
Materials Concrete and Prestressed Concrete Structures

1.1. Aggregates and Sand in Concrete

Broken stone material, gravel and sand are called *aggregates* for production of concrete. Unless otherwise specified in this book, aggregate refers to that from stone and used in concrete constructions. *Fine aggregate* is the basic stone material having a particle size less than 5 mm, and 90 to 100 per cent of which pass through 4.75 mm sieve. Natural sand and finely crushed stone are treated as fine aggregate. *Coarse aggregate* is the stone material most of which is retained on 4.75 mm sieve. Gravel or crushed stone are the usual coarse aggregate. There are other types of aggregates, like *broken brick-aggregate*, *cinder-aggregate*, *light-weight*, *slag and heavy-weight aggregate*, etc. that are used in special concrete constructions. Coarse and fine aggregates together are used in concrete whereas only fine aggregate with either cement or lime is used in mortar for plastering and jointing. Particles larger than 4.75 mm are grouped into coarse aggregate, particles between 4.75 mm and 60 microns (μm = micro millimeter) are considered to be fine aggregate, natural particles smaller than 60 microns and are larger than 2 microns are grouped under *silt* and still smaller particle material is called *clay*.

Fine aggregate should originate from rocky material. The fine aggregate is further classified into four sub-groups, as per the Indian Standards. Grade I is the coarsest and grade IV is the finest of the fine aggregate. For grade one, about 90 to 100 per cent of the material must pass through 4.75 mm sieve and about 60 to 80 per cent must pass through the next lower standard sieve, namely 2.36 mm. The first three graded zones are usually acceptable for reinforced or prestressed concrete construction. However, the grade four is too fine and not recommended for concrete construction. It can be used in plastering.

All-in-aggregate: Aggregate containing both coarse and fine aggregates is called all-in-aggregate.

Shape of aggregate: Aggregate shape can be either round, angular or a combination of the both. But it should not be flaky or oblong. It should not contain deleterious materials such as clay lumps, coal particles, soft material and too fine material that pass through 75 micron sieve. The maximum limit of combined deleterious materials in an aggregate is five per cent. *Size of a coarse aggregate* is specified by a sieve size. A 40 mm aggregate normally means that 100 per cent of the aggregate should pass through 63 mm IS sieve (that is next higher of 40 mm IS sieve), and 85 to 100 per cent pass through 40 mm IS sieve. And about 0 to 30 per cent may pass through the next lower size, i.e. 20 mm sieve. Commonly used size terminology of the aggregate is: Very large aggregate 80 mm to 150 mm large aggregate is 40 mm to 80 mm, medium size aggregate is 20 mm to 40 mm, and small size coarse aggregate is 4.75 mm to 20 mm. The Indian Standard (IS) sieves are designated by 63, 40, 20, 16, 12.5, 10, 4.75, 2.38, 1.18, (all in mm), 600, 300, 150, and 75 microns. The size of the sieve is specified by the nominal size of the aperture either in millimeters (mm) or in micrometers (microns).

The important characteristics that one has to look for in aggregate are:

1. **Shape, size and surface texture**, 2. **Specific gravity**, 3. **Void ratio**, 4. **Bulk density**, 5. **Moisture content**, 6. **Porosity and** absorption value, 7. **Aggregate crushing strength**, 8. **Abrasion value**, 9. **Flakiness index**, 10. **Elongation index**, 11. Presence of **deleterious materials**, 12. **Soundness**, 13. **Alkali Aggregate reaction**, and 14. **Fineness Modulus**.

Shape, size and surface texture of aggregate is either acquired from natural erosion or through crushing process. The roundness is indicated by the degree of wear of the faces of the particles. The compactness or compatibility of the aggregate depends on the shape of the aggregate. The angularity number of the spherical aggregate is zero, which means that the percentage of the solid volume of rounded aggregate is 67. The angularity number indicates the percentage of voids in excess of the rounded aggregate. The tensile strength of the mortar or concrete depends on the shape and texture of the aggregate.

Fineness Modulus (FM): All particles in an aggregate are not exactly of the same size. The aggregate consists of particles of different sizes in a range. The aggregate is specified by the distribution of the particles and it is analyzed by sieving through a set of standard sieves. The *fineness modulus* is defined as the sum of the cumulative percentages of aggregate retained on a set of standard sieves numbered 63, 40, 20, 10, 4.75, 2.36, 1.18 mm, and 600, 300, and 150 micron.

Table 1.1.1 indicates the range of fineness moduli of the aggregate. Smaller the fineness modulus means finer aggregate. The range of *FM* of fine aggregate is 1.0 to 3.5. The fineness modulus of 1.0 indicates the finest sand that can be used for plastering and not for mortar or for concrete. The fineness modulus of coarse aggregate is in the range of 5 to 7.5. Fineness modulus of aggregate is an important parameter in the design of the concrete mix.

TABLE 1.1.1 Ranges of fineness modulus of aggregates

Fine Aggregate		Coarse aggregate			Mixed aggregate		
Very fine	Fine	20	25	40	20	25	40
1.0-2.0	2.0-3.5	5.8-6.4	6.0-7.0	6.5-7.5	4.7-5.2	5.0-5.6	5.3-6.0

Specific gravity of a material is the ratio of its weight to the weight of the equivalent volume of distilled water. Stone may contain pores or capillary voids. The absolute specific gravity is the one that excludes the pores in the solid mass. *Absolute specific gravity* is the ratio of the mass (weight) of the solid in vacuum to the mass of distilled water. The absolute specific gravity is of academic interest only. *Apparent specific gravity* of the material is the ratio of the oven dried mass at 100 to 110 degrees Celsius for 24 hours to the weight of the equal volume distilled water. The volume referred here includes the pores in the aggregate. The apparent specific gravity is the most commonly used term or quantity in the engineering design. The specific gravity of a material in any form either in large or small aggregate is same as that of the base stone from which it is derived from. It varies from 2.6 to 2.85 for most stone based aggregate. Specific weight is the product of the specific gravity and the unit weight of water.

The *bulk density* of aggregate is the weight of unit bulk volume of material. The bulk density is measure in two ways, one loose bulk density and the other compact bulk density. Aggregate is pored in a standard container and levelled to the top in a specified manner. The ratio of weight of the loose aggregate measured from the container to the volume of the container is called as *loose bulk density*. In case of compact bulk density, the container is filled in three layers, and each layer is compacted by tamping with a 16 mm standard rod to a specified number of times. The ratio of the weight of the compacted aggregate to the volume of the container is called *compact bulk density*. The compact bulk density is commonly referred as the bulk density. The bulk density depends on the void ratio and it varies from 0.54 to 0.65 times the specific weight of the material. The range of bulk density is 1500 kg/cum to 1900 kg/cum. High-density aggregate may have a bulk density in the range of 1800 kg/cum to 2100 kg/cum.

Bulk aggregate contains solid particles and void spaces in between the particles. *Void ratio* is the ratio of the volume of the voids to that of the solid particles. The void ratio is determined by the following expression:

$$\text{Void ratio} = 1 - \text{bulk density/specific weight} \quad (1.1.1)$$

Void ratio in most single-size aggregate is around 0.42 to 0.46 and in graded aggregates it is around 0.38 to 0.44. Less is the void ratio better is the grading of the aggregate. The void ratio can be determined from the amount of water that is needed to fill the voids of a measured volume of the dry aggregate.

Porosity, Moisture content and absorption value: Aggregate contains pores some visible on the surface and others inside but not visible. If the pores are too small or the capillaries are very fine, the viscosity of water may delay the absorption of the water. *Saturated aggregate* is the one in which the pores are fully saturated with water. The saturation must be free from the surface wetness. In other words the percentage of saturation is measured in surface dry condition.

The saturated aggregate that is allowed to surface dry in room temperature is called *air dry aggregate*. Aggregate dried in oven for a prolonged period is called *oven dry* or *bone-dry aggregate*. Aggregate when exposed to rain and atmosphere collects moisture on its surface and absorbs certain portion of it through the pores in the particles. The total water content in the aggregate is divided into two parts. Moisture content increases the bulk volume of fine aggregate whereas the absorbed water content does not change the volume of the aggregate. The increase in volume of the sand due to surface moisture film pushing the particles apart is called *bulking of sand*. The volume of sand increases with increase in the moisture content upto a certain limit, but further increase in the moisture content reduces the bulk volume of the sand. The maximum bulking of the sand depends on the type of sand and it is about 30 per cent with normal occurrence around 8 per cent of the moisture content. The ratio of the volume of moist sand and that of dry sand is called *bulking factor*. The bulking factor varies from 1.0 to 1.35 depending on the moisture content and the type of sand.

Strength of aggregate: The strength of an aggregate depends on the nature of the basic rock from which it is derived, size distribution, shape and texture of the aggregate and the impurities present. Aggregate *crushing value* and *aggregate impact value* are the usual indices used to specify the strength quality of an aggregate. The aggregate crushing value is determined by a simple test. As per the Indian standards, a dry sample of aggregate passing through 12.5 mm sieve and retained on 10 mm sieve is subjected to compression test in a specified manner under 400 kN load. The crushed material that passes through 2.36 mm sieve is measured and the percentage of that material with respect to the original sample weight is called the *aggregate crushing value*. It would have been better to measure the strength by the percentage of the particles retained rather than passing through the 2.36 mm sieve. A crushing value more than 40 reflects a weak aggregate. Crushing value less than 30 mean a strong aggregate. The following maximum limits of crushing value are recommended:

For lean and plain concrete: 45,
for Plain concrete in dams and hydraulic structures: 40,
for reinforced concrete in buildings: 40,
for concrete roads and high strength concrete or High Performance Concrete: 30.

The toughness of the aggregate is measured by the impact test. An impact value of upto 30 indicates good quality aggregate; however, a value upto 45 is acceptable for plain concrete. Aggregate crushing value or impact value for concrete should not be more than 45 for ordinary concrete works, and for wearing surfaces such as roadways and runways it should not be more than 30.

The strength of aggregate is also determined by Los Angeles test. A specified sample of aggregate is loaded into a rotating drum machine in which steel balls are also loaded. The mixture is subjected to a specified number of revolutions and the percentage loss of the weight of the aggregate indicates the weakness or the strength of the aggregate. The Los Angeles test has some good characteristics that indicate the strength of the aggregate under wear and tear conditions. But this and impact tests make more noise compared to the compression test. A minimum of 80 MPa as core crushing strength of rock is normally acceptable for good concrete aggregate. This test is of academic interest. In general either aggregate crushing or impact or Los Angeles tests are preferred.

Abrasion value of aggregate: Concrete roads and runways are subjected to constant wear. In addition to good compressive strength, the aggregate must have good wear resistance. There are special abrasion apparatus such as Los Angeles; Deval machines designed to test the wear of an aggregate. The percentage of material lost in wear in the abrasion test that is performed on a sample of aggregate in a specified manner is considered as the abrasion value of the aggregate. More material lost, more is the abrasion value, and therefore the wear resistance of the aggregate is inversely proportional to the abrasion value.

Flakiness Index: Thin and flaky pieces aggregate may result if the rock is not crushed properly in the aggregate crusher or if the basic rock has thin layers. Sieving the aggregate through a set of sieves having oblong openings indicates the order of magnitude of the flakiness of an aggregate. *Flakiness index* is the total weight of aggregate passing through a set of special sieves designed exclusively to measure the property, expressed as a percentage of the total weight of the sample. Flaky aggregates shouldn't be used for reinforced or strong concrete.

Elongation Index: Oblong aggregate may result because of poor aggregate crushing mechanism or in sieve separation. Concrete produced with oblong aggregate results in poor strength of concrete. The oblong character of the aggregate is indicated by an index called elongation index. The nomenclature of the *elongation index* is not appropriate term to indicate the oblong property. However it is measured by sieving a sample of the aggregate through a set of sieves having oblong openings, specially designed to test the property. It is the total weight of the material retained on various length gauges, expressed as percentage of the sample.

Bond of aggregate: The cement is the bonding agent in concrete, and the shape, size, grading and texture of the aggregate influence the level of bond. The interlocking of the aggregate is an important property that will result in better bonding and better strength of concrete. Interlocking of the aggregate is inversely proportional to the flakiness index or the elongation index. As already mentioned earlier, the bond of the aggregate is directly proportional to the regular angularity and rough texture of the aggregate.

Soundness of an aggregate: Some aggregates disintegrate into smaller particles when exposed to weather and changing temperature even without load. Soundness is the property of the aggregate to withstand the weathering conditions. It depends on the chemical and physical properties of the aggregate. The soundness of an aggregate is measured by subjecting it to alternate wetting in saturated solution of sodium or magnesium sulphate and drying it in an oven through a set of cycles. The reduction in the particle size of the aggregate, which is obtained through a sieve analysis of the tested sample, indicates the soundness or unsoundness of the aggregate. The percentage absorption of moisture is a good indicator of soundness of the aggregate. Unsoundness is partly indicated by higher absorption of moisture. The soundness is more or less inversely proportional to the absorption.

Aggregate and alkali reaction: Sodium and potassium oxides are called as alkalis (Na_2O and K_2O). Small amounts of alkalis are normally present in cement. The alkalis in cement or in other materials of the concrete react with silica of the aggregate in the presence of moisture resulting into a gel. *The silica alkali gel* formation in the pores or in the planes of weakness aggregate increases the volume thus resulting in cracking of concrete. The gel also destroys the bond between the aggregate and the cement paste. The gel formation is a slow phenomenon

and takes years before it is manifested through cracking. The rate of gel formation increases with increase in temperature and moisture content. It is also proportional to the porosity of the aggregate. The absence of moisture or high humidity avoids the gel formation thus the alkali reaction. Hydraulic structures must be designed with sound aggregate and low alkali cements to avoid the alkali reaction. Alkali aggregate reaction is measured by mechanical and chemical tests. Mortar bar with pre-assigned alkali content, which is stored over water at about 380 C and then tested for expansion in time.

1.2. Portland Cement

The calcareous material such as limestone or chalk and argillaceous material such as clay or shale containing silica are mixed thoroughly and burnt at a clinkering temperature of about 13500 C to 15000 C. The clinker is then powdered with small amount of gypsum (about 3.5 per cent of clinker). The two basic methods of manufacturing of Portland cement are Dry process and Wet process. The principles of the methods of manufacturing are mentioned here. Figure 1.1 illustrates the basic principle and components in the manufacture of cement. Water is the medium by which the cement develops combining mechanism, therefore these cement are also referred as *hydraulic cements*.

Dry process: The granules also called pellets are baked by hot air and fed into a rotating kiln where the material undergoes chemical changes at temperature in the range of 13500 C to 15000 C. The clinker formed in the kiln is cooled and ground with gypsum in ball mills. The powder ground to a satisfactory level (about 1012 particles per Newton) is separated as cement.

Wet process: The slurry is fed into a rotary kiln from one end and pulverized coal is fed from the other end of the kiln and burnt. The slurry as it moves down in the kiln gets burnt and finally forms into clinker. The clinker is then let through cooling chambers and afterwards pulverized in ball mills along with gypsum. The powder ground to a satisfactory level is separated as cement.

The manufacture of cement is energy intensive; the wet process consumes more energy when compared to the dry process. More than fifty per cent of the expenditure is in the energy input. Further one kilogram of cement production results in producing one kilogram of carbon dioxide as pollution into the air. The dust pollution from cement industry is controlled to a great extent. The cement is packed in 50-kilogram bags and marketed in most countries. In advanced countries, cement is also packed in drums or even transported in bulk. India is yet to pick up bulk packaging and transportation

1.3. Principal Compounds of Portland Cement

The burning up of calcareous and argillaceous material at high temperature results into a clinker of chemical compounds made up of calcium oxide, silicate, aluminate and aluminoferrite. The main chemical compounds in the cement are Tricalcium silicate, Dicalcium silicate, and Tricalcium aluminate and Tetracalcium aluminoferrite. First tricalcium aluminate and Tetracalcium aluminoferrite are formed in the kiln, and then dicalcium silicate is formed, and after its saturation, tricalcium silicate is formed. Tricalcium silicate is mostly responsible in giving early strength of cement whereas the dicalcium silicate contributes to the strength at later stage. The tricalcium

aluminate contributes towards the strength developed in the first 48 hours. The principal chemical compounds and the range of percentage of the quantity of them in ordinary Portland Cement are listed in Table 1.3.1.

The basic chemical compounds in Portland cement are CaO , SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , K_2O , and Na_2O . And they are combined to form the principal compound listed in Table 1.3.1.

TABLE 1.3.1 Chemical compounds in Portland Cement

No.	Compound	Composition	Notation	%Range
1	Tricalcium Silicate	$3\text{CaO} \cdot \text{SiO}_2$	C3S	45–58
2	Dicalcium Silicate	$2\text{CaO} \cdot \text{SiO}_2$	C2S	15–32
3	Tricalcium Aluminate	$2\text{CaO} \cdot \text{Al}_2\text{O}_3$	C3A	6–13
4	Tetra Calcium Aluminoferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C4AF	6–12
5	Minor Compounds	MgO , K_2O , Na_2O		3–6

1.4. Physical Properties of Portland Cement

Some of the Cement chemical requirements of ordinary, rapid hardening and Portland pozzolana cements are given in table 1.4.1. The important physical properties that are of interest to construction and quality control engineers are briefly described in this section. The minimum requirements that are needed for different types of cements are listed by the codes of practice. The specifications listed by the Indian standard on cement are given in a table 1.4.1 The properties are:

- ❖ Fineness of cement, Normal consistency of cement, Initial setting time of cement, Final setting time of cement, Strength of cement, Soundness of cement, Heat of Hydration of cement.

TABLE 1.4.1 Chemical composition requirements in OPC, Rapid hardening and Pozzolana cement

No.	Substance	Percentage limits
1	Ratio of Lime to Silica, Alumina & Iron Oxide	$0.66 < p < 1.02$
2	Ratio of Alumina to that of Iron Oxide	Not less than 0.66%
3	Insoluble residue	Not more than 2%
4	Magnesia	Not more than 6%
5	Total sulphur content, sulphuric anhydride (SO_3)	Not more than 2.75%
6	Total loss on ignition	Not more than 5%

Fineness of cement: The cement is ground to such fineness, it is almost impossible to grind it to a single size particle. There are experiments that compute the surface area of unit weight of a powder. The chemical compound formation starts on the surface of the cement particles. Similarly the heat of hydration developed by the chemical reaction of cement with water depends on the surface area. The technology of grinding the cement powder is improving every day. The residue weight of the cement after sieving through 90-micron sieve also indicates the approximate size distribution of cement. The percentage residue on 90-micron sieve should not exceed 10 per cent for ordinary Portland cement. American specification list 45-micron

sieve instead of 90-micron sieve. The surface area of cement in square metres per one kilogram of cement is called *specific surface* of cement. The surface area should be in the range of 300 square metres per kilogram of cement. The minimum surface area that is required for ordinary Portland cement is 225 m² per kg of cement; however this is on the lower side. The present day cements have a specific surface more than 300 square meters per kilogram of the cement.

The particle size of powder can be determined by measuring the free fall of the particles in an inert medium using the principle of fluid mechanics of free falling bodies. The concentration of turbidity of the cement powder in kerosene can be measured by passing light through the solution and the amount of light passed through gives an indication of the number of particles in the solution. *Wagner turbidimeter* is the common instrument that is used in the determination of the specific surface of cement. This method not only indicates the size but also the type of shape of the particles. *Air permeability* test is another commonly used test for the determination of specific surface. Air is allowed pass through a bed of the particle at constant velocity under constant pressure. A manometer measures the pressure drop of the air that passes through a bed of the powder. The surface area is then computed using the specific gravity of cement, porosity of the bed, velocity of flow, and the pressure drop through the bed. There is another method called *Blaine air permeability* test that uses slightly different principle of the permeability. A known volume of air is allowed pass through at an average pressure through a bed of known porosity. The time taken for the air to pass through is measured from which the specific surface is computed. Specific surface of very fine powder such as fine flyash and silica fume cannot be determined by the permeability method. The gas absorption techniques are used in the determination of the specific surface of very fine powders. The silica fume is about ten to fifty times finer than the cement. There could be a variation in the result of specific surface measured by different methods. The codes of practice will indicate the method and the minimum specific surface requirement.

Normal (standard) Consistency of Cement

Cement reacts with moisture and forms complex compounds. This chemical reaction is termed as hydration and heat that is generated during the reaction of cement with water is called *heat of hydration*. The rate of hydration, the chemical kinetics and the physical behavior of the cement paste depend on the amount of water added to the cement. The percentage of water required to produce a reasonable workable cement paste under prescribed testing is called *the normal consistency or standard consistency* of cement. An instrument called Vicat apparatus is used in the determination of standard consistency. A standard plunger of 10 mm diameter is allowed to penetrate partly through a cement paste. The percentage of water that allows the plunger to penetrate a specified distance through a cement-water paste is taken as the *standard consistency* of the cement. The test is conducted under specified humidity and temperature conditions in a specified duration of time after mixing the cement and water. The range of acceptable normal consistency of Portland cement is 26 to 33 per cent of the mass of the cement.

Initial setting time of Cement: Cement paste changes from semi-fluid state to stiffened state, then to hard state and finally solid mass state. The process of transforming the cement paste from semi-fluid state to stiffened or hard state is called setting of cement. The transformation of states is measured through a prescribed test procedure using Vicat apparatus. The time

needed for the standard consistency cement paste to become stiffened in permitting 1.13 mm needle under specified weight, to penetrate through a specified distance in a standard mould is called initial setting of cement. The time that is required for the initial setting is called *initial setting time*. The cement mortar or concrete should give reasonable time for mixing, transporting, placing and finishing of the product. Concrete or mortar must be workable without developing bonding for about 30 minutes after the water is added to the Portland cement. The minimum initial setting time for most Portland cement is 30 minutes. The initial setting time is delayed by addition of some compounds in case the placement of cement takes more than 30 minutes.

False Setting: The premature stiffening or hardening of the cement paste is called false set. The false set of cement takes place much before the initial setting. In normal setting, heat of hydration takes place and no such heat is generated in the false set. The process of hardening of cement paste caused by the reaction of pure calcium aluminate may be the reason for false set. Or it may be due to the non-uniform distribution of gypsum in the cement. Gypsum is the material that delays fast setting of the cement. False set doesn't generate good bonding mechanism and hence the concrete can be re-mixed and finished in position. False set is avoided by addition of gypsum to the cement.

Final setting time: The time taken for initiation of hardening of cement paste from the time it is mixed with water is called final setting time. A standard procedure by Vicat apparatus measures the so-called initiation of hardening of the cement paste. The paste should become hard enough to withstand light pressure. A circular cutting edge needle fitted to the Vicat apparatus is gently lowered on to the surface of the stiffened mortar. The time that is taken to ensure that no indentation is made on the mortar specimen is called the final setting time. The concrete can resist minor disturbances or small pressures immediately after the final setting. However, it should not be disturbed till reasonable curing takes place. The chemical reactions between cement and water are very fast in the initial stages, considerable heat of hydration is generated during the first few hours of mixing of cement with water. As the reactions continue, the cement paste becomes harder and harder and the process may continue for a long period. The water that is added to the cement absorbs the heat of hydration in the initial stages may be upto twelve to twenty four hours depending on the water cement ratio. There after water has to be sprayed over the surface of the concrete to absorb the heat of hydration. The concrete or mortar can resist the loads only after it is cured as specified by the engineer. The final setting time of most Portland cements is about 10 hours.

Initial setting of cement indicates the beginning of noticeable stiffening of the cement paste and the final set indicates the beginning of the hardening of the paste. The normal consistency, initial and final setting times are determined by Vicat needle or by Gillmore needle tests. The limits of initial and final setting times are indicated in Table 1.4.2.

Strength of Cement

Strength of cement is determined by compression test on hardened cement-sand mortar specimen. Cement mortar cube specimens are made in the ratio of 1 : 3 cement and standard sand, and are cast in cubes of 50 cm² face. The specimens are cured in water for 28 days and tested under controlled conditions. The amount of water used in making the mortar is selected from the normal consistency of cement. The amount of water selected is equal to $(0.25p + 3)$ percent of

the combined weight of cement and sand, in which p is the percentage of the normal consistency of cement. Three cement mortar cubes are tested after one day, three days, seven days and 28 days of curing. The average strength of three cubes tested at a time is taken as a basis for acceptability criteria. The codes of practice specify the minimum average strength of required after one day, three days, seven days and twenty-eight days. The ordinary Portland cements of grade 33, 43 and 53 must give a minimum average strength of 33, 43, and 53 N/mm² respectively after 28 days of curing. The curing of the specimens is done in water at 200 C. Standard sand is siliceous, round and natural sand. The sand particles are graded between 80-micron to 1.6 mm. In India, sand available at Ennore in Tamil Nadu is considered to be the standard sand. The absolute minimum strength of mortar cubes of any type of cement must give 33 N/mm².

TABLE 1.4.2 Physical properties required of different cements

No.	Type of test	Ordinary grade 33	Rapid Hardening	Low Heat	Pozzolana
1	<i>Fineness of cement</i>				
	(a) Residue by weight shouldn't exceed (per cent) after sieving the cement through 90-micron IS sieve,	10	5	–	5
	Or	225	325	320	300
	(b) Specific surface (m ² /kg) by air permeability test method shouldn't be less than				
2	<i>Setting times</i>				
	Initial setting time shouldn't be less than	30	30	60	30
	Final setting time shouldn't be more than	600	600	600	600
3	<i>Minimum average compressive strength of standard mortar cube</i>				
	(a) 24 ± 0.5 hours	–	16	–	–
	(b) 72 ± 1 hours	–	27.5	10	–
		16	33	16	22
	(c) 7 days ± 2 hours	22		35	33
	(d) 28 days ± 4 hours	33			
	(14 days ± 4 hours for pozzolana)				
4	<i>Soundness (maximum)</i>				
	(a) Expansion (in mm) unaerated cement by Le Chatlier method	10	10	10	10
	(b) Expansion (in mm) of aerated sample by being spread out to a depth of 75 mm at relative humidity of 50 to 80% for seven days	5	5	5	5
	(c) Expansion unaerated cement by autoclave test (in per cent)	0.8	0.8	0.8	0.8
5	<i>Heat of Hydration in calories per gram</i>				
	(a) After 7 days			65	
	(b) After 28 days			75	

* Cement grades 43 & 53 are to give minimum average strength of 43 MPa & 53 MPa respectively on the 28 days curing. The 7 days strength is about 67 per cent of 28 day strength.

