VISVESVARAYA TECHNOLOGICAL UNIVERSITY
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CONCRETE TECHNOLOGY
(Subject Code : 21CV62)

LECTURE NOTES

(MODULE-4)

HARDENED CONCRETE

VI-SEMESTER

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Syllabus: HARDENED CONCRETE: Factors affecting strength, w/c ratio, gel/space ratio, maturity concept, Effect of aggregate properties, assessment of compressive strength, flexural strength, tensile strength, bond strength and modulus of elasticity, aggregate - cement bond strength, factors influencing strength and Codal provisions, Relation between modulus of elasticity and strength, factors affecting modulus of elasticity, Poisson Ratio.

HARDENED CONCRETE

Most important property of concrete is its strength, Here strength means Compressive strength, tensile strength and flexural strength. Usually failure of concrete occurs due to compressive force & shear force. The compressive strength of concrete is generally determined by testing cubes of concrete .

Compressive stress is resistance against compressive force extended by external loads . The cohesion & internal friction developed by concrete to resist failures is related to mainly W/C ratio .

For a given cement & acceptable aggregates , the strength that may be developed by workable , **properly placed mixture of cement ,aggregate &water (under the same mixing, curing and testing condition) is influenced by**

Factors influencing the mix

1. Ratio of cement to mixing water
2. Ratio of cement to aggregates
3. Grading, surface texture, shape, strength & stiffness of aggregate particles
4. Maximum size of aggregates

- **Water- Cement Ratio:-**

  It is the ratio of volume of water to volume of cement required to get a consistent &workable concrete mix . This indicates the strength of concrete primarily depends on the strength of the cement paste

  *strength of the paste increases with amount of cement content and decreases with more air and more water content .

  Following are the different equations to estimate strength of concrete

1. **Abram's formula:**Where, A = Constant 14,000lts/s

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

B=7

X=w/c ratio

2.Feret's formula:

$$S = K\left[\frac{C}{c+e+a}\right]^2$$

Where S= strength of concrete

c= volume of cement

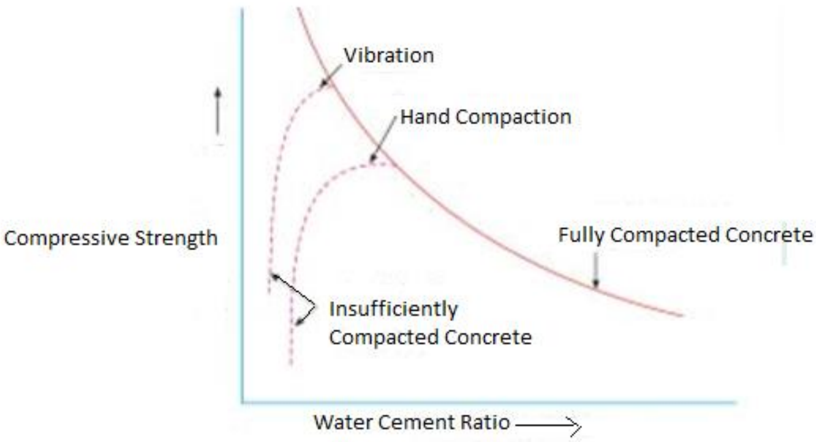
K= constant

e= volume of water

a= volume of air

Abrams W/C ratio formula states that strength of concrete is only depend on W/C ratio provided the mix is workable .

Relationship between Compressive Strength and W/C ratio



Relationship between Strength and Water Cement Ratio

Lower water cement ratio can be used when the concrete is vibrated t achieve higher strength, whereas comparatively higher water cement ratio is required when 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.

<u>Gel/Space Ratio:-</u>

Instead of relating strength to W/C ratio , the strength can be more correctly related to the solid products of hydration of cement to the space available for the formation of this product. Powers and Brown yard have established the relationship b/w strength and gel/space ratio.

The ratio is defined as the ratio of the volume of the hydrated cement paste to the sum of volume of the hydrated cement and of the capillary pores . The strength developed can be compared to the gel/ space ratio to estimate the compressive strength In other words Gel/ space ratio means amount of cement paste and the volume required to get that paste .if the amount of gel formed is known ,the strength can be estimated as follows.

Power's experiment showed the strength of concrete bears a specific relationship with gel /space ratio . He found the relationship to be $240x^3$, When x –gel/space ratio.

240 represents the Intrinsic strength of get in MPa for type of Cement &specimen used .

$$S = 240x^3$$

Gel/space ratio for complete hydration

$$Gel / Space\ ratio = x == \frac{Volume \text{ of gel}}{\text{Space Available}} = \frac{0.657C}{0.319C + W_0}$$

Where, C – weight of cement in gm; Vc- specific volume of cement 0.319ml/gm; Wo- volume of mixing water in ml

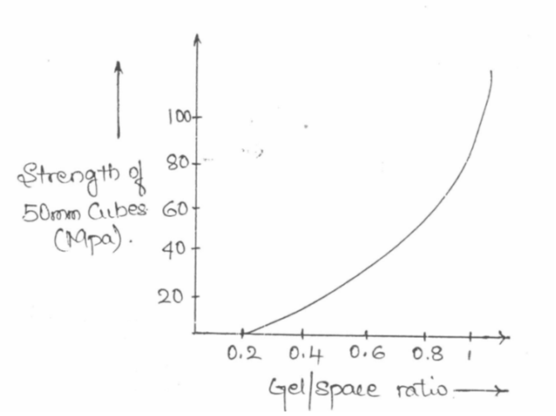
Gel/space ratio for partial hydration

$$x = \frac{2.06 \times 0.319 \times C\alpha}{0.319C\alpha + W_0}$$

α= Fraction of cement that has Hydrated (for Ex: if rate of hydration is 60%; α=0.6)

Gel/space ratio can be calculated at any age and for any fraction of hydration of cement .

Relation betweenthe compressive strength of mortar & gel /space ratio :-



It is pointed out that relationship between the strength and W/C 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 .

Factors affecting Gel /space ratio:-

There is a lot of difference b/w the theoretical strength of concrete and actual strength of concrete. Actual strength of concrete is much lower than the theoretical strength estimated on the basis of molecular cohesion and surface energy of a solid assumed to be perfectly homogenous & flawless.

The high stress concrete takes place around a few of the large flaws. This situation leads to failure of material at a much lower stress, intensity considering the whole process, presence of bigger flaws brings down the actual strength to a much lower value than the theoretical strength .

Cement Paste in concrete contains many discontinuous such as voids, bleeding concrete , rupture of bond due to drying shrinkage and temperature stresses.

Maturity concept of concrete:-

The development of strength of concrete depends on both time and temperature . Thus concrete strength is a function of summation of products of time and temperate. This is known as maturity concept.

The sample of concrete for 28 days is taken as fully matured concrete.

Thus, Maturity = Σ (time and temperature).

The temperature is reckoned from an origin lying between -12 and -10^{0}C. It was experimentally found that the hydration of concrete continues to take place up to -11^{0}C. Hence -11^{0}C is taken as datum line for computing maturity.

Where Σ indicates curing is done for different time intervals at different temperature at different days. Hence summation of time is required.

Maturity value of fully matured concrete:-

By **Plowman's** experiment,

A sample of concrete cured at 18^{0}C for 28days is taken as fully matured concrete. Its maturity would be equal to

Maturity =28X24X [18-(-11)] = 19488°Ch.

If the strength of fully matured concrete is known it is possible to estimate the strength of other identical concrete by using maturity concept.**In standard calculation maturity of fully cured concrete is taken as 19,800°Ch.**

$$\%\text{of Maturity strength} = A + B\log_{10}\left(\frac{Maturity}{1000}\right)$$

Where A& B are constant and are called Plowman's constant.

