Course Code: CE2102 **Course name: Concrete Technology**

Course content:

UNIT I: Concrete Big Picture **(Contact Hours:8)**

History and significance of concrete as a construction material.Advantages and Disadvantages of concrete. Role of concrete in "Sustainable Infrastructure Development"

UNIT II: Concrete Constituent Materials **(Contact Hours:8)**

Cement- Manufacturing –Basic Cement Chemistry – Hydration – Classification – Tests – Relevant IS Codes

Aggregate – Classification – Characteristics – Properties of aggregates – Tests on aggregates and their significance – Grading – Fineness Modulus - Relevant IS Codes

Water – Mixing water, Curing Water – Tests of water - Relevant IS Codes

Admixtures – Functions – Classifications – Types - Relevant IS Codes.

UNIT III: Fresh Concrete **(Contact Hours:6)**

Workability – definition, tests and interpretation, Rheology of fresh concrete, Effect of constituent materials on workability, Relevant IS Standards.

UNIT IV: Hardened Concrete **(Contact Hours:8)**

Strength criterion, Stress-strain characteristics of concrete , fracture mechanics approach, tensile strength considerations, behavior under compressive strength.

Factors affecting strength of hardened concrete: porosity, gel-space ratio, total voids in concrete, w/c ratio, degree of compaction, age etc.

Dimensional Stability- Elasticity, Shrinkage and creep

Permeability & Durability: Permeability, Sulphate attack, attack by sea water, Acid attack, Alkali- aggregate reaction, corrosion of reinforcement.

UNIT V: Production of concrete and quality control **(Contact Hours:8)**

Batching of materials, Mixing of concrete materials, transpiration, RMC, placing, compaction, finishing and curing, form work.

Factors causing variations in concrete quality, field control, advantages of quality control, statistical quality control.

UNIT VI: Proportioning of concrete mixes **(Contact Hours:7)**

Basic considerations, factors influencing choice of mix design proportions, methods of concrete mix designing – IS method, ACI method, British DoE method

Unit 3: Fresh Concrete

Fresh concrete or plastic concrete is a freshly mixed material which can be moulded into any shape. The relative quantities of cement, aggregates and water mixed together, control the properties of concrete in the wet state as well as in the hardened state.

Workability:

Degree of workability

To enable the concrete to be fully compacted with given efforts, normally a higher water/cement ratio than that calculated by theoretical considerations may be required. Function of water is also to lubricate the concrete so that the concrete can be compacted with specified effort. The lubrication required for handling concrete without segregation, for placing without loss of homogeneity, for compacting and to finish it sufficiently easily, the presence of a certain quantity of water is of vital importance.

Concrete satisfying above requirements is termed as workable concrete.

Every job requires a particular workability. A concrete which is considered workable for mass concrete foundation is not workable for concrete to be used in roof construction, or even in roof construction, concrete considered workable when vibrator is used, is not workable when concrete is to be compacted by hand. Similarly a concrete considered workable when used in thick section is not workable when required to be used in thin sections. Therefore workability depends on type of work, thickness of section, extent of reinforcement and mode of compaction.

Workability can be defined as “ease with which concrete can be compacted hundred per cent having regard to mode of compaction and place of deposition”.

Factors affecting workability:

Workable concrete is the one which exhibits very little internal friction between particle and particle.

The factors helping concrete to have more lubricating effect to reduce internal friction for helping easy compaction are given below:

(a) Water Content (b) Mix Proportions

(c) Size of Aggregates (d) Shape of Aggregates

(e) Surface Texture of Aggregate (f) Grading of Aggregate

(g) Use of Admixtures.

Water content:

The higher the water content per cubic meter of concrete, the higher will be the fluidity of concrete. More water can be added, provided a correspondingly higher quantity of cement is also added to keep the water/cement ratio constant, so that the strength remains the same.

Mix Proportions:

Aggregate/cement ratio is an important factor influencing workability. The higher the aggregate/cement ratio, the leaner is the concrete. In lean concrete, less quantity of paste is available for providing lubrication, per unit surface area of aggregate and hence the mobility of aggregate is restrained. On the other hand, in case of rich concrete with lower aggregate/cement ratio, more paste is available to make the mix cohesive and fatty to give better workability.

Size of Aggregate:

The bigger the size of the aggregate, the less is the surface area and hence less amount of water is required for wetting the surface and less matrix or paste is required for lubricating the surface to reduce internal friction. For a given quantity of water and paste, bigger size of aggregates will give higher workability. The above justification will be true within certain limits.

Shape of Aggregates:

The shape of aggregates influences workability in good measure. Angular, elongated or flaky aggregate makes the concrete very harsh when compared to rounded aggregates or cubical shaped aggregates. Contribution to better workability of rounded aggregate will come from the fact that for the given volume or weight it will have less surface area and less voids than angular or flaky aggregate. Frictional resistance is also greatly reduced due to less surface area.

Surface texture:

The influence of surface texture on workability is again due to the fact that the total surface area of rough textured aggregate is more than the surface area of smooth rounded aggregate of same volume. Rough textured aggregate will show poor workability and smooth or glassy textured aggregate will give better workability. A reduction of inter particle frictional resistance offered by smooth aggregates also contributes to higher workability.

Grading of Aggregates:

This is one of the factors which will have maximum influence on workability. A well graded aggregate is the one which has least amount of voids in a given volume. Other factors being constant, when the total voids are less, excess paste is available to give better lubricating effect. With excess amount of paste, the mixture becomes cohesive and fatty which prevents segregation of particles. Aggregate particles will slide past each other with the least amount of compacting efforts. The better the grading, the less is the void content and higher the workability.

Use of admixtures:

Admixtures show maximum influence on workability. Using air-entraining agents reduces the internal friction between the particles. They also act as artificial fine aggregates of very smooth surface. It can be viewed that air bubbles act as a sort of ball bearing between the particles to slide past each other and give easy mobility to the particles. Similarly, the fine glassy pozzolanic materials offer better lubricating effects for giving better workability.

Measurement of Workability:

The following tests are commonly employed to measure workability.

(a) Slump Test (b) Compacting Factor Test

(c) Flow Test (d) Kelly Ball Test

(e) Vee Bee Consistometer Test.

Slump test:

Slump test is the most commonly used method of measuring consistency of concrete which can be employed either in laboratory or at site of work. It is not a suitable method for very wet or very dry concrete.

The apparatus for conducting the slump test essentially consists of a metallic mould in the form of a frustum of a cone having the internal dimensions as under:

Bottom diameter: 20 cm

Top diameter: 10 cm

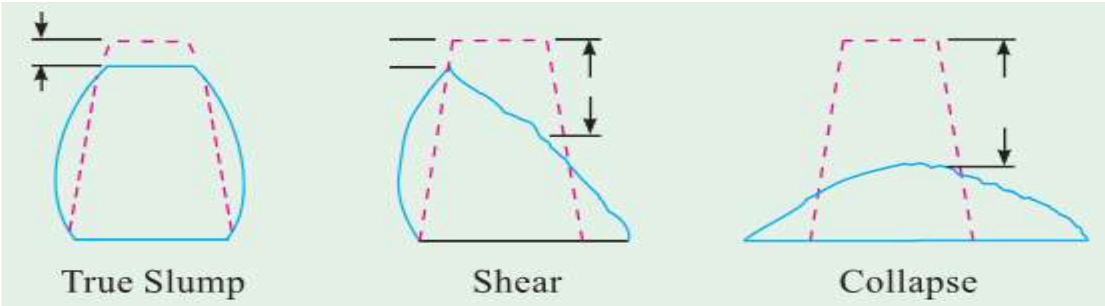
Height: 30 cm

Slump Test Apparatus

For tamping the concrete, a steel tamping rod 16 mm dia, 0.6 meter along with bullet end is used. The internal surface of the mould is thoroughly cleaned and freed from superfluous moisture and adherence of any old set concrete before commencing the test. The mould is placed on a smooth, horizontal, rigid and non-absorbant surface. Mould is then filled in four layers, each approximately 1/4 of the height of the mould. Each layer is tamped 25 times by the tamping rod taking care to distribute the strokes evenly over the cross section. After the top layer has been rodded, the concrete is struck off level with a trowel and tamping rod. The mould is removed from the concrete immediately by raising it slowly and carefully in a vertical direction. This allows the concrete to subside. This subsidence is referred as SLUMP of concrete. The difference in level between the height of the mould and that of the highest point of the subsided concrete is measured. This difference in height in mm is taken as Slump of Concrete.

