensures that the load is sensibly constant in spite of the fact that the specimen contracts with time. Under such conditions, creep continues for a very long time, but the rate of creep decreases with time.



Under compressive stress, the creep measurement is associated with shrinkage of concrete. It is necessary to keep companion unloaded specimens to eliminate the effect of shrinkage and other autogenous volume change. While this correction is qualitatively correct and yields usable results, some research workers maintained that shrinkage and creep are not independent and are of the opinion that the t wo effects are not additive as assumed in the test.

It is generally assumed that the creep continues to assume a limiting value after an infinite time under load. It is estimated that 26 per cent of the 20 year creep occurs in 2 weeks. 55 per cent of 20 year creep occurs in 3 months and 76 per cent of 20 year creep occurs in one year.

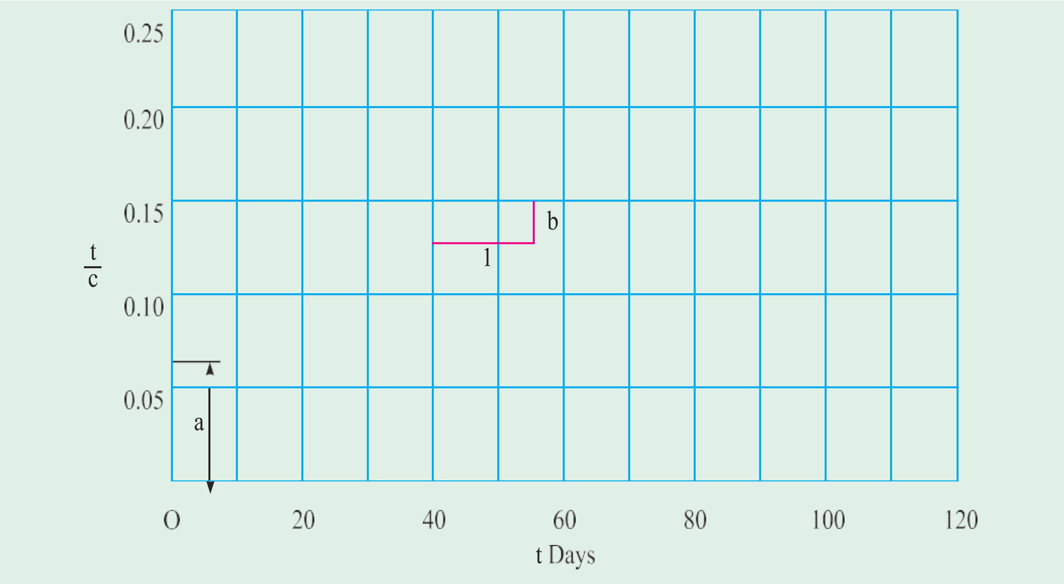
If creep after one year is taken as unity, then the average value of creep at later ages are:

1.14 after 2 years
1.20 after 5 years
1.26 after 10 years
1.33 after 20 years and

1.36 after 30 years

There are many expressions to give the magnitude of ultimate creep in concrete member. Ross suggested the relation between specific creep (creep strain per unit stress) '*c*' and time under load '*t*' in the form[8.4]

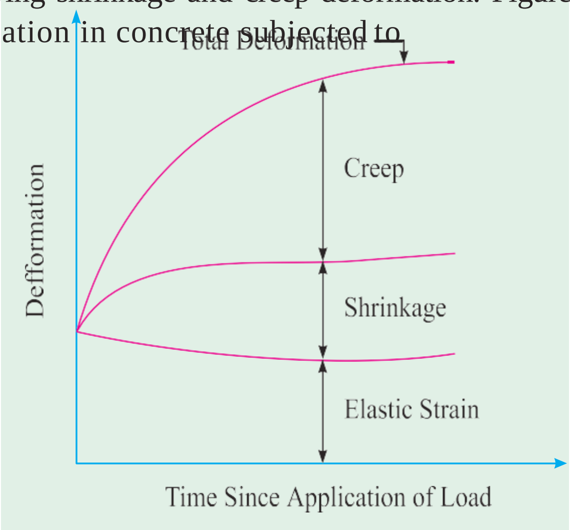
$$c = \frac{t}{a + bt}$$

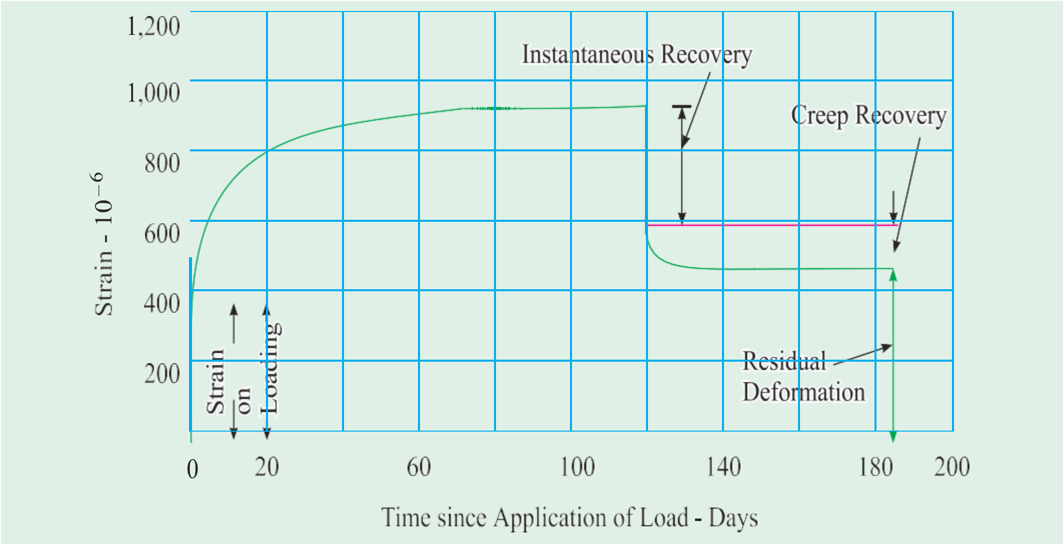


where '*a*' and '*b*' are constants. If a graph is drawn with *t* in the *x*-axis and *t*/*c* in the *y*-axis it shows a straight line of slope *b* and the intercept on the $\frac{t}{c}$ is equal to *a*.

Then the constant can be easily found out. Refer Figure 8.11. The ultimate crep at infinite time will be $\frac{1}{b}$ from the above expression. It is interesting to observe that when $t = a/b$, $c = \frac{1}{2}b$. *i.e.*, one half of the ultimate creep is realised at time $t = a/b$.