Plowman's Coefficients for maturity Equation

Strength after 18 days at 18^{0}C (Maturity of 19,800^{0}Ch):MPa	**Coefficient**	
	A	**B**
<17.5	10	68
17.5-35.0	21	61
35.0-52.5	32	54
52.5-70.0	42	46.5

Shrinkage:-

In addition to deformation caused by applying stresses. Volume changes due to shrinkage and temperature variation are of considerable importance because practically these movements are partly or fully retained and therefore they induce stresses .

Shrinkage is caused due to loss of water by evaporation or by hydration of cement and also by carbonation . Due to shrinkage there is a reduction in volume and the volumetric strain is equal to 3 times linear contraction and in practice will measure the shrinkage as linear strain .

Generally presence of cracks in floors and pavements is due to shrinkage.

Types of shrinkage

1. Plastic shrinkage
2. Drying shrinkage
3. Carbonation shrinkage
4. Autogenous shrinkage

1. Plastic Shrinkage:-

This type of shrinkage occurs as soon as the concrete is placed in the forms while the concrete is still in plastic state.

- The main causes of plastic shrinkage is due to loss of water by evaporation from the surface of concrete or by the absorption by aggregate or sub grade . This results in reduction of volume.
- Plastic shrinkage is mainly observed in floors and pavements where the surface area exposed to drying in large as compared to the depth.
- When this large surface is exposed to hot sun and dry wind the surface of the concrete dries very fast resulting shrinkage. (Forms cracks).
- Richer concrete also undergoes greater plastic shrinkage.

The main causes are

1. High W/C ratio

2. Badly proportioned mix

3.Rapid drying

4. Unintended vibration

5. Yielding of formwork

6. Greater bleeding

- Shrinkage occurs in a poorly made concrete with a high W/C ratio due to the fact that large quantity of water bleeds and accumulate at the surface when the water at the surface dries out the surface concrete collapses causing cracks .
- If concrete is subjected to an intended vibration or when former supports starts yielding it leads to plastic shrinkage.
- The causes of shrinkage are high W/C ratio rapid drying , greater bleeding, unintended vibration and also rich concrete.
- There are no of ways to reduce the plastic shrinkage, the rapid loss of water from the surface can be prevented by covering the surface with polythelyene sheets . by Nano molecular coatings, by fog Spray that keeps the surface moist ,by bulking at night, by vibration of concrete in a controlled manner and by use of aluminium powder etc.

2. Drying Shrinkage

Shrinkage that takes place after the concrete has set and hardened is called as dry shrinkage and most of it taken place within a few months after placing .

- Just as hydration of cement is an everlasting process the dry shrinkage is also a same
- The loss of free water contained in hardened concrete does not result in any appreciable dimension change. It is a loss of water held in the gel pores that causes the change in volume .
- It is seen that concrete made with smaller size aggregate shrinks more than concrete made with bigger sized aggregate.
- The magnitude of drying shrinkage is also a function of fineness of gel. The finer the gel more is the shrinkage .

- The grading of aggregate do not directly make any significant influence but since the quantum of paste and W/C ratio is effected by grading it definitely influences the drying shrinkage indirectly
- The magnitude of shrinkage can be reduced but cannot be eliminated.

Autogenous Shrinkage

Where no moisture movement to or from the paste is permitted ,when temperature is constant some shrinkage may occur . Theshrinkage of such conservative system is known asAutogenous shrinkage.

It is not of much importance for majority of situation except that of a large concrete dam . The autogenous shrinkage strain is about $100x10^{-6}$ at the age of five years.

Carbonation Shrinkage:-

The carbon dioxide (CO_2) presents in the atmosphere reacts in the presence of water with hydrated cement minerals, converting calcium hydroxides ($Ca(OH)_2$) to calcium carbonate ($CaCO_3$) . The carbonation penetrates beyond the exposed surface of concrete only very slowly . The rate of penetration of CO_2 depend on the moisture content & relative humidity. It occursby increase in weight of concrete &shrinkage. This shrinkage occurs mainly at intermediate humidifies. Carbonation of concrete increases strength & decreases permeability

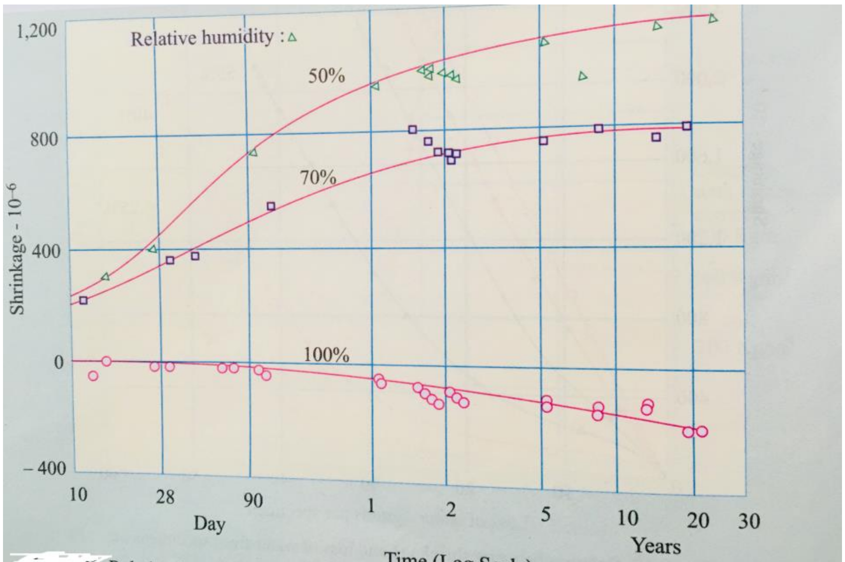
If depth of carbonation reaches steel reinforcement alkalinity reduces & steel starts for corroding. Because PH will reduce 13 to 8.3 the protective layer gets destroyed .

Factors Affecting shrinkage

1. Relative humidity
2. Time dependent
3. W/C ratio
4. Richness of concrete
5. Size and modulus of elasticity of aggregating
6. Grading of aggregate
7. Moisture movement

Relative Humidity:-

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



Relation between shrinkage and time for concrete stored at different relative humidities.

- The graph shows the magnitude of shrinkage increases with time and also with the reduction of relative humidity. The rate of shrinkage decreases rapidly with time.
- Another important factor which influences the shrinkage is w/c ratio of the compound.
- The richness of the concrete also has a significant influence on shrinkage.
  - Aggregates play an important role in the shrinkage properties of concrete. The quantum of an aggregate, its size and the modulus of elasticity influence the magnitude of drying shrinkage.
  - The grading of aggregates affects the quantum of paste and w/c ratio.
  - The harder aggregate does not shrink with the shrinkage of the paste where by it results in higher shrinkage stresses but low magnitude of total shrinkage.
  - Softer aggregates yields to the shrinkage stresses of the paste and there by experience lower magnitude of shrinkage stresses within the body but greater magnitude of total shrinkage.
  - The harder aggregate with high modulus of elasticity like quartz shrinks much less than softer aggregate such as sandstone.

- The light weight aggregate usually lead to higher shrinkage.
- The volume fraction of aggregate will have some influence on the total shrinkage. The ratio of shrinkage of concrete (S_c)to shrinkage of paste (Sp) depends on aggregate content in the concrete 'a' this can be written as.