If the concrete slumps evenly it is called true slamp. If one half

of the cone slides down, it is called shear slump. In case of a shear slump, the slump value is measured as the difference in height between the height of the mould and the average value of the subsidence. Shear slump also indicates that the concrete is non-cohesive and shows the characteristic of segregation.

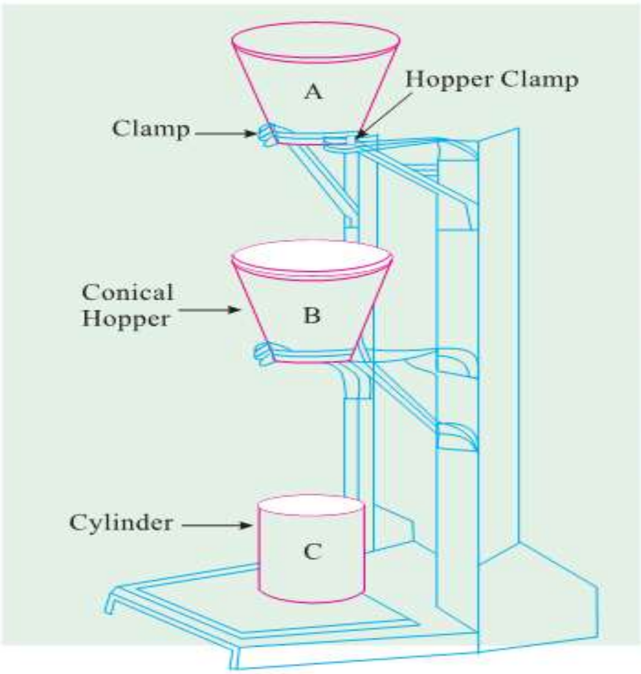


This test is not sensitive for a stiff-mix.

IS 456 of 2000 suggests that in the "very low" category of workability, workability is to be determined by compacting factor test. IS 456 of 2000 also suggests that in the "very high" category of workability, measurement of workability by determination of "flow" by flow test will be more appropriate.

Compaction factor test:

The compacting factor test is designed primarily for use in the laboratory but it can also be used in the field. It is more precise and sensitive than the slump test and is particularly useful for concrete mixes of very low workability as are normally used when concrete is to be compacted by vibration. Such dry concrete are insensitive to slump test.



Compacting Factor Apparatus

This test works on the principle of determining the degree of compaction achieved by a standard amount of work done by allowing the concrete to fall through a standard height. The degree of compaction, called the compacting factor is measured by the density ratio i.e., the ratio of the density actually achieved in the test to density of same concrete fully compacted.

Table 6.2. Essential Dimension of the Compacting Factor Appartus for use with Aggregate not exceeding 40 mm Nominal Max. Size

Upper Hopper, A	Dimension cm
Top internal diameter	25.4
Bottom internal diameter	12.7
Internal height	27.9
Lower hopper, B	
Top internal diameter	22.9
Bottom internal diameter	12.7
Internal height	22.9
Cylinder, C	
Internal diameter	15.2
Internal height	30.5
Distance between bottom of upper hopper and top of lower hopper	20.3
Distance between bottom of lower hopper and top of cylinder	20.3

The sample of concrete to be tested is placed in the upper hopper up to the brim. The trap-door is opened so that the concrete falls into the lower hopper. Then the trap-door of the lower hopper is opened and the concrete is allowed to fall into the cylinder. In the case of a dry-mix, it is likely that the concrete may not fall on opening the trap-door. In such a case, a slight poking by a rod may be required to set the concrete in motion. The excess concrete remaining above the top level of the cylinder is then cut off with the help of plane blades supplied with the apparatus. The outside of the cylinder is wiped clean. The concrete is filled up exactly upto the top level of the cylinder. It is weighed to the nearest 10 grams. This weight is known as “Weight of partially compacted concrete”. The cylinder is emptied and then refilled with the concrete from the same sample in layers approximately 5 cm deep. The layers are heavily rammed or preferably vibrated so as to obtain full compaction. The top surface of the fully compacted concrete is then carefully struck off level with the top of the cylinder and weighed to the nearest 10 gm. This weight is known as "Weight of fully compacted concrete".

The Compacting Factor = $\frac{Weight\ of\ partially\ compacted\ concrete}{Weight\ of\ fully\ compacted\ concrete}$

Table 6.1. Workability, Slump and Compacting Factor of Concretes with 20 mm or 40 mm Maximum Size of Aggregate

Degree of workability	Slump mm	Compacting factor		Use for which concrete is suitable
		Small appartus	Large appartus	
Very Low compacting factor is suitable	–	0.78	0.80	Roads vibrated by power-operated machines. At the more workable end of this group, concrete may be compacted in certain cases with hand-operated machines.
Low	25–75	0.85	0.87	Roads vibrated by hand-operated machines. At the more workable end of this group, concrete may be manually compacted in roads using aggregate of rounded or irregular shape. Mass concrete foundations without vibration or lightly reinforced sections with vibration.
Medium	50–100	0.92	0.935	At the less workable end of this group, manually compacted flat slabs using crushed aggregates. Normalreinforced concrete manually compacted and heavily reinforced sections with vibration
High	100–150	0.95	0.96	For sections with congested reinforcement. Not normally suitable for vibration. For pumping and tremie placing
Very High	–	–	–	Flow table test is more suitable.

Flow Test:

This is a laboratory test, which gives an indication of the quality of concrete with respect to consistency, cohesiveness and the proneness to segregation. In this test, a standard mass of concrete is subjected to jolting. The spread or the flow of the concrete is measured and this flow is related to workability.

The apparatus consists of flow table, about 76 cm. in diameter over which concentric circles are marked. A mould made from smooth metal casting in the form of a frustum of a cone is used with the following internal dimensions. The base is 25 cm. in diameter, upper surface 17 cm. in diameter, and height of the cone is 12 cm. The table top is cleaned of all gritty material and is wetted. The mould is kept on the centre of the table, firmly held and is filled in two layers. Each layer is rodded 25 times with a tamping rod 1.6 cm in diameter and 61 cm long rounded at the lower tamping end. After the top layer is rodded evenly, the excess of concrete which has overflowed the mould is removed. The mould is lifted vertically upward and the concrete stands on its own without support. The table is then raised and dropped 12.5 mm 15 times in about 15 seconds. The diameter of the spread concrete is measured in about 6 directions to the nearest 5 mm and the average spread is noted. The flow of concrete is the percentage increase in the average diameter of the spread concrete over the base diameter of the mould.