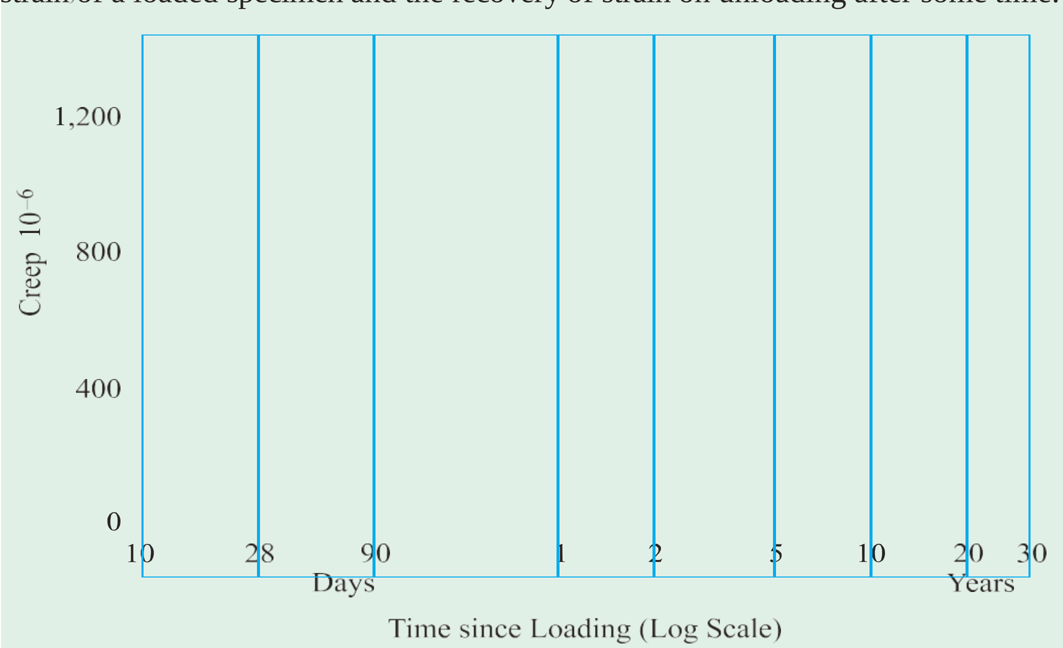
As indicated earlier if a loaded concrete member is kept in atmoshphere subjected to shrinkage, the member will undergo deformation from 3 different causes: namely elastic deformation, drying shrinkage and creep deformation. Figure 8.12 shows the time dependent deformation in concrete subjected to sustained load. In order to estimate the magnitude of creep in a member subjected to drying, a companion specimen is always placed at the same temperature and humidity condition and the shrinkage of the unloaded specimen is found and this magnitude of deformation is subtracted from the total deformation of the loaded member. Kno wing the instantaneous elastic deformation, the creep deformation can be calculated. In this, for simplicity sake it is assumed that the shrinkage of concrete does not effect the creep in addition to the load. In fact it is to be noted that in addition to the load,





the shrinkage also will have some influence on the magnitude of creep, and creep on shrinkage.

If a member is loaded and if this load is sustained for some length of time and then removed, the specimen instantaneously recovers the elastic strain. The magnitude of instantaneous recovery of the elastic strain is something less than that of the magnitude of the elastic strain on loading. With time, certain amount of creep strain is also recovered. It is estimated that about 15 per cent of creep is only recoverable. The member will have certain amount of residual strain. This shows that the creep is not a simply reversible phenomenon. Figure 8.13 shows the pattern of strain of a loaded specimen and the recovery of strain on unloading after some time.



Factors Affecting Creep

Influence of Aggregate: Aggregate undergoes very little creep. It is really the paste which is responsible for the creep. However, the aggregate influences the creep of concrete through a restraining effect on the magnitude of creep. The paste which is creeping under load is restrained by aggregate which do not creep. The stronger the aggregate the more is the restraining effect and hence the less is the magnitude of creep. Figure 8.14 shows the effect of the quality of aggregate on the magnitude of creep.

The grading, the shape, the maximum size of aggregate have been suggested as factors affecting creep. But it is later shown that the effect of aggregate and their properties mentioned above *per se* do not effect the creep , but indirectly they affect the creep from the point of view of total aggregate content in the concrete. The modulus of elasticity of aggregate is one of the important factors influencing creep. It can be easily imagined that the higher the modulus of elasticity the less is the creep. Light weight aggregate shows substantially higher creep than normal weight aggregate. Persuambly this is because of lower modulus of elasticity.

Influence of Mix Proportions: The amount of paste content and its quality is one of the most important factors influencing creep. A poorer paste structure undergoes higher creep. Therefore, it can be said that creep increases with increase in water/cement ratio. In other words, it can also be said that creep is inversely proportional to the strength of concrete. Broadly speaking, all other factors which are affecting the water/cement ratio is also affecting the creep. The following table shows the creep of concretes of different strength.

Creep of Concrete of Different Strength

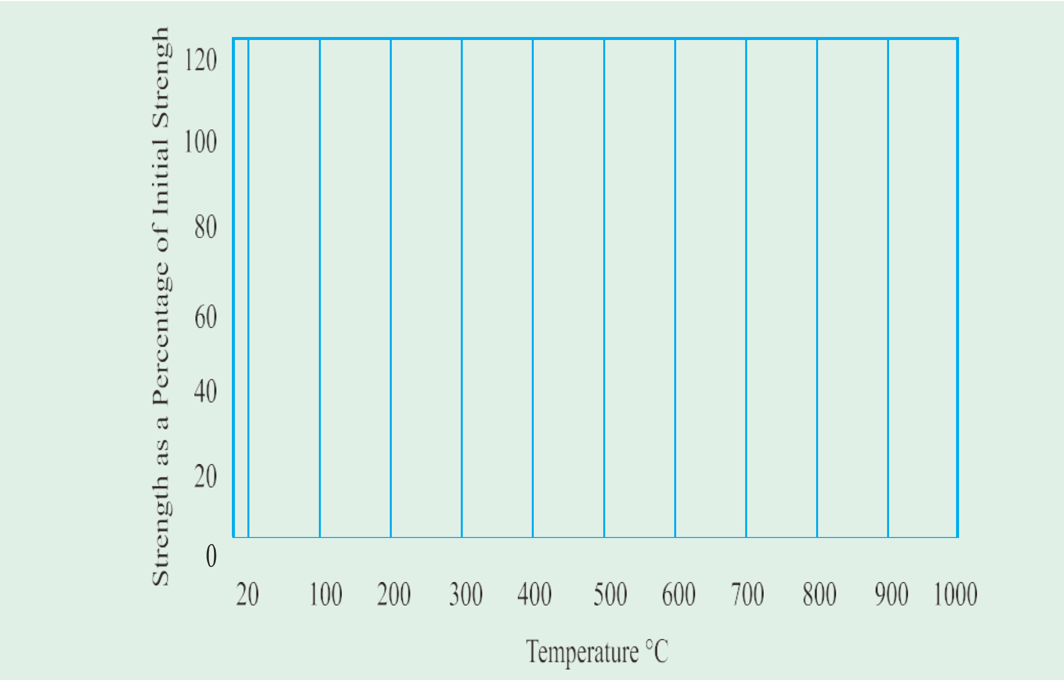
Compressive strength at the time of application of load MPa	*Ultimate specific creep 10^{-6} per MPa*	*Ultimate creep at stress-str ratiœngth cent of 30 per 10^{-6}*
14	999	933
28	114	1067
42	78	1100
56	57	1067

Figure 8.15. hows the specific creep as a function of water/cement ratio.