$S_c=S_p(1-a^n)$------------------------------- n varies from 1.2-1.7

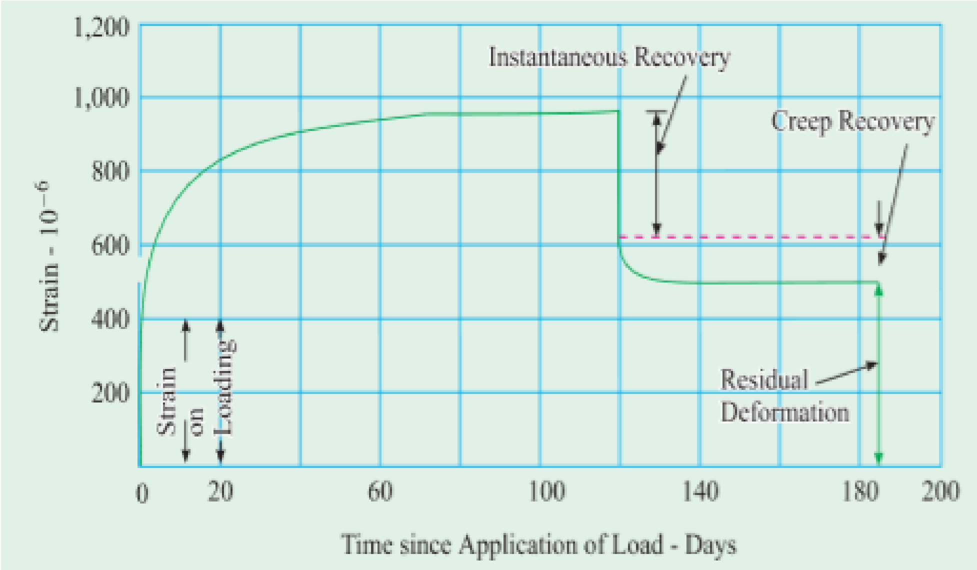
- Another aspect to be seen with respect to the drying shrinkage is that moisture loss takes place at the surface of the member which may not compensate in the same rate by the movement of moisture from interior to the surface.
- Magnitude of shrinkage varies considerably with the size and thickness of specimen. Shrinkage decrease with the increase in the size of the specimen.

Creep

- The degree of curvature of the stress stain relation depends upon any factor among which the intensity of stress and time for which the load is acting or in other words the relation between stress and strain for concrete is a function of time.
- The gradual increase in strain without increase in stress with time is due to Creep.

  OR
- It is defined as the time dependent part of the strain resulting from stress. The stress-strain relationship of concrete is not a straight line relationship but a curved one.

  OR
- Creep is also defined as the increase in strain under sustained stress.
- It is seen that all materials undergo creep under some conditions of loading to a greater or smaller extent but concrete creep for a long time.
- The creep of concrete is a lines function of stress up to 30-40% of its strength.
- The order of creep of concrete is much greater than that of other crystalline material and this phenomenon is associated with a gel structure of cement paste.
- Cement paste plays a major role in the deformation of concrete whereas the aggregate depending upon the type and proportion modifying the deformation characteristics.
- The following graph shows the relationship between stain and time under constant stress value of 150kg/cm^2.



From graph it can be seen that the specimen instantaneously recovers the elastic strain on the removal of flow.

- The magnitude of instantaneous recovery of the elastic strain is something less than that of the magnitude of elastic strain on loading with time certain of creep, strain is also recovered i.e 15%.The member will have certain amount of residual strain, this shows that the creep is not simply a reversible phenomenon.

Measurement of creep:-

It is usually determined by measuring the change with time in the strain of specimen subjected to constant stress and stored under appropriate condition. A typical testing device is shown in fig.

The spring ensures that the load is sensible constant in spite of the fact that the specimen contracts with time under such conditions creep continues for avery long time but the rate of creep decreases with time.

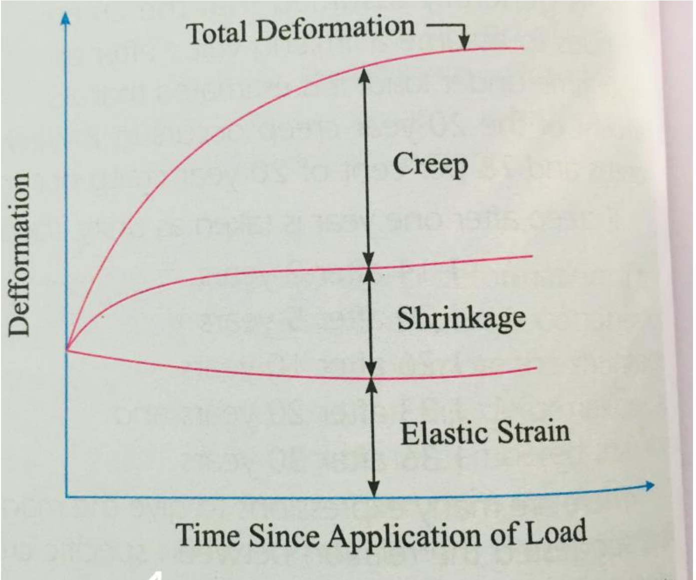


Fig. Time-dependent deformations in concrete subjected to a sustained load.

Effects of creep:-

- The magnitude of creep is dependent on many factors. The main factors being time and level of stress.
- In reinforced concrete beam creep increases the deflection with time and may be a critical consideration in design.
- In reinforced concrete column creep property of concrete is useful.
- Under load immediately elastic deformation takes place concrete creeps and deforms. It cannot deform independent of steel reinforcement.
- There will be gradual transfer of stress from concrete to steel. In eccentrically loaded column creep increases the deflection and lead to bucking.
- Creep property of concrete will be useful in all concrete structures to reduce the internal stresses due to non-uniform load or restrained shrinkage.
- In mass concrete such as dams an account of differential temperature condition at the interior and surfaces, creep is harmful and by itself may be a cause of cracking in the interior of dams. Hence care must be taken to see that increase in temperature does not take place in the interior of mass concrete structures.

Factors affecting Creep

The magnitude of creep depends upon the following factors.

1. **Aggregate:**Normally aggregate undergoes very little creep. It is the paste which is responsible for the creep. However the aggregate provide restrain effect, when the paste undergoes 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 also one of the important factors influencing creep. The higher the modulus of elasticity of aggregate the less is the creep. Light weight aggregate shows considerably higher creep than normal weight aggregate because of lower modulus of elasticity. It has been found that greater the maximum size of an aggregate, the less is the creep of concrete.

2. **Water / cement ratio.** A higher water / cement ratio increase the size of the pores in the paste structure.The amount of paste content its quality is one of the most important factors influencing creep. A poor paste structure undergoes higher creep.Creep increases with increases in water cement ratio. All the factors which are affecting the water /cement ratio creep of concrete.
3. **Age at the time of loading:**The quality of gel improves with time. Such gel creeps less, where as a young gel under load being not so stronger creeps more.Hence creep decreases with the age of concrete.

4. **Moisture content of the concrete**: Increase in moisture content of concrete, increases creep.

5. **Humidity of the ambient air:** Humidity of the air affects the seepage of moisture from the concrete. An increase in the humidity reduces the rate of loss of moisture and this reduces the seepage. Thus for a given concrete creep is higher, the lower the relative humidity drying of the concrete which under load enhances creep of concrete.

6. **Type of cement**: The type of cement inferences creep in so far it influences the strength of the cement at the time of application of the load. Under drying conditions Portland blast–furnace slag cement results in a higher creep than usual types of Portland cement.

Fineness of cement affects the strength development at early ages and thus influences creep. The finer the cement the higher its gypsum requirement so that re-girding cement in the laboratory without the addition of gypsum produces improperly retarded cement which exhibits high creep.

7. **Intensity and duration of stress:** In many tests a direct proportionality between creep & the applied stress has been found to exit. Troxell et al. found that specimens cured for 90 days and then loaded for 21 years showed 680,1000and 1450x10^{-6} creep strains, corresponding to sustained stress levels of 4MPa, 6MPa&8MPa respectively.

8. **Size of the specimen:** The size of specimen also affect the magnitude of creep .The magnitude of creep decrease with increase in the size of the specimen. This is due to the reduced seepage as the path travelled by the expelled water is greater with a visiting increase in the frictional resistance to the how of water from the interior.