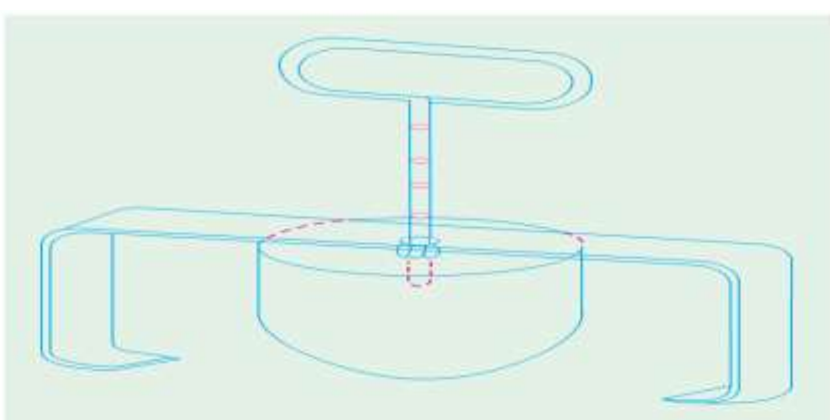
$$\text{Flow, per cent} = \frac{\text{Spread diameter in cm} - 25}{25} \times 100$$

The value could range anything from 0 to 150 per cent.

A close look at the pattern of spread of concrete can also give a good indication of the characteristics of concrete such as tendency for segregation.

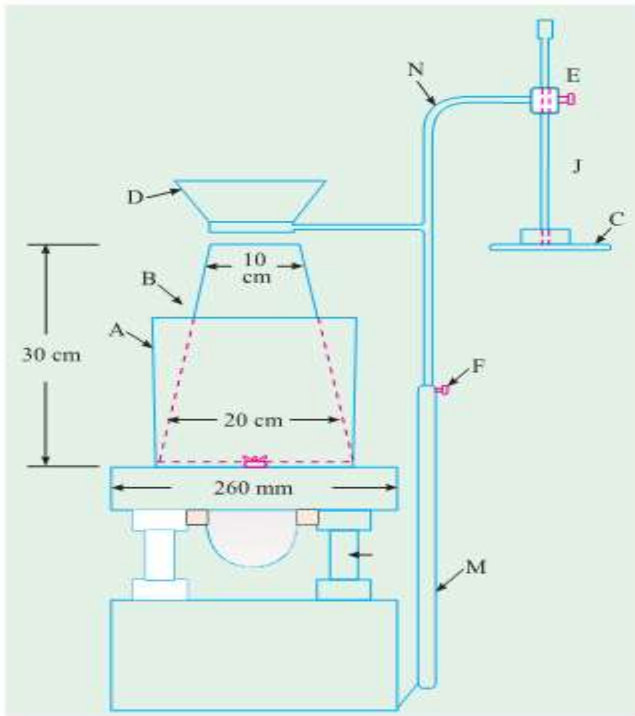
Kelly Ball Test:

The test has been devised by Kelly and hence known as Kelly Ball Test. The advantages of this test is that it can be performed on the concrete placed in site and it is claimed that this test can be performed faster with a greater precision than slump test. The disadvantages are that it requires a large sample of concrete and it cannot be used when the concrete is placed in thin section. The minimum depth of concrete must be at least 20 cm and the minimum distance from the center of the ball to nearest edge of the concrete 23 cm. The surface of the concrete is struck off level and the ball is lowered gradually on the surface of the concrete. The depth of penetration is read immediately on the stem to the nearest 6 mm. The test can be performed in about 15 seconds.



Vee Bee Consistometer Test:

This is a good laboratory test to measure indirectly the workability of concrete. This test consists of a vibrating table, a metal pot, a sheet metal cone, a standard iron rod.



Slump test is performed by placing the slump cone inside the sheet metal cylindrical pot of the consistometer. The glass disc attached to the swivel arm is turned and placed on the top of the concrete in the pot. The electrical vibrator is then switched on and simultaneously a stop watch started. The vibration is continued till such a time as the conical shape of the concrete disappears and the concrete assumes a cylindrical shape. This can be judged by observing the glass disc from the top for disappearance of transparency. Immediately when the concrete fully assumes a cylindrical shape, the stop watch is switched off. The time required for the shape of concrete to change from slump cone shape to cylindrical shape in seconds is known as Vee Bee Degree. This method is suitable for very dry concrete whose slump value cannot be measured by Slump Test.

Segregation:

Segregation can be defined as the separation of the constituent materials of concrete. A good concrete is one in which all the ingredients are properly distributed to make a homogeneous mixture. If a sample of concrete exhibits a tendency for separation of say, coarse aggregate from the rest of the ingredients, then, that sample is said to be showing the tendency for segregation. Such concrete is not only going to be weak; lack of homogeneity is also going to induce all undesirable properties in the hardened concrete.

Segregation may be of three types: firstly, the coarse aggregate separating out or settling down from the rest of the matrix, secondly, the paste or matrix separating away from coarse aggregate and thirdly, water separating out from the rest of the material being a material of lowest specific gravity.

The conditions favorable for segregation are the badly proportioned mix where sufficient matrix is not there to bind and contain the aggregates. Insufficiently mixed concrete with excess water content shows a higher tendency for segregation. Dropping of concrete from heights as in the case of placing concrete in column concreting will result in segregation.

Vibration of concrete is one of the important methods of compaction. Only comparatively dry mix should be vibrated. If too wet a mix is excessively vibrated, it is likely that the concrete gets segregated. It should also be remembered that vibration is continued just for required time for optimum results. If the vibration is continued for a long time, particularly, in too wet a mix, it is likely to result in segregation of concrete due to settlement of coarse aggregate in matrix.

Tendency for segregation can be remedied by correctly proportioning the mix, by proper handling, transporting, placing, compacting and finishing. At any stage, if segregation is observed, remixing for a short time would make the concrete again homogeneous. Use of certain workability agents and pozzolanic materials greatly help in reducing segregation. The use of air-entraining agent appreciably reduces segregation.

The pattern of subsidence of concrete in slump test or the pattern of spread in the flow test gives a fair idea of the quality of concrete with respect to segregation.

Bleeding:

It is a particular form of segregation, in which some of the water from the concrete comes out to the surface of the concrete, being of the lowest specific gravity among all the ingredients of concrete. Bleeding is predominantly observed in a highly wet mix, badly proportioned and insufficiently mixed concrete. In thin members like roof slab or road slabs and when concrete is placed in sunny weather show excessive bleeding.

Due to bleeding, water comes up and accumulates at the surface. Sometimes, along with this water, certain quantity of cement also comes to the surface. When the surface is worked up with the trowel and floats, the aggregate goes down and the cement and water come up to the top surface. This formation of cement paste at the surface is known as “Laitance”

In such a case, the top surface of slabs and pavements will not have good wearing quality. This laitance formed on roads produces dust in summer and mud in rainy season. If laitance is formed on a particular lift, a plane of weakness would form and the bond with the next lift would be poor. This could be avoided by removing the laitance fully before the next lift is poured.

Bleeding can be reduced by proper proportioning and complete mixing. Use of finely divided pozzolanic materials reduces bleeding by creating a longer path for the water to traverse. Use of air-entraining agent is very effective in reducing the bleeding. It is also reported that the bleeding can be reduced by the use of finer cement or cement with low alkali content. Rich mixes are less susceptible to bleeding than lean mixes.

Setting time of concrete:

Setting time of concrete differs widely from setting time of cement. Setting time of concrete does not coincide with the setting time of cement with which the concrete is made. The setting time of concrete depends upon the w/c ratio, temperature conditions, type of cement, use of mineral admixture, use of plasticizers–in particular retarding plasticizer. The setting parameter of concrete is more of practical significance for site engineers than setting time of cement. When retarding plasticizers are used, the increase in setting time, the duration upto which concrete remains in plastic condition is of special interest.

The setting time of concrete is found by penetrometer test. This method of test is covered by IS 8142 of 1976 and ASTM C – 403. The procedure given below may also be applied to prepared mortar and grouts.