Soundness of Cement

The word soundness here refers to the tendency of expansion of hardened cement mortar with time. Most of the chemical reactions must take place during the 28 days of curing of the cement or concrete. The micro-cracking of concrete leads to deterioration and failure of concrete. That is why, expansion of cement paste beyond a point is said to be unsound. Le Chatelier apparatus tests the expansion of cement caused by the free lime. The assembly as a whole along with the cement paste is placed at 2000 C and at 98% relative humidity for a prescribed period. The assembly is placed in water and the water is raised to boiling point in thirty minutes. The increase in the opening of the pointers is measured to determine the soundness of the cement. The admissible expansion of the pointers is specified by the codes of practice. A 25.4 mm side square bar of 254 mm length (one inch by 10 inches bar) is cured for 24 hours in humid air. The cured bar is placed in autoclave, the temperature of the water is raised to 2160 C at a pressure of 2 MPa, in 60 minutes and maintained for three hours. The expansion of the bar after cooling back to room temperature should be less than 0.8 mm.

The rise of temperature in the Le Chatelier or the autoclave test accelerates the hydration process and simulates the long term effects. Fine grinding of cement maximizes the free lime mixing with the other compounds and resulting in earlier hydration thus minimizing the unsoundness of the cement.

Heat of Hydration

The basic silicates and aluminates of cement combine with water resulting into insoluble solid compounds. Calcium silicate and tricalcium aluminate hydrates are the main resulting compounds. Calcium hydroxide is one of the other products in the hydration process. The heat developed during the chemical changes is called the heat of hydration.

The reaction of calcium aluminate is almost instantaneous and it may lead to false setting of the cement. The gypsum reacts with aluminate resulting calcium sulfoaluminate. Similarly the gypsum reacts with calcium aluminoferrite resulting calcium sulfoferrite. Most of the exothermic reaction of the cement with water takes place in about two hours. The cement paste becomes stiff during the hydration and then hardens into a solid mass. The calcium hydroxide that is generated from the hydrolysis of the calcium silicates provides an alkaline environment to the concrete.

Specific gravity of ordinary Portland cement varies from 3.12 to 3.16, and for all practical purposes, it is taken as 3.15. The percentage of voids in cement is around 40 and bulk density is about 18 to 20 kN/m³. Usually cement is supplied in bags of 50 kg.

1.5. Types of Portland Cements

Portland cement is produced in different grades and in different types in different countries. The classification of Portland cements varies with the country. The Indian code of practice classifies the Portland cement into the following classes.

Ordinary Portland Cement (grades 33, 43 and 53), **Rapid Hardening Portland Cement**, Portland Slag Cement, Portland **Pozzolana** Cement (flyash based), Portland Pozzolana Cement (**Calcined** clay based), **Low Heat** Portland Cement, **Sulphate** Resisting Portland Cement, **Hydrophobic** Cement.

There are other types of cements available in the global market and also in the Indian Market. The number is rather too large, only very commonly used types are mentioned here:

- ❖ Portland Blastfurnace Cement,
- ❖ White Cement,
- ❖ Very Rapid hardening Cement,
- ❖ Supersulphated Cement.

A brief description of some of the commonly used cements is given.

Ordinary Portland Cement (OPC) Grades 33, 43 and 53.

Ordinary Portland cement is known as just cement or simply ordinary cement for laymen. OPC is the most commonly used cement in building construction. A grade notation refers the strength of the cement. Cement whose standard sand mortar cube made with normal consistency water level should give a minimum strength of 33 N/mm^2 at 28 days of curing is assigned **grade 33**. Similarly **grades 43 and 53** are expected to give a minimum strength of cement mortar at 43 MPa and 53 MPa respectively. The strength refers to an average strength of three mortar cubes of face area 50 cm^2 . The strength of cement on 7 days curing is about two-thirds of that at 28 days strength. The cubes are made in a specific manner and tested on 28 days of curing in water. The expected strength after 2 days curing of grade 33 and 43 cement mortar cubes are 10 MPa (mega Pascal = one million Newton per square metre) and 20 MPa respectively. At the moment, the most commonly used grades of cement are 43 and 53 primarily because of marketing strategies of the cement companies. Cement **grade 63** is also available in the global market. The fineness of the cement increases with the increase in the grade of the cement and so the rate of heat of hydration increases with the increase of the grade of the cement. Some countries specify the maximum strength of the cement at 28 days to avoid abuse of high strength cements.

Rapid Hardening Cement

Special cement called rapid hardening cement also called as early strength cement is produced to meet the demand of quick setting. The strength developed by rapid hardening cements in about 3 days (72 hours) is equal to that of the ordinary cement developed in 28 days. The factors that influence the early strength are chemical composition, degree of chemical combination of the raw materials, blending, grinding and burning of the raw materials and the fineness of cement. The initial setting time of the rapid hardening cement is still about 30 minutes. The specific surface of the cement is in the **range of 450 to 600 square metres per kilogram** of cement. The rapid hardening cement is used when formwork is to be removed at an early age or the construction is under water. The rate of heat development in this cement is also higher when compared with the ordinary cement. Very rapid hardening cement or ultra early strength cements are also produced with specific surface more than **700 square metres per kilogram**. The percentage of tricalcium silicate in such cements is also high in the range of 60 per cent.

Portland Pozzolana Cement (PPC)

Pozzolana is a material that contains active silica that reacts with lime in the presence of moisture, producing calcium silicate. Pozzolana by itself is not an active binding material, but

in the presence of calcium oxide and moisture, develops the binding character. Flyash, rice husk that are fine and rich in silica are the common pozzolanas. Amorphous porous material like rice husk and silica fume have very high specific surfaces as high as ten times or even more than that of cement. There are natural pozzolanas such as diatomaceous earth. Cement produced by grinding Portland cement clinker and pozzolana with addition of gypsum is called Portland Pozzolana cement. A uniform blending of the Portland cement with fine pozzolana can also obtain it. The percentage of pozzolana in such cements varies from 10 to 30 (to 50) percent. There is also some cement with much higher percentage of pozzolanic material. Portland pozzolana cement produces less heat of hydration and offers greater resistance to the attack of aggressive waters. The initial setting time of the cement is same as the ordinary cement. It develops the strength at a slower rate when compared to the ordinary Portland cement with extended period of moist curing. However, the 28 days strength of PPC should be same as that of the OPC. At the moment it is reported that the consumption of Portland pozzolana cement in the world is higher than the ordinary Portland cement. India is yet to catch up with the world in the use of the pozzolana cement. It is particularly useful in marine and hydraulic structures and also for mass concrete construction.

Portland (Blast furnace) Slag Cement

Hot slag from blast furnace is granulated with cold water and then mixed with Portland cement clinker in different proportions. The grinding of the mixture with gypsum will result in Portland Slag cement. Blending of OPC with ground granulated slag can also produce it. The mixture along with some gypsum is ground to the same fineness as that of Portland cement. This cement yields about the same strength as that of the ordinary Portland cement and can be used in place of ordinary cement. Slag is considered to be a waste (better call it a byproduct) product in the production of pig iron. It is a mixture of silica, alumina and lime. The percentage of lime, silica and alumina in the slag are about 45, 35 and 10 respectively. However the chemical and physical quality of the slag differs with the process and the rate of cooling. About 300 kg of slag is produced for one tonne of pig iron. As the slag contains lime and silica, the ground-granulated slag (*ggbfs*) can also be used as a cementitious product to a limited extent. The percentage of slag in the slag cement may vary from 35 per cent to 95 per cent. The heat of hydration in the slag cement is less than that of the Ordinary Portland cement as the tricalcium and dicalcium content is less. This may be considered as low heat cement. The slag cements are further classified into two to three groups depending on the percentage of the slag. The seven days strength can be as low as forty per cent of that at 28 days but this shouldn't discourage use of this cement for masonry and similar constructions.

Low Heat Cement

Low heat cement is the one that produces lower heat of hydration when compared to the ordinary Portland cement. The percentage contents of tricalcium and dicalcium silicates are less in the low heat cement. Such cements may also contain pozzolana or ground granulated slag to control the heat of hydration. These cements are useful in mass concreting in which it is difficult to cure the interiors of the concrete. The net calcium oxide content is also less in such cements.

High Alumina Cement

Bauxite and lime stone are ground in appropriate proportions together and the mixture is subjected to high temperature to form into clinker. The kiln used in the Portland cement is not used in this process. Bauxite is the ore for aluminum. The main compounds are calcium aluminate, hydrates and hydrated colloidal alumina. The silica content is small and it may be in the range of 5 to 10 per cent. Bauxite is relatively more expensive when compared with the clay so the cement is more expensive. The alumina hydrates very fast and attains strength at an early stage. About eighty per cent of the strength is developed in the very first one day of curing. The 72 hours curing of the cement mortar will give about the same as that of Portland cement at 28 days curing. Most of the heat of hydration takes place in about first 24 hours, results in high heat of hydration. This cement can be used for underwater construction. Its use in mass concrete and concreting in dry weather is not desirable as it is difficult to control heat of hydration in mass concreting. The cement also resists sulphate and even acidic attacks. It also has refractory characteristics and withstands high temperatures.

White Cement

White cement is made out of chalk or limestone free from impurities and having very little of oxides of iron as raw material. Oil or gas is used as a fuel in place of coal ash in the kiln to produce the clinker. The clinkering temperature is taken to about 16500 C. Grinding of the clinker is done in special mill so as to avoid contamination by iron oxide. The specific gravity of white cement is slightly less than that of the *OPC*. White cement is used for architectural purposes, in mosaic floors, in fixing glazed tiles, etc. The colour of the white cement may fade away with time so some colour pigments are often mixed to give a more stable colour.

Expansive (or Expanding) Cement

Expansive agents such as gypsum, bauxite, calcite, etc. are burnt to form clinker. The clinker is then ground with Portland cement clinker to form cement. The tendency of shrinking of cement during drying is reduced in expansive cements. In the presence of water, calcium aluminate and calcium react to form calcium sulpho-aluminate hydrate resulting in expansion of the paste. A stabilizing agent such as Blastfurnace slag reacts with excess calcium sulphate and stabilizes the expansion. This cement usually contains 5 to 14 per cent of expansive agent, 10 per cent of stabilizer and the rest being Portland cement clinker.

Natural Cement

Cement rock containing clayey limestone upto 25 per cent is calcified and grounded to obtain natural cement. It is easier to manufacture natural cement and but it is somewhat inferior to Portland cement.

Masonry Cement

Masonry cement is obtained by inter grinding of mixture of Portland cement clinker with inert materials such as limestone, conglomerates, and dolomite, and gypsum and air entraining agent in suitable proportions. This has slow hardening and high workability and water retention properties. It is suitable for masonry construction.

Oil Well Cement

Hydraulic cement that is suitable for resisting high pressure and temperature in sealing water and gas pockets and setting castings during the drilling and repair of oil wells is called oil well cement. This cement contains reduced content of tricalcium aluminate and a retarding additive to suit the requirements.

Hydrophobic Cement

Ordinary Portland cement clinker when ground with an additive that will impart a water repelling property is called hydrophobic cement. The water repelling property is eliminated when the cement is mixed with water. This cement can be stored for long periods in wet and highly humid climates.

1.6. Pozzolanas and Admixtures

Admixtures are the materials that improve some properties of cement such as setting time, workability, colour, and impermeability and resistance aggressive agents when added to the cement. Some of the commonly used admixtures are:

Pozzolana, Flyash (powdered fuel ash), Rice husk ash, Silica fume, Metakoline, Ground granulated blast furnace slag,

Pozzolana

Pozzolana is a natural or artificial material containing large percentage of reactive silica. It is a fine powder of siliceous and aluminous material that reacts with calcium hydroxide in the presence of water to form cementing compounds. The silica in amorphous form reacts with calcium hydroxide to form cementing compound. The volcanic ash, Diatomaceous earth and burnt clay are the common natural pozzolanic material. Flyash and rice husk burnt at regulated temperature of about 6000 C are main artificial pozzolanic materials. One has to be selective in fly ash to ensure sound pozzolanic action. Coal is pulverized and fed into boilers for generation of thermal power. The ash is collected either mechanically or electrostatics in the chimneys. This ash is called flyash. The ash when pulverized is called pulverized fuel ash. The specific surface of the flyash suitable for Pozzolana can vary from 300 to 600 square metres per kilogram. The flyash also contains small amount of unburned coal particles. The coal particle size and quantity must be limited to a minimum value of not more than 3 per cent. The quality of flyash depends on the type of coal that is used in the burning. Flyash derived from Lignite is not considered to be very suitable unless it is processed. It is desirable to process the flyash before using it in the cement. In some sense, the flyash is not really an admixture since more than 30 percent of flyash can be added to the cement.

Burning kaolinitic clay at a temperature of about 7000 C and grinding it to a fine powder of specific surface in the range of 700 square metres obtains the Metakaolin. The Pozzolana is blended with cement either at the grinding stage or at powdered stage in desired proportions. The Pozzolana blended cement is called Pozzolana cement or Pozzolana blended cement. The percentage of Pozzolana in blended cements varies with the desired property. Following are some of the properties of pozzolanic cements when compared with ordinary Portland cements:

- (a) Total curing time required is likely to be more may be of the order of 20 per cent,
- (b) Heat of hydration developed is less than that of the ordinary Portland cement,
- (c) Gains strength slower than that of Portland in the first 15 days but by 28 days it is about the same,
- (d) Reacts less with salts and sulphates,
- (e) Reduced permeability because of the fine particles of the pozzolana,
- (f) Improved workability to some extent,
- (g) Reduce bleeding.

Silica Fume

Silica fume is an important pozzolanic material used in high performance concrete. It is obtained as a by-product in ferrosilicon alloy furnaces. It is also called as microsilica or condensed silica fume. It has very high active silica content and having a low bulk density of the order 200 to 300 kg/m³. The specific gravity of the silica fume is in the range of 2.2 and particle size in the range of atleast ten times finer than the cement particles. The specific surface can be in the order of 3000 to 10,000 square meters per kilogram. Because of its fineness and amorphous nature, it reacts well and fills up the fine voids in the cement paste. Silica fume is used in high performance concrete in strengths of 60 to 150 MPa. The finest particles reduce the permeability of the concrete. Silica fume is being much lighter than water and a fume rather than a powder, it is supplied in compressed pallets and packed well so as to not to get powdered in transportation. Silica fume pallets are fed while mixing with cement in the concrete mixer. Silica fume is mixed in about five to ten percent by weight of cement. It is not really an admixture as it is added as an essential ingredient to achieve very high strengths and low permeability. For lack of an alternate terminology, it is grouped under admixtures.

Admixtures are really additives to cement in small quantities to improve specific character of concrete or mortar. Most of them are artificial and the main purposes of admixtures are:

- (a) Improve **workability**,
- (b) **Accelerate** setting time,
- (c) **Reduce** setting time,
- (d) Aid in **curing**,
- (e) Decrease **permeability**,
- (f) Improve wear **resistance**,
- (g) Improve **durability**,
- (h) Reduce **shrinkage**,
- (i) Reduce **weight**,
- (j) Reduce **bleeding**,
- (k) Reduce heat of **hydration**.

The admixtures are usually finely ground powders having certain chemical or physical reactions with cement thus producing the desired action. Some admixtures may be obtained in liquid form. The admixtures are added to concrete at the time of actual mixing or sometimes they are premixed with cement just before use. The quantity of admixture is usually limited to one to three percent in most cases. Excessive use of admixture can have secondary effects that are not desirable.

Workability admixtures: Powdered hydrated lime, diatomaceous earth, bentonite and fly ash can be used as admixtures to improve workability. However, use beyond certain proportion and the strength of concrete will decrease, and shrinkage will increase. A number of patented artificial admixtures are available in the market and they are usually referred as plasticizers and super-plasticizers. Calcium chloride, stearate, some oily compounds which function as wetting or dispersing agents are used as workability admixtures. Air in the form of minute bubbles in the concrete also improves the workability. Foaming agent or a chemical that produces gas bubbles on reaction with cement is used as an air entrained agent. Natural resins, sulphonated soaps and oils are the common basic materials for this purpose. Aluminum and zinc powders, hydrogen peroxide are some of the elements used to produce gas in concrete to increase workability. Neutralized vinsol resin when added to cement disperses the cement particles and entraps air. Air entrained concrete is usually lighter and may be less strong when compared with ordinary concrete. Chloride in concrete accelerates corrosion of steel so it is not recommended for reinforced concrete construction. Ready mixed concrete is often pumped through pipeline to reach distances and heights. The slump of such concrete has to be more than 200 mm. Super-plasticizers are the most commonly used workability agent in pumped concrete.

Accelerators: Admixtures that accelerate the setting and hardening are called accelerators. Powdered calcium chloride is one of the commonly used accelerators. Calcium chloride of one to two per cent of cement content is likely to reduce the initial setting time by 10 to 15 minutes. Some soluble carbonates and silicates also help in reducing setting time. The heat of hydration is likely to be more in the first two days. Too much of accelerator can cause too early setting thus resulting in poor workability and consequently low ultimate strength. Chloride admixtures shouldn't be used in the reinforced concrete construction as the chlorine ion will cause corrosion of steel reinforcement. Some of the accelerators such as sodium silicate may result in poor strength and durability.

Retarders: Admixtures that prolong the setting and hardening of cement concrete are called retarders. Retarding agents are used when placement of concrete requires more time because of distance or transportation or other mechanical problems. Gypsum is one of the commonly used retarders. Indiscriminate use of retarders, can, however, affect the ultimate strength. Ready mixed concrete that has to be transported to long distances make use of retarders in combination with plasticizers.

1.7. Water Quality in Cement Concrete Construction

Water is one of the most important ingredients of concrete. Water that is used in mixing and curing of concrete should be free from solids, acids, alkalis, organic materials and salts. Potable and clean bathing water is normally acceptable for concrete mixing but not necessarily without any reservations. The actual solids or salts present in drinking or bathing water may be even higher than that required for durable concrete. The permissible limits of solids in water that can be used in making concrete are given in table 1.7.1. The water that is used in curing should also be of similar standard as that used in mixing the concrete.

TABLE 1.7.1 Permissible limits of solids in water
(pH value not less than 6)

Material	Maximum limit
1. Suspended	2000 mg/litre
2. Organic	200 mg/litre
3. Inorganic	3000 mg/litre
4. Sulfates as SO ₃	400 mg/litre
5. Chlorides	2000 mg/litre for plain concrete 500 mg/litre for reinforced concrete

1.8. Introduction to Concrete

Concrete is a hardened composite matrix consisting of cement, sand and coarse aggregate mixed with water and cured under moist condition. The composite wet mix ready for placement or placed in position but not hardened is called *green concrete*. Spray of water or supply of moisture to the setting concrete to gain strength and absorb heat of hydration is called *curing of concrete*. The word curing should not be misunderstood in the medical terminology as if the concrete is sick and needs curing. This heat of hydration if not dissipated properly, the solidified concrete mass will not gain full potential and further develops micro-cracks. Civil engineers and builders should be interested in the properties of the green as well as hardened concrete.

- (a) Lean Cement Concrete (LCC) may be called as Lean Concrete (LC), (LC may also refer to lime concrete),
- (b) Plain Cement Concrete (PCC or PC),
- (c) Reinforced Cement Concrete (RCC or simply RC),
- (d) Prestressed Concrete (PSC),
- (e) High strength concrete (HSC),
- (f) Ultra-High Performance Concrete (UHPC),
- (g) High Concrete Performance Concrete (HPC),
- (h) Light Weight Concrete (LWC), and
- (i) Heavy Weight Concrete (HWC).

The Indian Standard code (abbreviated as IS code) of practice on plain and reinforced concrete gives a classification of concretes as: *ordinary, Standard and High strength concrete*. The ordinary concrete has strength in the range of 10 N/mm² to 20 N/mm² (also called as grades M10 to M20). The range of grades of standard concrete is M25 to M60. The grade of high strength concrete is in the range of M60 to M150. All grades are at an incremental value of 5 N/mm². This classification appears to be somewhat arbitrary and not aimed at the common usage concrete. Further it is not necessary that the strength should increase at the rate of 5 N/mm² only.

Concrete is generally identified by its strength and referred as grade. A notation in specifying the grade of concrete by the Indian code of practice is prefixed by M. Letter M refers to mix. Grade M10 refers to a concrete having a characteristic strength of 10 N/mm². Similarly M15, M20, M25, M30, M35, M40, M45 etc are referred at an incremental value of 5 N/mm². The mother code IS: 456-2000(2005) lists grades up to M60, however, concretes upto grade M120

are produced in India at the moment. The days are not very far off when concrete of grade M150 and more will be used in construction. The notation of identifying the concrete may vary with a country. The grade identifies strength and this strength is referred as characteristic strength. The *characteristic strength is the strength of a material below which not more than five percent of the test results are expected to fall*. The strength data of most material follow normal distribution. If f_k is the characteristic strength of a material, then the probability of not more than a specified sample fall below it can be expressed as:

The probability that f (strength) should not fall below f_k is = 5 per cent

$$P(f < f_k) = p_f$$

where

P = probability distribution function,

f_m = mean strength of the sample,

p_f = is the accepted probability,

f = sample strength, and

It is observed that the distribution of strength of most materials follows a normal distribution. The above expression can be rewritten for normal distribution as:

$$\phi\left(\frac{f_k - f_m}{s}\right)$$

where

ϕ = Normally distributed probability function,

s = standard deviation of the sample strength.

The inverse of the probability equation can be expressed as:

$$\frac{f_k - f_m}{s} = -k$$

where

k = is the accepted probability of failure,

A negative sign is assigned to k as the quantity is at the left tail end of the distribution.

For 5 per cent acceptability of failure, the value of k can be obtained from normal distribution table as 1.6.5. Therefore the above equation reduces to:

$$f_m = f_k + ks$$

The significance of the above expression is to aim the mean strength of the samples higher than the characteristic strength by about the product of the acceptable probability and the standard deviation.

The characteristic strength of concrete (f_{ck}) can be written as:

$$f_{ck} = f_m - 1.65s$$

where

f_{ck} = is the characteristic strength of concrete

Lean Cement Concrete

Lean cement concrete (LCC) also called as lean concrete (LC) is made of very small proportion of cement. Lean concrete is not a structural concrete and doesn't resist loads. It is used as a base-course in flooring and foundations, and at times it is also used as a filler material. The thickness of the leveling course of the lean concrete varies 75 mm to 150 mm depending on the ground conditions and the strength of the structural concrete that is placed over it. 120 mm thick layer is the most common one. The coarse aggregate used in the lean mixes is in the range of 40 mm to 63 mm size and depends on the thickness of the concrete. The size of the aggregate should be one third or less than the thickness of the concrete layer. Nominal mixes used in the lean concretes with mix proportions in volume are listed in table 1.8.1. The lean concrete can be broken easily by pickaxe.

TABLE 1.8.1 Nominal mix proportions by volume

Grade (approximate)	Nominal mix
Lean concrete M5	1:5:10
Lean concrete M7.5	1:4:8
Plain concrete M10	1:3:6
M15	1:2:4
M20	1:1.5:3

Phases of Concrete

Concrete goes through six phases of transformation. The approximate duration of the periods of these phases for ordinary Portland cement are:

- Phase 1: *Initial Hydration*, first 15 minutes after mixing with water,
- Phase 2: *Induction period*, from 15 minutes to about 4 hours,
- Phase 3: *Setting process*, 4 hours to 8 hours,
- Phase 4: *Hardening period*, 8 hours to 24 about hours,
- Phase 5: *Curing period*, 24 hours to upto 28 days and
- Phase 6: Service period: about 28 days of curing on wards.

In the first phase, the nucleation of cement hydration products is formed. The hygroscopic particles of cement react with water and chemical kinetics set in at a very fast rate. The surface of the cement is coated with the hydration products. Lot of ionic reactions also takes place in the short duration. Some admixtures may interface with the chemical kinetics of cement even at this stage. The admixture will influence active reaction of the cement. Reaction of the Tricalcium aluminate with water results into hydrates of calcium aluminates during the induction period. In case of inadequate supply of gypsum, flash set of the cement takes place. In case of excess of gypsum, false set of cement takes place during this period. Nucleation of gypsum crystals takes place during the period. The concrete can be re-mixed in flash or false set of cement. The setting of the other compounds of cement also introduced during this period.

The third phase is dominated by the setting of cement. The cement compounds combine with water and result into hydrates of calcium silicates etc. The final setting time for most types of cements is 10 hours. Admixtures can influence the setting time. Retarders that are

often used in ready mixed concrete delay especially the initial set. Too much of the retarder can even effect the final setting time of the cement, and consequently the setting of the concrete. Too much delay in the final setting also affects the strength of the concrete. An admixture that reacts with the cement compound can affect the crystallization of the hydrates. The fourth phase is the hardening of concrete. Setting of cement even though leads to some hardening of concrete, the real combination of aggregate with hydrates and concrete solid development takes place during the fourth stage. The period is indicated as 24 hours but the plasticizer and the retarder again influence it. Incompatible two admixtures when used can delay the hardening for longer period. Plasticizer or super-plasticizer along with retarder is added to the ready mixed concrete. Depending on the dosage of the retarder, the hardening of the concrete may be delayed considerably. Sometimes it takes four or even more time to transport and pump the ready mixed concrete because of other reasons such as mechanical, power or formwork problems. That is why more than one dose of retarder is added to the concrete.

The fifth phase of the concrete is curing state. A more detailed discussion on curing is given elsewhere in this chapter. This phase is very important often neglected. Builder is very much interested in laying good concrete but not pay same attention to the curing of the concrete. The final state is the service state. It is often said that the concrete needs no maintenance. This is an over simplification or a poor excuse for bad maintenance of the concrete. Concrete needs care and maintenance to sustain it for the designed life. A scheme of maintenance, quick repairs and protection against aggressive agents is needed for durable concrete.