9. **Temperature:** The temperature to which concrete is exposed can have two counteracting effects on creep. If a concrete member is exposed to a higher than normal temperature as a part of the curing process before it is loaded, the strength will increase and the creep stain would be less than that of a corresponding concrete stored at a lowers temperature. On the other hand, exposure to high temperature during the period under load can increase creep. The influence of temperature on creep is of considerable interest to nuclear pre-stressed concrete reactor vessel (PCRV).

   Naseer and Neville found that at a stress strength ratio of 70 percent the 350 day creep can increase 3-5 times if the surrounding temperature is raised from 21°C to 71°C.

TESTS ON HARDENED CONCRETE

Testing of hardened concrete plays an important role in controlling and confirming the quality of cement concrete work. Systematic testing of raw materials, fresh concrete and hardened concrete are inspirable part of any quality programme of concrete which helps to achieve highs efficiency concrete with regard to both strength and durability.

Flexural Strength of concrete:-

Concrete as we know to relatively strong in compression and weak in tension.In reinforced concrete members, little dependence is placed on the tensile strength of concrete. Since steel reinforcing bars are provided to resist all tensile forces. However, tensile stresses are likely to develop in concrete due to drying shrinkage, rusting of steel reinforcement, temperature gradient and many other reasons. Therefore the knowledge of tensile strength of concrete is of importance.

A concrete road slab is called upon to resist tensile stress from two principal sources wheel loads and volume changes into the concrete. Wheel loads may cause high tensile stress due to bending when there is a subgrade support.

Volume change resulting from changes in temperature & moisture may cause tensile stress, due to warping and due to the movement of the slab along the subgrade.

Stress due to volume changes alone may be high. The longitudinal tensile stress in the bottom of the prevent caused by restrained and temperature warping frequently as much as 2.5MPa at certain period of year and the corresponding stress in the transverse direction is approximately 0.9MPa.The stresses are additive to these produced by wheel loads in unsupported portion of the slab.

Types of test on flexural strength of concrete are

1. Determination of tensile strength of concrete
2. Determination of Split tensile strength of concrete.

Determination of Tensile Strength:

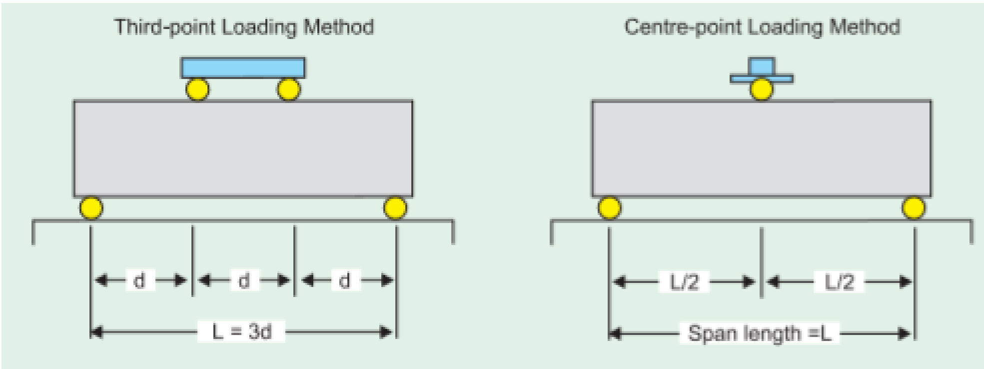
The beam tests are found to be dependable to measure flexural strength property of concrete. The value of modulus of rupture (extreme fibre stress in bending) depends on the dimension of the beam and manner of loading. The systems of loading are central point loading and third point loading.

In the central point loading maximum fibre stress will come below the point loading where the bending moment (BM) is maximum

In the case of symmetrical two point loading the critical crack may appear at any section not sound enough to resist the stress within the middle third where the BM is maximum. It can be expected that two point loading will yield or lower value of the modulus of rupture than the point loading.

The size of the specimens are 15x15x70cm.Alternatively the normal size of the aggregate does not exceed 20mm,Specimen 10x10x50cm may be used should be of metal, preferably steel or iron and metal should be of sufficient thickness prevent spreading or warping.

The testing machine may be of any reliable type of sufficient capacity for the test and capable of applying the load at the rate specified. The permissible error should not be greater than 0.5% of the applied load where a high degree of accuracy is required. It is as shown in fig.



Procedure:

Test Specimens are stored in water at a temperature of 24°C to 30°C for 48hrs before testing. They are tested immediately on removal from the water.

The bearing surfaces of the supporting and loading rollers are wiped clean and any loose material should be cleaned from the surface of the specimen where they are to make contact with the rollers. The specimen is then placed in the machine such a manner that the load is applied to the uppermost surface as cast in the mould along two lines spaced 20 or 13.3cm apart. The load is applied without shock and increasing continuously at a rate such that the extreme fibre stress increases at approximately 0.7kg/sq.cm/min. The load is increased until the specimen fails.

The flexural strength of the specimen is expressed as the modulus of rupture f_b , if 'a' equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of specimen in cm, is calculated to the nearest 0.05MPa as follows.

$$f_b = \frac{Pl}{bd^2}$$

Where ‘a’ is > 20cm for 15cm specimen OR 'a' is > 13.3cm for 10cm specimen

Or

$$f_b = \frac{3pa}{bd^2}$$

Where a < 20cm but >17cm for 15cm specimen; OR<13.3cm but >11cm for 10cm specimen.

b = width in cm of specimen.

d =measured depth in cm of the specimen at the point of failure.

l= length in cm of the span on which specimen was supported.

p= max load in kg applied to the specimen.

- **Indirect Tension Test:**

Direct measurement of tensile strength of concrete is difficult. Neither specimen nor testing strength of concrete is difficult. Neither specimen nor testing apparatus have been designed which assure uniform distribution of the pull applied to concrete while a number of investigation involution the direct measurement of tensile strength have been made. Beam test are found to be dependable to measure flexural strength property of concrete.

Splitting Tension Test (Indirect Tension Test):

This test is carried out by placing a cylindrical specimen horizontally between the loading surfaces of a compression testing machine and the load is applied until the failure of the cylinder along the vertical diameter takes place. When the load is applied on an element on the vertical diameter of the cylinder is subjected to a

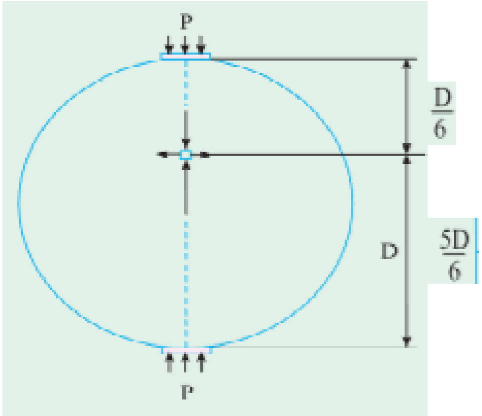
1. Vertical compressive stress of $\frac{2P}{\pi LD}\left(\frac{D^2}{r(D-r)}\right)-1$

2. Horizontal compressive stress of $\frac{2P}{\pi LD}$

Where, P -> Compressive load on the cylinder

L -> Length of the cylinder

D -> diameter and r (D-r) are the distance the element from the two loads respectively.



The loading condition produces a high compressive stress immediately below the loads but the larger portion corresponding to depth is subjected to uniform tensile stress acting horizontal. It is said that the compressive stress is acting about 1/6th depth and the remaining 5/6th depth subjected to tension.

In order to reduce the magnitude of compressive stresses near the point of application of the load narrow packing strips of suitable material such as plywood are placed between the specimen and the loading plate on the testing machine. The packing strips should be soft enough to allow distribution of load over a reasonable area, yet narrow and thin enough to prevent large contact area. Normally a plywood strip 25mm wide, 3mm thick and 30cm long is used.