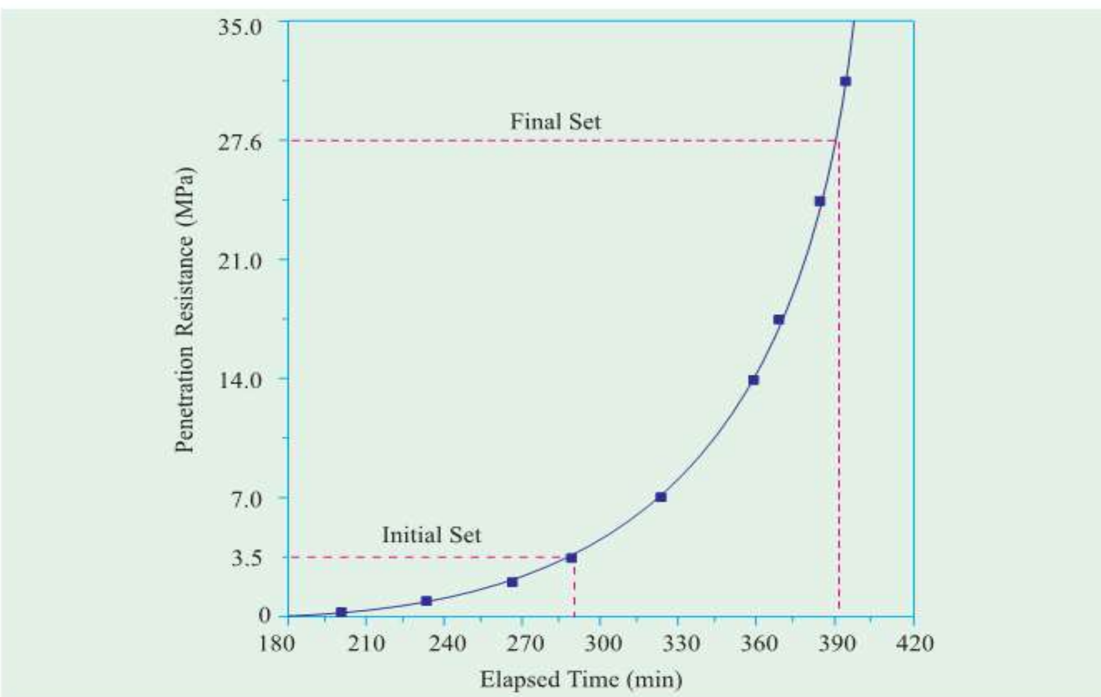
The apparatus consist of a container which should have minimum lateral dimension of 150 mm and minimum depth of 150 mm.

There are six penetration needles with bearing areas of 645, 323, 161, 65, 32 and 16 mm2. Each needle stem is scribed circumferentially at a distance of 25 mm from the bearing area.

A device is provided to measure the force required to cause penetration of the needle.

The test procedure involves collection of representative sample of concrete in sufficient quantity and sieves it through 4.75 mm sieve and the resulting mortar is filled in the container. Compact the mortar by rodding, tapping, rocking or by vibrating. Level the surface and keep it covered to prevent the loss of moisture. Remove bleeding water, if any, by means of pipette. Insert a needle of appropriate size, depending upon the degree of setting of the mortar in the following manner. Bring the bearing surface of needle in contact with the mortar surface. Gradually and uniformly apply a vertical force downwards on the apparatus until the needle penetrates to a depth of 25 ± 1.5 mm, as indicated by the scribe mark. The time taken to penetrate 25 mm depth could be about 10 seconds. Record the force required to produce 25 mm penetration and the time of inserting from the time water is added to cement. Calculate the penetration resistance by dividing the recorded force by the bearing area of the needle. This is the penetration resistance. For the subsequent penetration avoid the area where the mortar has been disturbed. The clear distance should be two times the diameter of the bearing area. Needle is inserted at least 25 mm away from the wall of container.

Plot a graph of penetration resistance as ordinate and elapsed time as abscissa. Not less than six penetration resistance determination is made. Continue the tests until one penetration resistance of at least 27.6 MPa is reached. Connect various points by a smooth curve. From penetration resistance equal to 3.5 MPa, draw a horizontal line. The point of intersection of this with the smooth curve, is read on the x-axis which gives the initial setting time. Similarly a horizontal line is drawn from the penetration resistance of 27.6 MPa and point it cuts the smooth curve is read on the x-axis which gives the final set.



Unit IV: Hardened concrete

Factors affecting strength of hardened concrete:

Compressive strength of concrete is one of the most important and useful properties of concrete. In most structural applications, concrete is primarily used to resist compressive stresses. In those cases where strength in tension or in shear is of primary importance, the compressive strength is frequently used as a measure of these properties. Compressive strength is also used as a qualitative measure for other properties of hardened concrete. No exact quantitative relationship between compressive strength and flexural strength, tensile strength, modulus of elasticity, wear resistance, fire resistance, or permeability have been established. However, approximate or statistical relationships, in some cases, have been established and these give much useful information to engineers. It should be emphasized that compressive strength gives only an approximate value of these properties and that other tests specifically designed to determine these properties should be useful if more precise results are required.

When concrete fails under a compressive load, the failure is essentially a mixture of crushing and shear failure. The mechanics of failure is a complex phenomenon.

Strength of hardened concrete depends on w/c ratio, ii) gel space ratio, iii) age,

i) w/c ratio:

Strength of paste increase with cement content and decreases with air and water content.

In 1918 Abrams presented his classic law in the form:

$$S = \frac{A}{B^x}$$

where x =water/cement ratio by volume and for 28 days results the constants A and B are 14,000 lbs/sq. in. and 7 respectively. Abrams water/cement ratio law states that the strength of concrete is only dependent upon water/cement ratio provided the mix is workable.

Abrams' water/cement ratio law is held valid even today as a fundamental truth in concrete-making practices though some modifications have been suggested to Abram's law.