Plain Concrete (Plain Cement Concrete)

The plain concrete is structural concrete used in foundations, retaining walls, roads, dams and similar applications. There are many structures such as retaining walls, hydraulic dams in which the mass and weight of the structure plays an important role. In such structures the tensile stresses developed are small when compared with the compressive stresses. In roads, foundations and in floors where the plain concrete is used, load is mostly bearing type and doesn't cause much bending moment. The commonly used range of the grades of the concrete is from *M10* to *M30*. There is no restriction to limit the plain concrete to grade *M30* however the plain concrete constructions beyond *M35* are rare. The size of the aggregate used in the plain concrete varies widely. The size of the aggregate can be as much as 150 mm, in mass concrete structures like in hydraulic dams. While in road construction, it can be 40 mm down to 20 mm, and similar size is used in the foundations. The size of the aggregate should be less than one sixth of the thickness of the structure or element, preferably less than one tenth. Curing of mass concrete is not as easy as the curing in thin and slender elements. Use of Portland pozzolana cement in mass concrete is better as the rate of heat of hydration is less.

Reinforced Concrete (Reinforced Cement Concrete, RC or RCC)

Concrete in which reinforcement is embedded is called reinforced concrete. Reinforced concrete is the most extensively used structural material. The reinforcement bars should not slip from the concrete surface when subjected to forces. Further the reinforcement must be protected against any corrosion or rusting. Exposure of steel reinforcement to moisture and oxygen will cause corrosion of the steel; therefore, the concrete must be impermeable. Porous and honey combed concrete is not suitable to reinforced concrete or in fact any type of structural work.

The grade of the concrete that is normally used in the reinforced concrete is in the range of *M20* to *M40*. However grade *M20* concrete is not acceptable in many advanced countries even though it is permitted by the Indian code of practice for mild exposure condition. Even though there is no upper limit to the strength of concrete to be used in reinforced work, *M40* is invariably considered as an upper bound either because of economics or because of other considerations such as deflections etc. The commonly used reinforcement is high yield deformed bars or cold twisted bars. The proof strength of these bars is in the range of 415, 500 and 550 N/mm². 20 mm size is the commonly used aggregate; of course the graded aggregate is preferred. The normal weight of the reinforced concrete is 24 kN/m³ to 25 kN/m³.

Prestressed Concrete

Concrete in which stresses are induced even before the external loads act on the structure is called *Prestressed Concrete*. Prestressed concrete structures are commonly used for bridges, towers, water tanks, shell structures, folded plates, nuclear reactors, and long span girders. Tensioned high-tension steel wires and cables and anchored to the concrete apply prestressing force on the concrete. The grades of concrete used in the construction start from *M35* onwards. Till recently, concrete grade *M60* was about the upper limit in many constructions. However with the introduction of high performance concrete, concrete grades in the range of *M80* to *M150* are coming into practice. The size of the aggregate is very similar to that used in reinforced concrete, namely 20 mm aggregate but graded to give maximum density to the concrete. The water cement ratio is limited to the least value and it is normally less than 0.45. The water-cement ratio as low as 0.3, along with super-plasticizers is used in high performance concrete. The tensile proof strength of the high tensile steel wires is of the order 1500 to 2000 N/mm². The shrinkage strain of concrete is comparable with the allowable strain in the mild and medium grade steels, so only high tensile steels are used in this construction. The concrete also has to be high strength concrete to match with the strength of the steels and to compensate the losses of prestress. Prestressed concrete is the main solution for long span structures. The normal weight of the prestressed concrete is about 25 to 26 kN/m³.

High Performance Concrete (HPC)

Very high strength concrete that has the desired strength and workability is often called *high performance* concrete. The technology of high performance concrete is about fifteen years old and becoming popular in prestressed concrete construction. Strong well-graded aggregate with silica fume and low water cement ratio are used in high performance concrete. Silica fume sometimes called as micro-silica is a very fine powder (in fact a fume), and it is ten times finer than the cement. The specific surface of the fume is in the range of 3000 to 10,000 m² per kilogram. It is amorphous active silica, reacts with lime forming calcium silica hydrates in the microform. It fills up the finest voids in the concrete, making the concrete impermeable and very strong. Silica fume is more expensive when compared to cement. It is byproduct of Ferro-silica alloys and at the moment it is being imported in to India. The quantity of silica fume used in high performance concrete is about five to ten percent of cement. Use of super-plasticizer is a must to obtain good workability of the concrete. The present range of high performance concrete is *M60* to *M150*. Sooner than expected, the strength of the concrete will go beyond 150 N/mm².

Ultra-High Performance Concrete

Ultra-High Performance Concrete (UHPC), also known as Reactive Powder Concrete (RPC), is a high-strength, ductile material formulated by **combining Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibbers**. The material provides compressive strengths up to 150 MPa and flexural strengths up to 25 MPa.

The materials are usually supplied in a **three-component premix**: powders (**Portland cement, silica fume, quartz flour, and fine silica sand**) pre-blended in bulk-bags; super plasticizers; and organic fibbers. The ductile behaviour of this material is a first for concrete, with the capacity to deform and support flexural and tensile loads, even after initial cracking. The use of this material for construction is simplified by the elimination of reinforcing steel and the ability of the material to be virtually self placing or dry cast.

The superior durability characteristics are due to a combination of fine powders selected for their grain size (maximum 600 micrometer) and chemical reactivity. The net effect is a maximum compactness and a small, disconnected pore structure.

The following is an example of the range of material characteristics for UHPC:

Strength

Compressive: 120 to 150 MPa

Flexural: 15 to 25 MPa

Modulus of Elasticity: 45 to 50 GPa

Durability

Freeze/thaw (after 300 cycles): 100%

Salt-scaling (loss of residue): < 60 g/m² Abrasion (relative volume loss index): 1.7 Oxygen

permeability: <10-20 m² Cl - permeability (total load): < 10 C Carbonation depth: < 0.5 mm

Manufacturing and Installation

The precast canopy components were individually cast and consist of **half-shells, columns, tie beams, struts, and troughs**. The columns and half-shells were injection cast in closed steel forms. Troughs were cast through displacement moulding, while struts and tie beams were produced using conventional gravity two-stage castings.

The columns were installed on the concrete platform first. Then, the right and left half-shells, along with the tie beams, were pre-assembled in the plant and transported to the site where they were lifted (by crane) over the railway tracks, for placement on the columns. Upon arrival at the site, the canopies were set on temporary scaffolding, and struts were attached to the shells and previously installed columns with welded connections.

The material's unique combination of superior properties and design flexibility facilitated the architect's ability to create the attractive, off-white, curved canopies. Overall, this material offers solutions with advantages such as speed of construction, improved aesthetics, superior durability, and in permeability against corrosion, abrasion and impact which translates to reduced maintenance and a longer life span for the structure.

Concrete High-Performance American Concrete Institute

“A concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing and curing practices”. The requirements may involve enhancements of characteristics such as placement and compaction without segregation, long-term mechanical properties, and early age strength or service life in severe environments. Concretes possessing many of these characteristics often achieve High Strength, but High Strength concrete may not necessarily be of High Performance. A classification of High Performance Concrete related to strength is shown below.

Compressive strength (MPa)	50	75	100	125	150
High Performance Class	I	II	III	IV	V
Advantages					

Reduction in size of the columns, Speed of construction, More economical than steel concrete composite columns, Workability and pump ability, Most economical material in terms of time and money, Increased rentable\useful floor space, Reduced depth of floor system and decrease in overall building height, Higher seismic resistance, lower wind sway and drift, Improved durability in aggressive environment, Wearing resistance, abrasion resistance, Durability against chloride attack, Increased durability in marine environment, Low shrinkage and high strength, Service life more than 100 years, High tensile strength, Reduced maintenance cost.

Light Weight Concrete

Lightweight concrete uses lightweight aggregate and is lighter than the normal concrete. A porous aggregate results in to lightweight material. Further the filling up the voids in the coarse aggregate by fine aggregate is minimized and air content is increased. The aim is to obtain more voids in the concrete and at the same time make it homogeneous. The range of the density of the lightweight concrete is quite wide. The weight of the lightweight concrete varies from 400 kg/m^3 to 1900 kg/m^3 . Some lightweight concrete is lighter than water and is used for thermal and sound insulation. Very light concrete is also called as *cellular concrete* and coarse aggregate is not used in such concrete. Further large volume of air bubbles is introduced into the concrete with lightest aggregate. Finally there is the structural lightweight concrete having a unit weight of 1400 to 1900 kg/m^3 and having a minimum compressive strength of 15 N/mm^2 . Pumice stone, slag, cinder etc are the common lightweight aggregates. Artificial lightweight aggregate is manufactured using industrial byproducts.

Heavy Weight Concrete

Heavy weight concrete is the one that is made of heavy-density aggregate. Heavy-density aggregate such as hematite, an iron ore material is extensively used in heavy weight concrete. This concrete is used in industrial floors where considerable wear and tear is expected. It is also used in nuclear containment vessel constructions. The unit weight of heavy weight concrete is more than 2600 kg/m^3 .

Concrete Plant

A concrete plant, also known as a batch plant or batching plant, is a device that combines various ingredients to form concrete. Some of these inputs include sand, water, aggregate (rocks, gravel, etc.), fly ash, potash, and cement. There are two types of concrete plants: *ready mix* plants and *central mix* plants. A concrete plant can have a variety of parts and accessories, including but not limited to: mixers (*either tilt-up or horizontal* or in some cases both), cement batchers, aggregate batchers, conveyors, radial stackers, aggregate bins, cement bins, heaters, chillers, cement silos, batch plant controls, and dust collectors (to minimize environmental pollution).

The centre of the concrete batching plant is the mixer. There are three types of mixer: Tilt, pan, and twin shaft mixer. The twin shaft mixer can ensure an even mixture of concrete and large output, while the tilt mixer offers a consistent mix with much less maintenance labour and cost.

A *ready mix* plant combines all ingredients except for water at the concrete plant. This mixture is then discharged into a ready mix truck (also known as a concrete transport truck). Water is then added to the mix in the truck and mixed during transport to the job site.

A *central mix* plant combines some or all of the above ingredients (including water) at a central location. The final product is then transported to the job site. Central mix plants differ from ready mix plants in that they offer the end user a much more consistent product, since all the ingredient mixing is done in a central location and is computer-assisted to ensure uniformity of product. A *temporary batch plant* can be constructed on a large job site. A concrete plant becomes central mix with the addition of a concrete mixer.

Concrete batching plants are widely used to produce various kinds of concrete including quaking concrete and hard concrete, suitable for large or medium scale building works, road and bridge works and precast concrete plants, etc.

More recently is the availability of the mobile concrete batch plant. This innovative device was designed for the production of all types of concrete, mixed cements, cold regenerations and inertizations of materials mixed with resin additives. The design includes multiple containers that separately transport all the elements necessary for the production of concrete, or any other mixture, at the specific job site. In this way, the operator can produce exactly what he wants, where he wants and in the quantity he wants through the use of an on-board computer. Once production is started, the various components enter the mixer in the required doses and the finished mixed product comes out continuously ready for final use. It is also suitable for the recovery of materials destined for landfill disposal, such as cement mixtures regenerated from masonry rubble. The mobile batching plant is easy to transport. It can be fixed-mounted on a truck, mounted on a truck with tipping box or mounted on an interchangeable cradle.

Modern concrete batch plants (both ready mix and central mix,) employ computer aided control to assist in fast, accurate measurement of input constituents or ingredients, as well as tie together the various parts and accessories for coordinated and safe operation. With concrete performance so dependent on accurate water measurement, systems will often use moisture probes to measure the amount of water that is part of the aggregate (sand and rock) material while it is being weighed, and then automatically compensate the mix design water target.

A non-profit association brings together all of the main concrete plant manufacturers on common matters related to the industry. According to the CPMB's website, "The National

Ready Mixed Concrete Association (NRMCA) endorses the members of the Concrete Plant Manufacturers Bureau as the preferred providers of concrete plants and associated equipment as providing quality equipment conforming to the standards and specifications of NRMCA's plant certification program and the concrete plant manufacturers' standards.' ” “The primary function of the CPMB is to establish minimum standards for rating various components of concrete plants for the protection and assurance to the user that the plated components of the plants conform to these Standards.

1.9. Important Properties of Concrete

A number of characteristics and properties of concrete are of importance to the structural engineer and builder. Many properties are interdependent and should be studied together. Some properties influence in manufacturing the concrete and some in resisting the loads and environmental forces. The important properties relevant to structural and construction engineer are:

- ❖ Workability of concrete,
- ❖ Segregation and Bleeding,
- ❖ Curing of concrete,
- ❖ Shrinkage and Creep,
- ❖ Strength, and
- ❖ Durability of concrete.

As the concrete is a matrix having a number of components, the end product depends on several factors. The main factors that affect the characteristics of the concrete are:

- ❖ Quality of ingredients, such as aggregate, sand, cement, water and admixtures,
- ❖ Relative proportions of the ingredients,
- ❖ Making of green concrete, mixing time, transportation, laying etc.,
- ❖ Methods in making, laying, finishing of concrete,
- ❖ Protection of green concrete and curing,
- ❖ Temperature and weather conditions during laying and curing,
- ❖ Exposure conditions and maintenance.

Some properties are associated with the making and some with the hardened concrete. Different properties of the concrete are briefly discussed in the following sections.

1.10. Workability of Concrete

Workability of concrete is the property that indicates the ease in mixing, placing, compacting and finishing with least segregation of the particles. So the workability involves the following aspects:

- ❖ Ease in mixing the ingredients,
- ❖ Ease in placing the concrete in position,
- ❖ Ease in compacting,

- ❖ Achieving the homogeneity and no segregation, and
- ❖ Finishing the surface of the concrete.

Workability of concrete is a function of relative mix proportions, the quality of the aggregate and cement, water cement ratio, mixing time and method of mixing, admixtures, time of transportation and the method of placing. Layman thinks that the concrete is more workability with more water. The laborer who handles the mixing of concrete is happy to add more water to make the concrete easily workable. But water beyond a point weakens and strength and durability of the concrete. The workability requirement depends on the size of the element, amount of reinforcement, location of placing the concrete and the weather conditions at the time of concreting. One needs more workable concrete if the percentage of the reinforcement is higher under similar situations. Therefore the workability specification depends on many factors. The influences of different factors on the workability of concrete are discussed briefly here:

- (a) *Water-cement ratio.* The workability increases with increase in the water-cement ratio, however the strength and durability of the concrete decrease if the ratio is beyond a point. It is therefore desirable to limit the water-cement ratio to the minimum possible based on the strength criterion. For high strength and high performance concrete, the water-cement ratio is to be limited to 0.45 or even down to 0.30. The real quantity of water required to complete the chemical reaction of the cement may be about 30 percent by weight of cement. Even the water applied during curing of the concrete assists in the formation of the hydrates. Such a low water-cement ratio will not give workable concrete unless a super-plasticizer is added in making the concrete. It is always advisable to lower the water-cement ratio and use a water reducing agent or super-plasticizer for better quality. Some more discussion will be given on the water-cement ratio on strength of concrete.
- (b) *Size of aggregate:* Coarse aggregate improves the workability of the concrete. Larger the size of the aggregate, better is the workability. Higher the size of the aggregate, higher is the strength of the concrete. However the size of member, percentage of reinforcement, cover and surface finish specifications also control the size of the aggregate. 20 mm or 25 mm size of aggregate is recommended for reinforced concrete. The desired size of the aggregate depends not so much on the workability but on the type of structural elements, and cover to the reinforcement. Fine aggregate decreases the workability of the concrete.
- (c) *Grading of aggregate:* A well-graded aggregate will result in better compaction and minimum segregation. The specification on size of the aggregate normally refers to the largest value used in the concrete. But it is desirable to use at least two different sizes of the coarse aggregate for good concrete compaction and strength. For example one can use 20 mm and 10 mm combination in the coarse aggregate selection. Better workability and strength are obtained by the well-graded aggregate.
- (d) *Shapes of aggregate:* Rounded and angular shape aggregates are the basic desirable shapes for good concrete. The rounded aggregate demands least amount of water

when compared with that for the other shapes. Angular aggregate with almost equal size faces is good for interlocking and strength. The angles between the faces of the aggregate should not be acute or obtuse. Angular aggregate is preferred for strength consideration aspect. Crushed aggregate is usually an angular shaped one.

- (e) *Flakiness of the aggregate:* Flaky or oblong aggregate decreases the workability and also the strength of the concrete. Therefore such aggregate should not be used in making of concrete.
- (f) *Aggregate-cement ratio:* More cement means more water for the same water-cement ratio. Consequently the increase in the aggregate content with respect to the cement decreases the ratio of the water to the total mass of the concrete. Normally the aggregate-cement ratio is chosen for a given water-cement ratio to obtain a desirable strength of the concrete. Higher aggregate-cement ratio decreases the workability as well as the strength of the concrete.
- (g) *Air content in concrete mix:* Air in green concrete acts as a lubricant and increases the fluidity and consequently the workability. Sometimes air entraining agents are added to concrete to increase the workability at a lower water-cement ratio. However the entrapped air must be driven out by proper vibration for good consolidation of concrete.
- (h) *Time of transit:* A minimum mixing time is needed for a given water-cement ratio to obtain good workability of concrete. The transit time of concrete from the mixer to the location of placement needs to be as minimum as possible. Green concrete gets stiffened during transit even before the initial setting of the cement. Five minutes of transit time is desirable, at the most ten minutes can be considered as a last resort. A retardant must be added if the transit time is more than ten minutes. Ready mixed concrete needs more transit time. It can be anywhere from 30 minutes to four hours. Addition of retardant in the transit mix is very common. The retardant may have to be added in periodically depending on the transit time. Too much of retardant can effect the hardening and the final setting time and strength. Four hours of retarding the setting time is probably on the higher side. Concretes with four hours of initial setting time will effect the final setting time.
- (i) *Admixture to concrete:* Workability admixtures such as air entraining agent or plasticizer or super-plasticizer are often used in high strength concretes to improve the workability at low water-cement ratio. Super-plasticizer is a must in the high performance concrete. Selection of minimum water-cement ratio to achieve good strength at low cost and then addition of super-plasticizer to obtain the desired workability is the best strategy in good concrete practice.

Workability of concrete is quantified and measurable by a number of tests. That is mixing, placing, compacting, finishing and obtaining good homogeneity. The following are the tests that measure the workability of concrete:

- (a) Slump test,
- (b) Compaction factor,

- (c) Vee-bee (or *V-B* or *Vebe test*) consistometer,
- (d) Flow test,
- (e) Remolding test,
- (f) Ball penetration or Kelley ball test, and
- (g) Two-point test.

Slump test is the most extensively used test to measure the workability of the concrete. It is probably the simplest to apply in field with least equipment. A frustum of a conical tube of 300 mm high, 200 mm diameter at bottom, 100 mm at top with two handles attached to the surface at about the middle height is used as a mould. Concrete is placed in three layers, each layer being consolidated by 25 tamping of a rod and then the top surface is leveled. The mould is pulled up and the wet molded concrete is allowed to slump or slide down. The magnitude of the slump of the concrete from the 300 mm height is called *slump of the concrete*. It is considered to be reasonably good for low slump or high slump but not very good for the middle range of the slump. The fresh concrete is classified into four broad groups based on slump, and they are listed in table 1.10.1.

TABLE 1.10.1 Classification of fresh concrete based on slump

Class->	Low	Medium	High	Very high
Slump (mm)	0-30	40-75	80-150	160 & above

The concrete gets stiffened with time even in a small duration of 10 minutes transit. The slump of the concrete at time of placing is likely to be less than that measured at mixing time. The phenomenon of reduction of slump with time is called slump loss. Ready mixed concrete is transported for longer distance and duration when compared to the site mixed concrete.

The required slump is always expected to be at the time of placing the concrete. The normally recommended slump for different types of concreting environment in dry weather condition is listed in table 1.10.2. Slump test is the most preferred test in field.

TABLE 1.10.2 Recommended concrete slump for environment

Type of work	Slump
PCC, Shallow slabs & beams with nominal reinforcement	Low
Beams and columns with reasonable reinforcement	Medium
Heavily reinforced concrete members and Prestressed	High
Deep members with heavy reinforcement (pumped concrete)	Very high

Compacting Factor Test

The compacting factor test is based on the degree of compactness achieved in placing (or dropping) the concrete from a specific height. The ratio of the density of the concrete actually achieved to the density that is possible in fully compacted condition is called compacting factor. Two conical hoppers with doors at bottom are placed one over the other at a specified distance. The top hopper is bigger than the lower one. A cylindrical mold of 150 mm by 300

mm is placed below the hoppers. The top hopper is filled with fresh concrete without any compaction. On opening of the bottom door of the top hopper, the concrete falls into the lower hopper. The concrete fills up the lower hopper by gravity and then overflows. Similarly the bottom door of the lower hopper is released and the concrete is allowed to fall and fill the bottom cylinder. The density of the concrete in the cylinder is calculated. The ratio of this density to that of the fully compacted density of the concrete in the cylinder is called the compacting factor. The workability of the concrete based on the compacting factor can be divided into four classes and they are listed in table 1.10.3.

TABLE 1.10.3 Classification of workability of fresh concrete based on compacting factor

Class	Low	Medium	High	Very high
Compacting factor	0.75	0.85	0.92	0.95

There is some correlation of the classification of the workability of concrete based on the slump and compaction factor but not necessarily having a one to one correspondence.

Vebe Test

The Vebe test equipment consists of vibrating table with slump cone placed in a shallower cylindrical tube. The table is set in light vibration after the slump cone is lifted. The time taken for the freestanding concrete cone to fill the cylinder is measured. The time required for remolding the concrete from the conical shape to that of cylinder is measured in seconds. The time in *Vebe test* vary from 5 seconds to 25 seconds depending on the inverse of the workability of the concrete. Five seconds of time of *Vebe test* represents highly workable concrete and 25 seconds is stiff concrete. The *vebe* test is less commonly used when compared to the two tests mentioned earlier.

1.11. Curing of Concrete

Curing of concrete is a misleading word for a common man. Curing means to cure one from a problem or disease. Curing of concrete has altogether a different meaning. Cement when comes in contact with moisture, reacts chemically on the surface of the cement particles. Bonding with the surrounding particles of cement is developed during the chemical reaction of cement. The process of formation of compounds of cement with water is called hydration. The hydration of cement generates heat and the heat is called heat of hydration. The hydration process is initiated at about eighty percent of humidity environment. Uncontrolled heat of hydration causes micro cracking in concrete. Further, moisture is needed continuously for some period in and around cement particles to continue with the formation of hydrates of cement. Therefore moist environment is a necessity for the hardening concrete. Supply of moisture or water to the hardening concrete to dissipate the heat of hydration and to aid further chemical reaction of cement is called *curing of concrete*. The chemical reaction gets accelerated with increase of the temperature of the water or moisture.

The concrete gains strength with increase in duration of curing. An approximate strength of concrete at 90 days with different periods of moisture curing is given table 1.11.1. Concrete

that is allowed to gain strength by exposing to air is called air curing. It is not really any curing but given a notation for no curing with water and for lack of better terminology.

TABLE 1.11.1 Strength of concrete with curing

Days of water curing	>	0	3	7	28
Ratio of strength on 90 days to that at 28 days curing	>	0.5	0.75	1.0	1.2

Moist curing: The concrete after casting should be allowed to reach almost the final setting time of cement. The concrete is considered to be green till about the final setting time of cement. The final setting time of cement is not necessarily the final set of the concrete. The final setting time of most cements is about 10 hours but the concrete after placing in position under normal temperature of the order 20 degrees Celsius is likely to set in about six hours. Five to ten hours of pre-curing time is adequate in hot weather conditions as in most parts of India. The hardening of concrete in warm weather of about 30+ degrees Celsius is faster so the curing with moisture can start after eight hours of casting. After about 6 to 10 hours of casting, the exposed surfaces of hardening concrete must be kept continuous under damp or wet condition by sprinkling of water. Or the surface can be covered with jute sacks that are kept under wet condition. The concrete can be kept under submerged condition wherever feasible for curing. This is probably done in pre-cast concrete construction. The concrete test samples are always cured in water submerged condition. But such a situation is hardly available for most structures. Commonly accepted practice is to cover the concrete with wet jute bags and sprinkling of water as frequently as needed to keep the bags wet all the time. Most asked question is how frequently the water must be sprinkled? The frequency of spraying water depends on the weather conditions. In rainy season when the humidity is high, the sprinkling of water can be once in four or five hours. But in the dry summer, sprinkling has to be more frequent. The aim is to keep the gunny bags wet all the time. In any case, the surface of the concrete should be wet or under 80 percent humidity condition. Another question that is asked is how long the curing of concrete be continued without interruption? 28 days curing is the best and most desirable to result into a strong and durable concrete. Under no circumstances the period of curing should be less than 7 days. A canvas or polyethylene sheet placed over the wet surface of the concrete helps in reducing loss of moisture from the concrete. Seven days of water curing will atleast give strength of that of 28 days cured value on 90th day. However one must remember the durability of the concrete will be affected even if the strength is achieved if the curing time is cut down.

Curing of many concrete structures built in the unorganized sector in India is given the lowest importance. The sprinkling of water over the concrete is usually handed over to a small boy or a woman worker or a watchman. Further, the construction is in progress while some portion requiring curing. Many parts of the structure are not easily accessible to the helpless boy who is supposed to maintain the wetness of the surface of the concrete. The engineer and the supervisor must pay more attention to the curing of the concrete. Curing of slabs is about the easiest, and curing of the concrete in columns is about the most difficult one. The slabs being relatively thin and are flat, pounding of water on the top face of the slab may be adequate.

However the bottom face of the slab is sprayed with water now and then. The concrete slabs have built-in higher factor of safety because of continuity in two directions when compared to that available to columns. The slabs will collapse only after developing a yield line mechanism. Columns are the most critical elements and are the least compacted and least cured in common practice. Covering the columns with wet jute bags and keeping the bags under wet condition is a must. The side faces of the beams are the other items that are not properly cared/cured.

Curing of mass concrete: Thick concrete members such as raft slabs, pile caps and other thick concrete sections need special attention in curing. Concrete raft slabs of the order 1000 mm to 1500 mm or even more thicker are common in large constructions. Since the bottom face is resting on lean concrete, loss of moisture on that surface is almost none. The lean concrete need to be atleast M7.5 grade concrete. Concrete sections thicker than 1500 mm need special curing arrangements. The temperature of the concrete at the time of laying need to be about 15 degrees Celsius or even less in mass concrete. Ice cold water can be used in mixing the concrete so that the interior of the concrete is at a lower temperature to start with. Surface curing will not reach the interiors of such thick members. If the thickness of the concrete is more than 2000 mm, cooling pipelines have to be laid in the concrete so that cool water can be circulated through such lines for curing. Rigid perforated pipes or tubes can be embedded in mass concrete at the time of laying the concrete. Cold water is pumped through the pipes to provide heat absorption and to maintain 80 per cent humidity inside. Too much of un-dissipated heat of hydration can cause micro cracking and damage to the mass concrete.