Influence of Age: Age at which a concrete members is loaded will have a predominant effect on the magnitude of creep. This can be easily understood from the fact that the quality of gel improves with time. Such gel creeps less, whereas a young gel under load being not so stronger creeps more. What is said above is not a very accurate statement because of the fact that the moisture content of the concrete being different at different age, also influences the magnitude of creep.

Effects of Creep: The magnitude of creep is dependent on many factors, the main factors being time and leval of stress. In reinforced concrete beams, creep increases the deflection with time and may be a critical consideration in design.

In reinforced concrete columns, creep property of concrete is useful. Under load immediately elastic deformation takes place. Concrete creeps and deforms. It can not deform independent of steel reinforcement. There will be gradual transfer of stress from concrete to steel. The extra load in the steel is required to be shared by concrete and this situation results



in employment and development of full strength of both the materials. However, in eccentrically loaded columns, creep increases the deflection and can load to buckling.

In case of statically indeterminate structures and column and beam junctions creep may relieve the stress concentration induced by shrinkage, temperatures changes or movement of support. Creep property of concrete will be useful in all concrete structures to reduce the internal stresses due to non-uniform load or restrained shrinkage.

In mass concrete structures such as dams, on account of differential temperature conditions at the interior and surface, creep is harmful and by itself may be a cause of cracking in the interior of dams. Therefore, all precautions and steps must be taken to see that increase in temperature does not take place in the interior of mass concrete structure.

Loss of prestress due to creep of concrete in prestressed concrete structure is well known and provision is made for the loss of prestress in the design of such structures.

Shrinkage

It has been indicated in the earlier chapter that concrete is subjected to changes in volume either autogenous or induced. Volume change is one of the most detrimental properties of concrete, which affects the long-term strength and durability. To the practical engineer, the aspect of volume change in concrete is important from the point of view that it causes unsightly cracks in concrete. We have discussed elsewhere the effect of volume change due to thermal properties of aggregate and concrete, due to alkali/aggregate reaction, due to sulphate action etc. Presently we shall discuss the volume change on account of inherenet properties of concrete "shrinkage".

One of the most objectionable defects in concrete is the presence of cracks, particularly in floors and pavements. One of the important factors that contribute to the cracks in floors and pavements is that due to shrinkage. It is difficult to make concrete which does not shrink and crack. It is only a question of magnitude. Now the question is how to reduce the shrinkage and shrinkage cracks in concrete structures. As shrinkage is an inherent property of concrete it demands greater understanding of the various properties of concrete, which influence its shrinkage characteristics. It is only when the mechanism of all kinds of shrinkage and the factors affecting the shrinkage are understood, an engineer will be in a better position to control and limit the shrinkage in the body of concrete.

The term shrinkage is loosely used to describe the various aspects of volume changes in concrete due to loss of moisture at different stages due to different reasons. To understand this aspect more closely, shrinkage can be classified in the following way:

(a) Plastic Shrinkage ; (*b*) Drying Shrinkage;

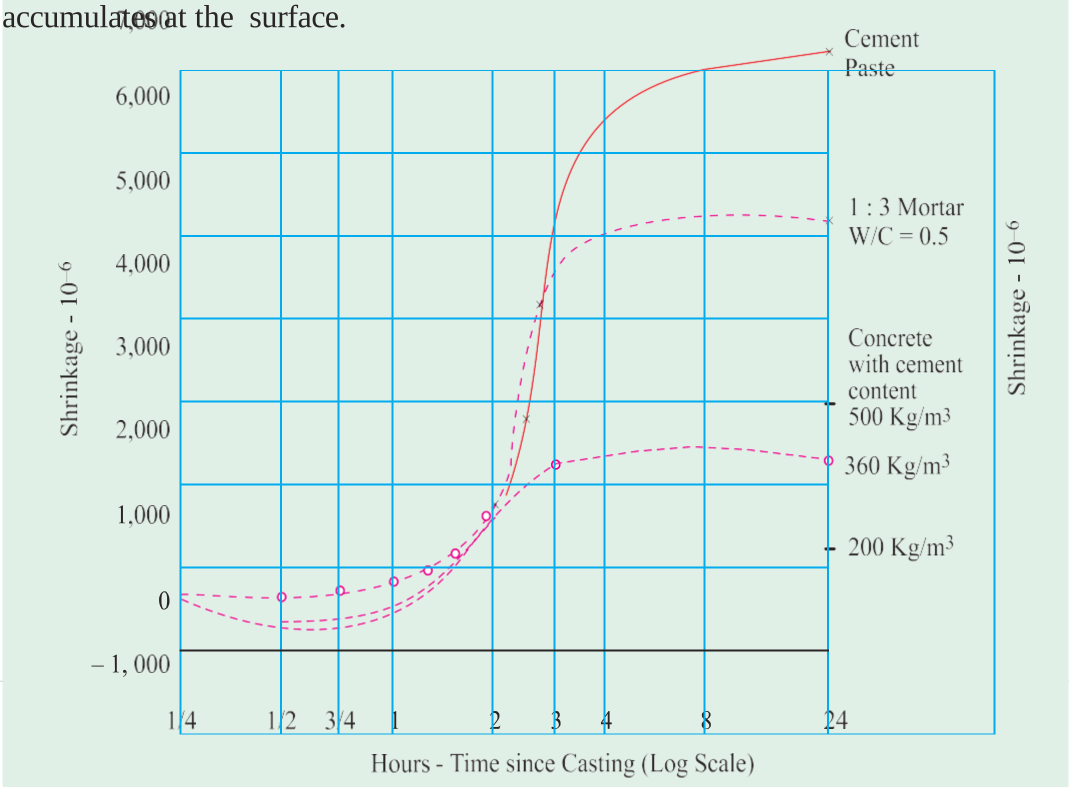
(*c*) Autogeneous Shrinkage; (*d*) Carbonation Shrinkage.