The main advantage in this method is that the same type of specimen and the same testing machine as used for the compression test can be employed for this test that is why this test is gaining popularity. The splitting test is simple to perform & gives more uniform results than others tension test. Strength determined in a splitting test is believed to be closed to the true tensile strength of the concrete.

Relation between Compressive & tensile strength:-

1. Tensile strength of concrete indicates the ability of concrete to resist tensile force which acts in concrete member in the following from

a) Direct tension

b) Tension occurring because of flexure.

c) Tension due to flexure i.e. tensile stresses developing in a concrete member when it is subjected to a bending load.

Ex:- Bottom portion of a beam comes under tension another Ex: road slab.

2 The measurement of tension is not directly done but it can be measured in the form of flexural strength.Flexural strength can be determined applying a compressive load on the concrete beam.

3. <u>Flexural strength is related to compressive strength of a concrete Member:</u>

- Higher the compressive strength, higher is the tensile strength, but rate of increase of tensile strength decreases.
- The type of coarse aggregate influence the relation between compressive strength and tensile strength or flexural strength.
- Crushed aggregate gives relatively higher flexural strength as compared to natural aggregate. Rougher is the surface higher is the bond strength and hence higher is the flexural strength.
- The addition of pozzolonic material increases the flexural strength of concrete

DURABILITY

The durability of cement concrete is defined as its ability to resist weathering action, cheinical 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

For a variety of reasons, there is a general awareness now that designers of structures must evaluate the durability characteristics of the construction materials under consideration as carefully as other aspects, such as mechanical properties and initial cost. First, there is a better appreciation of the socioeconomic implications of durability. Increasingly, repair and replacement costs of structures arising from materials failure have become a substantial portion of the total construction budget. For example, it is estimated that, in industrially developed countries, about 40 percent of the total resources of the construction industry are being applied to repair and maintenance of existing structures and only 60 percent to new installations. The escalation in replacement costs of structures and the growing emphasis on the life-cycle cost rather than the first cost are forcing engineer's to-pay serious attention to durability issues. Next, there is a realization that a close relation exists between durability of materials and ecology. Conservation of natural resources by making the construction materials last longer is therefore an ecological step. Failure of offshore steel structures in Norway, Newfoundland, and other parts of the world has shown that both the human and economic costs associated with sudden failure of the material of construction can be very high. Therefore, the uses of concrete are being extended increasingly to severe environments, such as offshore platforms in the North Sea, and concrete containers for handling liquefied gases at cryogenic temperatures.

Permeability

Permeability of concrete is most important factor for the durability of concrete. Micro cracks at transition zone are a consideration for permeability whereas W/C ratio may not get involved directly. It may be mentioned that micro cracks in the initial stage are so small that they may not increase the permeability. But propagation of micro cracks with time due to drying shrinkage, thermal shrinkage and externally applied load will increase the permeability of the system.

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 7×10^{-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 ofcapillary 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 unduly 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 unregimented cavities, which is responsible for the permeability of paste.

The 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.

Sulphate Attack

Most soils contain some sulphate in the form of calcium, sodium, potassium and magnesium. They occur in soil or ground water. Because of solubility of calcium sulphate is low; ground waters contain more of other sulphates and less of calcium sulphate.

Ammonium Sulphate is frequently present in agricultural soil and water from the use of fertilizers or from sewage and industrial effluents. Decay of organic matters in marshy land, shallow lakes often leads to the formation of H_2S, which can be transformed into sulphuric acid by bacterial action. Water used in concrete cooling towers can also be a potential source of sulphate attack on concrete. Therefore sulphate attack is a common occurrence in natural or industrial situations.

Solid sulphates do not attack the concrete severely but when the chemicals are in solution, they find entry into porous concrete and react with the hydrated cement products 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 volumeof the solid phase which can go up to 227 per cent, a gradual disintegration of concrete takes place.

The reactions of the various sulphates with hardened cement paste is shown below

Let us take the example of Sodium Sulphate attacking Ca (OH) 2

$Ca(OH)_2 + Na_2SO_4.10H_2O \longrightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O$

The reaction with calcium aluminate hydrate is as follows

$2(3CaO .Al_2O_3 . 12H_2O) + 3(Na_2SO_4. 10H_20) \longrightarrow$

$3CaO .Al_2O_3 .3CaSO4 . 31H_20 + 2Al (OH)_3 + 6NaOH + 17 H_2O$

Calcium sulphate attacks only calcium aluminate hydrate producing calcium sulpho aluminate ($3CaO. Al_2O_3 .3CaSO4 . 32H_20$) known as ettringite. Molecules of water may be 32 or 31.

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.

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 C3 A 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 C_3AH_6 into a less reactive phase a rid 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.

(f) Use of High Alumina Cement

High alumina cement contains approximately 40% alumina, a compound very susceptible to sulphate attack, when in normal portland cement. But this percentage of alumina present in high alumina cement behaves in a different way. The primary cause of resistance is attributed to formation of protective films which inhibit the penetration or diffusion of sulphate ions into the interior. It should be remembered that high alumina cement may not show higher resistance to sulphate attack at higher temperature.

Chloride Attack

Chloride attack is one of the most important aspects for consideration when we deal with the durability of concrete. Chloride attack is particularly important because it primarily causes corrosion of reinforcement. Statistics have indicated that over 40 per cent of failure of structures is due to corrosion of reinforcement.

Due to the high alkalinity of concrete a protective oxide film is present on the surface of steel reinforcement. This protective layer also can be lost due to the presence of chloride in the presence of water and oxygen. In reality the action of chloride in inducing corrosion of reinforcement is more serious than any other reasons,

Chloride enters the concrete from cement, water, aggregate and sometimes from admixtures. The present day admixtures are generally contain negligible quantity of chloride or what they call chloride free. Chloride can enter the concrete by diffusion from environment. Chloride available limit is 0.1%

The amount of chloride required for initiating corrosion is partly dependent on the pH value of the pore water in concrete, at a pH value less than 11.5, corrosion may occur without the presence of chloride. At pH value greater than 11.5, a good amount of chloride is required.

Carbonation

Carbonation of concrete is a process by which carbon dioxide from the air penetrates into concrete and reacts with calcium hydroxide to form calcium carbonates. We have seen earlier that the conversion of $Ca(OH)_2$ into $CaCO_3$ by the action of CO_2 results in a small shrinkage.

In the presence of moisture, CO_2 changes into dilute carbonic acid which attacks the concrete and also reduces alkalinity of concrete).

The pH value of pore water in the hardened concrete is generally range from 12.5 to 13.5 depending upon the alkali content of cement. The high alkalinity forms a thin passivating layer around steel reinforcement and protect, it from action of oxygen and water. As long as steel is placed in a highly alkaline condition, it is not going to corrode. Such condition is known as passivation.'

In actual practice CO_2 present in atmosphere in smaller or greater concentration, permeates into concrete and carbonates the concrete and reduces the alkalinity of concrete. The pH value of pore water in the hardened cement paste which was around 13 will be reduced to around 9.0. When all the $Ca(OH)_2$ has become carbonated, the pH value will reduce upto about 8.3. In such a low pH value, the protective layer gets destroyed and the steel is exposed to corrosion.

Freezing and Thawing

The lack of durability of concrete on account of freezing and thawing action of frost is not of great importance to Indian conditions. But it is of greatest considerations in most part of the world however, certain regions in India, experience sub-zero temperatures in winter.