Steam curing: Concrete can be cured by controlled steam. The concrete must be allowed to harden for about 3 hours, then it is covered under tarpaulin or put in steam chambers. Pre-cast concrete elements can be placed in steam chambers. Steam at about 800 to 1000 C is allowed over the concrete, gradually raising temperature of the concrete chamber upto 700 C in about 2 hours time. The steam curing cycle consists of four parts. Pre-heating period, heating period, steaming period and post-steam period. The pre-steam period is the period the concrete is allowed to set partly and it may be two to three hours. Too early exposure of concrete to the steam can cook the concrete resulting in bubbling or boiling surface. The concrete shouldn't be subjected to sudden rise in temperature. The heating period is the period in which the steam is allowed into the chamber at atmospheric pressure to heat the chamber. This period depends on the mass of the concrete and the size of the member and the arrangements of steaming such as chamber or tarpaulin. May be couple of hours of heating is adequate. Steam curing for about 8 to 10 hours can be considered as the minimum required obtaining an equivalent 7 days strength of water cured concrete. Steam curing of 18 to 24 hours gives strength equal to that of 28 days water cured one. The entire cycle of steam curing can be about 18 to 24 hours. The steam is cut off slowly in about an hour's time and the concrete is allowed to cool in the chamber for another hour. Improperly done steam curing can cause cooking and spalling of the surface concrete. Steam curing is normally done for prestress concrete or pre-cast concrete members. It is a matter of economics of storage and supply of the product, reuse of prestressing equipment and the bed for quick turn over. The steam curing appears to be economical in producing prestressed concrete pole, railway sleepers, pipes etc.

1.12. Shrinkage and Creep of Concrete

Shrinkage of concrete is the decrease in volume due to evaporation of moisture from concrete and hardening of the concrete. The shrinkage is divided into three types, and they are *plastic shrinkage*, *drying shrinkage* and *thermal shrinkage*. There is some settlement or subsidence of concrete even before the concrete gets hardened, and this reduction in volume of fresh concrete is called *plastic shrinkage*. Stiffening of the top layer of the concrete may cause settlement of the inside concrete. The plastic shrinkage may be caused by bleeding, absorption of water by subgrade soil, settlement of formwork, and rapid evaporation of moisture from the surface etc. Plastic shrinkage produces horizontal cracking on the top surface. All precautions should be taken to minimize the loss of moisture from the surface and into the sub-grade to minimize or eliminate the plastic shrinkage.

Fresh concrete when exposed to ambient humidity undergoes volume change due to change in the moisture content in the concrete. The humidity in the fresh concrete is normally more than the ambient humidity. Therefore a reduction in the volume of the concrete takes place. The decrease in volume of the concrete due to change in the moisture caused by ambient condition is called *drying shrinkage*. Thermal shrinkage is the one that is caused by the cooling of the concrete. Decrease in volume of the concrete takes place as it is exposed to the ambient temperature that is lower than that of the concrete. The decrease in the volume of concrete either due to plastic shrinkage or dry shrinkage or thermal shrinkage will result in cracking, sometime visible and or invisible. The drying shrinkage can be reversed to some extent by induction of moisture into the concrete. Curing of the concrete at right time and for the right period minimizes the shrinkage.

The shrinkage of concrete is proportional to the amount of water added at the time of mixing and the amount of cement content. Some aggregate characteristics will also influence the shrinkage. Finer cement reacts faster and develops heat of hydration at faster rate thus resulting in shrinkage of the concrete. Temperature at the time of placement of the concrete influences the thermal shrinkage. Higher the temperature at placement, higher is the shrinkage. Pre-cooling of the concrete either with cold water or cooled aggregate reduces the shrinkage. The shrinkage of concrete takes place for a long period. In some constructions, the elements may be cast at different periods. There may be a reasonable difference between the castings of concretes in different parts of the structure. The concrete cast at different periods will shrink at different rates. The difference in the shrinkage of the different parts is called the differential shrinkage. Part of the shrinkage is recoverable by wetting of the concrete. Structural engineer is primarily interested in the total and differential shrinkage. The quality control should look after the different components to minimize each of the shrinkage. The shrinkage is a function of the following factors:

- ❖ Shrinkage decreases with increase in the aggregate-cement ratio,
- ❖ Shrinkage increases with increase in the cement content,
- ❖ Shrinkage increases with increase in the water-cement ratio,
- ❖ Shrinkage decreases with increase in the curing period.

The plastic shrinkage is irrecoverable, whereas the drying shrinkage is partly recoverable by adding moisture to the dried concrete. Half of the shrinkage takes place in the first one-

month, and seventy five per cent in the first six months after commencement of drying of concrete. The plastic shrinkage can be reduced considerably by protecting the surface of the concrete immediately after casting of the concrete. The best principle to reduce the shrinkage is to reduce cement and water-cement ratio, and then add an admixture or plasticizers to improve the workability. The shrinkage of concrete can be eliminated by use of expansive cement, the cement that expands while setting.

Shrinkage is basically a strain without stress, and yet produces cracking in the concrete. Restraint on the shrinkage will cause stresses in the concrete. The shrinkage starts at the surfaces of the concrete and extends into the interior. Approximate shrinkage strain for a water-cement ratio of 0.7 can be as much as 0.0007 while it is about 0.0003 for a water-cement ratio of 0.45.

The total free shrinkage for most reinforced concrete construction that is cured for 28 days is taken as 0.0003.

$$\epsilon_{sh} = 0.0003$$

In practice, the columns are cast on one day and the beam and slab are cast may be few days later. Or the slab including the beams is cast in different stages. The members cast on different days will have different rates of shrinkage. In bridge building, the beams may be pre-cast members and the concrete slab is placed at site over the pre-cast beams. The difference in of shrinkage of the two or more members is called *differential shrinkage*. Differential shrinkage produces interface forces in the members and even cracking.

Creep of Concrete

Concrete when subjected to loads undergoes elastic strain to start with. The stress in the member produces strain and the strain increases if the stress is maintained for a longer duration. The time depended strain under constant stress at 100 percent humid concrete is called *basic creep*. Basic creep of concrete takes place in mass concrete structures. The time dependent strain under constant stress at normal conditions is called *creep strain*. The creep strain per unit stress is called *specific creep*. The ratio of creep strain to the elastic strain is called *creep coefficient*. On unloading, most of the elastic strain is recovered and only part of the creep strain is recovered with time. Creep is a function of relative proportions of aggregate, water, cement, type of aggregate, porosity of concrete, curing period, level of stress and age of loading.

Creep of concrete increases with increase in cement content and water-cement ratio. It also increases with decrease in the age of concrete at loading. Creep also increases with increase in the exposed temperature of the concrete. The creep normally referred is the ultimate creep. Seventy percent of the creep strain takes place in the first one month and the balance may take place in the next three years period time.

Creep strain relation is:

$$\epsilon_{cc} = Cc \epsilon_{se}$$

where

ϵ_{cc} = creep strain, Cc = creep coefficient, and ϵ_{se} = elastic strain

The total strain at any given period is equal to the sum of creep strain and elastic strain. The creep coefficients are given in table 1.12.1.

TABLE 1.12.1 Creep coefficients

Age of concrete at loading	Creep coefficient
7 days	2.2
28 days	1.6
1 year	1.1

As the creep strain increase, deflections in the beams and slabs also increase. The deflection caused by the dead load is to be multiplied by the creep coefficient to obtain the creep deflection. However because of the reinforcement doesn't creep at the same rate as that of concrete, the creep deflection of the reinforced concrete members is only a portion of the creep coefficient. Some redistribution of the stresses takes place indirectly due to creep. In case of columns, the concrete will undergo creep and transfer part of the load to the reinforcement. Therefore the reinforcement in columns under direct compression is subjected to higher levels of stress than that estimated by simple compatibility condition. The creep can cause failure of a structure because of excessive strain in the concrete. This can happen when the dead load is much higher than the live load. In such situations, the permanent load dominates the total strain.

1.13. Strength of Concrete

Strength of concrete is its ability to resist load before collapse. The coarse aggregate in concrete is like a bone skeleton in human structure. The bone primarily resists compression, so much so the aggregate in concrete is the prime source to resist the compression. Aggregate can also resist tension to some extent but in the concrete matrix, there are other weak links in tension and hence the aggregate doesn't control tension problem. The cement-sand mortar in concrete is like muscle in human body. The mortar fills the voids in the aggregate and binds it together to form in to a homogeneous mass. Water in the concrete is like the life giving blood of human being. Water by itself may not resist load except hydraulic load, but when combined with cement, it results into compounds of strength and durability. The strength of concrete is measured by its ability to resist compressive stress. 150 mm concrete cube is taken as basic specimen to measure the compressive strength in India and few other parts of the world. 200 mm cube is considered as a standard testing specimen in some parts of Europe. 150 mm by 300 mm cylinder is the compression test specimen in North America. Therefore the strength of concrete is referred with respect to a test specimen and it bears a relation with the concrete prism. The compressive strength of prism in direct compression is different from the under bending compression. The strength of concrete is associated with the hardened concrete and depends on several factors as listed below:

1. *Strength decreases with increase in water-cement ratio.* Water-cement ratio is one of the most **important factors in determining the strength of concrete. This can be compared to the ratio of the blood** content to the weight of a person. There is always an optimal value of this ratio. Too less blood causes anemic and too much of it can cause high blood pressure or other effects. It is already mentioned that the decrease in the water-cement ratio decreases the workability of the concrete. The

advantage of the low water-cement ratio is obtained only if good consolidation of the concrete is achieved. The water-cement ratio shouldn't be indiscriminately decreased leading to poor workability of concrete. Workability agents such as super-plasticizers have to be added to achieve required workability and consequently good consolidation and strength. Some of the water that is added into the concrete mix is directly consumed for chemical reactions, and over and the water available beyond that is required for chemical reaction remains as free water in the concrete. This free water in the hardened concrete evaporates leaving micro-voids in the concrete. The voids in concrete decrease the strength of concrete. More water added at mixing of concrete results in more shrinkage and porosity. One has to strike a balance between strength and workability. The workability can be improved by adding admixtures to cement, so it is wiser to use low water cement ratio.

2. *Strength increases with increase in cement content.* Cement acts as a binder in the presence of moisture. More cement means, more binding material. The binding material helps in binding aggregate in to a homogeneous solid mass. Cement content beyond a point is of no use and in fact it may cause bad side effects. Protein is good for human body but if one eats too much of proteins, the body will go sick, therefore an optimal cement content must be added for a given situation. More cement also means more heat of hydration and more shrinkage. Further, cement is the expensive material among the basic components of the concrete. It is therefore necessary to make an optimal use of cement in making concrete.
3. *Strength of concrete increases with increase in the size of aggregate.* Strength of the concrete depends on the strength, shape and size of the aggregate. As already mentioned, the aggregate is the filler and the strength giver. Basic strength of the aggregate is important and reflects in the final strength of the concrete. Every thing else being same, the strength of the concrete increases marginally with increase in the size of the aggregate. The type of construction, size of the members and intensity of reinforcement and cover requirement control the size of the aggregate that can be used in the concrete. In plain and mass concrete, one would like to select larger aggregate. 20 mm aggregate is the most commonly used aggregate in reinforced and prestressed concretes. Aggregate crushing value less than 45 is recommended in ordinary plain and reinforced concrete. A value of 30 is preferred in prestressed concrete and reinforced concrete exposed to very severe environment. 30 or 25 mm size aggregate is recommended in road pavement with aggregate crushing value not less than 30.
4. *Strength of concrete depends on the grading, shape and texture of aggregate.* Well-graded aggregate results into compact homogeneous mass therefore better strength. About equal angles of angular shaped aggregate gives better interlocking therefore gives higher strength. Round aggregate also gives good strength. The texture of the aggregate needs to be rough and not smooth to provide good interlocking. Flaky or oblong aggregate should be avoided in making concrete.
5. *Strength increases with curing period of concrete.* As mentioned earlier, cement generates heat of hydration during its reaction with water. This heat of hydration if not absorbed

by external agency, produces cracking in the concrete thus leading to a poor product. The heat of hydration can be absorbed by water that is sprinkled on the surface of the concrete. The process of dissipating the heat of hydration and also assisting in saturated chemical reaction of hardening concrete is called *curing of concrete*. In the process curing, the heat of hydration is dissipated and calcium silicates are formed and the concrete gains strength with time. Curing of concrete normally starts after about 10 hours of casting of concrete. The methods of curing may differ but the essentiality of curing is to protect the concrete surface from the loss of moisture and maintenance of wet surface around the concrete. The strength of concrete increases with curing. The suggested standard curing period is 28 days. All standard test specimens must be cured for twenty-eight days. Similarly the concrete structures need to be cured for 28 days to gain full potential strength. Concrete with ordinary Portland cement gains about two-thirds of the 28 days strength in seven days of curing. The rate of gain in strength of concrete with curing increases with curing period but its gain is rapid to start with and slows down with time. The gain of strength beyond 28 days of curing is considered to be marginal and may be about 30 per cent in a year period. If the curing is stopped after 7 days, then the concrete will not give its full potential. The gain in strength in such a case will be about eighty to eight-five percent of its full potential.

6. *Concrete gains strength faster with increase in the temperature at curing.* Temperature helps in accelerating in the formation of chemical compounds. It doesn't mean hot water should be poured on concrete. The temperature of the curing water needs to be increased slowly. Hot water is not recommended in curing but faster curing is achieved with warmer water when compared with cold water. Cold water is used in curing the mass concrete. Curing of concrete with steam is also practiced for very quick results. One day of steam curing is considered to be equal to 28 days of water curing. However there is a method of applying the steam curing.

Approximate strength in relation with the age of concrete with respect to that of 28 days curing is given in Table 1.13.1 The designer may give an appropriate correction to the strength of concrete when he is certain about the time of actual application of the load. However the revised code of practice on plain and reinforced concrete doesn't permit correction to the strength of the concrete with age.

TABLE 1.13.1 Strength of concrete with age

Age of concrete	Relative strength with respective to 28 days
7 days	0.65 to 0.7
28 days	1.0
3 months	1.10 to 1.15
6 months	1.15 to 1.20
12 months	1.20 to 1.25

Strength and Stress-strain Behaviour

Strength and stress-strain behaviour of concrete is measured by uni-axial compressive test performed on concrete cube or cylinder specimen. 150 mm concrete cube is the standard specimen accepted in India and some other countries. The mould of the specimen must be either cast iron or steel, machined to high dimensional accuracy. Concrete is placed in the mould and vibrated by a specified method and cured in water for 28 days. After 28 days, the cube surface is dried and tested in a compression-testing machine at a prescribed rate of loading. Typical stress-strain behavior of concrete cube is indicated in Figure 1.3.1.

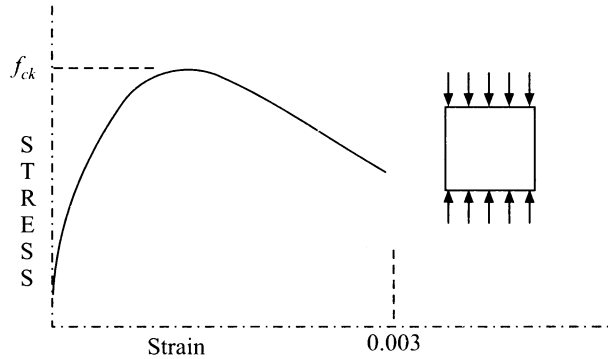


Figure 1.13.1 Stress-strain of concrete.

The testing is under controlled rate of loading rather than the strain controlled. The rate of loading is 2.5 N/mm²/sec. The stress-strain curve of concrete in compression is linear upto 30 percent of the strength, and then an increase in the rate of strain from 30 to 50 per cent of the strength, and from there to about 85 per cent of the strength, the rate of increase in strain is faster. It is difficult to control the rate of loading after the load reaches 75 per cent of the strength, and the crushing of the concrete takes place suddenly. The maximum bending compressive strain in concrete is idealized to 0.0035. The limiting strain can be higher in case of strain controlled tests. The crushing strain in direct compression is limited to 0.002. The instantaneous loading on concrete indicates an increase in the strength. This loading may be termed as impact loading and the strength reading of the concrete with impact will be higher. Repeated cyclic loading of about 5000 cycles on concrete cube can reduce the strength to 70 percent. Similarly sustained load can decrease the strength to about 80 percent of the normal test load. The cylinder strength of concrete is about 85 percent of the cube strength. It is therefore seen

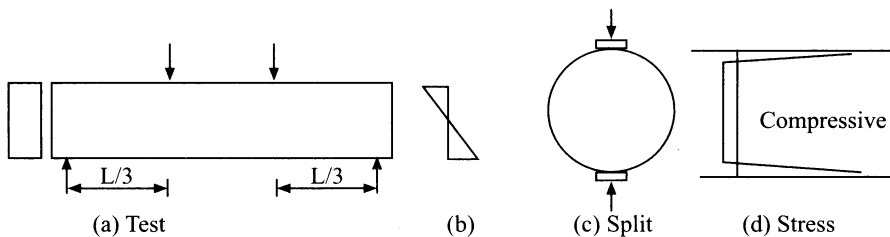


Figure 1.13.2 Flexure and split cylinder tests.

that the procedure in testing of the concrete has to be standardized to aim at consistency in understanding of the strength of the concrete.

There are other strengths such as prism, flexure, tension, split, shear, bond, etc., which are generally inter-related with the cube strength.

The tensile strength in bending, which is called strength in flexure of concrete is obtained by a flexure test of plain concrete beam specimen. The codes of practice specify a standard specimen subjected to two concentrated loads at one-third span points as shown in Figure 1.13.2

The bending tensile strength of concrete from the flexure test is also called as modulus of flexure and it is:

$$f_{cr} = \frac{M}{Z} = \frac{2WL}{bh^2}$$

where

M = bending moment in the pure bending moment zone = $WL/3$

W = concentrated load at one-third span

L = Span of the test beam, b = width of the section, and h = depth of the section

In the absence of a flexure test, one can get the approximate bending tension of the concrete from the compression strength of the concrete and it is given by:

$$\text{Modulus of rupture} = \text{bending tensile strength} = f_{cr} = 0.7 \sqrt{f_{ck}}$$

The direct tensile strength of concrete is sometimes needed in design of specific members. Unfortunately it is difficult to design a test to determine direct tensile strength of concrete. There used to be a test called briquette test for the determination of direct tensile strength. A specially designed specimen called briquette with gripping ends was suggested at one time. But it is found that it is almost impossible to apply axial tension load without causing bending on the specimen. Therefore the test was considered to be not good enough to determine the real tensile strength of the concrete. An empirical expression is often used to get an approximate direct tensile strength of concrete and it is:

$$\text{Direct tensile strength} = f_{ct} = 0.35 \sqrt{f_{ck}}$$

where

f_{ct} = direct tensile strength of the concrete.

Another test called split cylinder test was developed to estimate tensile strength of the concrete. The test is also called a Brazilian test. A 150 mm by 300 mm concrete solid cylinder is laid horizontal between the two platens of a compression-testing machine and subjected to compression load on diagonally opposite faces of the cylinder. Figure 1.13.2(c) illustrates the test and Figure 1.13.2(d) illustrates the stress distribution across the depth of the cylinder. The split tensile strength can be computed as:

$$f_{ct} = \frac{P}{\pi DL}$$

where

P = compressive force, L = length of the cylinder, D = diameter of the cylinder.

The direct tensile strength of the concrete is approximately equal to about sixty percent of the flexure strength of the concrete. The cracking strength of concrete is normally referred as

that equal to the split cylinder strength. The tensile strength of the concrete in bending is equal to the modulus of rupture in case of beams subjected to bending. The allowable tensile stress is obtained by dividing the tensile strength by partial factor of safety.

The reinforcement bars are embedded in concrete and the bar should not slip from concrete when it is subjected to pull or push. The bonding capacity of the concrete with the bar is called bond strength of the concrete. The bond strength of the concrete is determined by pullout test. A bar is embedded in a concrete cylinder and pulled from one end. Pulling force is applied at one end of the bar and slip at the other end of the bar is measured. The bond strength is determined in two stages. One that corresponds to no slip condition and the other is slip condition of the bar. The load at which the slip is initiated is called the no slip bond strength. The ultimate bond strength is the bond stress corresponding to load at which 0.25 mm slip takes place. The bond stress is equal to the pulling force divided by the surface area of the embedded bar. Table 1.13.1 gives different strengths of the concrete recommended for design.

TABLE 1.13.1 Modulus of rupture and bond strength (stress in N/mm^2)

Concrete strength = f_{ck} =	10	15	20	25	30	35	40	45
Modulus rupture	2.2	2.7	3.1	3.5	3.8	4.1	4.4	4.7
Bond stress for 0.25 mm slip								
Plain bars	–	1.9	2.4	2.9	3.3	3.4	3.5	3.5
Deformed bars	–	3.5	4.4	5.2	5.8	6.3	6.5	6.6
Bond stress for no slip:								
Plain bars	–	1.5	1.7	2.0	2.2	2.5	2.7	2.8
Deformed bars	–	1.9	2.1	2.5	2.8	3.1	3.4	3.5

Cube test: Concrete cube under compression has its top and bottom faces in contact with the compression platens. As the cube is subjected to uni-axial compression, the cube will get shortened and the lateral dimensions tend to expand by the Poisson's effect. However the contact top and bottom faces of the cube are constrained against the lateral expansion. The fracture of the cube is influenced by the frictional force on the top and bottom faces of the cube in addition to the axial compression. The failure is not by uni-axial compression but by combined action of the forces on the cube. The failure or the crushing pattern of the test cube is like a double symmetrical pyramid. Figure 1.13.3 illustrates the failure pattern of a concrete cube. The failure is brittle and is due to the combined effect of compression and friction on the faces. On the other hand when a concrete prism is subjected to uni-axial compression, the surface friction of the platens at the top and bottom faces damp out in short length and the middle portion of the prism experiences direct compression or uniaxial compression. The compressive strength of the concrete prism has a relation with that of the cube.

TABLE 1.13.2 Compressive strength of prism with respect to that of 150 mm cube

Length/width	0.5	1.0	2.0	3.0	4.0	5 and more
Relative strength	1.5	1.0	0.8	0.72	0.68	0.67

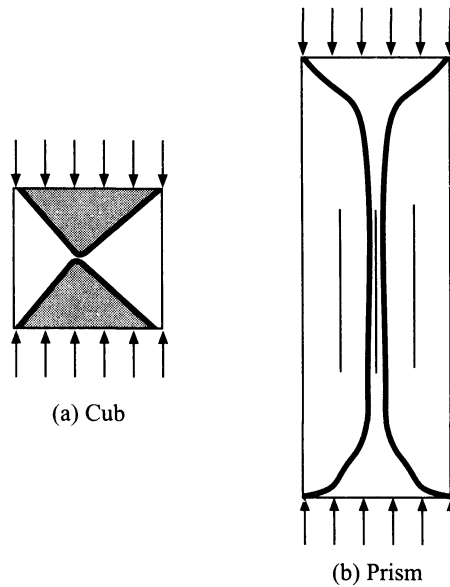


Figure 1.13.3 Failure pattern of concrete cube and prism under uni-axial compression.

The strength of a prism specimen decreases with increase in height-to-side ratio and converges to a value when this ratio is 4 or 5. The compressive strength of prismatic element where the length to thickness ratio is five or more, is 0.67 times that of the 150 mm cube. Similarly the 150 by 300 mm cylinder strength is about 0.80 times that of the 150 mm cube.

TABLE 1.13.3 Strength of concrete cubes with respect to that of 150 mm cube

Cube size (in mm) =	100	150	200	300
Relative strength wrt. 150 mm cube	1.05	1.0	0.95	0.87

The strength that is indicated by a cube specimen is estimated to be more than that by the cylinder specimen. The size of the cube and the diameter of the cylinder are to be same. Its relation is:

$$f_{cu} = (0.75 \text{ to } 0.80) f_{cy}$$

where

f_{cy} = cylinder strength having height to diameter ratio equal to two, and

f_{cu} = strength of concrete cube having the same size as that of the diameter of the cylinder.

The lower value applies to smaller sizes.

Moisture content in concrete provides lubrication effect and reduces the strength when compared with a dry sample.

Strength of a dry sample = (1.1 to 1.20) times the strength of the saturated sample.

Modulus of Elasticity of Concrete

Modulus of elasticity of a material is defined as the ratio of the uni-axial stress to the corresponding strain within the elastic limit. The stress-strain relation in concrete is almost linear up to 30 percent of the crushing strength and then it is non-linear. Therefore the measurement of elastic modulus in concrete is not as clear as that of steel. Three different moduli are mentioned in such non-linear materials.

Tangent modulus: The slope of the tangent drawn at a point to the stress-strain curve is called tangent modulus. This value depends on the point chosen on the curve. It decreases with increase in the stress level chosen. It is useful in the study of non-linear behavior of concrete structure.

Scent modulus: The slope of a line drawn from the origin of the stress-strain curve to a point at 40 per cent of the ultimate stress is called the scent modulus. This probably is realistic in the determination of elastic deflection of concrete structures.

Chord modulus: As the name indicates, it is the slope of the chord drawn between two points on the stress-strain curve. This is of very little practical usefulness.

Dynamic modulus: The tangent modulus measured at the starting stress-strain curve is considered to be the dynamic modulus of elasticity. This can be obtained from the compression test of a cube or a cylinder. This value is likely to be at least 20 to 40 per cent higher than the scent modulus.