Plastic Shrinkage

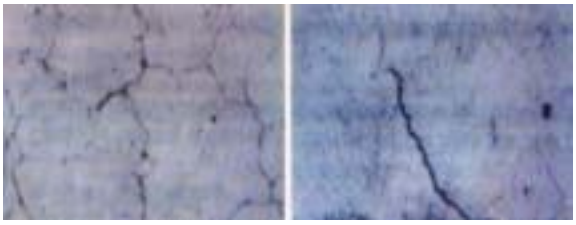
Shrinkage of this type manifests itself soon after the concrete is placed in the forms while the concrete is still in the plastic state. Loss of water by evaporation from the surface of concrete or by the absorption by aggregate or subgrade, is believed to be the reasons of plastic shrinkage. The loss of water results in the reduction of volume. The aggregate particles or the reinforcement comes in the way of subsidence due to which cracks may appear at the surface or internally around the aggregate or reinforcement.

In case of floors and pavements where the surface area exposed to drying is large as compared to depth, when this large surface is exposed to hot sun and drying wind, the surface of concrete dries very fast which results in plastic shrinkage.

Sometimes even if the concrete is not subjected to severe drying, but poorly made with a high water/cement ratio, large quantity of water bleeds and accumulates at the surface.



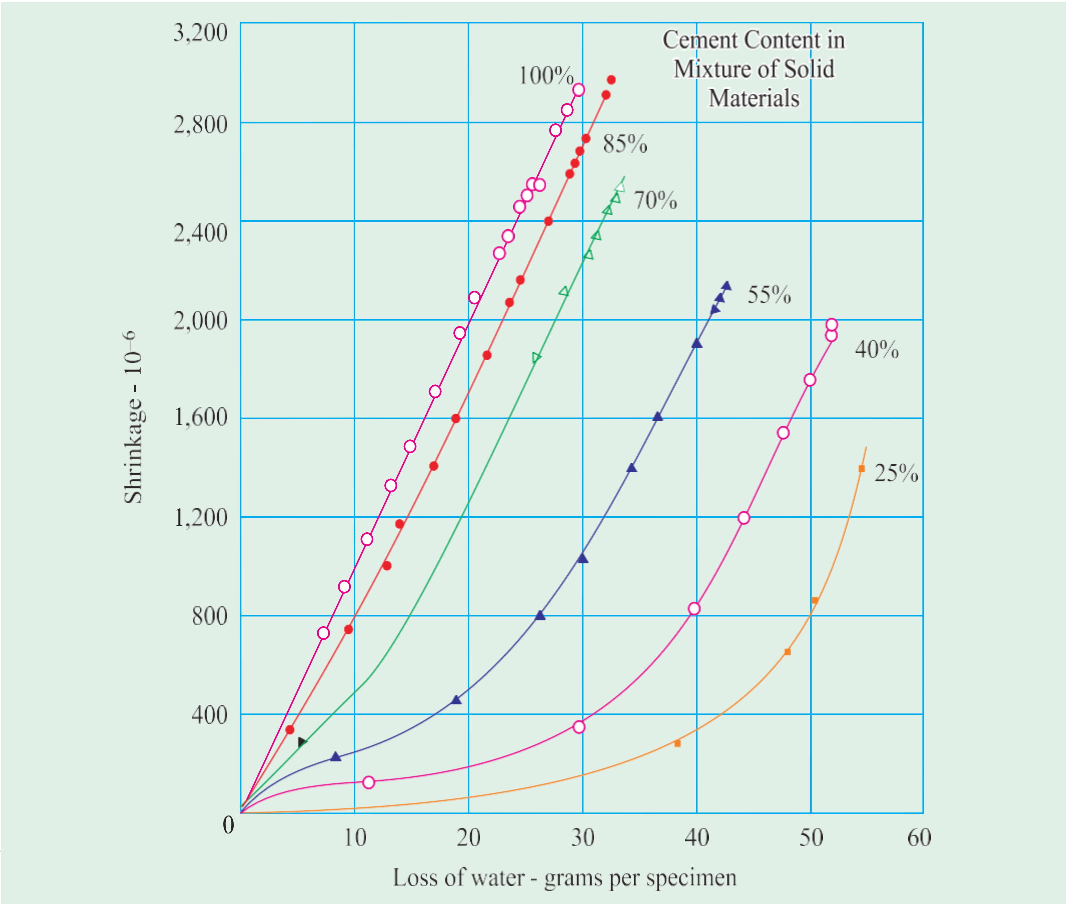
When this water at the surface dries out, the surface concrete collapses causing cracks.



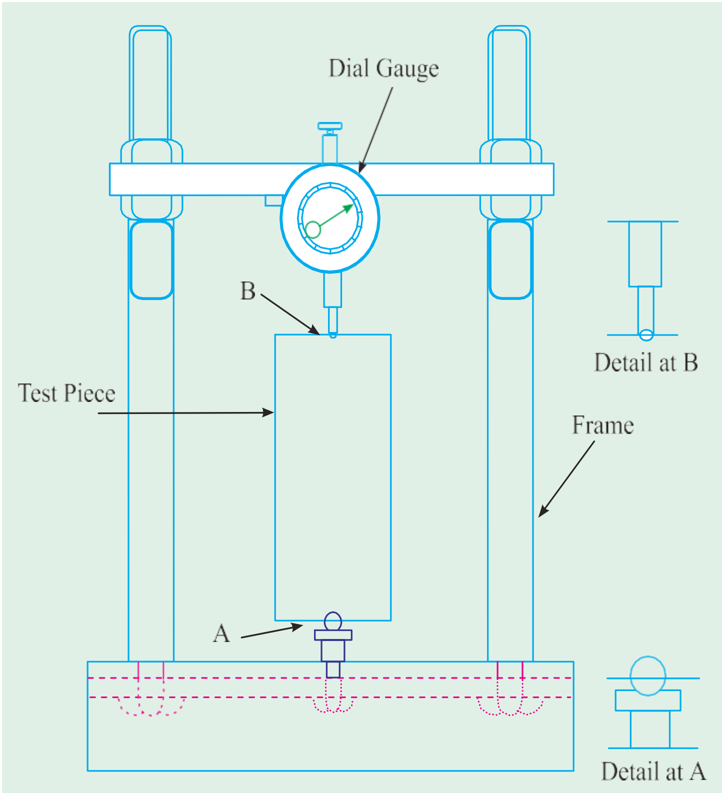
Typical Plastic Shrinkage cracks due to rapid evaporation of water from hot sun and drying wind.