It is very well known that fresh concrete should not be subjected to freezing temperature. Fresh concrete contains a considerable quantity of free water if this free water is subjected to freezing temperature discrete ice lenses are formed. Water expands about 9% in volume during freezing. The formation of ice lenses formed in the body of fresh concrete disrupt the fresh concrete causing nearly permanent damage to concrete. The fresh concrete once subjected to frost action, will not recover the structural integrity, if later on allowed to harden at a temperature higher than the freezing temperature. Therefore, the fundamental point to note in dealing with cold weather concreting is that the temperature of the fresh concrete should he maintained above 0°C.The hardening concrete should not be subjected to an extremely low temperature. It has been estimated that the freezing of water in the hardened concrete may exert a pressure of about 14 MPa. The strength of concrete should be more than the stress to which it is subjected at any point of time to withstand the damaging action.

The fully hardened concrete is also vulnerable to frost damage, particularly to the effect of alternate cycles of freezing and thawing. The severest conditions for frost action arise when concrete has more than one face exposed to the weather and is in such a position that it remains wet for a long period.

Factors Contributing to Cracks in Concrete

- **Plastic Shrinkage Cracks**

Water from fresh concrete can be lost by evaporation, absorption by subgrade, formwork and in hydration process. When the loss of water from surface of concrete is faster than the migration of water from interior to the surface, the surface dries up. This creates moisture gradient which results in surface cracking while concrete is still in plastic condition: The magnitude of plastic shrinkage and plastic shrinkage cracks are depending upon ambient temperature, relative humidity and wind velocity. In other words, it depends upon the rate of evaporation of water from the surface of concrete

Rate of evaporation in excess of I kg/m^2 per hour is considered critical. In such a situation, the following measures could be taken to reduce or eliminate plastic shrinkage cracks.

- Moisten the subgrade and formworks.
- Erect temporary wind breakers to reduce the wind velocity over concrete.
- Erect temporary roof to protect green concrete from hot sun.
- Reduce the time between placing and finishing. If there is delay cover the concrete with polythylene sheets.
- Minimise evaporation by covering concrete with burlap, fog spray and curing compound.

- **Settlement Cracks**

Plastic concrete when vibrated or otherwise settles. If the concrete is free to settle uniformly, then there are no cracks. If there is any obstruction to uniform settlement by way of reinforcement or larger piece of aggregate, then it creates some voids or cracks. This is called settlement cracks. This generally happens in a deep beam.

Concrete should be poured in layers and each layer should be properly compacted. Building up of large quantity of concrete over a beam should be avoided.

Sometimes, the settlement cracks and voids are so severe it needs grouting operators to seal them off. Revibration, if possible is an effective step. Otherwise, they effect the structural integrity of the beam or any other member and badly affects, the durability.

- **Constructional Effects**

In many construction sites, properly designed standard formworks are not used. Formworks are made in an adhoc manner. Such formworks may fail to maintain their rigidity and firmness when wet concrete is placed and vibrated. Sinking, bending, settlement or lack of rigidity of formwork may cause cracks or deformation in plastic concrete, after compaction, which may go unnoticed.

It is well known that excess vibration causes segregation which affects the uniformity of concrete mix. These days high consistency concrete is used either for pumping requirements or on account of using superplasticizers. Care must be taken to vibrate such high slump concrete; otherwise, segregation is sure to take place. Segregated concrete matrix, devoid of coarse aggregate, shrinks more than homogeneous concrete and exhibits high shrinkage cracks.

Finishing becomes an important operation in situations where abrasion resistance is an important factor, such as roads and airfield pavements, factory floor, dock yard, warehouse floor etc. Ideally, cement paste must be contained by fine aggregate and matrix must be contained by coarse aggregates. Such a uniform mixture, devoid of excess paste on the surface will suffer from almost no shrinkage and exhibit good abrasion resistance. The stiffness of concrete at the time of trowelling, extent of trowelling and method of trowelling will all become important, to improve the abrasion resistance and durability of concrete surface.

- **Thermal Expansion**

Concrete is a material used in all climatic regions for all kinds of structures. Knowledge of thermal expansion is required in long span bridge girders, high rise buildings subjected to variation of temperatures, in calculating thermal strains in chimneys, blast furnace and pressure vessels, in dealing with pavements and construction joints, in dealing with design of concrete dams and in host of other structures where concrete will be subjected to higher temperatures such as fire, subsequent cooling, resulting in cracks, loss of serviceability and durability.

- **The important properties that will be discussed are:**
  - Thermal conductivity
  - Thermal diffusivity
  - Specific heat.
  - Coefficient of thermal expansion

- **Thermal conductivity:**

This measures the ability of material to conduct heat. Thermal conductivity is measured in joules per second per square metre of area of body when the temperature deference is 1°C per metre thickness of the body.

The conductivity of concrete depends on type of aggregate, moisture content, density, and temperature of concrete. When the concrete is saturated, the conductivity rangesgenerally between about 1.4 and 3.4 j/m^{2}s °c/m

- **Thermal diffusivity:**

Diffusivity represents the rate at which temperature changes within the concrete mass.

Diffusivity is simply related to the conductivity by the following equation.

$$Diffusivity = \frac{Conductivity}{CP}$$

where C is the specific heat, and P is the density of concrete. The range of diffusivity of concrete is between 0.002 to 0.006 m^2/h

- **Specific heat:**

It is defined as the quantity of heat required to raise the temperature of a unit mass of a material by one degree centigrade. The common range of values for concrete is between 840 and 1 170 j/kg per °C.

- **Coefficient of thermal expansion:**

Coefficient of thermal expansion is defined as the change in unit length per degree change of temperature. In concrete it depends upon the mix proportions. The coefficient of thermal expansion of hydrated cement paste varies between 11 x 10-6 and 20 x 10-6 per °C. Coefficients of thermal expansion of aggregates vary between 5 x 10-6 and 12 x 10-6 per °C. Limestones and Gabbro's will have low values and Gravel and Quartzite will have high values of coefficient of thermal expansion. Therefore the kind of aggregate and content of aggregate influences the coefficient of thermal expansion of concrete.

- **Transition Zone**

Micro cracks in transition zone are a strength limiting factor. Concrete is a brittle material which develops micro cracks even before any load is applied. On account of the dissimilar material, lack of bond, higher W/C ratio, and bleeding water, the transition zone becomes the weakest link in concrete mass. Under load, micro cracks propagate further starting from largest micro cracks. At a stress level of 70 per cent of the ultimate strength, the mortar matrix develops small cracks. With increasing stress level, the matrix cracks gradually and spreads throughout the mass. The micro cracks in the transition zone at the interface with steel reinforcement becomes more permeable and admits air and water to promote corrosion of steel reinforcement incidentally these micro cracks increases the depth of carbonation also.

- **Structural Design Deficiencies**

Sometimes inadequate provision of main steel reinforcement or inadequate provision for temperature reinforcement, or wrong spacing of bars, or absence of corner reinforcement may cause unacceptable cracks in concrete. One of the most common occurrences is the displacement of top bars in cantilever thin chajjas, by the movement of concreting gang, causes cracks at the junction point of cantilever chajja.

Innumerable examples can be cited such as congestion of reinforcement and difficulties in proper compacting concrete, particularly at the column and beam junctions, deep beams, the negative reinforcement over T and L beams, should be taken care. In the absence of such care concrete is sure to crack.

In certain structures the ultimate creep deformation must be considered, otherwise more than the permissible deflection due to excess creep and unacceptable width of cracks will affect durability.

The permissible width of crack depends upon the functions of the structural members and on the exposure conditions of the concrete. Reis et al suggest the following permissible crack widths.

- Interior members 0.35 mm
- Exterior members under normal exposure conditions 0.25 mm
- Exterior members exposed to aggressive environment 0.15 mm

Factors affecting Durability

1. Plastic shrinkage:-

Plastic shrinkage occurs soon after the concrete is placed in the forms while the concrete is still in the plastic state. Lossof water by corporation from the surface of concrete or by absorption from aggregates is the reasons of plastic shrinkage. The loss of water results in reduction of volume. Sometimes even if the concrete is not subjected to severe drying but poorly made with as high w/c ratio, large quantity of water bleeds and accumulates at surface.