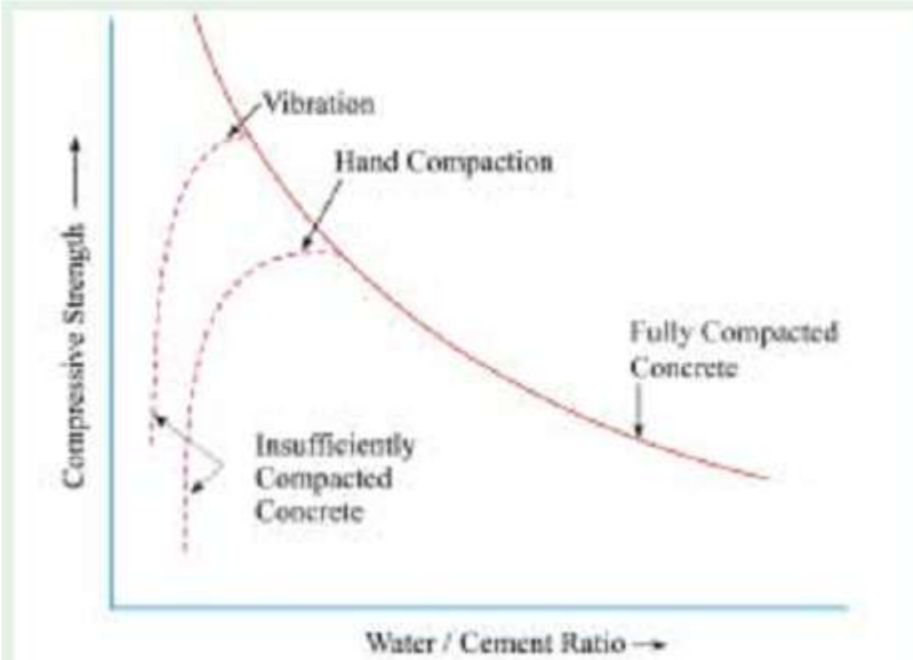


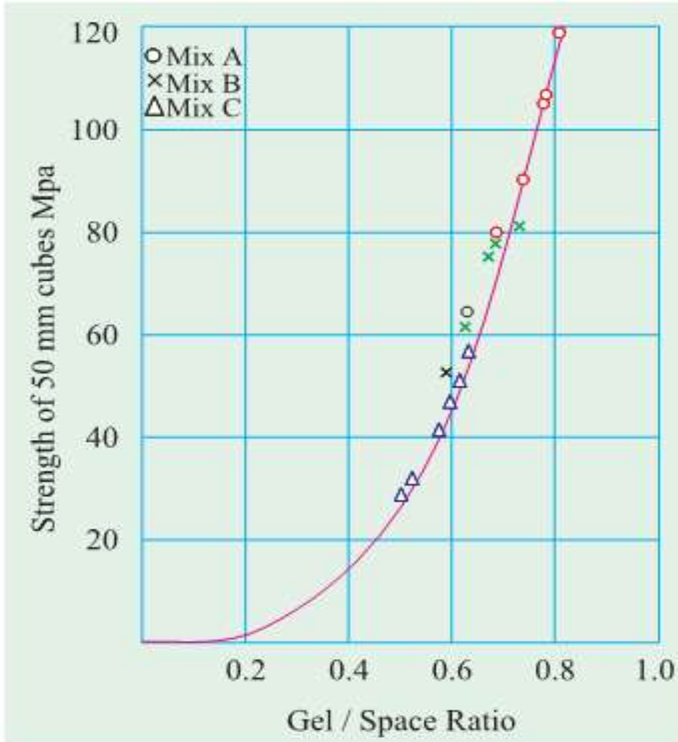
Fig. 7.1. The relation between strength and water/cement ratio of concrete.

From the above graph, it can be seen that lower water/cement ratio could be used when the concrete is vibrated to achieve higher strength, whereas comparatively higher water/cement ratio is required when concrete is hand-compacted. In both cases when the water/cement ratio is below the practical limit the strength of the concrete falls rapidly due to introduction of air voids.

ii) Gel space ratio:

Many researchers commented on the validity of Abram's law as it does not include other factors which affect strength of concrete. Some of the limitations are that the strength at any water/cement ratio depends on the degree of hydration of cement and its chemical and physical properties. Strength also depends on the temperature at which the hydration takes place, the air content in case of air entrained concrete, the change in the effective water/cement ratio and the formation of fissures and cracks due to bleeding or shrinkage. Instead of relating the strength to water/cement ratio, the strength can be more correctly related to the solid products of hydration of cement to the space available for formation of this product.

Powers and Brownyard have established the relationship between the strength and gel/space ratio. This ratio is defined as the ratio of the volume of the hydrated cement paste to the sum of volumes of the hydrated cement and of the capillary pores.



Relationship between the strength and water/cement ratio will hold good primarily for 28 days strength for fully compacted concrete, whereas, the relationship between the strength and gel/space ratio is independent of age.

iii) Gain of strength with age:

The concrete develops strength with continued hydration. The rate of gain of strength is faster to start with and the rate gets reduced with age. It is assumed that concrete attains full strength at 28 days. Actually concrete develops strength beyond 28 days also. The increase in strength beyond 28 days used to get immersed with the factor of safety. As per IS 456 of 2000, the design should be based on 28 days characteristic strength of concrete unless there is an evidence to justify a higher strength for a particular structure due to age”

Table 7.2. Grades of Concrete as per IS - 456 of 2000

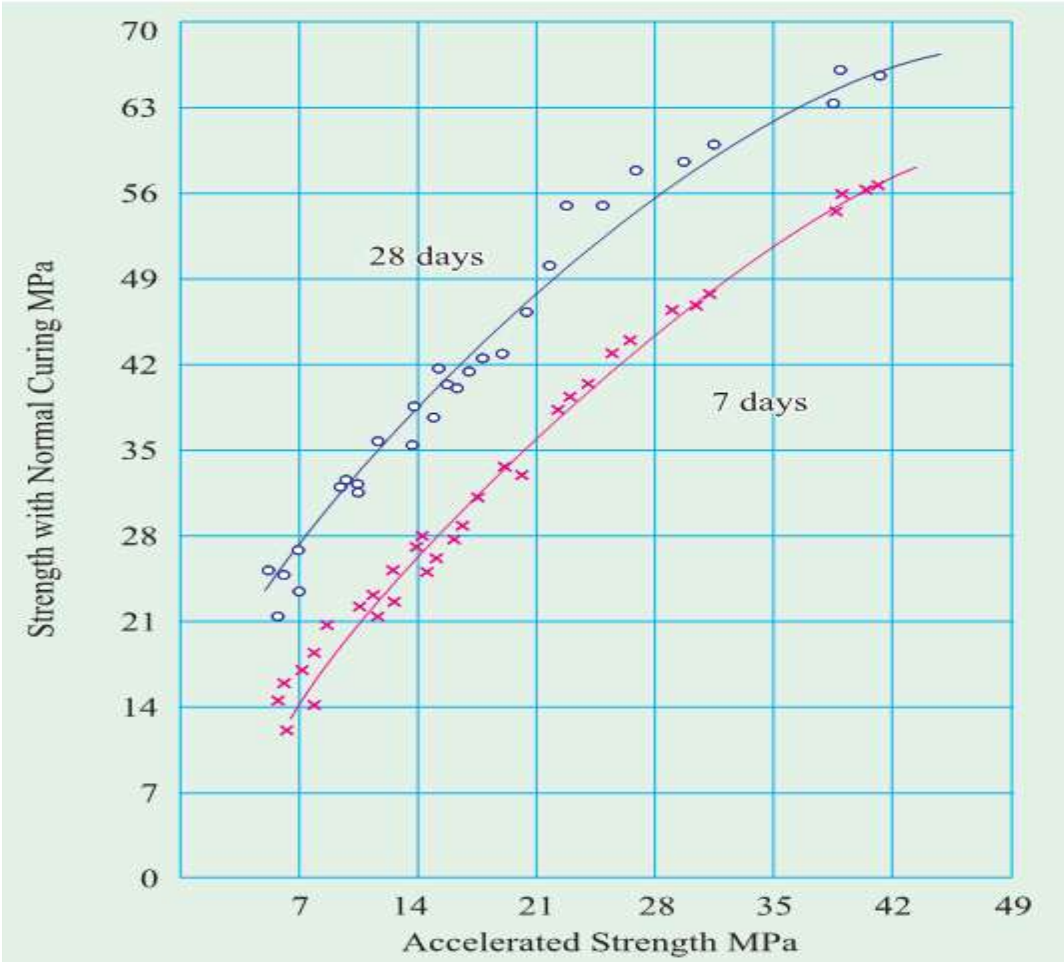
Group	Grade Designation	Specified characterstic compressive strength of 150 mm cube at 28 days in N/mm^2
Ordinary Concrete	M 10	10
	M 15	15
	M 20	20
Standard Concrete	M 25	25
	M 30	30
	M 35	35
	M 40	40
	M 45	45
	M 50	50
	M 55	55
High Strength Concrete	M 60	60
	M 65	65
	M 70	70
	M 75	75
	M 80	80

Many a time it may be necessary to estimate the strength of concrete at an early age. One may not be able to wait for 28 days. Many research workers have attempted to estimate the strength of concrete at 1, 3 or 7 days and correlate it to 28 days strength. The relationship between the strength of concrete at a lower age and 28 days depends upon many factors such as compound composition of cement, fineness of grinding and temperature of curing etc.

There are many methods for predicting the 28 days strength, within a short period of casting. Out of these, the method suggested by Prof. King is found to have good field correlations.

Accelerated Curing test:

In the accelerated curing test, standard cubes are cast and are covered with top plate and the joints are sealed with special grease to prevent drying. Within 30 minutes of adding water, the cubes having sealed effectively, are placed in an air-tight oven which is then switched on. The oven temperature is brought to 93°C in about one hour time. It is kept at this temperature for 5 hours. At the end of this period the cubes are removed from oven, stripped, cooled, and tested. The time allowed for this operation is 30 minutes. The strength of concrete is determined within 7 hours of casting and this accelerated strength shows good relationship with 7 and 28 days strengths of normally cured concrete. The figure below shows relationship between accelerated strength and normally cured concrete strength at 7 and 28 days.