Plastic concrete is sometimes subjected to unintended vibration or yielding of formwork support which again causes plastic shrinkage cracks as the concrete at this stage has not developed enough strength. From the above it can be inferred that high water/cement ratio, badly proportioned concrete, rapid drying, greater bleeding, unintended vibration etc., are some of the reasons for plastic shrinkage. It can also be further added that richer concrete undergoes greater plastic shrinkage. Figure 8.16 shows the influence of cement content on plastic shrinkage.[8.5]

Plastic shrinkage can be reduced mainly by preventing the rapid loss of water from surface. This can be done by covering the surface with polyethylene sheeting immediately on finishing operation; by monomolecular coatings by fog spray that keeps the surface moist; or by working at night. An effective method of removing plastic shrinkage cracks is to revibrate the concrete in a controlled manner. Use of small quantity of aluminium power is also suggested to offset the effect of plastic shrinkage. Similarly, expansive cement or shrinkage

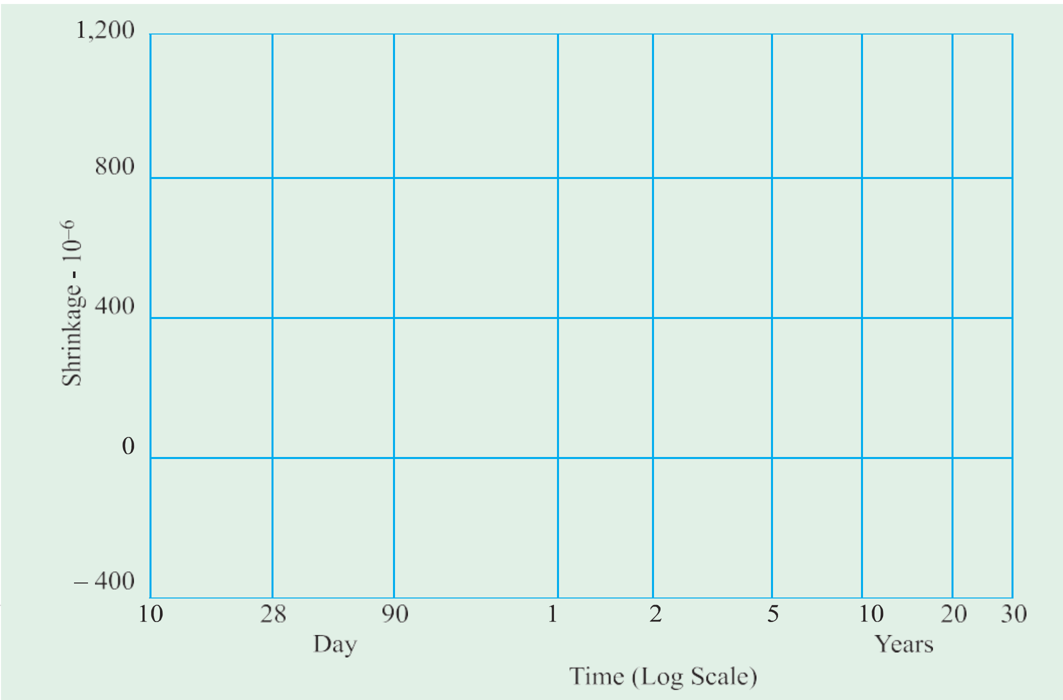


compensating cement also can be used for controlling the shrinkage during the setting of concrete. The principal property of such cement is that the expansion induced in the plastic concrete will almost offset the normal shrinkage due to loss of moisture. Under correct usage, the distance between the joints can sometimes be tripled without increasing the level of shrinkage cracking. Further, use of unneeded high slump concrete, over sanded mix, higher air entraining should be discouraged in order to reduce the higher plastic shrinkage.



Drying Shrinkage

Just as the hydration of cement is an ever lasting process, the drying shrinkage is also an ever lasting process when



concrete is subjected to drying conditions. The drying shrinkage of concrete is analogous to the mechanism of drying of timber specimen. The loss of free water contained in hardened concrete, does not result in any appreciable dimension change. It is the loss of water held in gel pores that causes the change in the volume. Figure 8.17 shows the relationship between loss of moisture and shrinkage. Under drying conditions, the gel water is lost progressively over a long time, as long as the concrete is kept in drying conditions. It is theoretically estimated that the total linear change due to long time drying shrinkage could be of the order of 10,000 x 10^{-6}. But values upto 4,000 x 10^{-6} have been actually observed. Figure 8.18 shows the typical apparatus for measuring shrinkage.

Cement paste shrinks more than mortar and mortar shrinks more than concrete. Concrete made with smaller size aggregate shrinks more than concrete made with bigger size aggregate. The magnitude of drying shrinkage is also a function of the fineness of gel. The finer the gel the more is the shrinkage. It has been pointed out earlier that the high pressure steam cured concrete with low specific surface of gel, shrinks much less than that of normally cured cement gel.

Factors Affecting Shrinkage

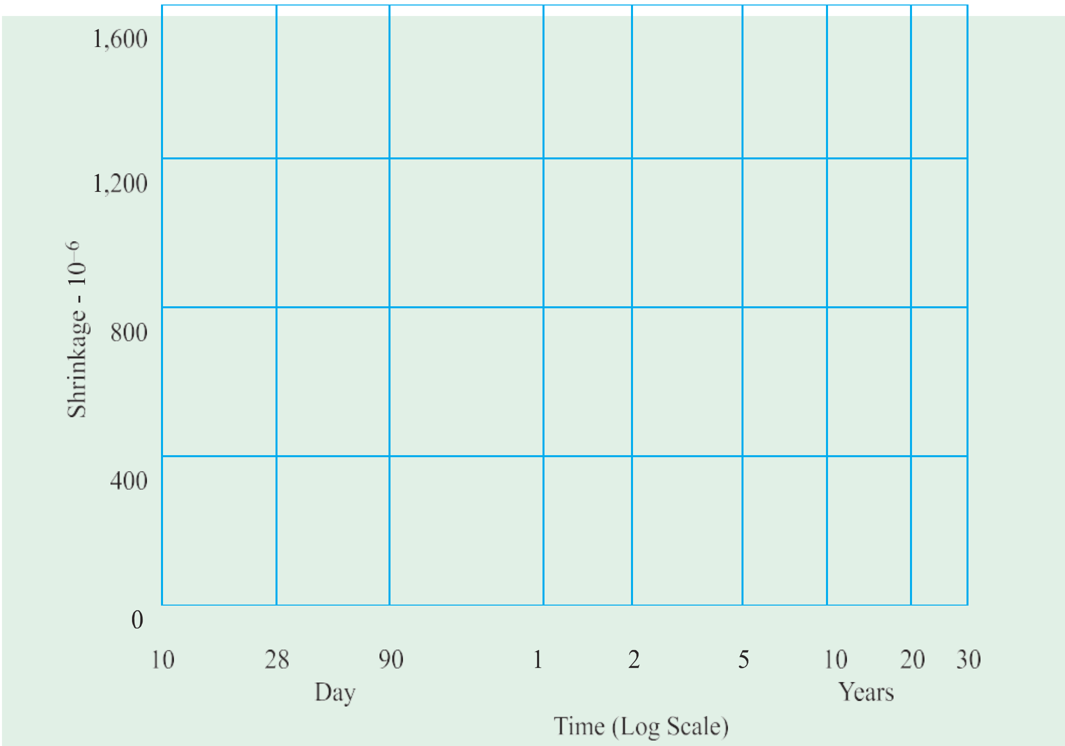
One of the most important factors that affects shrinkage is the drying condition or in other words, the relative humidity of the atmoshphere at which the concrete specimen is kept. If the concrete is placed in 100 per cent relative humidity for any length of time, there will not be any shrinkage, instead there will be a slight swelling. The typical relationship between shrinkage and time for which concrete is stored at different relative humidities is shown in Figure 8.19. The graph shows that the magnitude of shrinkage increases with time and also with the reduction of relative humidity. The rate of shrinkage decreases rapidly with time. It is observed that 14 to 34 per cent of the 20 year shrinkage occurs in 2 weeks, 40 to 80 per cent of the 20 year shrinkage occurs in 3 months and 66 to 85 per cent of the 20 year shrinkage occurs in one year.