Flexural modulus of elasticity: A simply supported plain concrete beam is subjected to concentrated load at mid-point and the deflection of the beam is measured for incremental loads. Flexural modulus of elasticity is computed from the load deflection relation of a simply supported beam. The test beam has to be slender so that the deflection due to shear is negligible. The flexural modulus of elasticity is given by:

$$E_c = \frac{WL^3}{48I_v}$$

The modulus of elasticity of concrete is essential to compute deflections of structures. The modulus of elasticity of concrete is taken close to the flexural modulus of elasticity. The code of practice suggests the modulus of elasticity in terms of the strength of the concrete. The Indian code of practice on plain and reinforced concrete suggests the following. The modulus of elasticity of the concrete E_c (in N/mm^2) can be taken as

$$E_c = 5000 \sqrt{f_{ck}}$$

A linear stress distribution across the depth of a beam is assumed for a beam subjected to bending moment. As the bending moment increases, the plain concrete beam fails when the tensile stress in concrete at the extreme fibre reaches the flexural strength. All the tensile force is resisted by the reinforcement in reinforced concrete beam under bending. Redistribution of stresses in concrete compression zone takes place as the load tends to failure level. Consequently the strength of concrete in bending is higher than that in direct compression. There is no such redistribution of stress in columns under compression.

1.14. Durability of Concrete Structures

The property of concrete structure to withstand the environmental effects along with loads is the durability property. The durability is measured on qualitative scale rather than a specific quantitative scale. The internal and external factors that influence the durability and life of a structure are listed and explained briefly in this section. The degree of the effect is different for different factors. A list of parameters that influence the durability is given and explained later.

Physical and mechanical factors:

Chemical Factors:

Biological and Environmental factors

1. Non-structural factors

(a) *Physical Internal factors:*

Compaction of concrete, Porosity and permeability of concrete, Surface finish of concrete, Duration of curing of concrete; Cover to the reinforcement and Surface cracking to start with.

(b) *External factors:*

Abrasion and erosion (wear & tear),

Exposure to wetting and drying (moisture) and Freezing and thawing

2. *Chemical Factors:*

Chemical composition of Aggregate, Quality of cement and water used, Exposure to acidic environment, Sulphate attack, Aggregate alkaline reaction, Other chemical aggressive actions.

3. *Biological and Environmental factors*

Biological growth, such a moss, algae etc on the surface of concrete

4. *Non-structural factors*

Shape and size of structural elements, Drainage from the structure, Joints, Inserts, Bearings, Railings, Anchorage and Fixtures.

There is interdependence between the factors that are listed above.

Physical Factors

The main physical factors that influence the durability of concrete are explained in brief:

- ❖ **Compaction of concrete and Moisture transport:** Production of good concrete should be the aim of any builder. Good workable concrete leading to dense and well-compacted concrete minimizes the transport of moisture within. The porosity or permeability of the concrete is a direct result of poor compaction of concrete. Transportation of moisture induces physical and chemical reactions that are responsible for the deterioration of the concrete. Diffusion of air, carbon dioxide and chloride ions etc. into concrete combined with moisture add to the problem. The carbonation of concrete leads to increase in volume and cracking. Similarly the presence of moisture and air leads to corrosion of reinforcement.
- ❖ **Surface Finish:** Water in contact with the concrete surface is transported through capillary action even in well-compacted concrete. Uneven and rough surface retains moisture and transports. Micro-cracked surfaces of concrete permit the movement of water freely into the concrete. An impermeable concrete surface is the most ideal

finish even though not possible, but even such surfaces develop micro cracking in due course because of changes in temperature and chemical actions. Adequate precautions must be taken to maintain an even and un-cracked surface of concrete.

- ❖ **Wetting and drying:** Water carries dissolved salts such as sulphates, chlorides, carbonates etc. into the pores of the concrete under wet condition. The moisture in the concrete evaporates during drying leaving dissolved salts in crystallized state. The accumulation of such crystals increases the volume leading to cracking of the concrete. Further the concentrated crystallized chemical act on the aggregates and reinforcement causing carbonation and corrosion as the case may be. Efflorescence of crystallized salts at the surface of concrete is also a result of wetting and drying.
- ❖ **Freezing and Thawing:** Water or moisture transported into the pores of the concrete when exposed to freezing and thawing causes volume changes in addition to the acceleration of chemical degradation. This leads to cracking of the concrete and deterioration.
- ❖ **Chemical Factors**
Chemical reactions take place due to internal concrete structure or external exposure environment. Some of the important chemical attacks on concrete are briefly mentioned. Moisture transportation aids the chemical attacks.
- ❖ **Carbonation, Acid formation and attack:** Moisture along with environmental gases, liquids and solids lead to formation of acids that react with hydrates of cement. The chemical attack breaks the chemical bonds in the calcium silicates and hydrates thus destroying the strength of the concrete. The extent of deterioration depends on the density and porosity of the concrete, cement and aggregate properties and the environmental conditions.
- ❖ **Sulphate attack:** The sulphate ions from soil or water or even from cement react with calcium hydroxide in the concrete forming sulphates. The increase in volume due to formation of sulphates within the pores of the concrete result in cracking and further degradation of the concrete. The presence of aluminates in cement has a tendency to expand in volume on reaction with sulphates.
- ❖ **Alkali and chemical attacks:** Concrete is initially saturated with lime therefore has an alkali environment. The sodium and potassium ions in the alkali solutions attack the silica of the aggregate. The rate of attack depends on the active silica in the aggregate and dust particles, porosity of the concrete and moisture transport. Concrete surface when exposed to acidic environment reacts with aggregates resulting in increase of volume and consequent cracking.
- ❖ **Biological and Environmental Factors**
Continuous presence of moisture on the surface of concrete promotes biological growth such as moss, algae and small plants. Penetration of plant roots and biological products into concrete results in cracking and deterioration.
- ❖ **Corrosion of Reinforcement**
Oxides of iron and steel are formed when the reinforcement is exposed to moisture and oxygen. Similarly the chloride ions accelerate the formation of oxides of iron. The alkali environment in the concrete with pH value in the range of 12 provides good

protection against formation of iron oxides. The diffusion of carbon dioxide into concrete reacts with calcium hydroxide forming calcium carbonate. Therefore the pH value in concrete decreases to 9 and the protection to the reinforcement decreases. The dissolution of positively charged iron ions and the combination of the released electrons with moisture and oxygen results into hydroxyl ions. The ion activates the formation of ferric oxide. The formation of ferric oxide on the surface of the reinforcement results into increase in volume of rusted surface. The increase can be as much as 50 to 200 percent of the iron content.

The high alkalinity and relatively high electrical resistivity of Portland cement under moist condition protects the embedded reinforcement in concrete. Factors that are likely to cause corrosion to the reinforcement are:

- (a) Inadequate cover to reinforcement,
- (b) Cracking of the concrete,
- (c) Honey combing of concrete,
- (d) Carbonation of hydrates,
- (e) Electrolysis.

Good concrete with well-finished surface and having adequate cover to the reinforcement provide good protection to reinforcement against corrosion. Cracks or voids in the concrete provide an access to moisture, air and other environmental chemical agents. Rusted steel will expand in volume thus causing cracking along the reinforcement. The hydrated cement when exposed to carbon dioxide gets carbonated and results in increased shrinkage and cracking. The alkali protection to the reinforcement is lessened. Similarly passage of electricity or development of static potential difference around the reinforcement causes oxidation and corrosion. The following are recommended to protect the reinforcement against corrosion. The main aim is to minimize the permeability.

- ❖ The most important is to place good concrete with excellent surface finish and cure it well.
- ❖ Select lowest feasible water-cement ratio.
- ❖ Minimize the use of admixtures containing calcium chloride, or soluble chlorides. Restrict the entry of salts through the water used either in the concrete mix or in curing.
- ❖ At least 14 days of uninterrupted curing be done so that good hydration takes place without micro-cracking.
- ❖ Adequate cover to the reinforcement be provided.
- ❖ **Stress Corrosion in Pretension Steel**
The oxidation of stressed steel wires results in sudden splitting of the wires. This phenomenon is present in stressed steels of prestressed concrete constructions.
- ❖ Non-Structural Component Factors.

The discontinuities in construction, construction and expansion joints are liable for problems. Corrosive and even non-corrosive fixtures and inserts exposed to moisture are liable for causing cracking in the concrete. Such non-structural elements must be planned, positioned, placed, protected and maintained carefully.

As per the IS: 456:2000(2005), the code of practice of plain and reinforced concrete, the factors influencing the durability of concrete structures include:

- ❖ The Environment,
- ❖ The cover to the embedded steel,
- ❖ Type and quality of construction material,
- ❖ Cement content and water-cement ratio of concrete,
- ❖ Workmanship to obtain full compaction and efficient curing,
- ❖ The shape size of the member.

1.15. Durability Design Considerations

The exposure conditions of a structure decide the selection of structural and architectural materials, design and detailing of the elements. The basic five exposure conditions for the durability design considerations are:

1. Mild exposure,
2. Moderate exposure,
3. Severe exposure,
4. Very severe exposure, and
5. Extreme exposure.

Mild exposure: The mild exposure condition may be called as protected environment. Interiors of dwellings, offices, commercial complexes and workshops of non-aggressive environment and other structures protected against weathering, wetting and drying are classified in this group.

Moderate exposure: Foundations buried under non-aggressive soils and ground water, structures exposed to rain and not under frequent wetting and drying, outside non-aggressive environment, high humidity halls, running water (canals, dams, weirs etc.) bath rooms and water tanks come under this class.

Severe exposure: Structures exposed to frequent wetting and drying of ordinary water, partially submerged under water, occasional freezing situations, structures in coastal regions, structures subjected to constant vibrations, foundations in aggressive soils are considered to be under this classification.

Very severe exposure: Structures exposed to sea water spray, extreme freezing, chemical fumes, colour dying halls, partially submerged sea water (all harbor structures in contact with sea water), septic tanks come under this classification.

Extreme exposure: Concrete roads; structures under constant abrasion in wet and dry conditions, direct contact with aggressive chemicals, floors of chemical plants are classified in this category.

The important parameters are listed here. Table 1.15.1 lists the desirable specifications for the different materials etc for the five exposure conditions.

(a) **Materials:**

- Quality and Quantity of aggregate,
- Type and Quantity of cement,

Water Quality, Water-Cement ratio,
Admixtures if any to be used,
Concrete mix design and its workability,
Reinforcement and
Inserts and Fixtures.

(b) **Detailing and Workmanship:**

Surface finish, shape and texture,
Cover to the reinforcement and precautions,
Finishing of joints,
Drainage of water,
Curing of concrete,
Accessibility for maintenance and
Quality assurance scheme.

(c) **Maintenance:**

Inspection regulations,
Systematic maintenance scheme and implementation,
Immediate attention to damages,
Replacement and Repairs,
Renovation and Prevention of accumulation of water.

TABLE 1.15.1 Recommended limits for durability considerations
(unless otherwise stated it is by weight)

Material / Property	Exposure Classification			
	Mild (1)	Moderate (2)	Severe (3)	Very Severe & extreme (5)
Aggregate	Normal	Normal	Good	Good
Grading	40	40	30	30
Crushing value (Max.)	2000	2000	2200	2400
Aggregate density (kg/cm) (minimum)				
Amount of Silts/clay/fine (less than 0.15 mm) (Maximum %)				
In Coarse	2	2	1	1
In Sand	4	3	2	2
Sulphates Admissible (max %)	1	1	0.5–1.0	0.5–1.0
2. Cement (OPC)				
Minimum(kg/cum)				
PCC	220	240	250	260–280
RCC	300	300	320	340–360
PSC	350	350	400	400–400
Maximum content (kg/cum)<-----	450	----->		

(unless special considerations are given)

3.	Maximum Water Cement ratio				
	PCC	0.60	0.60	0.50	0.45–0.40
	RCC	0.55	0.50	0.45	0.45–0.40
	PSC	0.50	0.50	0.45	0.45–0.35
	(Better avoid PSC in highly aggressive environment)				
4.	Minimum grade on concrete				
	PCC	M10	M15	M20	M20, M25
	RCC	M20	M25	M30	M35, M40
	PSC	M35	M40	M45	M45–150
5.	Water quality for mixing minimum. pH value	4.5	6.0	6.0	6.5
6.	Maximum chloride content Maximum acid soluble Chloride content as % of chloride ion by mass of concrete				
	PCC	1%			
	RCC	0.15%			
	PSC	0.10%			
7.	Minimum cover (in mm) to reinforcement bars in RCC (The cover specification applies to main and secondary reinforcement)				
	Slab	20	20	25	30 to 35
	Walls	20	20	25	30 to 35
	Beams	25	30	45	50 to 60
	Columns	40	40	45	50 to 75
*	(1) A wearing or maintenance protective coat to be provided to the concrete in extreme exposure condition (Reinforcement be coated with protective coating) (2) Cover should not be less than the maximum size of bar				
8.	Inserts projecting beyond the concrete surface should be made of:	Steel	GI	GI	Stainless steel
9.	Minimum clear spacing of reinforcement	Diameter of the bar, or Maximum size of aggregate + 5 to 10 mm,			
10	Minimum cover (in mm) to prestressed concrete wires or cables				
	Slabs	20	25	25	25–30
	Beams	25	30	45	45–75
11.	Recommended maximum crack widths (in mm)	0.3	0.2	0.1	0.1
12.	Minimum clear spacing of cables ducts in PSC	<----- 1.5 to 2 times the diameter of the ducts (preferably 2 times the dia of duct.)----->			

Structural Concrete: The constituents of concrete, namely aggregate, cement, water and admixtures must satisfy the standard requirements. Further there are limits on quantities and qualities of the basic materials to suit the exposure requirements. Similarly the mix proportions, methods of mixing, laying, consolidation, finishing, formwork and curing are important. Testing methods and quality assurance must be given adequate importance.

Aggregate: Normal aggregate well graded and containing least amount of fine particles (less than 0.15 mm) should be selected. The crushing value of the aggregate reflects the grading and angularity. Some recommended limits on aggregate are given in Table 1.15.1. Some variations in the limits are permitted based on the type of construction such as Plain concrete, Reinforced concrete etc.

Cement and Water: Portland cements of grades 33, 43 and 53 are suitable for structural concrete. Portland composite (Pozzolana) cements can also be used depending on the type of construction conditions. 53-grade cement is faster in hardening when compared with the 33 grade. A minimum quantity of cement content, especially in reinforced concrete is required to provide adequate alkaline environment to protect the steel from corrosion. Similarly maximum limit is suggested to minimize shrinkage and heat of hydration effects. Shrinkage of concrete increase with water contents hence a reduction in water-cement ratio enables higher cement content. Water used in concrete making should conform to the standards and should not contain oil, organic matter, humic acid etc. The water-cement ratio should be as low as possible not only for strength consideration but also to minimize the porosity of the concrete.

Admixtures: Admixture added to cement or concrete to improve the properties such as workability, setting time or to decrease the permeability should not normally exceed 5 per cent and preferably in the range of 2 per cent or as recommended by the manufacturer. Admixtures or additives should not contain any chlorides in any form in reinforced or prestressed concrete constructions.

Strength of concrete: Strength of concrete need not necessarily indicate the durability, but yet it is considered as a desirable index for durability. Concrete must have a minimum strength for durability considerations. It indirectly reflects the quality of production and porosity. Minimum acceptable grades of concrete under different exposure conditions in the opinion of the author are listed in Table 1.17. The ones suggested by the code is listed separately.

Reinforcement: Some suggestions on cement and water contents were already explained and the limits are indicated in the Table 1.17 to protect the reinforcement from corrosion. The other suggestions and design parameters are:

- (a) Uninterrupted curing to avoid micro-cracking and complete hydration,
- (b) Blended cements with slag or fly ash or silica fumes can be used,
- (c) Limit the total sodium oxide to a maximum of 0.6%,
- (d) Use Low water-cement ratio, and
- (e) Provide adequate cover to the reinforcement and not less than that mentioned in Table 1.15.1.

Proper placing of reinforcement to ensure the cover to the reinforcement is ensured. Unfortunately cover to the reinforcement is the most neglected factor as the workers trample during construction. Table 1.15.1 suggests the minimum cover to be provided to the reinforcement.

Similarly the clear spacing of the bars and cables should be adequate enough to achieve sound concrete around the bars. A special protective treatment to the concrete surface or to the reinforcement should be provided in aggressive environment as of extreme exposure.

Inserts: Steel or galvanized iron or stainless steel inserts can be embedded in concrete depending on the exposure conditions. Wrongly placed or wrong inserts exposed to moisture or retention of moisture because surface damages, which leads to deterioration of the structure. Table 1.15.1 recommends desirable type of inserts.

The minimum cement contents and the water-cement ratio as suggested by the code are listed in table 1.15.2.

TABLE 1.15.2 Minimum quantity of cement or cementitious material required, and Maximum W/C ratio permitted as per IS: 456-2000(2005)

Exposure	Plain Concrete		Reinforced Concrete		Minimum Grade Concrete	
	Min. Cements (kg/m ³)	Max. free w/c	Min. Cements (kg/m ³)	Max. free w/c	Plain Concrete	Reinforced Concrete
Mild	220	0.6	300	0.55	-	M20
Moderate	250	0.60	300	0.50	M15	M25
Severe	260	0.50	350	0.45	M20	M30
Very Severe	280	0.45	375	0.45	M20	M35
Extreme	300	0.40	375	0.40	M25	M40

Note: Cement content specified is irrespective of grade of cement,

It is inclusive of additions made to concrete such as flyash, blast furnace slag etc., with respect to water cement ratio, Minimum grade of concrete for plain concrete is not specified for mild exposure conditions.

TABLE 1.15.3 Adjustment to Minimum Cement contents for aggregate other than 20mm Nominal size

Nominal size of aggregate (mm)	Adjustment to minimum cement content of Table 1.18 (kg/m ³)
10	+40
20	0
40	-30

Maximum Cement Content: The code on practice of plain and reinforced concrete specifies maximum cement content. Cement paste shrinks on drying, more cement means more shrinkage. Further, heat of hydration is also increases with increase in cement content. Heat of hydration leads to micro cracking. Micro cracking further leads to ingress of water and

ultimately deterioration of concrete, corrosion of reinforcement. It is therefore desirable to limit the maximum quantity of cement content. The maximum cement content recommended by the Indian code of practice is 450 kg/m^3 unless otherwise approved by the engineer in-charge.

Chlorides in Concrete: The chloride ion may be present in the components of concrete, such as water, aggregate, sand, admixtures, and cement. Or chloride may be diffusing from the environment into the exposed surface of the concrete. The chloride ion causes corrosion of reinforcement at an accelerated rate.

Maximum limit in sulphate: Sulphates are present in many aggregates, and even in cement. The soil on which the structure stands may also contain sulphates. Even the environment contains some forms of sulphur and sulphates. Sulphates combining with water results in compounds of higher volume. It is necessary to limit the total sulphur trioxide (SO_3) content in the concrete to 4 per cent by mass of the cement. This limit doesn't apply to super-sulphated cement complying to IS: 6909.

Alkali-aggregate reaction: Almost all aggregates contain silica as the main element. Alkalis such as sodium (Na_2O) and potassium (K_2O) react with silica in the aggregate producing expansive compound. This reaction is produced if the concrete is exposed to high moisture. The cement or the aggregate may contain alkali reactive constituents. Increase in the volume of the reacted aggregate will cause cracking and deterioration of the concrete. The following precautions should be taken.

- ❖ Use non-reactive aggregate,
- ❖ Use fly ash conforming to IS: 3812 or blast furnace slag conforming to IS: 12089. Or use Portland Pozzolana cement etc.,
- ❖ Protect the concrete from constant exposure to moisture,
- ❖ Limit the alkalis to 1.1% in cement.

1.16. Fire Protection Specifications

Domestic facilities such as cooking gas and electric power lines are provided in most homes. A liability of fire hazards to homes exists. Modern buildings has large amount of combustible material such as clothes, wooden furniture, books and paper, plastic items and wall and curtain hangings etc. The permanent buildings are built with brick and concrete. These building materials resist the fire well. The strength of the material deteriorates fast under fire. The increase in vertical heights of the buildings and compactness of the multistory buildings make the fire fighting a complex problem. The buildings must be built to resist fire to desirable safe levels. This section is only an introduction to the fire protection specifications of simple buildings. Fire protection measures to tall buildings are not dealt in this book. The time period for which a building can withstand fire without serious damages is called fire rating. The basic fire ratings and the protection specifications to the structural materials based on the code suggestions are mentioned in this section. Minimum dimensions and minimum cover required to the reinforcement for different periods of fire exposure are listed in tables 1.16.1 and 1.16.2.

TABLE 1.16.1 Minimum required dimensions for members (in mm) for fire rating in hours

Rating hours	Beam & floor dimensions			Column dimension		Wall thickness	
	Beam width	Rib width	Floor thickness	Fully exposed	One face exposed	0.4% < p < 1.0%	p > 1%
0.5	200	125	75	150	100	100	100
1.5	200	125	110	250	140	140	100
2.0	200	125	125	300	160	160	100
4.0	280	175	170	450	240	240	180

p = percentage of reinforcement

It can be seen that the code has come with precise minimum dimensions and minimum covers to the reinforcement. In the present practice the minimum thickness of ribs of waffle slabs are made in the range of 100 mm as against 125 mm now recommended. The thickness of such waffle floor slabs may even start from 60mm at the moment as against 75 mm thickness suggested for half an hour fire rating.

TABLE 1.16.2 Nominal cover requirement to reinforcement (in mm)

Rating	Beams		Slabs		Ribs		Columns
In hours	Ss	Cont.	Ss	Cont.	Ss	Cont.	
1.0	20	20	20	20	20	20	40
1.5	20	20	25	20	35	20	40
2.0	40	30	35	25	45	35	40(45)*
3.0	60	40	45	35	55	45	40(55)
4.	70	50	55	45	65	55	40(65)

Ss = simply supported, Cont. = continuous, *the values given in the brackets recommended by the author on the assumption that if the ribs need 45 mm cover the columns that are exposed to the same order of heat should have atleast that much cover. Columns at about the middle height of the floors are seen to have had maximum damaged in fire.

The waffle slabs are usually provided in large halls for public gatherings and also in tall buildings. The minimum fire rating of such public halls is 1.5 hours and above. If that is the case, the waffle slab thickness can't be less than 110 mm. The minimum cover to the reinforcement in ribs for 1.5 hours of fire rating is 35 mm in simply supported waffle slabs. The minimum width of the rib will be atleast 160 mm. Further the cover requirement as per the present code applies to main as well as secondary reinforcement.

1.17. Quality Assurance in Concrete Structures

Concrete is a powerful material leading to innovative structures and methods of construction. The innovative structures require innovative and quality controls to give high reliability. The concrete construction uses a wide spectrum of skilled and semi-skilled workers. Experienced

engineers and construction companies, build outstanding structures with excellent quality controls; and on the other end of the spectrum, skilled and semi-skilled workers build concrete houses for common man with little or no supervision. The quality assurance of concrete structures varies from reliability level to uncertainty level. There are many non-engineered buildings being built in India. There is a need to educate the semi-skilled and engineers on the quality assurance of concrete structures.

A number of questions do arise on the quality assurance programme. The questions are how and what exactly is to be assured? How a quality of a structure can be assured? In the final analysis, it is the quality of the structure to be assured and not only the quality of the materials as dominantly observed today. Components that control the quality of a structure are:

1. Quality of the basic materials such as aggregate, cement, water, admixtures, etc.
2. Mix proportions of concrete and its production,
3. Construction and fabrication of the structure, formwork,
4. Transportation, placing, compaction and finishing of concrete,
5. Tolerances in quantities and qualities, and detailing,
6. Curing of concrete,
7. Strength and serviceability design of the structure,
8. Durability specifications and maintenance,
9. Life expectance.

At the moment, the quality control is leaning heavily towards items one and two of the above list because of the historical and technological background. The idea that the quality control in the basic materials and the production of the concrete ensures the quality of the final structure is a necessary condition but not sufficient. Input of excellent material doesn't guarantee an excellent product. There are a number of inter links between the quality of basic materials and the final structure. Between the cup and the lip, there are a number of slips.

Code Provisions on Quality Control

The clauses on the quality control of concrete structures given in the code are primarily on materials and production of concrete and not on the final structure. Characteristic strength of the concrete is the centre of focus in the design and even construction of concrete structures. The characteristic strength is defined as the strength of the material below which not more than five percent of the test results fall. Strength of concrete, as a matter of fact, strength of any material will follow a normal distribution. Figure 1.17.1 illustrates a normal distribution curve in which the five-percent cumulative value is indicated.

The characteristic strength in terms of probability of failure definition can be expressed as:

$$P(f_c < f_{ck}) = pf$$

For a normally distributed strength of concrete where pf is the accepted probability of failure. The above probability acceptance can be expressed as:

$$\phi(f_{ck} - f_m)/s = pf$$

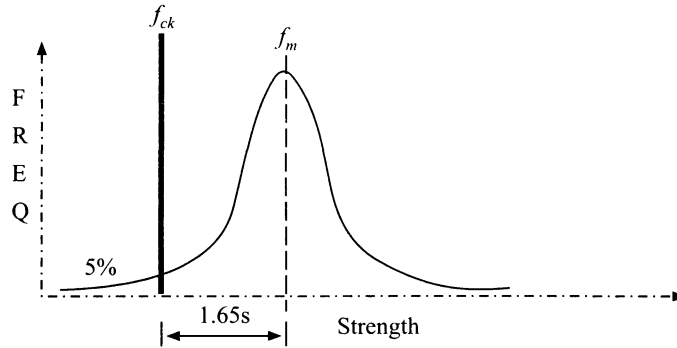


Figure 1.17.1 Normal distribution curve.

where

f_m and s are the population mean value and standard deviation of the normal distribution, f_{ck} characteristic strength, ϕ is the cumulative normal distribution function.

The expression can be inverted to establish the relation between the mean and characteristic strengths, and it is:

$$\phi^{-1}(pf) = (f_{ck} - f_m)/s = -k$$

where k is an index that signifies the acceptable probability of failure. The minus sign is assigned as the five per cent is on the negative end of the curve. The value of k is 1.65 for five-per cent acceptability of failure.