Plastic concrete is sometimes subjected to unintended vibration shrinkage cracks as the concrete at this stage has not developed enough strength. It has been also observed that richer concrete undergoes greater plastic shrinkage.

Plastic shrinkage can be reduced by covering the surface with polyethylene sheeting immediately on finishing operation by fog spray that keeps the surface moist. Similarly expansive or shrinkage compensating cement also can be used for controlling the shrinkage during setting of concrete.

2. Segregation:-

Segregation can be defined as the separation of the constituent materials of concrete.It may be of 3 types.

a) Coarse aggregates separating out or setting down from the rest of matrix.

b) Paste separating away from coarse aggregate.

c) Water separating out from the rest of the material being a material of lowest specific gravity.

A well-made concrete, taking into consideration various parameters such as grading size shape and surface texture aggregates with optimum quantity of water makes a cohesive mix. Such concrete will not exhibit any tendency for segregation.

1. Badly proportioned mix where sufficient matrix is not there to bind and contain the aggregates.
2. Insufficiently mixed concrete with excess water content.
3. Dropping of concrete from heights as in the case of placing concrete in column concreting.
4. When concrete is discharged from a badly designed mixer or from a mixer with worn-out blades.

5. Conveyance of concrete by conveyor belts, wheel barrow, long distance how by dumper, long lift by skit & hoist.

3. Bleeding:-

Bleeding in concrete is referred as water gain. It is a particular form of segregation in which some of the water from the concrete comes out to the surface of concrete being of the lowest specific gravity among all the ingredients of concrete.

Bleeding of concrete can be prevented by.

1. Proper proportioning and complete mixing.
2. Air entraining agent is very effective in reducing the
3. Use of finely divided pozzolanic materials reduces bleeding by creating a longer path for the water to traverse.
4. Use of finer cement with low alkali content.

4. Delayed curing:-

Fundamental requirement for good concrete is to maintain uninterrupted hydration especially at early age,when the hydration process is faster. If young concrete dries up fast due to hot sun, drying winds &lower relative humidity, the top surface of concrete is devoid of enough water for continuous hydration process. This results in formed hydration products and all other deformities in the structure of hydrated cement paste.

5. Constructional effects:-

In many construction sates, properly designed standard form works are not used .Form works are made in adhoc manner. Such form works may fail to maintain this rigidity and firmness when wet concrete is placed and vibrated sinking bending, settlement or lack of rigidity of from work may cause cracks of deformation in plastic concrete after completion which may go unnoticed.

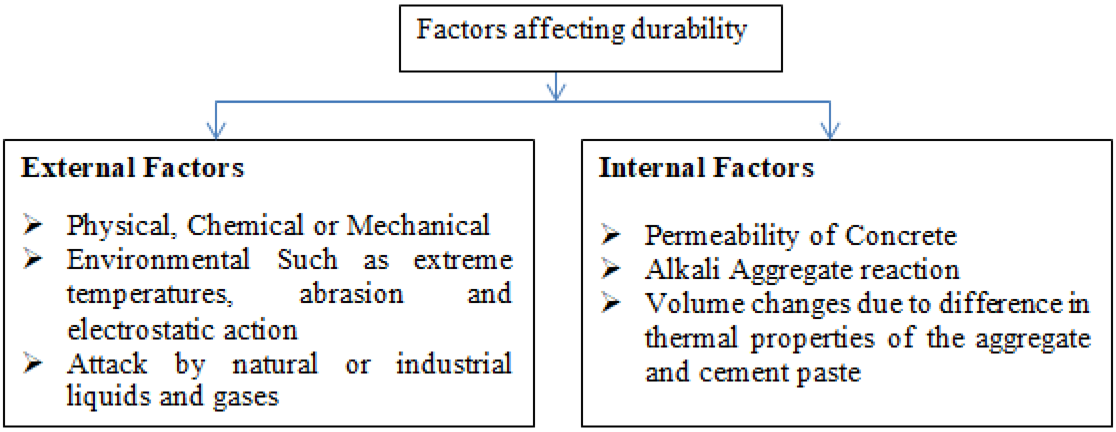
6. Unsound materials :-

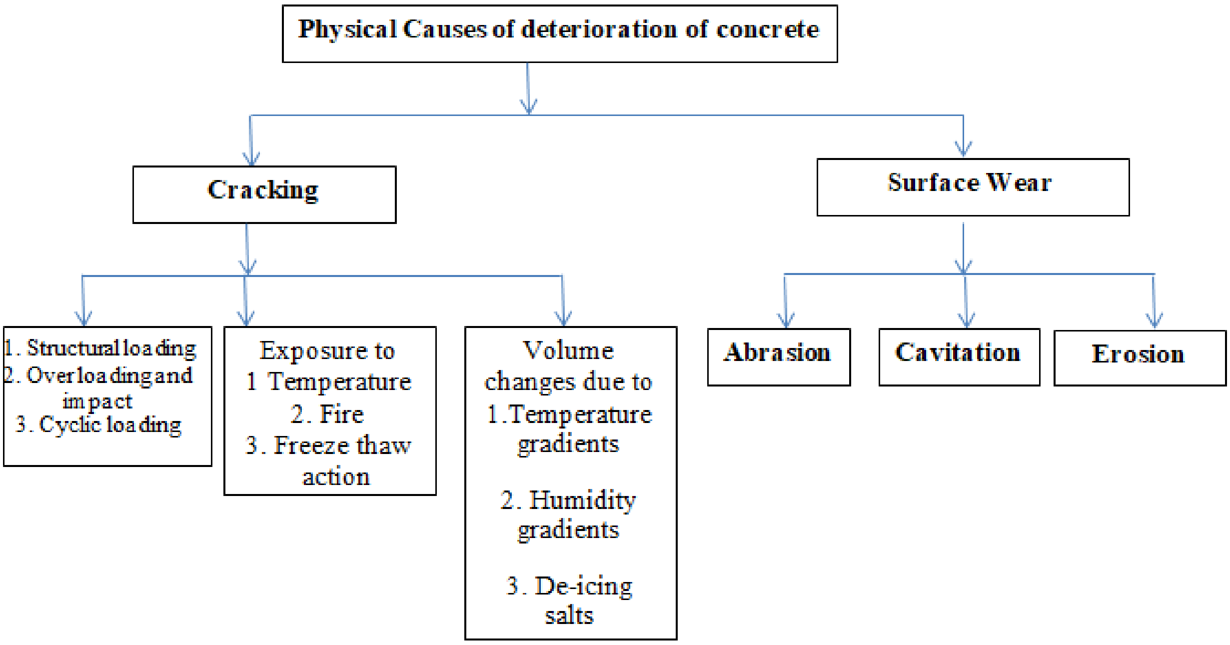
Cement or aggregate is convicted unsound when they cause unacceptable extent of volume change in hardness concrete or mortar which causes cracks and affects durability. In cement if the raw materials contain more time that can combine with other oxide oxides or if the raw materials are not properly burnt to the required temperature for the time to get fully combined with other oxides cement becomes unsound similarly the presence of MgO. which reacts with water in the similar manner as caO can also cause unsoundness.

7. <u>Drying shrinkage:-</u>

The drying shrinkage is on everlasting process where concrete is subjected to drying conditions. The loss of water contained in hardened concrete does not results in any dimension change. It is the loss of water in gel pores that cause the changes in the volume. Under drying conditions the gel water is lost progressively over a long time, as long as concrete is kept in drying conditions. The magnitude of drying shrinkage is a function of the fineness of gel. The finer the gel the more is the shrinkage.