Another important factor which influences the magnitude of shrinkage is water/cement ratio of the concrete. As mentioned earlier, the richness of the concrete also has a significant influence on shrinkage. Table 8.3 shows the typical values of shrinkage of mortar and concrete specimens, for different aggregate/cement ratio, and water/cement ratio.

Typical Values of Shrinkage of Mortar and Concrete Specimens, 125 mm square in cross-section; Stored at a Relative Humidity of 50 per cent and 21°C.[8.8]

Aggregate/cement	*Shrinkage after six months (10^{-6}) for water/cement ratio ratio of*			
	0.4	0.5	0.6	0.7
3	800	1200	–	–
4	550	850	1,050	
5	400	600	750	850
6	300	400	550	650
7	200	300	400	500

Aggregate plays an important role in the shrinkage properties of concrete. The quantum of an aggregate, its size, and its modulus of elasticity influence the magnitude of drying



shrinkage. The grading of aggregate by itself may not directly make any significant influence. But since it affects the quantum of paste and water/cement ratio, it definitely influences the drying shrinkage indirectly. The aggregate particles restrain the shrinkage of the paste. The harder aggregate does not shrink in unison with the shrinking of the paste whereby it results in higher shrinkage stresses, but low magnitude of total shrinkage. But a softer aggregate yields to the shrinkage stresses of the paste and thereby experiences lower magnitude of shrinkage stresses within the body, but greater magnitude of total shrinkage.

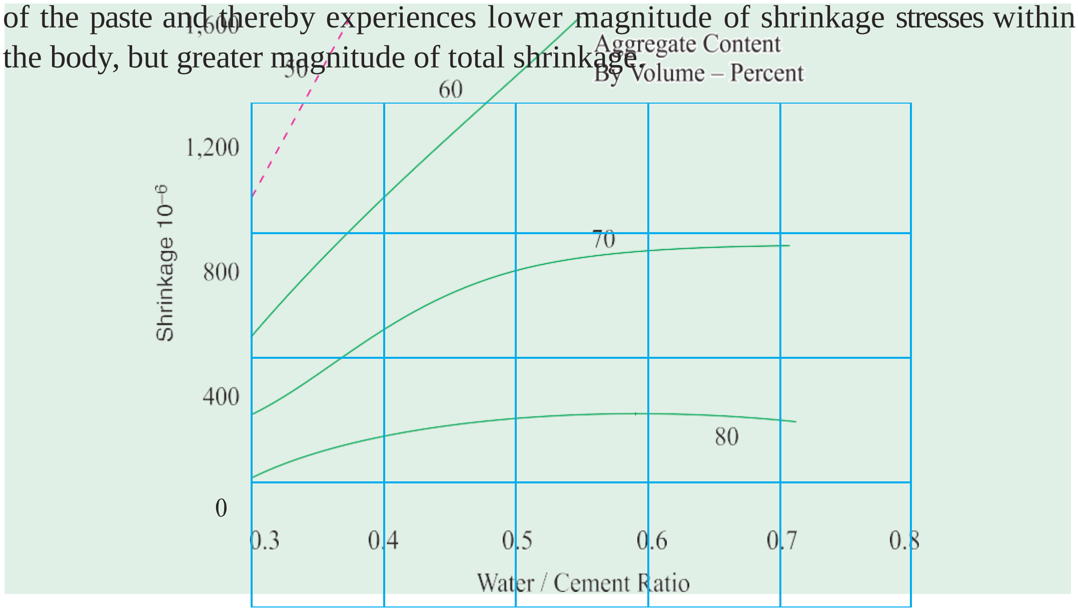


Figure 8.20 shows the typical values of shrinkage of concrete made with different kinds of aggregate. It can be seen from the sketch that a harder aggregate with higher modulus of elasticity like quartz shrinks much less than softer aggregates such as sandstone. It is to be also noted that internal stress and the resultant micro cracks will also be more in case of quartz than that of the sandstone on account of shrinkage stress. The light-weight aggregate usually leads to higher shrinkage, largely because such aggregate having lower modulus of elasticity offers lesser restraint to the potential shrinkage of the cement paste.

The volume fraction of aggregate will have some influence on the total shrinkage. The ratio of shrinkage of concrete S_c to shrinkage of neat paste S_p depends on the aggregate content in the concrete, *a*. This can be written as