The inverse of the equation can be rearranged as:

$$f_m = f_{ck} + 1.65s$$

The minimum size of the sample needs to be about fifty in general for a normal distribution, however the code accepts the size of thirty. Even that is not a practicable size for day to day quality control of concrete. Three concrete cube specimens form a sample. In most constructions, thirty-sample size is not practicable in day-to-day control, therefore four consecutive non-overlapping samples are considered to be a practicable size to test the acceptability of the concrete. As the size is smaller than the minimum population size, a modification to the acceptability expression is suggested. An expression, which satisfies the five percent acceptability criterion with a sample smaller than thirty, is given by:

$$f_{m1} = f_{ck} + 1.65 s (1 - 1/\sqrt{n})$$

in which n is the size of the sample and f_{m1} is the mean value of the smaller size sample. The equation reduces to the earlier one for n tending to infinity and the mean value comes out to be same as characteristic strength for a single sample.

The above equation for four non-overlapping samples reduces to:

$$f_{m1} = f_{ck} + 0.825 s$$

Besides the pre-assigned checks on the input materials, the main clauses on the quality control acceptability of concrete as per IS: 456-2000(2005) is:

(a) The concrete is said to acceptable if the following relation is satisfied

$$f_{m1} \geq f_{ck} + 0.825 s ; \text{ or}$$

$$f_{m1} \geq f_{ck} + A, \text{ and}$$

$$f_i \geq f_{ck} - B$$

where f_{ck} = characteristic strength,

f_{m1} = mean strength of any four consecutive non-overlapping samples,

f_i = strength of a sample,

$A = 3$ MPa for $M15$ concrete and 4 MPa for $M20$ grade concrete and above

$B = 3$ MPa for $M15$ concrete and 4 MPa for $M20$ grade concrete and above

The concrete is liable for rejection if it is porous or honeycombed, improper construction joints and tolerances on size of the members. It can also be rejected for improper placement of reinforcement and inadequate cover, and not following the specifications.

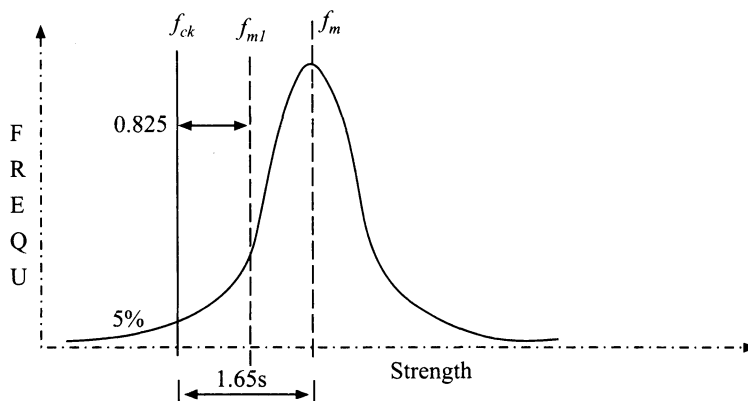


Figure 1.17.2 Mean value for 4 sample acceptance.

The mean strength requirement set up by the code is on the liberal side especially for concretes of $M35$ and above. The mean strength of four consecutive samples needs to be four Newtons per square mm or 0.825 times the standard deviation is easy to satisfy. The value 0.825 derived from the normal distribution of the statistics is acceptable if the sample size is large. Consider a case of eight sets of four consecutive non-overlapping samples. Let each of the samples satisfies the criterion of the mean value greater than the characteristic strength by 0.825 times standard deviation. But when all the thirty two samples are considered as a large sample, the global quality control expression demands that the mean value should be greater than the characteristic strength by 1.65 time the standard deviation of the total sample. The standard deviation of the total sample will be more than the standard deviation of any one of the eight samples. Further the multiplier of the standard deviation is 1.65 . The chances of satisfying the acceptance criterion of the large population of thirty-two samples are not high.

The acceptability criteria are supposed to be valid for all concretes upto 60 MPa. That may mean even if the concrete is of $M60$ grade, the mean value of the order 64 MPa of four

consecutive samples is acceptable. In that sense the section is liberal. To say that strength of every sample should have a value greater than characteristic strength minus 4 MPa is more stringent. For example that for M60 concrete, no sample strength should be less than 56 MPa. This could cause some problem because the margin for individual sample strength is rather small. For example, the Indian Road Congress (IRC) permits strength of a sample not less than 80 per cent of the characteristic value, and the earlier version also permitted this eighty-per cent.

Concrete Cube Test

As per Indian building code of practice, a concrete sample consists of three 150 mm-cube concrete specimens, cured for 28 days in water and tested under moist surface dry condition. The sample is subject to the following conditions:

1. Sample should be selected randomly,
2. The mould of the cube is well-finished steel or cast iron,
3. The concrete is placed and vibrated under careful control conditions,
4. Cured under good moist condition,
5. Tested on 7th or 28th day of curing the sample.

The concrete CUBE TEST has become a demi-god in quality assurance of concrete structures. It is a hope that the concrete in the structure has the same qualities of the sample! The code further states the following on the Inspection and Testing of the structure:

Care should be taken to see that:

- (a) Design and details are being capable of being executed,
- (b) Clear instructions on the inspection standards,
- (c) Clear instructions on the permissible deviations,
- (d) "Elements critical to workmanship, structural performance, durability and appearance are identified"
- (e) There is a system to verify the quality is satisfactory in the individual parts, especially the critical.

Other Deficiencies of Acceptable Criteria in Cube Test

A concrete sample consists of 3 specimens to be tested on 7th day, another 3 specimens to be tested on 28th day after casting and curing. Standard also specifies how the samples to be collected, cast, cured and tested. The small constructions in India are mostly site mixed. Even though concrete is made by weigh batching, the batching plant itself is not necessarily automated in many cases. Consequently, there are some inherent deficiencies in the acceptability cube test criterion. Compressive and flexural strength tests are specified of which the flexural strength test is considered only in special conditions. Some of the weak points in the acceptance criteria are:

- (1) The concrete batch from which the samples are collected may be prepared with care even though the samples are supposed to be randomly chosen,
- (2) Filling, compaction of samples is different from placing and vibration of the concrete in the structure,

- (3) The formwork and shuttering to the concrete in structure is not as grout leak proof like the cube mould,
- (4) The time difference in transportation and lying of the concrete in position could be different from that of the preparation of cube specimens,
- (5) The congestion of reinforcement that might cause honey combing is not reflected in making of the cubes,
- (6) The curing of cubes is done systematically when compared to the curing of the concrete in structure,
- (7) Testing of 3 specimens as a sample and taking an average strength of the sample is not dependable. Even if more number of samples is considered but the total number in a batch of construction is not high for a statistically acceptable level.
- (8) There is a likelihood of less quality control in real concrete structure, detailing of reinforcement, formwork and curing as the actual concrete is not subjected to any testing.

In case where the tensile strength of the concrete plays an important role, flexure test is recommended by the code.

1.18. Non-destructive Testing of Concrete Structures

Methods of non-destructive testing are developed during the last four decades. Reliable equipment for such non-destructive testing is manufactured only in recent times. Further a number of non-destructive tests are available. Ultra sonic non-destructive testing has been accepted as a reliable method of testing of welding in all-important steel structures. At the moment, rebound hammer test, ultrasonic test, and core-cutting tests are considered to be dependable tests in concrete construction. Of these, ultrasonic test has its own advantages and considered being efficient in locating honeycomb and porous concrete. The core cutting sampling test is adapted to a limited extent because of practical difficulties associated with core drilling, specimen preparation and drilling in thin elements etc. Rebound hammer test that indicates the hardness of concrete surface reflects the strength of the concrete indirectly. This test is used quite extensively in assessing the quality of actual concrete in the structure. The test can be carried out quite extensively and a reliable statistical approach can be applied for acceptance of the test. Some of the strong points in quality control through rebound hammer test are:

- (1) A very large number of test readings can be taken in short duration,
- (2) Large number of locations on the structure can also be selected,
- (3) A statistical approach with high degree of confidence can be applied,
- (4) Actual structure is tested, therefore the test result reflects the totality of the final product indicating the concrete mix, its consolidation, surface finish, formwork and curing,
- (5) The builder/contractor or even the supervisor will be careful during the real concreting because the actual structure is under testing.

An indiscriminate application of the non-destructive testing without proper correlation factors can lead to misleading results. Number of precautions and correction factors to the results of concrete rebound hammer test are needed. These special aspects are:

- (1) Surface texture preparation,
- (2) The size or the thickness of the element under testing,
- (3) Moisture content in the concrete,
- (4) Level of maturity of the concrete with respect to 28 days strength,
- (5) Accuracy of the test hammer,
- (6) Stability of the supporting base used during testing.

The results may have the marginal variation if the method of testing and speed of impact is not uniform, so while calibrating the equipment, the person actually testing can be involved to reflect the method of testing.

The following are some of the observations regarding the concrete test hammer results:

- (1) Moist concrete surface will show a lower strength when compared with a dry one,
- (2) Thin elements such as slabs, reflect higher strength when compared with thick elements and mass concrete,
- (3) Rough surface will give a lower reading when compared with smooth one,
- (4) Grout coated or plastered surface will also show lower strength when compared with the original concrete,
- (5) A direct reading on aggregate surface will indicate a higher value.

Since very large sampling can be done even on a single element without much effort, data will reflect the final quality of the concrete. A rationalized statistical approach to obtain the strength of the concrete is dependable when compared to the results of standard cube tests. Many Engineers feel that the results of the concrete rebound hammer gives the strength of the concrete on the surface of the structure but does not reflect the quality of concrete inside. Testing of the surface extensively should give much more confidence when compared to cube strength randomly selected and tested. As per present practice, a cube test consisting of 3 to 6 cubes is expected to represent the quality of the concrete of the structure irrespective of where and from which portion of the structure the concrete cube is supposed to have been taken as a sample. If one can accept such a concrete cube as representative sample, there is no need to doubt the reliability of statistically arrived result based upon concrete rebound hammer test.

Acceptable Criteria of Non-destructive Test

The present section deals primarily with rebound hammer test.

Sampling and Acceptable criteria:

- (1) Minimum number of locations should be 10 for an element or for a given pour of concrete,
- (2) At least 10-hammer reading should be taken at each location. A location means a spot of about 75 mm square.
- (3) All readings beyond 20% of the average value should be rejected. If the number of readings to be rejected exceeds 20% of the readings, then the reliability of the location should be examined. There could be a special problem such as honey combing or porous concrete at such locations.

- (4) The total number of readings should be atleast 100 for given element or of a pour of concrete.
- (5) The co-efficient of variation of the readings should be within 15%. The characteristic strength of the concrete should be calculated after converting each of the readings to the equivalent strengths with appropriate correction factors.
- (6) The characteristic strength of the concrete can be calculated by the formula given below:

$$f_{ck} = fm - 1.65s$$

In which fm = mean value of the strength; s = standard deviation

This implies that the probability of the strength falling below the specified value is not more than Five per cent.

- (7) In case 20% of the locations have fallen under the rejected, then the quality of concrete is considered not acceptable.

Example

A simple illustration of results of non-destructive test undertaken on roof slab of a building is given in this example.

The example gives statistics and frequency distribution of the data in table 1.18.1. Table 1.18.2 also gives most probable characteristic strength predicted by the computer program design exclusively for NDT test. There is a considerable scope in predicting a reliable strength of the concrete based upon of the statistical analysis of the test results.

TABLE 1.18.1 Statistics of non-destructive test(Data in N/mm²)

Frequency Distribution: for MIN. CHI-SQ. value	
Total number of samples:	80
Max. Value of the data:	36.30
Min. value of the data:	10.70
Number of interval:	7
Class interval width:	3.71
Final class is extended upto +ve infinity	

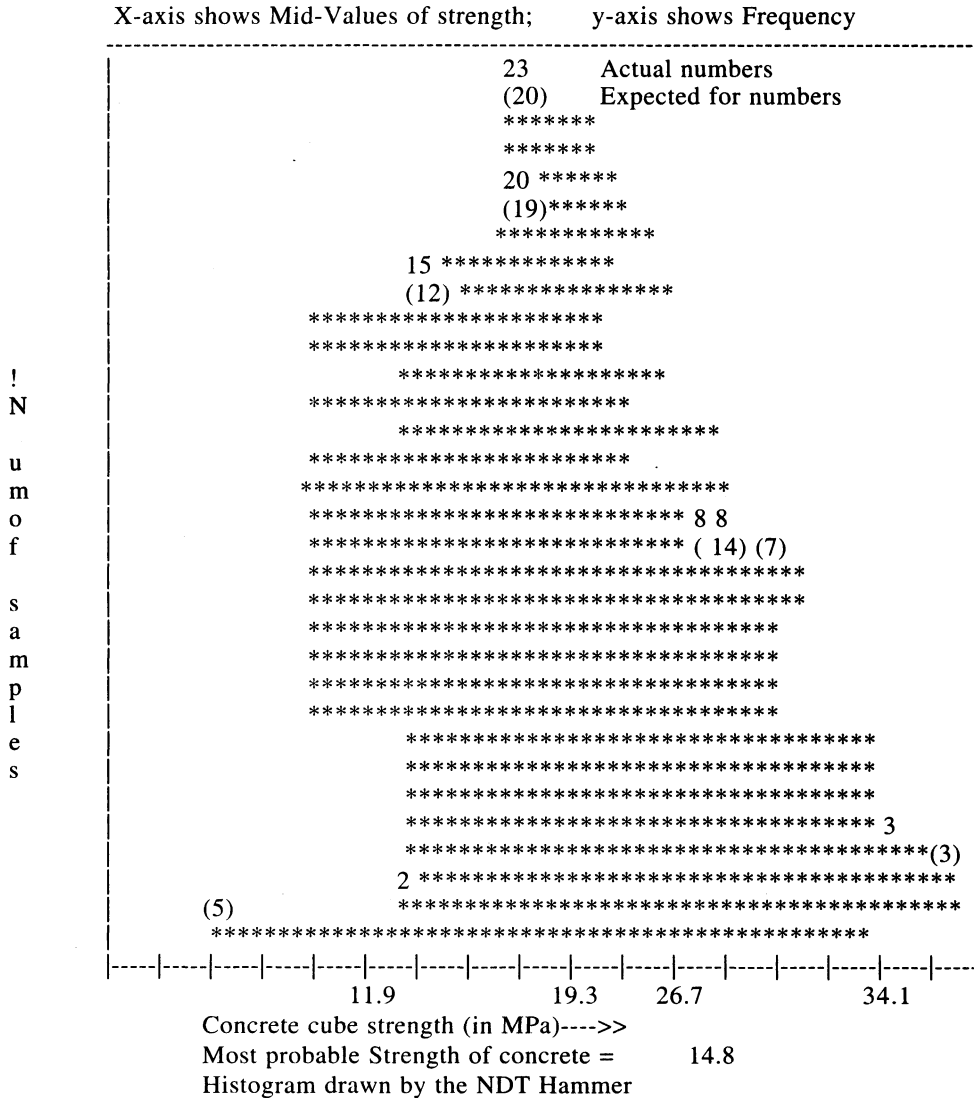
Remaining LEFT side area under normal curve is considered as a separate class interval

Class-Interval	Actual.	Cum.	Expected	Cum. Expected.
.1000E+02 .1371E+02	2	2	5.08	6.86
.1371E+02 .1743E+02	15	17	11.83	18.69
.1743E+02 .2114E+02	20	37	18.55	37.24
.2114E+02 .2486E+02	23	60	19.57	56.81
.2486E+02 .2857E+02	8	68	13.89	70.70
.2857E+02 .3229E+02	8	76	6.63	77.34
.3229E+02 .3600E+02	3	79	2.66	80.00

MEAN: 21.64
 MODE: 21.76
 SKEWNESS Coefficient: .596
 CHI-SQUARE: 0.38308E+02
 Correlated STD DEV: 4.6407,

MEDIAN: 21.63
 Standard Deviation: 5.8009
 KURTOSIS Coefficient: 2.203
 CONFIDENCE Level:0.000
 Coefficient of Variation:0 .21440

Specified Strength of the Concrete = 20.0
 Most probable Characteristic Strength = 14.8



1.19. Definition

Prestressed concrete may be defined as the concrete in which effective internal stresses are induced artificially with tensioned steel before loading the structure. A simple engineering example which has used the principle of prestressing since several centuries is that of the formation of a wooden barrel. As steel ropes or bands are wound around wooden staves and tightened, compressive stresses are produced in the barrel. Under working load conditions, the liquid in the barrel will cause tensile stresses which are counterbalanced by the previously induced compressive stresses. This type of operation of tightening the steel bands before working operations is called prestressing.

Concrete is poor in tension, so at sections of concrete where tension is expected, compressive stresses are introduced before working loads. There are several methods of tensioning the steel and transferring the steel force to the concrete. The prestressing steel, when used in concrete members, is usually called tendon. The systems and operations of prestressing are discussed later.

An eccentric force acting on a column causes direct thrust and bending moment. The bending moment caused by the eccentric force is equal to the product of the axial force (P) and the eccentricity (e) with respect to the centroid of the section. In case of T-beam or unequal flanged symmetrical sections, the distances of the top and bottom fibre from the centroid of the cross-section are different. The extreme stresses are caused at the top or bottom fibres (also called extreme fibres) due to eccentric load. If the eccentricity is more than the kern distance, the extreme fibre away from the load axis will be subjected to tension. Assuming that no cracking takes place in the cross-section and the material follows a linear stress-strain relation the stresses caused by an eccentric load on slender members can be obtained from simple beam-column theory. They may be expressed using simple column and beam theories.

$$\text{Stress due to axial compression} = -\frac{P}{A} \quad (1.19.1)$$

$$\text{Stress due to moment} = \frac{My}{I} \quad (1.19.2)$$

in which

A = area of the cross-section

I = moment of inertia of the section

y = distance of the fibre from centroidal axis (CA)

M = bending moment on the section.

Let σ_t and σ_b are the stresses caused by P and M at the top and bottom extreme fibres which are situated at top & bottom fibre distances y_t and y_b from the centroid. Then

$$\sigma_t = -\frac{P}{A} + \frac{My_t}{I} \quad (1.19.3)$$

$$\sigma_b = -\frac{P}{A} + \frac{My_b}{I} \quad (1.19.4)$$

In which the tensile stress is treated as positive and the compressive stress as negative. The negative sign for M_{y_t} is assigned assuming the bending moment is such it causes compression on the top fibre. The explanation given here is with reference to a member whose axis is horizontal. This is given as a matter of convenience and can be extended to any element in any orientation. In most cases, tensile stress is treated positive but in case of concrete structures, the concrete is mostly under compression. The notation is only for convenience and will be modified at times for simplicity in the formulation of the expressions. In case of a beam column in which the axial force is acting with an eccentricity 'e', the bending moment caused by the force produces tension at the top fibre. Therefore the moment is

$$M = -Pe \quad (1.19.5)$$

The substitution of Eq. 1.19.5 in Eqs. 1.19.3 and 1.19.4 gives

$$\sigma_t = -\frac{P}{A} + \frac{Pe y_t}{I} \quad (1.19.6)$$

$$\sigma_b = -\frac{P}{A} - \frac{Pe y_b}{I} \quad (1.19.7)$$

The above two equations can be modified by setting $I = Ar^2$ in which r = radius of gyration :

$$\sigma_t = -\frac{P}{A} \left(1 - \frac{e y_t}{r^2} \right) \quad (1.19.8)$$

$$\sigma_b = -\frac{P}{A} \left(1 + \frac{e y_b}{r^2} \right) \quad (1.19.9)$$

The bounds for eccentricity of a thrust for which no tension is caused can be obtained from Eqs. 1.19.8 and 1.19.9, and they are :

$$\frac{P}{A} \left(1 - \frac{e y_t}{r^2} \right) > 0 \quad \text{and} \quad (1.19.10)$$

$$\frac{P}{A} \left(1 + \frac{e y_b}{r^2} \right) > 0 \quad (1.19.11)$$

The two inequivalities 1.19.10 and 1.19.11 give

$$e < \frac{r^2}{y_t} \quad (1.19.12)$$

$$e > -\frac{r^2}{y_b} \quad (1.19.13)$$

For symmetrical sections $y_t = y_b = \frac{h}{2}$

where h = overall depth of the section.

The ineqs. 1.19.11 and 1.19.13 give

$$-\frac{2r^2}{h} < e < \frac{2r^2}{h} \quad (1.19.14)$$

in case of rectangular sections the value of r^2 is given by

$$r^2 = h^2/12.$$

Therefore, the ineq. 1.19.14 for rectangular sections reduces to

$$\frac{-h}{6} < e < \frac{h}{6} \quad (1.19.15)$$

The bounds given by ineq. 1.19.14 are referred as the *kern* distances.

Let there be an external bending moment M acting on the cross-section. The moment is considered positive if it is causing compression on the top fibre of the section. Such a moment causes a compression equal to My_t/I at the extreme top fibre and tension My_b/I at the extreme bottom fibre. The final stresses caused by an eccentric thrust on a cross-section which is subjected to a moment M can be obtained by simple superimposition. They are :

$$\sigma_t = \frac{-P}{A} + \frac{Pey_t}{I} - \frac{My_t}{I} \quad (1.19.16)$$

$$\sigma_b = \frac{-P}{A} - \frac{Pey_b}{I} + \frac{My_b}{I} \quad (1.19.17)$$

The above equations can be rewritten as:

$$\sigma_t = \frac{-P}{A} \left(1 - \frac{ey_t}{r^2} \right) - \frac{My_t}{I} \quad (1.19.18)$$

$$\sigma_b = \frac{-P}{A} \left(1 + \frac{ey_b}{r^2} \right) + \frac{My_b}{I} \quad (1.19.19)$$

Depending on the relative magnitudes of each of the terms in the Eqs. 1.19.18 and 1.19.19, the stresses σ_t and σ_b can either be positive (i.e., tension) or negative.

In most concrete structures, the tensile stresses in concrete are usually avoided or neglected.

It is also desirable to review the difference between the centroidal axis and the neutral axis in association with the set of equations generated so far. The centroidal axis is associated with the property of the section alone and it is the axis passing through the centroid of the section. Stress caused by moment ($\sigma = My/I$) at the centroidal axis is always zero. It can be seen from the fact that as y is equal to zero so the stress is zero. The neutral axis is defined as the axis at which the stress (or more often it is the strain) changes from positive to negative. At this level the stress is equal to zero and the nature of the stresses on either side of the axis, are different. When the direct stress, P/A is superimposed on the stress caused by the bending moment My/I , the net stress is $P/A \pm My/I$. In such a case, the stress at the centroidal axis equal to P/A and the neutral axis does not coincide with the centroidal axis. This is what really happens in all beam columns and prestressed beams. The neutral axis may or may not fall within the section. If the value of P/A is more when compared with the maximum of My/I then the neutral axis falls outside the section.

1.20. Stress Distribution

The distribution of stress and strain on a section in a simply supported beam is shown in Figure 1.20.1 assuming that the plane section remains plane even after bending. Certain amount of tension is produced in the bottom fibre by the external loads and, because concrete is poor in tension, some kind of tension-bearing capacity has to be induced in the tensile zone. The tension capacity is provided in two ways : (i) sufficient steel can be embedded in the beam at the tension zone to resist the tension directly. This method is defined as reinforced concrete construction : (ii) a precompressive stress can be induced at the tension fibre through tensioned steel. A prestressed concrete construction is the one in which the concrete is precompressed by tensioned steel to compensate the tensile stress which is likely to be developed by working load.

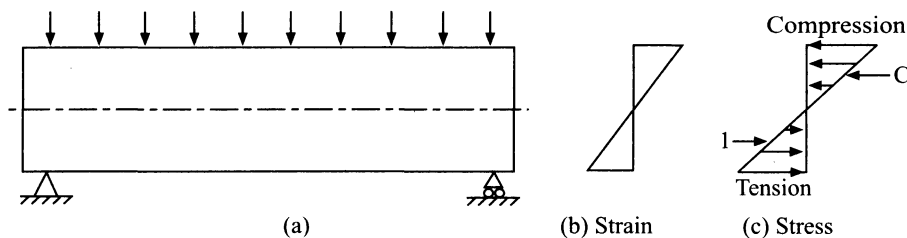


Figure 1.20.1 Simply supported beam (strain and stress distribution due to bending).

If a section is first subjected to prestressing force of P , then the stresses are given by

$$\sigma_t = \frac{-P}{A} \left(1 - \frac{ey_t}{r^2} \right) - \frac{My_t}{I} \quad (1.20.1)$$

$$\sigma_b = \frac{-P}{A} \left(1 + \frac{ey_b}{r^2} \right) + \frac{My_b}{I} \quad (1.20.2)$$

where

P = prestressing force introduced through the tendon

A = area of cross-section

I = moment of inertia

r = radius of gyration

e = eccentricity

y_t = distance of the extreme top fibre from CGC

y_b = distance of the extreme bottom fibre from CGC

σ_t = stress at top fibre ($= \sigma_1$)

σ_b = stress at bottom fibre ($= \sigma_2$)

M = bending moment caused by external load

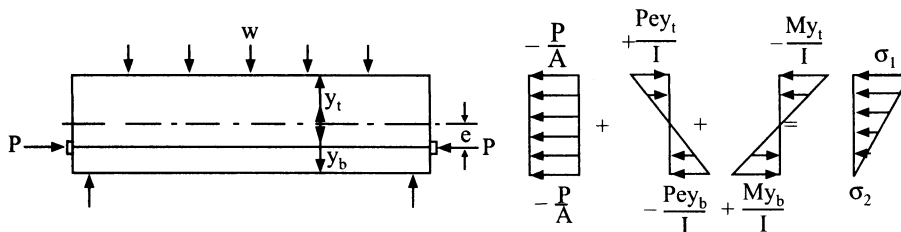


Figure 1.20.2 Simply supported beam with prestress (stress variation).

Eqs. 1.20.1 and 1.20.2 illustrate that some of the stresses caused by prestressing force are of opposite in nature of those caused by the external moment. The prestressing force and the eccentricity of the force can be adjusted to compensate a desired amount of the stress caused by the external loads. Figure 1.20.2 shows the nature of stress distribution across the depth of a beam caused by prestressing force and external load. Example 1.20.1 illustrates the effect of prestressing force on stresses in a beam.

P cannot be increased arbitrarily just to compensate the tensile stress. As P increases, σ_b also increases so the allowable compressive stress of concrete governs. Compensation of tensile force can also be achieved by increasing the eccentricity ' e '; but as the eccentricity increases, σ_t in eq. 1.20.1 might turn out to be a tensile stress beyond allowable limits. The values of P and e have to be carefully selected. The advantage of providing thrust P at the bottom is illustrated in example 1.20.1.