One of the main factors that affect the rate of gain of strength is the fineness of cement. It has been estimated that particles of cement over 40 micron in size contribute to the compressive strength of concrete only over long periods, while those particles smaller than 25 to 30 micron contribute to the 28 days strength, those particles smaller than 20 to 25 micron contribute to the 7 days strength, and particles smaller than 5 to 7 micron contribute to the 1 or 2 days strength.

Relation between compressive and tensile strength:

In reinforced concrete construction, the strength of the concrete in compression is only taken into consideration. The tensile strength of concrete is generally not taken into consideration. But in the design of concrete pavement, slabs are often based on the flexural strength of concrete. Therefore, it is necessary to assess the flexural strength of concrete either from the compressive strength or independently.

The tensile strength of concrete, as compared to its compressive strength, is more sensitive to improper curing. This may be due to the inferior quality of gel formation as a result of improper curing and also due to the fact that improperly cured concrete may suffer from more shrinkage cracks.

The use of pozzolanic material increases the tensile strength of concrete.

From the extensive study, carried out at Central Road Research Laboratory (CRRI) the following statistical relationship between tensile strength and compressive strength were established.

(i) $y = 15.3x - 9.00$ for 20 mm maximum size aggregate.

(ii) $y = 14.1x - 10.4$ for 20 mm maximum size natural gravel.

(iii) $y = 9.9x - 0.55$ for 40 mm maximum size crushed aggregate.

(iv) $y = 9.8x - 2.52$ for 40 mm maximum size natural gravel. Where y is the compressive strength of concrete MPa and x is the flexural strength of concrete MPa.

The flexural strength of concrete was found to be 8 to 11 per cent of the compressive stength of the concrete for higher ranges of concrete strength (greater than 25 MPa) and 9 to 12.8 per cent for lower ranges of concrete strength (less than 25 MPa).

Flexural strength of concrete is usually found by testing plain concrete beams. Two methods of loading of the beam specimen for finding out flexural strength are practiced:

Center point loading and three point loading:

Experience shows that the variability of results is less in third-point loading. The results of the flexural strength tested under central and third-points loading with constant span to depth ratios of 4 were analyzed statistically and the following general relationship was obtained at Central Road Research Laboratory.

$$x1 = x2 + 0.72$$

where, x1 = flaxural strength (MPa) of concrete under central point loading and x2 = flexural strength (MPa) of concrete under third point loading.

In all the cases the central loading gave higher average value than the third-point loading irrespective of the size of the sample. The higher strength obtained in the case of central loading may be attributed to the fact that the beam is being subjected to the maximum stress at a pre-determined location not necessarily the weakest. In the standard methods for finding the flexural strength of concrete, the span to depth ratio of the specimen is kept at 4. If the span to depth ratio is increased or decreased, the flexural strength was found to alter. A change in this ratio by 1 induced 3 per cent and 2.5 per cent change in strength when tested by third-point and central point loading respectively. With the increase in span to depth ratio the flexural strength decreased.

The rate of stress application was found to influence the flexural strength of concrete to a very significant extent. The strength increased upto about 25 per cent with increase in stressing rate compared to the standard rate of 0.7 MPa per minute. The increase was found more with the leaner mixes.

There are number of empirical relationships connecting tensile strength and compressive strength of concrete. One of the common relationships is shown below.

Tensile Strength = K (Compressive Strength)^n where, value of K varies from 6.2 for gravels to 10.4 for crushed rock (average value is 8.3) and value of n may vary from 1/2 to 3/4.

The Indian Standard IS = 456 of 2000 gives the following relationship between the compressive strength and flexural strength.

$$\text{Flexural Strength} = 0.7\sqrt{f_{ck}}$$

where f_{ck} is the characteristic compressive strength of concrete in N/mm^2.

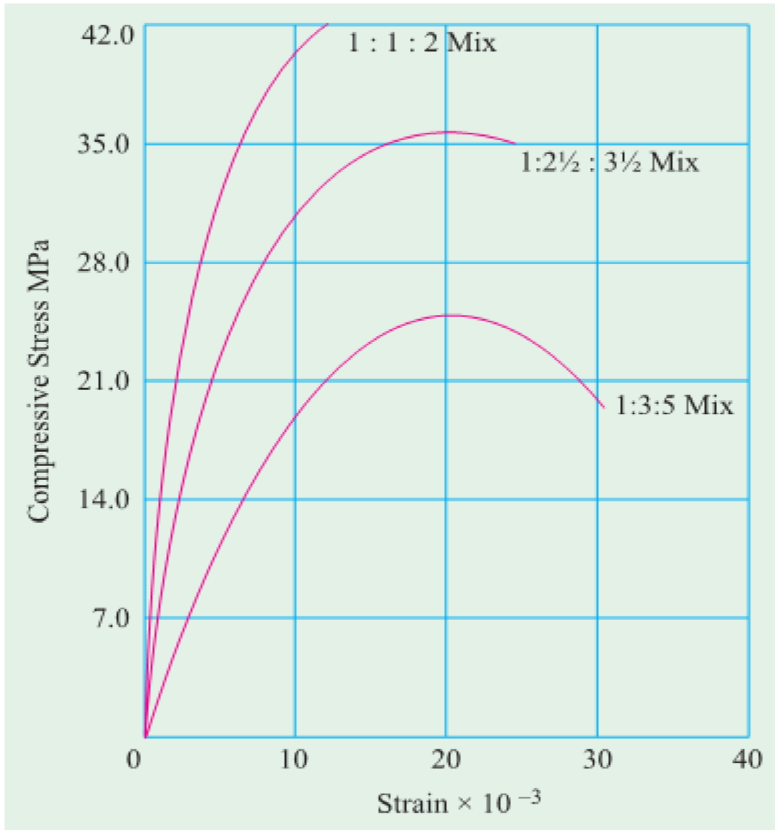
Elasticity of concrete:

Deformation of concrete depends upon the magnitude of the load, the rate at which the load is applied and the elapsed time after which the observation is made. In other words, the rheological behavior of concrete i.e., the response of concrete to applied load is quite complex.

The knowledge of rheological properties of concrete is necessary to calculate deflection of structures, and design of concrete members with respect to their section, quantity of steel and stress analysis.

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

Up to about 10-15% of the ultimate strength of concrete, the stress-strain graph is not very much curved and hence can give more accurate value. For higher stresses the stress-strain relationship will be greatly curved and as such it will be inaccurate.



Relation between modulus of elasticity and strength:

Modulus of elasticity of concrete increases approximately with the square root of the strength. IS 456 of 2000 gives the Modulus of elasticity as $E_C = 5000\sqrt{f_{ck}}$

where E_C is the short term static modulus of elasticity in N/mm^2.

The modulus of elasticity determined by subjecting a concrete beam to bending is called static modulus of elasticity.

Creep:

Creep can be defined as "the time-dependent" part of the strain resulting from stress. The relation between stress and strain for concrete is a function of time. The gradual increase in strain, without increase in stress, with the time is due to creep. From this explanation creep can also be defined as the increase in strain under sustained stress.

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

Under sustained stress, with time, the gel formed, the adsorbed water layer, the water held in the gel pores and capillary pores yields, flows and readjust themselves, which is termed as creep in concrete.

Factors affecting creep:

i) Influence of aggregates:

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

The modulus of elasticity of aggregate is one of the important factors influencing creep. It can be easily imagined that the higher the modulus of elasticity the less is the creep. Light weight aggregate shows substantially higher creep than normal weight aggregate which may be because of lower modulus of elasticity.

ii) Influence of mix proportions:

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

iii) Influence of Age:

Age at which a concrete member is loaded will have a predominant effect on the magnitude of creep. This can be easily understood from the fact that the quality of gel improves with time. Such gel creeps less, whereas a young gel under load being not so stronger creeps more.