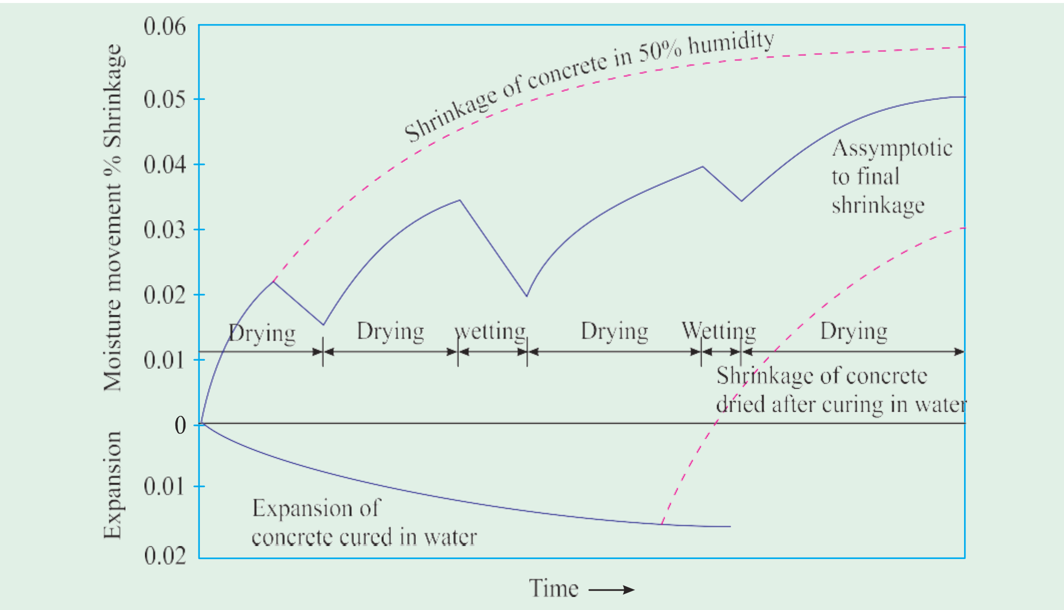
$$S_c = S_p (1-a)^n$$

Experimental values of '*n*' vary between 1.2 and 1.7. Figure 8.21 also shows the influence of water/cement ratio and aggregate content on shrinkage.

It is to be viewed that the drying shrinkage is one of the most detrimental properties of concrete. From the mechanism of shrinkage it can be seen that the long term drying shrinkage is an inherent property of concrete.

At best, by taking proper precautions the magnitude of shrinkage can only be reduced, but cannot be eliminated. The restraining effect of aggregate and reinforcement causes high internal stresses and induces internal micro cracks which not only impairs the structural integrity and strength but also reduces the durability of concrete. Another aspect to be seen with respect to the drying shrinkage is that moisture loss takes place at the surface of the member, which may not be compensated in the same rate by the movement of moisture from interior to the surface. As a result, moisture gradient is set up in a concrete specimen. The moisture gradient induces differential stresses, which again induces cracks.

As the drying takes place at the surface of the concrete, the magnitude of shrinkage varies considerably with the size and thickness of the specimen. Investigations have been carried out to find out the influence of the size of specimen on shrinkage. It is observed that



shrinkage decreases with an increase in the size of the specimen. But above some value, the size effect is no longer apparent.

It is pertinent at this point to bring out that the concrete or cement product undergoes long term drying shrinkage in varying magnitude depending upon the various factors mentioned in the proceeding paragraphs. The effect of this shrinkage is to cause cracks in the concrete. Ordinary Portland cement does not show good extensibility (the property to withstand greater, volume change without being cracked). In this respect low heat cement or Portland pozzolana cement will have higher extensibility. It may not be out of place to point out that addition of a certain quantity of lime will improve the extensibility of ordinary cement concrete. The superiority of lime mortar for internal plaster over cement mortar is from the point of view of the superior extensibility of lime mortar over cement mortar by about 7 times. A continuous surface, like plaster on the wall, undergoes tremendous change in volume, and as such cement mortar having low extensibility, is not able to withstand the volume change without cracking, where lime mortar or gauged mortar having higher extensibility gives better performance.

Moisture Movement

Concrete shrinks when allowed to dry in air at a lower relative humidity and it swells when kept at 100 per cent relative humidity or when placed in water. Just as drying shrinkage is an ever continuing process, swelling, when continuously placed in water is also an ever continuing process. If a concrete sample subjected to drying condition, at some stage, is subjected to wetting condition, it starts swelling. It is interesting to note that all the initial drying shrinkage is not recovered even after prolonged storage in water which shows that the phenomenon of drying shrinkage is not a fully reversible one. For the usual range of concrete, the irreversible part of shrinkage, represents between 0.3 and 0.6 of the drying shrinkage, the lower value being more common. Just as the drying shrinkage is due to loss of adsorbed water around gel particles, swelling is due to the adsorption of water by the cement gel. The water molecules act against the cohesive force and tend to force the gel particles further apart as a result of which swelling takes place. In addition, the ingress of water decreases the surface tension of the gel.

The property of swelling when placed in wet condition, and shrinking when placed in drying condition is referred as moisture movement in concrete. Figure 8.22 shows the typical moisture movement of 1:1 cement mortar mix, stored alternatively in water and dried in air to 50 per cent relative humidity. The moisture movement in concrete induces alternatively compressive stress and tensile stress which may cause fatigue in concrete which reduces the durability of concrete owing to reversal of stresses.

Autogeneous Shrinkage

In a conservative system i.e. where no moisture movement to or from the paste is permitted, when temperature is constant some shrinkage may occur. The shrinkage of such a conservative system is known as a autogeneous shrinkage.

Autogeneous shrinkage is of minor importance and is not applicable in practice to many situations except that of mass of concrete in the interior of a concrete dam. The magnitude of autogeneous shrinkage is in the order of about 100 x 10^{-6}.

Carbonation Shrinkage

Carbonation shrinkage is a phenomenon very recently recognised. Carbon dioxide present in the atmoshphere reacts in the presence of water with hydrated cement. Calcium hydroxide [$Ca(OH)_2$] gets converted to calcium carbonate and also some other cement compounds are decomposed. Such a complete decomposition of calcium compound in hydrated cement is chemically possible even at the low pressure of carbon dioxide in normal atmoshphere. Carbonation penetrates beyond the exposed surface of concrete only very slowly.

The rate of penetration of carbon dioxide depends also on the moisture content of the concrete and the relative humidity of the ambient medium. Carbonation is accompanied by an increase in weight of the concrete and by shrinkage. Carbonation shrinkage is probably caused by the dissolution of crystals of calcium hydroxide and deposition of calcium carbonate in its place. As the new product is less in volume than the product replaced, shrinkage takes place.

Carbonation of concrete also results in increased strength and reduced permeability, possibly because water released by carbonation promotes the process of hydration and also calcium carbonate reduces the voids within the cement paste. As the magnitude of carbonation shrinkage is very small when compared to long term drying shrinkage, this aspect is not of much significance. But carbonation reduces the alkalinity of concrete which gives a protective coating to the reinforcement against rusting. If depth of carbonation reaches upto steel reinforcements, the steel becomes liable for corrosion.

UNIT 5

Mix Design

4.1 INTRODUCTION

The common method of expressing the proportions of ingredients of a concrete mix is in the terms of parts or ratios of cement, fine and coarse aggregates. For e.g., a concrete mix of proportions 1:2:4 means that cement, fine and coarse aggregate are in the ratio 1:2:4 or the mix contains one part of cement, two parts of fine aggregate and four parts of coarse aggregate. The proportions are either by volume or by mass. The water-cement ratio is usually expressed in mass.