Example 1.20.1 A simply supported beam of span 8 m is loaded with a uniformly distributed load of 5000 N/m. The cross-section of the beam is 30 cm by 80 cm. Determine the stresses with and without a horizontal thrust of 240,000 N acting at 20 cm below the centroidal axis.

Solution

Bending moment at midsection is given by

$$M = \frac{wL^2}{8} = \frac{5000(64)(100)}{8} = 4 \times 10^6 \text{ N cm}$$

$$I = \frac{bh^3}{12} = \frac{30(80)^3}{12} = 1.28 \times 10^6 \text{ cm}^4$$

The stresses caused by the moment at extreme top and bottom fibres are

$$\sigma_{1l} = \frac{My_1}{I} = \frac{4(10^6)(-40)}{1.28(10^6)} = -125 \text{ N / cm}^2$$

$$\sigma_{2l} = \frac{My_2}{I} = \frac{4(10^6)(40)}{1.28(10^6)} = 125 \text{ N / cm}^2$$

where the subscripts 1 and 2 indicate extreme top and bottom fibres. The subscript l indicates live load. Tensile stresses are assumed to be positive unless otherwise clearly assigned as compressive stress.

Let σ_{1p} and σ_{2p} are stresses caused by the prestressing force, then

$$\begin{aligned}\sigma_{1p} &= -\frac{P}{A} - \frac{Pe y_1}{I} \\ &= -\frac{240,000}{80(30)} - \frac{240,000(20)(-40)}{1.28(10^6)} \\ &= -100 + 150 = 50 \text{ N / cm}^2\end{aligned}$$

$$\sigma_{2p} = -\frac{P}{A} - \frac{Pe y_2}{I} = -100 - 150 = -250 \text{ N / cm}^2$$

where $y_1 = -40$ cm, $y_2 = 40$ cm and Pe is the bending moment causing compression on the bottom fibre which is considered negative.

Prestressing force causes a tension of 50 N/cm² at top fibre whereas the live load produces a compressive stress of 125 N/cm². So the effective stress at extreme top fibre is

$$\sigma_1 = \sigma_{1l} + \sigma_{1p} = -125 + 50 = -75 \text{ N / cm}^2$$

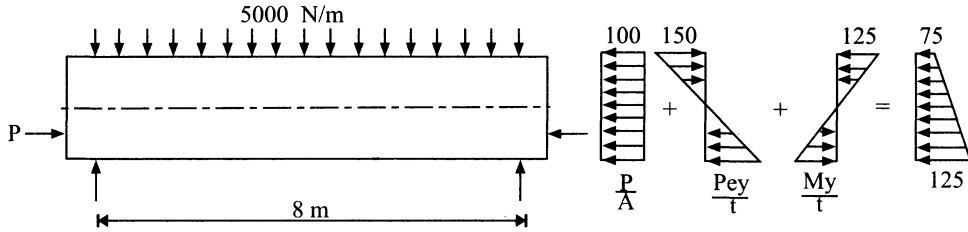


Figure 1.20.3 Stress distribution at mid-section.

Similarly the effective stress at the extreme bottom fibre is

$$\sigma_2 = \sigma_{2l} + \sigma_{2p} = 125 - 250 = -125 \text{ N/cm}^2$$

The stresses at both the extreme fibres are compressive so the entire cross-section is under compression. The prestressing force eliminates the tensile stresses caused by the external loads thus safeguarding concrete against tension. The stresses at the end section where external moment is zero are

$$\sigma_1 = -\frac{P}{A} - \frac{Pe y_1}{I} = 50 \text{ N / cm}^2$$

$$\sigma_2 = -\frac{P}{A} - \frac{Pe y_2}{I} = -250 \text{ N / cm}^2$$

1.21. Profile of Tendons

It may be seen from example 1.20.1 that there are two critical sections, one at mid-span and another at end-span. The stress distributions of these two sections are shown in Figure 1.21.1. The stress distribution at the end section is more dominant than that at middle of the beam. The stress distribution due to external bending moment starts with zero values at the end and reaches a maximum at the centre of the beam, whereas the stress distribution provided by the horizontal thrust stays constant throughout the beam. The critical stress distribution at the end section can easily be avoided by providing zero eccentricity at the end while keeping the 20 cm eccentricity at the middle of the beam. Now it is necessary to discuss the profile of the eccentricity along the span. The stress variation along the span due to the uniformly distributed load is parabolic; so a tendon of parabolic profile will be effective to compensate the tensile stresses due to the external loads. Sometimes the profile is also taken as two straight lines with a bend at the middle of the section. These profiles are shown in Figure 1.21.2. The eccentricity of the tendon at the end of the beam need not necessarily be zero. To provide for a steep curvature, a negative eccentricity can also be given.

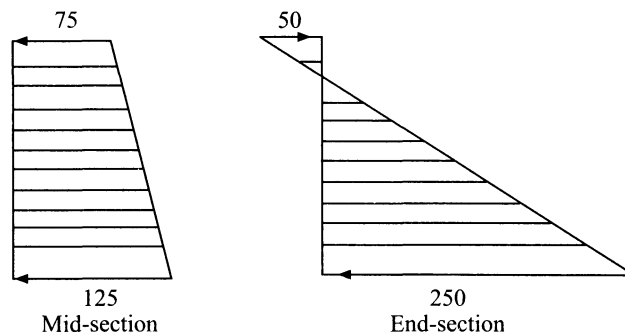


Figure 1.21.1 Stress distribution—Example 1.20.1. (stresses in N/cm^2).

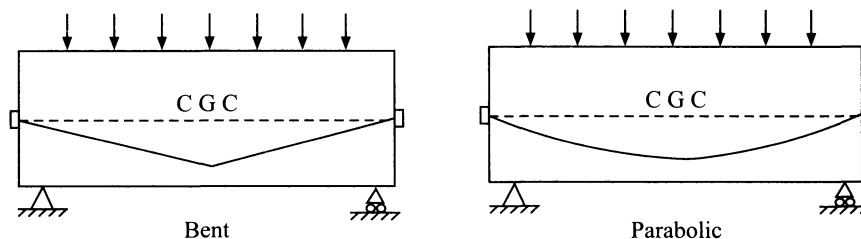


Figure 1.21.2 Possible profiles of tendons.

Example 1.21.1 Same as example 1.20.1 with a modification in the profile of the tendon : The eccentricity at the end is -10 cm and at the mid-section it is 20 cm with straight line variation. Determine the stresses at the end and mid-section (negative sign of e indicates eccentricity above centroidal axis, CA). Figure 1.21.3 illustrates the cable profile.

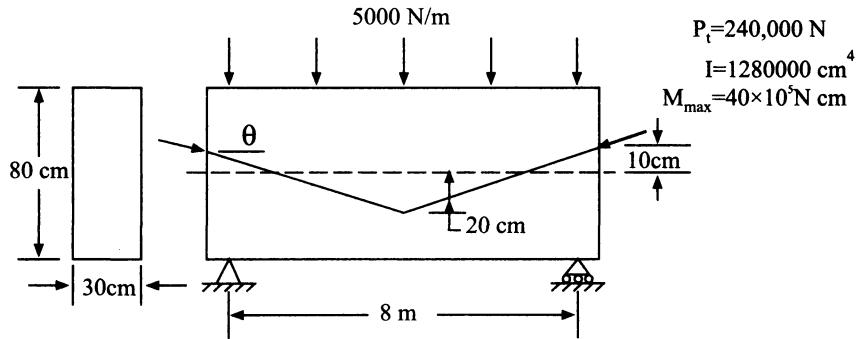


Figure 1.21.3 Example 1.21.1

Solution

Stresses at the end section where $e = -10$ cm are

$$\begin{aligned}\sigma_1 &= -\frac{P}{A} - \frac{Pey_1}{I} \\ &= \frac{-240,000}{2400} - \frac{240,000(-10)(-40)}{1.28(10^6)} = -100 - 75 \\ &= -175 \text{ N/cm}^2\end{aligned}$$

$$\sigma_2 = -\frac{P}{A} - \frac{Pey_2}{I} = -100 + 75 = -25 \text{ N/cm}^2$$

Stresses at midsection where $e = 20$ cm are

$$\begin{aligned}\sigma_1 &= -\frac{P}{A} - \frac{Pey_1}{I} + \frac{My_1}{I} = -100 + 150 - 125 \\ &= -75 \text{ N/cm}^2 \\ \sigma_2 &= -\frac{P}{A} - \frac{Pey_1}{I} + \frac{My_2}{I} = -100 - 150 + 125 \\ &= -125 \text{ N/cm}^2\end{aligned}$$

where $y_1 = -40$ cm, and $y_2 = 40$ cm.

Figure 1.21.4 shows the stress distribution at the end and middle sections of the beam. It may be seen from the two previous examples that the profile of the cable has considerable effect on the distribution of stress at different sections of the beam. Another two examples are given to illustrate the effect of the cable profile on the stresses in the beam.

(Note: The stress pointing towards the beam is assumed to be compression as given in the figures).

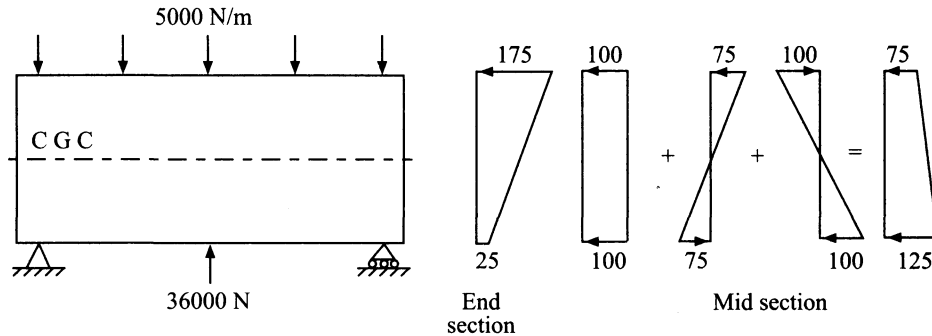


Figure 1.21.4 Stress distribution- Example 1.21.1 (stress in N/cm^2).

Example 1.21.2 Same as example 1.21.1 except that the eccentricity at the ends is 10 cm instead of -10 cm.

Solution

The stress distribution due to the external load and prestressing force computed as done in example 1.21.1 and shown in Figure 1.21.5.

The stresses at the end section are

$$\sigma_1 = -\frac{P}{A} - \frac{Pey_1}{I} = -100 + 75 = -25 \text{ N/cm}^2$$

$$\sigma_2 = -\frac{P}{A} - \frac{Pey_2}{I} = -100 - 75 = -175 \text{ N/cm}^2$$

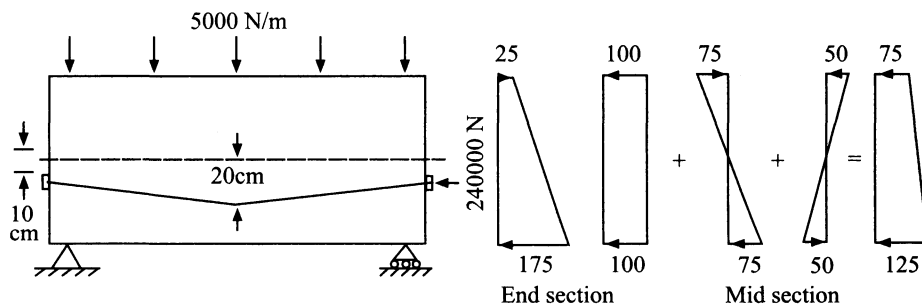
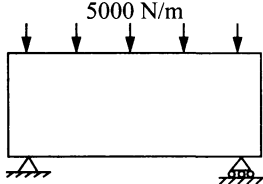
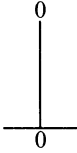
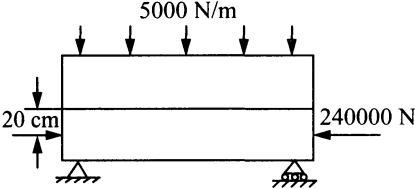
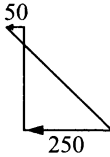
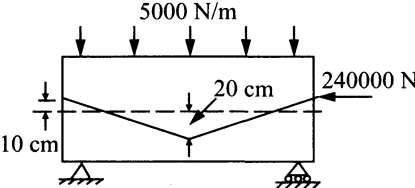
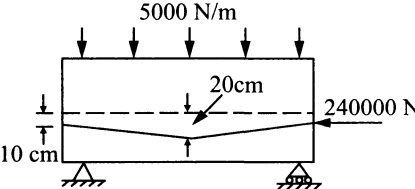
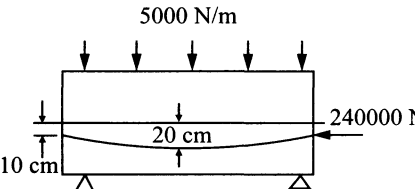
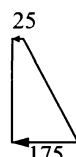


Figure 1.21.5 Stress distribution-Example 1.21.2 (stresses in N/cm^2).

A comparative study of stress distribution of the five examples is given in table 1.21.1. Beams 2 to 5 have used the same amount of material under same external load conditions except for the profile of the tendon. It can be seen that the profile and the eccentricity of the tendon has considerable effect on the stress.

TABLE 1.21.1 Stress distribution on beam with tendon (stresses in N/cm^2)

S No	EXAMPLE	END SECTION	MID SECTION
1			
2			
3			
4			
5			

1.22. Load Balancing Method

A prestressing cable in concrete exerts a set of forces on concrete so it can be replaced by the set of forces for the purpose of analysis. T. Y. Lin (1.1)* is one of the early investigators who explained the concept and used it in design of prestressed concrete beams. Consider an infinitesimal length of a cable as shown in Figure 1.22.1. The equilibrium of force of the element in the vertical direction for a constant force in the cable is given by

$$P \sin \theta_2 - P \sin \theta_1 + w_b \delta x = 0 \quad (1.22.1)$$

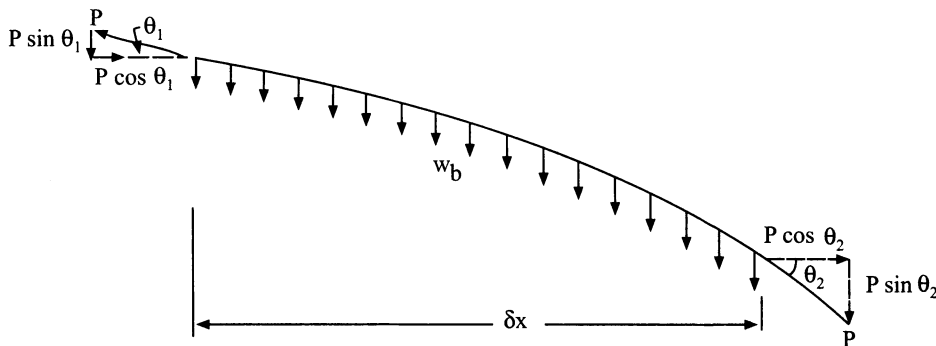


Figure 1.22.1 Equilibrium of a small cable.

where θ_1 and θ_2 are the slopes of the cable, w_b is the balancing force and δx is the length of the element. w_b is considered positive if acting downwards. In case of a shallow curved cable, the slope of the cable is very small as compared to unity, so

$$\sin \theta_2 = \theta_2 \text{ and } \sin \theta_1 = \theta_1$$

Eq. 1.22.1 can be rewritten as

$$P(\theta_2 - \theta_1) = -w_b \delta x \quad (1.22.2)$$

If the slope of the curve is differentiable θ_1 and θ_2 can be expressed as

$$\theta_1 = \frac{de}{dx}, \theta_2 = \frac{de}{dx} + \frac{d^2e}{dx^2} \delta x$$

and eq. 1.22.2 reduces to

$$P \frac{d^2e}{dx^2} = -w_b \quad (1.22.3)$$

where e is the ordinate of the cable profile measured positive downward from the CA.

A cable can be replaced by an equivalent set of forces and the beam can be analysed for such a set. Anchorage force can be replaced by axial, shear and bending forces and the shallow curve by a vertical force proportional to the curvature. The axial force through CGC will not

* The numerals in the bracket indicate the reference listed at the end.

cause any moment for small deflection theory. The transverse component acting at a support point is directly transferred to the support. Otherwise if it is situated in between the supports, it will cause moment. Moments caused by eccentricities and radial components of the cable force will have to be included in the analysis.

It can be stated from eqs. 1.22.2 and 1.22.3 that the balancing force is given by the product of the cable force and the rate of change of slope of the cable. The cable can be replaced by an equivalent force which is equal to w_b as given in eqs. 1.22.2 or 1.22.3.

If the balancing force is constant, i.e. $w_b = \text{constant}$, integration of eq. 1.22.2 gives

$$Pe = -w_b \frac{x^2}{2} + c_1x + c_2 \quad (1.22.4)$$

where c_1 and c_2 are constants of integration.

Profile of a cable to balance a *UDL* is a second order curve as given by eq. 1.22.4. The constants of integration can be evaluated from the boundary conditions of the cable.

Example 1.22.1 A simply supported beam of 8 m is subjected to a *UDL* of 5000 N/m inclusive of self weight. Determine a cable profile which will balance 3000 N/m.

Solution

In a simply supported beam the moments at support ends are zero so eccentricity of the cable at the two supported ends must be equal to zero. The boundary conditions are :

$$e = 0 \text{ at } x = 0 \text{ and } x = L$$

Substitution of the above boundary conditions in eq. 1.4.4 gives

$$c_2 = 0 \text{ and } c_1 = w_b L/2$$

Eq. 1.22.4 reduces to

$$Pe = w_b x (L - x)/2 \quad (1.22.5)$$

Let g = maximum sag in the cable which is at $x = L/2$, then from eq. 1.22.5,

$$Pg = \frac{w_b L^2}{8} \text{ or } w_b = \frac{8Pg}{L^2}$$

If the balancing load is made equal to 3000 N/m

$$w_b = 3000 \text{ N/m}$$

$$Pg = \frac{w_b L^2}{8} = \frac{3000 \times 8 \times 8}{8} = 24,000 \text{ Nm}$$

The sag of the cable is normally constrained by the depth of the beam. The maximum sag that can be permitted allowing an effective cover of 10 cm is

$$g = d/2 - 10 = 30 \text{ cm so}$$

$$P = \frac{24,000}{g} = \frac{24,000}{0.3} = 80,000 \text{ N}$$

Slopes of the cable at the supports are

$$\text{at } x = 0 \quad \theta_1 = \left(\frac{de}{dx} \right) = \frac{w_b L}{2P} = \frac{4g}{L}$$

$$\text{at } x = L \quad \theta_2 = \left(\frac{de}{dx} \right) = -\frac{4g}{L}$$

Figure 1.22.2 illustrates the cable with load on the beam along with the equivalent load of the cable. The effective load acting on the beam is obtained as a difference of the external and cable equivalent loads and it is shown in the Figure 1.22.2.

Effective load acting on a beam can be obtained from the difference of the external load and the cable equivalent forces.

$$w_e = w - w_b \quad (1.22.7)$$

where w and w_e are external and effective loads respectively. In addition to the equivalent distributed load of w_e , the cable produces horizontal thrust equal to $P \cos \theta$ and vertical load equal to $P \sin \theta = P \theta$ at each supports as shown in Figure 1.22.2.

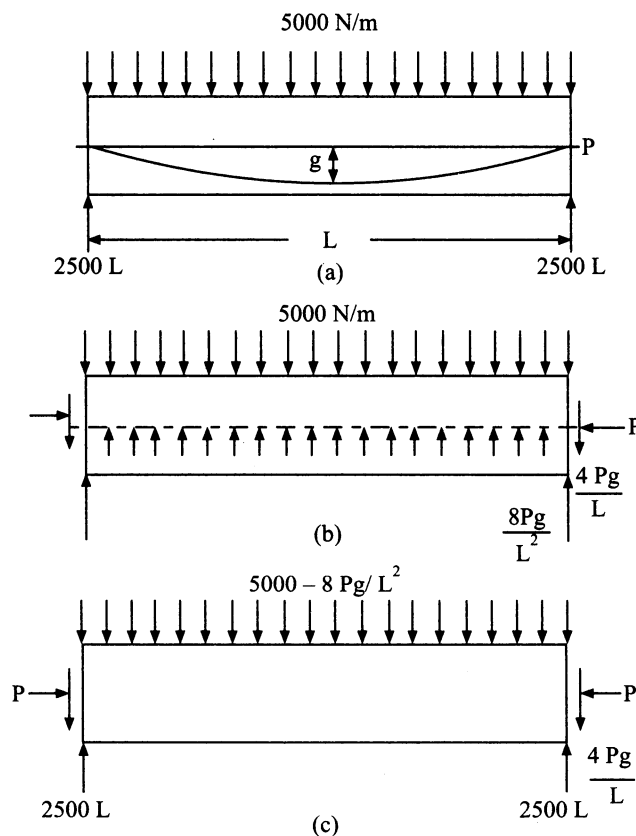


Figure 1.22.2 UDL load balancing cable in a simply supported beam.

Example 1.22.2 The cross-section of the beam of example 1.22.1 is 30 cm by 80 cm. Determine the stresses at mid-span using balancing load concept.

Solution

Effective load = $w_e = 5000 - 3000 = 2000$ N/m

Bending moment at mid-span is

$$\begin{aligned} M &= \frac{w_e L^2}{8} = \frac{2000 \times 8 \times 8}{8} \\ &= 16,000 \text{ Nm} = 160,000 \text{ Ncm} \end{aligned}$$

Stresses at mid-span are

$$\begin{aligned} \sigma_1 &= -\frac{P}{A} - \frac{My_1}{I} = -\frac{80,000}{2400} - \frac{1,600,000 \times 4}{1,280,000} \\ &= -100/3 - 50 = -83.33 \text{ N/cm}^2 \\ \sigma_2 &= -\frac{P}{A} + \frac{My_2}{I} = -\frac{100}{3} + 50 = 16.67 \text{ N/cm}^2 \end{aligned}$$

Alternate approach. The stresses at mid-span can also be obtained by superposition principle discussed in the previous section.

$$\sigma_1 = -\frac{P}{A} + \frac{Pe y_1}{I} - \frac{M_w y_1}{I}$$

where $M_w = BM$ caused by the external load

$$\begin{aligned} &= \frac{5000 \times 8 \times 8 \times 100}{8} = 40 \times 10^5 \text{ N/cm} \\ \sigma_1 &= -\frac{80,000}{2400} + \frac{8000(30)(40)}{1,280,000} - \frac{4,000,000 \times 40}{1,280,000} \\ &= -\frac{100}{3} + \frac{300}{4} - \frac{500}{4} = -83.33 \text{ N/cm}^2 \\ \sigma_2 &= -\frac{P}{A} - \frac{Pe y_2}{I} + \frac{M_w y_2}{I} \\ &= -\frac{100}{3} + \frac{200}{4} = 16.67 \text{ N/cm}^2 \end{aligned}$$

The values are same as those obtained from the balancing forces approach.

Example 1.22.3 A concentrated load of W is acting at mid-span of a simply supported beam of span L . Suggest a cable profile such that the concentrated load is balanced.

Solution

The load to be balanced is not a continuous load so eq. 1.22.2 in which δx tends to a point will hold good in which case $W_b \delta x$ tends W_b . Since there is no moment at the ends of the beam,

eccentricities at the support ends should be zero. The balancing load at all points except at mid-span is identically equal to zero which gives the equation of the profile as

$$e = c_1 x + c_2$$

and at

$$x = 0, e = 0, \text{ so } c_2 = 0$$

The cable profile is a straight line with kink at mid-span. Let the change in slope at mid-span is 2θ then from symmetry $\theta_2 = \theta_1 = \theta$. Eq. 1.22.2 gives

$$P(2\theta) = W_b \text{ or } P\theta = \frac{W_b}{2}$$

If g is the sag at mid-span, then for shallow sags

$$\theta = \frac{g}{L/2} = \frac{2g}{L} \text{ and}$$

$$P\theta = \frac{2Pg}{L} = \frac{W_b}{2} \text{ or}$$

$$Pg = \frac{W_b L}{4} \text{ or } W_b = \frac{4Pg}{L}$$

Figure 1.22.3 shows the cable's and the equivalent forces on the beam.

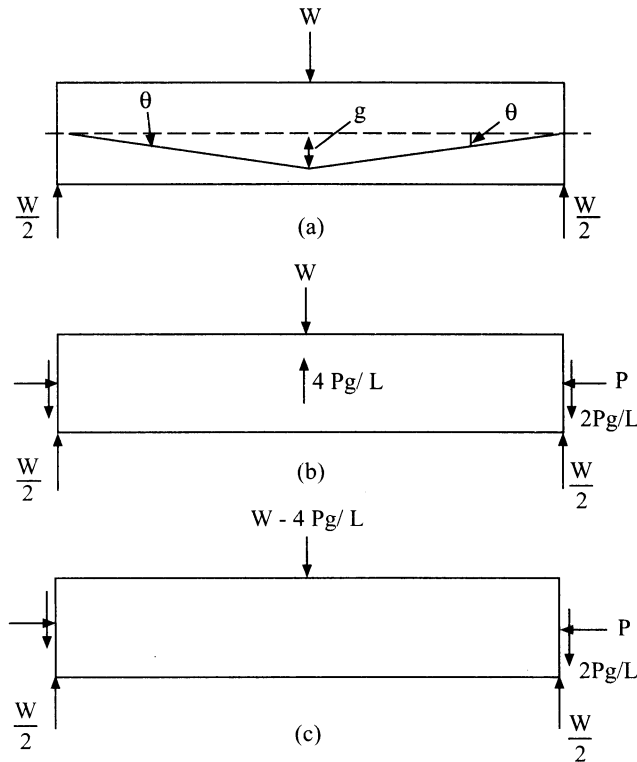


Figure 1.22.3 Balancing cable for concentrated load.

Example 1.22.4 A cantilever beam of span L is subjected to UDL of w . Design a cable profile such that a load of w is balanced by the cable.