Shrinkage:

Volume change is one of the most detrimental properties of concrete, which affects the long-term strength and durability.

One of the important factors that contribute to the cracks in floors and pavements is due to shrinkage.

The term shrinkage is used to describe various aspects of volume changes in concrete due to loss of moisture at different stages due to different reasons.

Types of shrinkage:

Shrinkage is classified into the following ways:

a) Plastic shrinkage

b) Drying shrinkage

c) Autogeneous shrinkage

d) Carbonation shrinkage

a) Plastic Shrinkage:

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

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

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

From the above it can be inferred that high water/cement ratio, badly proportioned concrete, rapid drying, greater bleeding, unintended vibration etc., are some of the reasons for plastic shrinkage.

Plastic shrinkage can be reduced mainly by preventing the rapid loss of water from surface. This can be done by covering the surface with polyethylene sheeting immediately on finishing operation; by monomolecular coatings by fog spray that keeps the surface moist; or by working at night. An effective method of removing plastic shrinkage cracks is to re-vibrate the concrete in a controlled manner.

b) Drying shrinkage:

Just like hydration of cement, the drying shrinkage is also an everlasting process when concrete is subjected to drying conditions. Loss of water held in gel pores causes drying shrinkage. Under drying conditions, the gel water is lost progressively over a long time, as long as the concrete is kept in drying conditions. The magnitude of drying shrinkage is also a function of the fineness of gel. The finer the gel the more is the shrinkage.

c) Autogeneous Shrinkage:

In a conservative system i.e. where no moisture movement to or from the paste is permitted, when temperature is constant some shrinkage may occur. The shrinkage of such a conservative system is known as autogeneous shrinkage. Autogeneous shrinkage is of minor importance and is not applicable in practice to many situations except that of mass of concrete in the interior of a concrete dam. The magnitude of autogeneous shrinkage is in the order of about 100×10^{-6}.

d) Carbonation Shrinkage:

Carbonation shrinkage is a phenomenon very recently recognized. Carbon dioxide present in the atmosphere reacts in the presence of water with hydrated cement. Calcium hydroxide [Ca(OH)2] gets converted to calcium carbonate and also some other cement compounds are decomposed. Such a complete decomposition of calcium compound in hydrated cement is chemically possible even at the low pressure of carbon dioxide in normal atmosphere. Carbonation penetrates beyond the exposed surface of concrete very slowly.

Magnitude of carbonation shrinkage is very small when compared to long term drying shrinkage and hence this aspect is not of much significance.

Factors affecting shrinkage:

One of the most important factors that affect shrinkage is the drying condition or in other words, the relative humidity of the atmosphere at which the concrete specimen is kept. If the concrete is placed in 100 per cent relative humidity for any length of time, there will not be any shrinkage, instead there will be a slight swelling.

Magnitude of shrinkage increases with time and also with the reduction of relative humidity. The rate of shrinkage decreases rapidly with time. It is observed that 14 to 34 per cent of the shrinkage occurs in 2 weeks, 40 to 80 per cent of the shrinkage occurs in 3 months and 66 to 85 per cent of the shrinkage occurs in one year.

Another important factor which influences the magnitude of shrinkage is water/cement ratio of the concrete. With increase in w/c ratio, shrinkage increases.

Aggregate plays an important role in the shrinkage properties of concrete. The grading of aggregate by itself may not directly make any significant influence. But since it affects the quantum of paste and water/cement ratio, it definitely influences the drying shrinkage indirectly. The aggregate particles restrain the shrinkage of the paste.

Harder aggregate with higher modulus of elasticity, like quartz, shrinks much less than softer aggregates such as sandstone.

By taking proper precautions the magnitude of shrinkage can only be reduced, but cannot be eliminated.

Durability:

Concrete structures built in highly polluted urban and industrial areas, aggressive marine environment, harmful sub-soil water in coastal area and many other hostile conditions are not durable because materials used for construction are found to be non-durable in those conditions.

Advancement in concrete technology is mostly concentrated on the strength of concrete. But now, it is recognized that strength of concrete alone is not sufficient, the degree of harshness of the environmental condition to which concrete is exposed over its entire life is equally important. Therefore, both strength and durability are to be considered at the design stage.

Definition of Durability:

The durability of cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. Durable concrete will retain its original form, quality, and serviceability when exposed to its environment.

Significance of Durability:

When designing a concrete mix or designing a concrete structure, the exposure condition at which the concrete is supposed to withstand is to be assessed in the beginning with good judgment. In case of foundations, the soil characteristics are also required to be investigated. The environmental pollution is increasing day by day particularly in urban areas and industrial atmospheres. It is reported that in industrially developed countries over 40 per cent of total resources of the building industries are spent on repairs and maintenance.

Chemical Action:

When dealing with the durability of concrete, chemical attack which results in volume change, cracking of concrete and the consequent deterioration of concrete becomes an important part of discussion. Under chemical attack, sulphate attack, alkali-aggregate reaction, acid attack and effect of sea water will be discussed.

Sulphate attack:

Most soils contain some sulphate in the form of calcium, sodium, potassium and magnesium. They occur in soil or ground water. Of all the sulphates, magnesium sulphate causes maximum damage to concrete. A characteristic whitish appearance is the indication of sulphate attack.

The term sulphate attack denote an increase in the volume of cement paste in concrete or mortar due to the chemical action between the products of hydration of cement and solution containing sulphates. In the hardened concrete, calcium aluminate hydrate (C-A-H) can react with sulphate salt from outside. The product of reaction is calcium sulphoaluminate, forming within the framework of hydrated cement paste. Because of the increase in volume of the solid phase which can go up to 227 per cent, a gradual disintegration of concrete takes place.

The rate of sulphate attack increases with the increase in the strength of solution. A saturated solution of magnesium sulphate can cause serious damage to concrete with higher water cement ratio in a short time. However, if the concrete is made with low water cement ratio, the concrete can withstand the action of magnesium sulphate for 2 or 3 years.

Concentration of sulphates is expressed as the number of parts by weight of SO3 per million parts. 1000 PPM is considered moderately severe and 2000 PPM is considered very severe, especially if MgSO4 is the predominant constituent.

Methods of Controlling Sulphate Attack:

(a) Use of Sulphate Resisting Cement:

The most efficient method of resisting the sulphate attack is to use cement with the low C3A content. In general, it has been found that a C3A content of 7% gives a rough division between cements of good and poor performance in sulphate waters.

(b) Quality Concrete:

A well designed, placed and compacted concrete which is dense and impermeable exhibits a higher resistance to sulphate attack. Similarly, a concrete with low water/cement ratio also demonstrates a higher resistance to sulphate attack.

(c) Use of air-entrainment:

Use of air-entrainment to the extent of about 6% (six per cent) has beneficial effect on the sulphate resisting qualities of concrete. The beneficial effect is possibly due to reduction of segregation, improvement in workability, reduction in bleeding and in general better impermeability of concrete.

(d) Use of pozzolana:

Incorporation of or replacing a part of cement by a pozzolanic material reduces the sulphate attack. Admixing of pozzolana converts the leachable calcium hydroxide into insoluble non-leachable cementitious product. This pozzolanic action is responsible for impermeability of concrete. Secondly, the removal of calcium hydroxide reduces the susceptibility of concrete to attack by magnesium sulphate.

(e) High Pressure Steam Curing:

High pressure steam curing improves the resistance of concrete to sulphate attack. This improvement is due to the change of C3AH6 into a less reactive phase and also to the removal or reduction of calcium hydroxide by the reaction of silica which is invariably mixed when high pressure steam curing method is adopted.