4.2 Factors to be considered for mix design

- The grade designation giving the characteristic strength requirement of concrete.
- The type of cement influences the rate of development of compressive strength of concrete.
- Maximum nominal size of aggregates to be used in concrete may be as large as possible within the limits prescribed by IS 456:2000.
- The cement content is to be limited from shrinkage, cracking and creep.
- The workability of concrete for satisfactory placing and compaction is related to the size and shape of section, quantity and spacing of reinforcement and technique used for transportation, placing and compaction.

4.3 Procedure for Concrete Mix Design – IS456:2000

1. Determine the mean target strength ft from the specified characteristic compressive strength at 28-day f_{ck} and the level of quality control.

   $$f_t = f_{ck} + 1.65\ S$$

   Where, S is the standard deviation obtained from the Table of approximate contents given after the design mix.

2. Obtain the water cement ratio for the desired mean target using the empirical relationship between compressive strength and water cement ratio so chosen is checked against the limiting water cement ratio. The water cement ratio so chosen is checked against the limiting water cement ratio for the requirements of durability given in table and adopts the lower of the two values.

3. Estimate the amount of entrapped air for maximum nominal size of the aggregate from the table.

4. Select the water content, for the required workability and maximum size of aggregates (for aggregates in saturated surface dry condition) from table.

5. Determine the percentage of fine aggregate in total aggregate by absolute volume from table for the concrete using crushed coarse aggregate.

6. Adjust the values of water content and percentage of sand as provided in the table for any difference in workability, water cement ratio, grading of fine aggregate and for rounded aggregate the values are given in table.

7. Calculate the cement content form the water-cement ratio and the final water content as arrived after adjustment. Check the cement against the minimum cement content from the requirements of the durability, and greater of the two values is adopted.

8. From the quantities of water and cement per unit volume of concrete and the percentage of sand already determined in steps 6 and 7 above, calculate the content of coarse and fine aggregates per unit volume of concrete from the following relations:

$$V = \left[W + \frac{C}{S_c} + \frac{1}{p}\frac{f_a}{S_{fa}}\right] \times \frac{1}{1000}$$

$$V = \left[W + \frac{C}{S_c} + \frac{1}{1-p}\frac{C_a}{S_{ca}}\right] \times \frac{1}{1000}$$

Where, V = absolute volume of concrete = gross volume ($1m^3$) minus the volume of entrapped air

S_c = specific gravity of cement

W = Mass of water per cubic metre of concrete, kg

C = mass of cement per cubic metre of concrete, kg

p = ratio of fine aggregate to total aggregate by absolute volume

fa, Ca = total masses of fine and coarse aggregates, per cubic metre of concrete, respectively, kg, and

S_{fa}, S_{ca} = specific gravities of saturated surface dry fine and coarse aggregates, respectively

9. Determine the concrete mix proportions for the first trial mix.

10. Prepare the concrete using the calculated proportions and cast three cubes of 150 mm size and test them wet after 28-days moist curing and check for the strength.

11. Prepare trial mixes with suitable adjustments till the final mix proportions are arrived at.

4.4 CONCRETE MIX DESIGN EXAMPLE – M50 GRADE CONCRETE

Grade Designation = M-50
Type of cement = O.P.C-43 grade
Brand of cement = Vikram (Grasim)
Admixture = Sika [Sikament 170 (H)]
Fine Aggregate = Zone-II

Sp. Gravity
Cement = 3.15
Fine Aggregate = 2.61
Coarse Aggregate (20mm) = 2.65
Coarse Aggregate (10mm) = 2.66

Minimum Cement (As per contract) =400 kg / m3
Maximum water cement ratio (As per contract) = 0.45

Mix Calculation: –

1. Target Mean Strength = 50 + (5 X 1.65) = 58.25 Mpa

2. Selection of water cement ratio:-

Assume water cement ratio = 0.35

3. Calculation of water: –

Approximate water content for 20mm max. Size of aggregate = 180 kg /m^3 (As per Table No. 5, IS : 10262). As plasticizer is proposed we can reduce water content by 20%.

Now water content = 180 X 0.8 = 144 kg /m^3

4. Calculation of cement content:-

Water cement ratio = 0.35
Water content per cum of concrete = 144 kg
Cement content = 144/0.35 = 411.4 kg / m^3
Say cement content = 412 kg / m^3 (As per contract Minimum cement content 400 kg / m^3)
Hence O.K.

5. Calculation for C.A. & F.A.: –

Volume of concrete = 1 m^3
Volume of cement = 412 / (3.15 X 1000) = 0.1308 m^3
Volume of water = 144 / (1 X 1000) = 0.1440 m^3
Volume of Admixture = 4.994 / (1.145 X 1000) = 0.0043 m^3
Total weight of other materials except coarse aggregate = 0.1308 + 0.1440 +0.0043 = 0.2791 m^3

Volume of coarse and fine aggregate = 1 – 0.2791 = 0.7209 m^3
Volume of F.A. = 0.7209 X 0.33 = 0.2379 m3 (Assuming 33% by volume of total aggregate)

Volume of C.A. = 0.7209 – 0.2379 = 0.4830 m^3

Therefore weight of F.A. = 0.2379 X 2.61 X 1000 = 620.919 kg/ m^3

Say weight of F.A. = 621 kg/ m^3

Therefore weight of C.A. = 0.4830 X 2.655 X 1000 = 1282.365 kg/ m^3

Say weight of C.A. = 1284 kg/ m^3

Considering, 20 mm: 10mm = 0.55: 0.45
20mm = 706 kg.
10mm = 578 kg.
Hence Mix details per m^3
Increasing cement, water, admixture by 2.5% for this trial

Cement = 412 X 1.025 = 422 kg
Water = 144 X 1.025 = 147.6 kg
Fine aggregate = 621 kg
Coarse aggregate 20 mm = 706 kg
Coarse aggregate 10 mm = 578 kg
Admixture = 1.2 % by weight of cement = 5.064 kg.

Water: cement: F.A.: C.A. = 0.35: 1: 1.472: 3.043

Observations from Concrete Mix Design: –

A. Mix was cohesive and homogeneous.
B. Slump = 120 mm
C. No. of cube casted = 9 Nos.
7 days average compressive strength = 52.07 MPa.
28 days average compressive strength = 62.52 MPa which is greater than 58.25MPa
Hence the mix accepted.

Percentage strength of concrete at various ages:

The strength of concrete increases with age. Table shows the strength of concrete different ages in comparison with the strength at 28 days.

Age	Strength per cent
1 day	16%
3 days	40%
7 days	65%
14 days	90%
28 days	99%