Solution

As the load is UDL , the eq. 1.4.4 can be used

$$Pe = -w_b \frac{x^2}{2} + c_1 x + c_2$$

Let the origin of the above equation be at the free end as shown in Figure 1.22.4. Since there is no end moment or end shear force, the profile of the cable should be such that it will neither cause moment nor shear force which means the eccentricity as well as the slope of the cable at the free end must be zero

$$e = \frac{de}{dx} = 0 \text{ at } x = 0$$

The profile reduces to

$$Pe = \frac{-w_b x^2}{2} \quad (1.22.8)$$

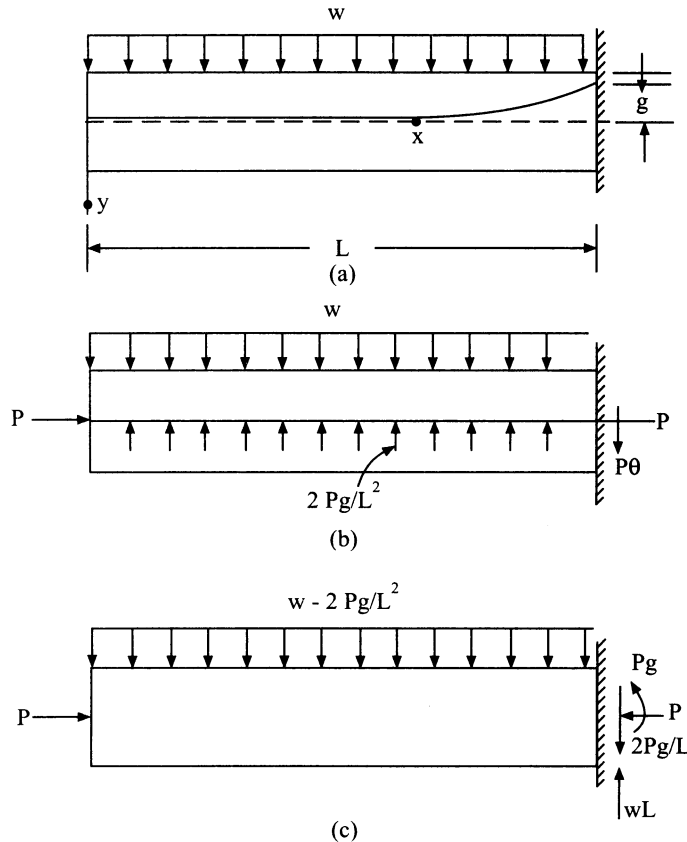


Figure 1.22.4 Load balancing cable in a cantilever beam.

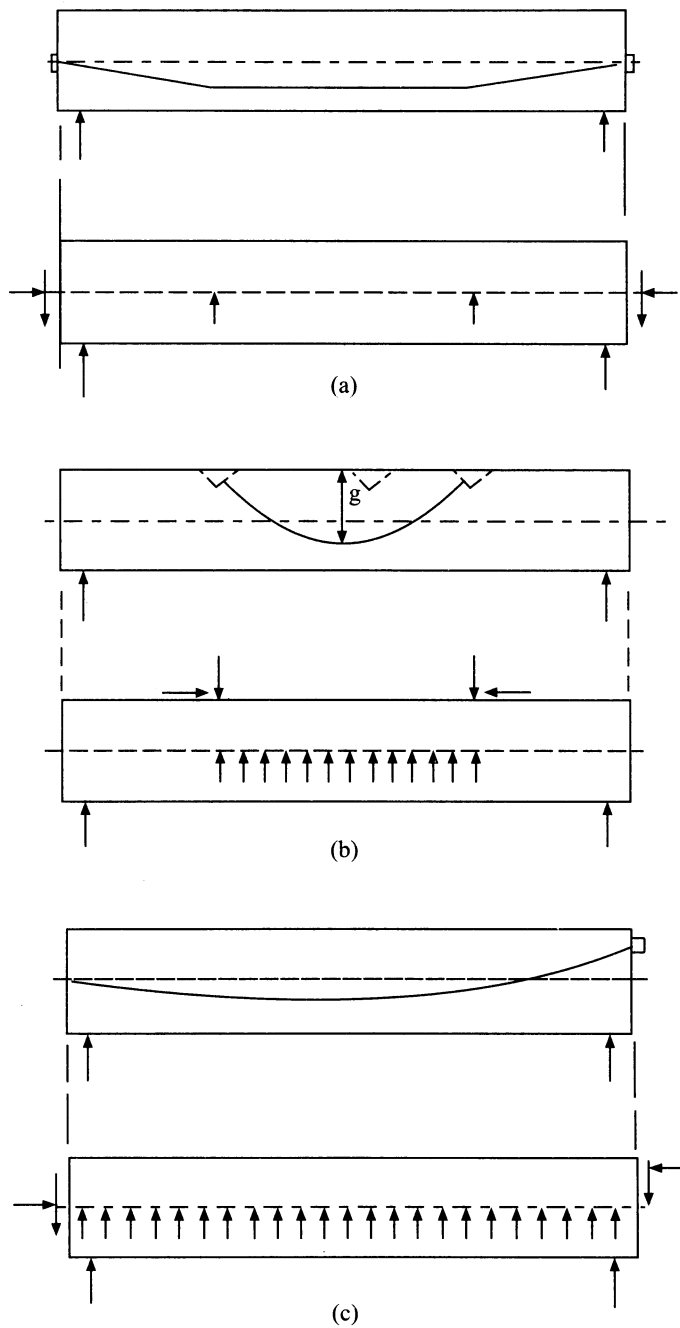


Figure 1.22.5 Typical cables and equivalent forces.
 (a) Three straight line segment cable
 (b) Cable in a segment of a beam
 (c) Eccentrically anchored cable

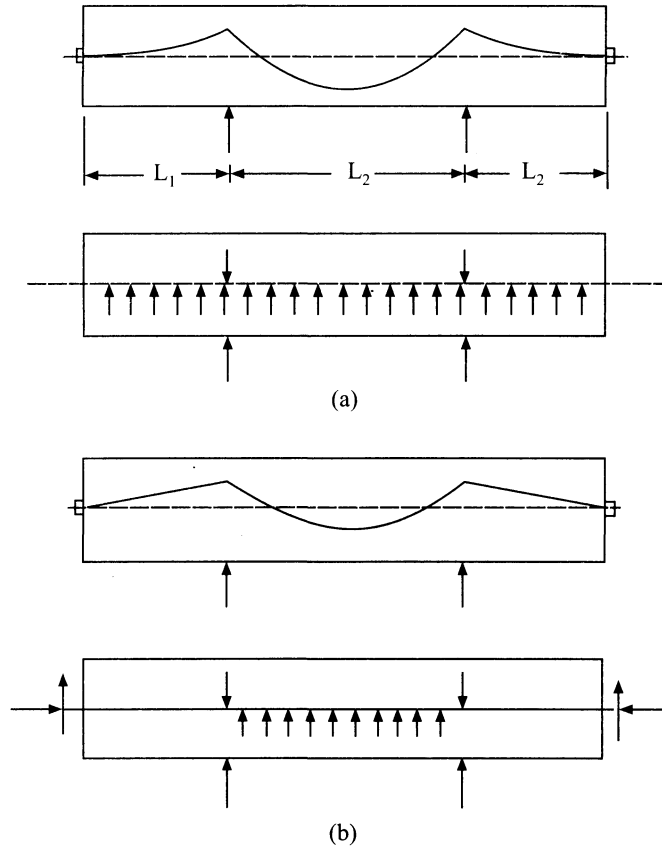


Figure 1.22.6 Typical cables and equivalent force double overhang beam,
(a) Curved cable, (b) Curved and linear cable.

Let g = sag at fixed end, then

$$Pg = -w_b L^2/2 \text{ or}$$

$$g = -\frac{w_b L^2}{2P} \quad (1.22.9)$$

The negative sign for g indicates the sag is above the centroidal axis. Figure 1.4.4 gives the details of the loads.

It is possible to arrive at any desirable balancing loads through a set of cable profiles. Typical cable profiles and the corresponding equivalent forces shown in figures. 1.22.5 and 1.22.6. The reader is advised to make a close study of the figures and workout some examples giving numerical values. Assume all the cables as shallow ones.

1.23. Basic Phases of Loading in Prestressed Construction

Prestressed concrete structures are subjected to different load conditions of which only few are critical. The main load conditions for which a structure should be designed are :

1. Transfer of prestress from the jacks or from the anchor abutments to the structure. This condition is usually called transfer or initial condition. In this condition the concrete has the least strength whereas the prestressing force is maximum. The external load acting on the structure is only self weight.
2. Working load condition in which normal working loads such as live as dead loads are placed on the structure so as to cause critical stresses. In this condition the loads are supposed to act for long periods of time so the permissible stresses are taken lower than those in the transfer condition.
3. Handling and transportation load condition is not common to all structures. The structure, if it is to be transported to the site, then the handling procedure should be specified and design be made so as to withstand the handling load. The permissible stresses in this load condition are usually higher than those in the working load.
4. Combined wind or earthquake load condition may not be critical for many simple structures. However, large structures should be designed to resist wind and earthquake loads. The permissible stresses in this load condition are usually higher than those in the working load condition as the duration of peak wind and earthquake actions are of small duration.

1.24. Materials

This section is devoted to basic materials used in the prestressed concrete construction. Because of variety of reasons seen later, it is necessary to have some concept about the material properties used in the construction. The basic two materials used in the prestressed concrete construction are : (i) steel and (ii) concrete.

Steel : Mild and hard-drawn steels used in reinforced concrete have a yield stress of 240 MPa to 360 MPa. If this steel is used in prestressed concrete and tensioned to about 200 MPa at the initial stage, the effective prestressing force available after shrinkage and creep of concrete and creep of steel will be negligible. The approximate loss of prestressing due to shrinkage of concrete, creep of concrete and steel is estimated to be of the order of 175 to 250 MPa. Obviously no prestressing force will be left in the mild steel after the losses. The high tensile steels (HTS) have ultimate strength capacity as high as 1000 to 2100 MPa and the use of such steels will provide considerable amount of effective prestressing force even after losses in prestress.

TABLE 1.24.1 Properties of high tensile steel (HTS) wire

<i>Diameter (in mm)</i>	3	4	5	7	8
(1) Ultimate stress (MPa)					
(Cold-drawn)	1900	1750	1600	1500	1400
(As-draw wires)	1800	1750	1600	—	—
(2) Percentage elongation	2.5	3	4	6	8

High tensile (HT) steel available is mainly in the form of wires which are cold or as-drawn from high tensile steel bars. The process of cold drawing tends to realign the crystals and the strength of the wires is increased by each drawing so that the strength of the wire increases as its diameter decreases. However, the cold drawing process decreases the ductility of the material which is a disadvantage. High tensile steel wires are also obtained as 'as-drawn' wires. These wires have low proportional limit and to increase the proportional limit, the wires are subjected to stress-relieving processes. A typical variation of ultimate stress of HT steel with respect to the diameter of the wire is shown in Figure 1.24.1.

The prestressing steel is also available in the form of strands which are obtained by twisting wires together. By using strands, the number of units to be handled decreases. Small diameter wires of very high tensile strength can be used for strands. Approximate chemical composition of the high tensile steel wires is :

carbon = 0.60 to 0.85%; manganese = 0.7 to 1.0%,
phosphorus = 0.05%, sulphur = 0.055 % and a small amount of silicon.

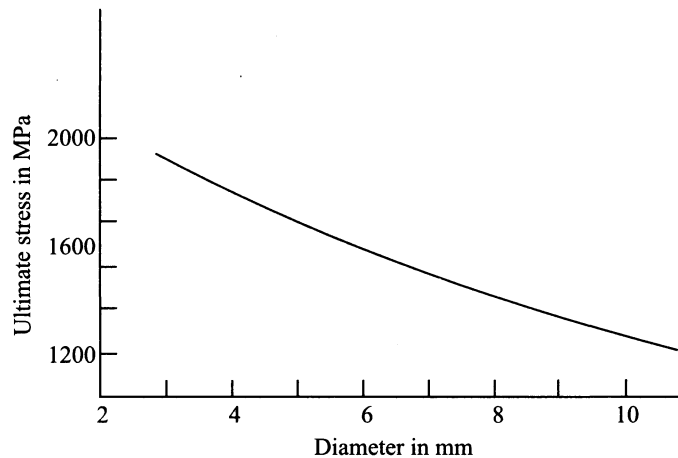


Figure 1.24.1 Typical variation of ultimate strength of HT steel wires.

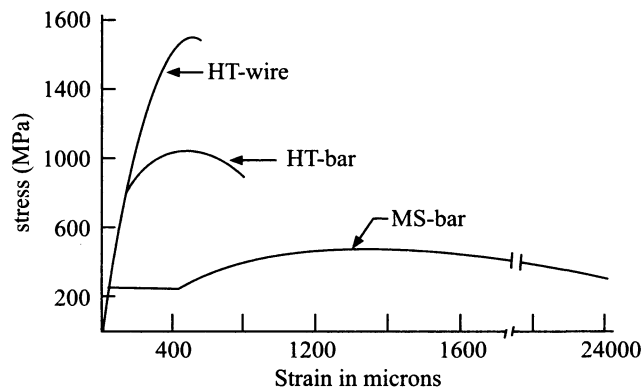


Figure 1.24.2 Typical stress strain variation of steels.

Physical properties : The proportional limit of high tensile steel is rather hard to find as the yield point does not exist. A typical stress strain curve of a high tensile steel is shown in Figure 1.24.2.

From Figure 1.24.2 it can be observed that the proportional limit or yield of high tensile steel is not very clearly seen. The yield stress is replaced by proof stress in HT steel and it is taken to be equal to the stress at which 0.2 per cent permanent strain is obtained. Table 1.24.2 gives approximate values of proof stresses of different steels.

TABLE 1.24.2 Approximate Yield and Proportional Limits

Wire	(Proof stress)/ f_p'	(Proportional stress) f_p'
Wire as drawn	0.75	0.35
Prestretched	0.85	0.55
Temp, treated wires	0.87	0.70
Strands-stress relieved	0.90	0.75

f_p' = ultimate stress of pretension steel

The modulus of elasticity of high tensile steel may be taken as 2.00 GPa.
The creep characteristics of high tensile wires are given in Figure 1.24.3.

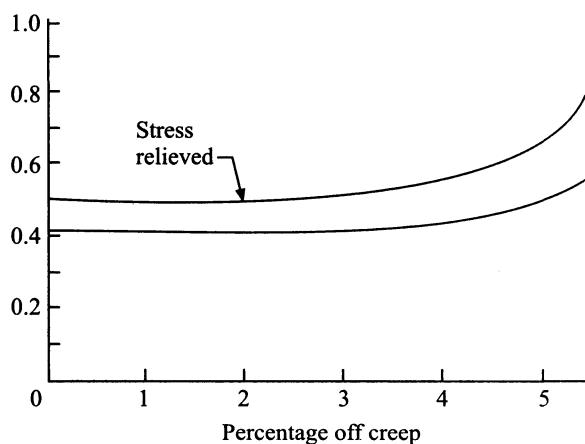


Figure 1.24.3 Creep in steel.

In most of the high tensile wires, the creep is negligible up to $0.45 f_p'$, and it is about 3% at $0.55 f_p'$ stress level. The steel is subjected to high tension during the first stages of construction, so most of the creep occurs in the early stage of construction. The wires and strands are generally supplied in coils of sufficient big diameter as not to cause any inelastic deformation.

Concrete : Consequent to the use of high tensile steel in prestressed concrete construction, the concrete has to be of high strength character. The Indian code of practice suggests a minimum

cube strength of 400 MPa for pre-tensioned system and 300 MPa for post-tensioned system. A typical concrete strength vs. water-cement ratio is shown in Figure 1.24.4.

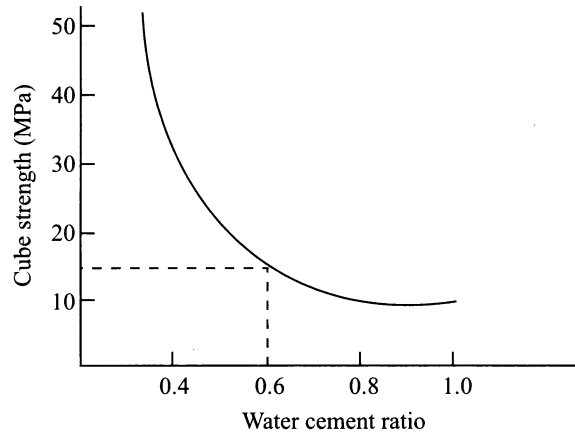


Figure 1.24.4 Effect of water cement ratio on strength of concrete.

As the water-cement ratio increases, the strength of concrete decreases. For most prestressed concrete constructions, a water-cement ratio in the range of 0.35 to 0.45 is used. For water-cement ratio less than 0.4, the workability of concrete decreases, with the result that compact and high density concrete is difficult to obtain. High workability with less water-cement ratio requires a higher percentage of cement and well graded aggregate. 12 mm to 25 mm slump is used with controlled vibration.

The strength of the concrete referred in this book is always to be that of a 15 cm cube after 28 days of water curing unless otherwise stated. The actual concrete strength after several months of casting will be higher than that of 28 days strength. A typical relation between strength of concrete with age is shown in Figure 1.24.5.

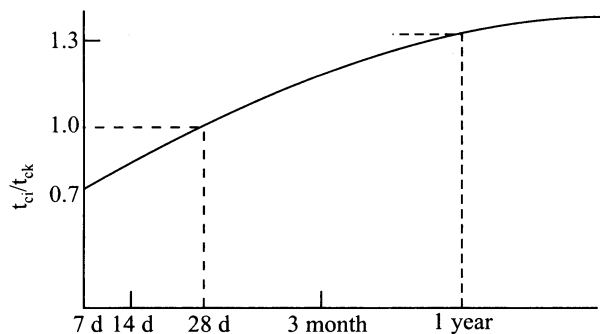


Figure 1.24.5 Relative strength variation of concrete with time.

A typical stress-strain curve of a well graded concrete is shown in Figure 1.24.6 and the stress strain relation (1.3) may be expressed as

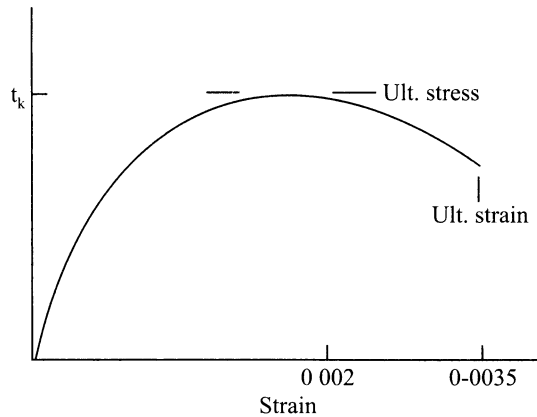


Figure 1.24.6 Stress-strain relation of concrete.

$$\sigma_c = E_c \epsilon \left(1 - \frac{\epsilon}{2\epsilon_0} \right) \quad (1.24.1)$$

where ϵ_0 = ultimate strain (about 0.004) and ϵ = strain.

Determination of Young's modulus for concrete is not as specific as it is for steel. This can be easily observed from the curve. There have been many formulae developed to determine Young's modulus of concrete. It can be taken as

$$E_c = 5700 \sqrt{f_{ck}}$$

where f_{ck} is the 28 days 15 cm cube strength for a portland cement and 7 days cube strength for a rapid-hardening cement.

Young's modulus is considered to be a function of the ultimate strength of the concrete. The modulus of elasticity plays an important role in computations of the deformation and loss of prestress characteristics. A certain amount of tolerance has to be assumed in the use of Young's modulus. The Poisson's ratio for prestressed concrete varies from 0.10 to 0.22 and an average of 0.15 may be adopted in the calculations.

Time dependent character of concrete shrinkage in concrete : As concrete is cast, cured and exposed to weather conditions, some drying and chemical changes take place. Consequently, the concrete undergoes change in volume depending upon time, aggregate moisture content, initial water-cement ratio, and weather conditions. The change of deformation independent of stress and temperature is called shrinkage. The amount of shrinkage varies from 0 to 0.001. Some amount of the shrinkage is recoverable upon restoring the moisture content in the concrete. The amount of shrinkage is proportional to the water-cement ratio. It is desirable to use a low water-cement ratio to reduce the effect of shrinkage. In some extreme wet conditions with certain aggregate, the concrete is likely to expand. The aggregate properties also affect the shrinkage. Aggregate with low percentage absorption will give less shrinkage. The chemical decomposition of cement or even the chemical reactions in the cement will have some influence on the shrinkage. For purposes of design, the shrinkage may be assumed as 0.0002 to 0.0004.

Creep in concrete : The creep strain is defined as the time dependent deformation resulting from the presence of stress. The creep deformation is a complex phenomenon especially in concrete. Most materials subjected to a particular stress level will continue to deform for a certain period even without any change in the stress level. Normally there is no creep at low stress level, but as the stress level increases the creep also increases. The creep of concrete is a function of several quantities such as : (i) stress level, (ii) the duration of stress, (iii) age of concrete, (iv) previous history of stress, (v) water-cement ratio, (vi) strength of concrete, (vii) aggregate, (viii) cement, and (ix) weather conditions to which the concrete is exposed. The creep of concrete assumes an asymptotic behaviour tending to stabilise the strain in a long period. However, most of the creep occurs in the first year. The ratio of the final strain to the initial of concrete is called the creep coefficient. A typical creep curve is shown in Figure 1.24.7. The creep of concrete decreases with moisture and weather conditions. For the purposes of design the creep coefficient of concrete is taken as 2.0 to 3.0.

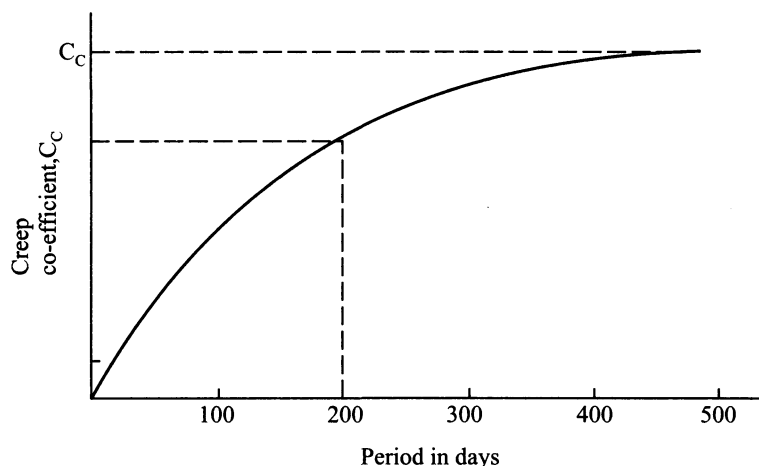


Figure 1.24.7 Creep of concrete.

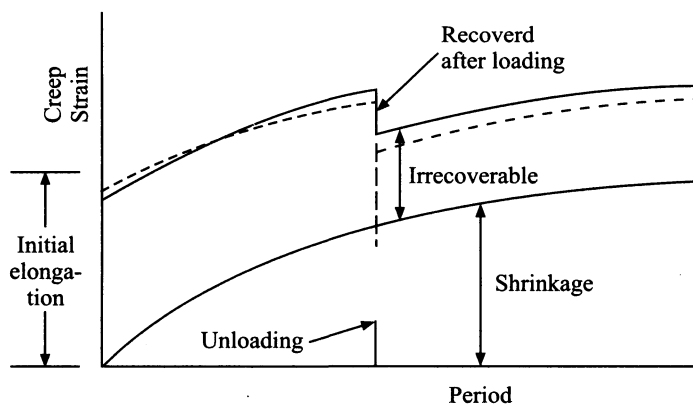


Figure 1.24.8 Creep concrete.

Figure 1.24.8 illustrates the recoverable and irrecoverable creep strain along with shrinkage strain. Creep coefficients given by Indian code of practice (1.2) are given in Chapter II.

PROBLEMS

- 1.1 A simply supported beam of span L and depth h is subjected to self weight w_g and a live load of w_e . Both the loads are distributed uniformly over the span. Find a cable and profile so that a load of $w_g + w_e/2$ is balanced by the cable.
- 1.2 A simply supported beam of span L and depth h is subjected to self weight w_g uniformly distributed and four concentrated loads of each F , spaced at equal interval. Find load balancing cables for these loads. Adopt two different cables for the two load systems.
- 1.3 A double overhang beam has the middle span as L and the overhang span on either side as $L/4$. Determine a prestressing cable for balancing a uniformly distributed load on the entire beam.
- 1.4 A hollow box section has 10 cm by 30 cm inside dimensions and 25 cm by 50 cm outside dimensions. The beam is simply supported on 4.5 m span and subjected to a live load of 2kN/m. The beam is prestressed with an axial force of 300kN. Determine the stresses without the live load.
- 1.5 A solid rectangular cross-section of 100 cm by 15 cm is provided with an axial force of 1.2 MN with 2 cm eccentricity at mid-span. If the beam is simply supported on a span of 3 m and subjected to a load of 2 kN/m calculate the stresses at working load. Working load includes the self weight and live load.
- 1.6 Calculate the balancing cable force in problem 2.5 if the maximum sag in the cable is 2 cm at mid-span. Also calculate the effective loads on the beam.
- 1.7 A simply supported beam of span 8 m is carrying a live load of 10 kN/m. The self weight of the beam is 5 kN/m and its total depth is 40 cm. Design a parabolic cable of sag 10 cm such that it balances full self weight and 50 per cent of live load.
- 1.8 A 6 m cantilever beam of rectangular cross-section is provided with two sets of cables. One set of cable is balancing the self weight and other set of cables are balancing 12 kN/m live load. The cross-section at free end is 20 cm by 80 cm and at fixed end is 40 cm by 80 cm. Design the cables. (Hint: Provide zero eccentricity and zero slope for both the cables at free end. The self weight is uniformly varying so the profile of the cable will be a third order curve.)
- 1.9 A double overhang beam with 1 m overhangs on either side and 4 m within the supports is provided with a continuous cable. Assuming the self-weight of the beam as 3 kN/m design a cable to balance the total self weight. The depth of the beam is uniform and it is 20 cm. (Hint: Provide zero eccentricity and zero slope at each free ends of the beam. Calculate bending moments at support and at midspan. Select the eccentricities of the cable at these two locations and a cable force such that the moments are completely balanced. Provide a parabolic cable with negative curvature.)
- 1.10 If there are two concentrated loads of each 15 kN at each free end of the beam in problem 1.9, design a cable to balance the loads.