Alkali-Aggregate Reaction:

Alkali-aggregate reaction (AAR) is basically a chemical reaction between the hydroxyl ions in the pore water within concrete and certain types of rock minerals which sometimes occur as part of aggregates. Since reactive silica in the aggregate is involved in this chemical reaction it is often called alkali-silica reaction (ASR).

The reaction produces alkali-silica gel of unlimited swelling type under favorable conditions of moisture and temperature in voids and cracks and further it causes disruption and pattern cracking. The crack width can range from 0.1 mm to as much as 10 mm.

Alkali content (Na_2O + 0.658 times K_2O content of clinker) in cement should be less than 0.6 per cent by mass of cement. Alkali content of 0.6 could be considered as a threshold point of high alkali cement.

Alkali-silica reaction takes place only at high pH values. The pH of the pore water depends on the alkali content of cement. Heigh alkali cement may lead to a pH of about 13.5 to 13.9 and low alkali cement results in a pH of about 12.7 to 13.1. Therefore, low alkali cement which produces low pH value in the pore water is safe against potentially reactive aggregate.

Alkalis not only comes from cement but also comes from sand containing sodium chloride, admixtures, mixing water, sea water penetration, fly ash, blast furnace slag and deicing salt getting into concrete. Alkalis from all these sources must be included in finding the total alkalis.

Acid Attack:

Concrete is not fully resistant to acids. Most acid solutions will slowly or rapidly disintegrate portland cement concrete depending upon the type and concentration of acid. Certain acids, such as oxalic acid and phosphoric acids are harmless. The most vulnerable part of the cement hydrate is Ca(OH)2, but C-S-H gel can also be attacked. Silicious aggregates are more resistant than calcareous aggregates.

Concrete can be attacked by liquids with pH value less than 6.5. But the attack is severe only at a pH value below 5.5. At a pH value below 4.5, the attack is very severe.

If the attack proceeds, all the cement compounds are eventually broken down and leached away, together with any carbonate aggregate material. With the sulphuric acid attack, calcium sulphate formed can proceed to react with calcium aluminate phase in cement to form calcium sulphoaluminate, which on crystallisation can cause expansion and disruption of concrete.

Concrete in Sea Water:

Large numbers of concrete structures are exposed to sea water either directly or indirectly. For several reasons, effect of sea water on concrete deserves special attention. The coastal and offshore structures are exposed to simultaneous action of a number of physical and chemical deterioration process. The concrete in sea water is subjected to chloride induced corrosion of steel, freezing and thawing, salt weathering, abrasion by sand held in water and other floating bodies.

Sea water generally contains 3.5 per cent of salt by weight. The ionic concentration of Na^+ and Cl^- are the highest, typically 11,000 and 20,000 mg/litre respectively. It also contains Mg^{2+} and SO_4^{2-}, typically 1400 and 2700 mg/litre respectively. The PH of sea water varies between 7.5 and 8.4. The average value is 8.2. Sea water also contains some amount of CO_2.

Magnesium sulphate reacts with free calcium hydroxide in set Portland cement to form calcium sulphate, at the same time precipitating magnesium hydroxide. MgSO4 also reacts with the hydrated calcium aluminate to form calcium sulpho aluminate. These have often been assumed to be the actions primarily responsible for the chemical attack of concrete by sea water.

Concrete will have lost some part of lime content due to leaching. Both calcium hydroxide and calcium sulphate are considerably more soluble in sea water and this, will result in increased leaching action. Concrete undergoes several reactions concurrently when subjected to sea water.

As concrete is not 100% impervious, water that permeates into the concrete cause corrosion of steel. The product of corrosion being of higher volume than the material they replace, exert pressure which results in lack of durability to reinforced concrete. It is also seen that the lack of durability is more in case of reinforced concrete than the identical plain concrete.

Using rich concrete with low water/cement ratio mainly makes the concrete impervious to the attack of sea water, and also having very little capillary pores does not hold water, to cause expansion either by freezing or by crystallisation of salt. Provision of adequate cover is another desirable step for increasing durability of reinforced concrete. Use of pozzolanic material is yet another desirable step that could be taken to improve durability against sea water.

Corrosion of Steel:

It can be noted that no corrosion takes place if the concrete is dry or probably below relative humidity of 60 percent because enough water is not there to promote corrosion. It can also be noted that corrosion does not take place if concrete is fully immersed in water because diffusion of oxygen does not take place into the concrete. Probably the optimum relative humidity for corrosion is 70 to 80 per cent.

The products of corrosion occupy a volume as many as six times the original volume of steel depending upon the oxidation state. The increased volume of rust exerts thrust on cover concrete resulting in cracks, spalling or delamination of concrete. With this kind of situations concrete loses its integrity. The cross section of reinforcement progressively reduces and the structure is sure to collapse.

Corrosion control:

It has been reported that 40% of failure of structures is on account of corrosion of embedded steel reinforcement in concrete. Therefore corrosion control of steel reinforcement is a subject of paramount importance.

Proper mix design, use of right quality and quantity of cement for different exposure conditions is to be adopted.

Use of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (ggbs), silica fume etc. are required to be used as admixtures or in the form of blended cement in addition to lowest possible W/C ratio to make concrete dense. These materials improve more than one properties of concrete which will eventually reduce corrosion of reinforcement. Tests on mortar containing ggbs have shown that water permeability is reduced by a factor up to 100.

In short it can be said that if we make good concrete with low permeability and improved microstructure, it will be durable by itself and also it can take care of the reinforcement contained in it to a great extent.

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

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

Permeability:

Permeability of concrete is also an important point for durability of concrete in addition to w/c ratio.

Permeability of cement paste:

The cement paste consists of C-S-H gel, Ca(OH)2 and water filled or empty capillary cavities. Although gel is porous to the extent of 28 per cent, the gel pores are so small that hardly any water can pass through under normal conditions. The permeability of gel pores is estimated to be about 7 x 10–16 m/s. That is approximately about 1/100 of that of paste. Therefore, the gel pores do not contribute to the permeability of cement paste.

The extent and size of capillary cavities depend on the W/C ratio. It is one of the main factors contributing to the permeability of paste. At lower W/C ratio, not only the extent of capillary cavities is less but the diameter is also small. The capillary cavities resulting at low W/C ratio, will get filled up within a few days by the hydration products of cement.

Only large cavities resulting from higher W/C ratio (say more than 0.7) will not get filled up by the products of hydration, and will remain as unsegmented cavities, which is responsible for the permeability of paste.

Cement paste even with high W/C ratio of 0.70 is quite impervious as that of granite with coefficient of permeability of 5.35 x 10^{-11} m/s.

However in actual practice, it is noticed that mortar and concrete exhibit much high permeability. Higher permeability of mortar or concrete in actual structures is due to the following reasons.

(a) Formation of micro-cracks developed due to long term drying shrinkage and thermal stresses.

(b) The large micro-cracks generated with time in the transition zones.

(c) Cracks generated through higher structural stresses.

(d) Due to volume change and cracks produced on account of various minor reasons.

(e) Existence of entrapped air due to insufficient compaction

Coefficient of permeability increases more than 100 times when W/C ratio increased from 0.4 to 0.7

Permeability of Concrete:

Theoretically, the introduction of aggregate of low permeability into cement paste, it is expected to reduce the permeability of the system because the aggregate particles intercept the channels of flows and make it take a circuitous route. Compared to neat cement paste, concrete with the same W/C ratio and degree of maturity, should give a lower coefficient of permeability. But in practice, it is seen from test data it is not the case. The introduction of aggregate, particularly larger size of aggregates increases the permeability considerably. This may be because of formation of micro cracks.

Drying shrinkage, thermal shrinkage and externally applied load may cause cracks in weak transition zone (cavities formed around aggregates) at the young age. It is reported that the size of the cracks in transition zone is much bigger than most of the capillary cavities present in cement paste.

The use of pozzolanic materials in optimum proportion reduces the permeability of concrete.