Factors effecting durability





Corrosion of Steel (chloride induced)

Corrosion of Steel in concrete is an electrochemical process. When there is a difference in electrical potential along the steel reinforcement in concrete an electrochemical cell is set up. In the steel one part becomes anode & other part becomes cathode connected by electrolyte in the form of pore water in the hardened cement paste.

The positively charged ferrous ions **Fe^{++}** at the anode pass into solution while the negatively charged free electrons **e^-** pass through the steel into cathode where they are absorbed by the constituents of the electrolyte with water and oxygen to form hydroxyl ions (OH^-) .These travel through the electrolyte and combine with the ferrous ions to form ferric hydroxide which is converted by further oxidation to rust.

Anodic reactions

$Fe \rightarrow Fe^{++} + e^-$

$Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2$ (Ferrous hydroxide)

$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$ (Ferric Oxide)

$4e^- + O_2 + H_2O \rightarrow 4(OH)^-$

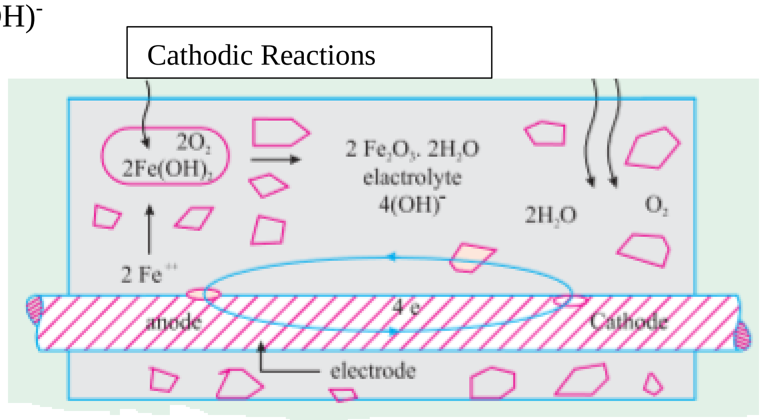


Fig: Simplified Model Representing Corrosion Mechanisms.

It can be noted that no corrosion takes place if the concrete is dry or probably below relative humidity of 60% 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 takes place into the concrete. The products of corrosion occupy a volume as many as six times the original volume of steel depending upon the corrosion. The increased volume of rust exist thrust on cover concrete resulting in cracks spelling or delaminating of concrete as shown in Fig.

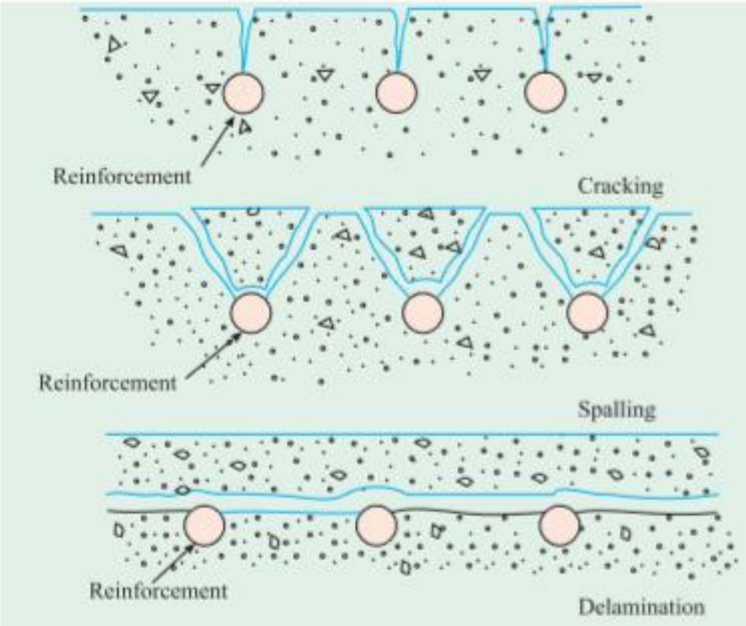


Fig: Diagrammatic representation of damage induced by corrosion

Remedial Measures to control the corrosion of Steel reinforcement.

1. Metallurgical methods.
2. Corrosion inhibitors.
3. Coatings to reinforcement.
4. Cathodic to protection.
5. Coatings to concrete.
6. Design and detailing.

1. Metallurgical Methods

Steel can be made more corrosion resistant by altering its structure through metallurgical process. Different methods such as rapid quenching of the hot bars by series of water jets or by keeping the hot steel bars for a short time in a water bath and by such other process, the mechanical properties and corrosion resistance properties of steel can be improved.

2. Corrosion Inhibitors:-

Corrosion can be prevented or delayed by chemical method by using certain corrosion inhibiting chemicals such as nitrates, phosphates etc.

The most widely used admixtures are based on calcium nitrates. It is added to the concrete during mixing of concrete.

The typical dosage is of the order of 10-30 litre/m^3 of concrete depending on chloride levels in concrete.

3. Coatings to reinforcement:-

The object of coating to steel bar is to provide durable barrier to aggressive materials such as chlorides.

The Coatings must be robust to withstand fabrication of reinforcement cage and pouring of concrete and compaction by vibrating needle.

Simple cement slurry coating is the cheap method for temporary protection against rusting of reinforcement in storage.

Central Electro – Chemical Research Institute (CECRI) Karaikudi have suggested a method for prevention of corrosion in steel reinforcement in concrete.

1. **De- rusting**

The reinforcement are cleaned with derusting solution .This is followed without delay by cleaning the rod with wet waste cloth & cleaning powder.

2. **Phosphating**

Phosphate jelly is applied to the bars with fine brush. The jelly is left for 45 to 60min and then removed by the wet cloth. An inhibitor solution is then brushed over the phosphorous surface.

3. **Cement Coating**

The slurry is made by the mixing inhibitor solution with Portland and applied on the bar. The sealing solution is brushed after the rods are air cured. The second coat of slurry is then applied and the bars are air dried.

4. **Sealing**

Two coats of sealing solution are applied to the bars in order to seal the micro-pores of the cement and to make it impermeable to corrosive salts.

- **Fusion Bonded Epoxy Coating**

It is one of the effective methods of coating re-bars. Plants are designed to coat the straight bars in the process. Initially the bars are shot blasted to remove all mill scale and to give the kind of surface finish required. This ensures an adequate bond between Epoxy and steel.

- **Limitations of Epoxy coated Bars.**
  1. After the treatment, cutting and bending may injure the steel which needs certain side treatment.
  2. The bars cannot be welded.
  3. The epoxy is not resistant to ultraviolet rays of sun. The bars should not be exposed to sun for long duration before use.

4. The coating may get damaged during vibration of the concrete which is uneconomical porous.

- **Galvanized Reinforcement**

Galvanizing of reinforcement consist of dipping the steel bars in molten zone. These results in a coating of zinc bonded to the surface of steel. The zone surface reads with calcium hydroxide in the concrete to form a passive layer and prevents corrosion.

- **Cathodic Protection**

It is one of the effective well known and extensively used method for prevention of corrosion in concrete structures.

- Due to high cost and long-term monitoring required for this meted it is not used very much in India.
- The cathodic protection comprises of application of impressed current to an electrode laid on the concrete above steel reinforcement.
- This electrode serves as Anode and steel reinforcement which is connected to the negative terminal of a D.C source acts as cathode.

In this process the external anode is subjected to corrode and the cathodic reinforcement is protected against corrosion and hence the name catholic protection.

- **Design and Detailing**

The structural designer should take all precaution in designing and detailing with respect to spacing between bars for the concrete to flow between reinforcement, to facilitate vibration of concrete, to give proper cover to the steel reinforcement, to resist the crack width etc.

Nominal cover to reinforcement

1. For longitudinal reinforcement bars in a column nominal cover in any case not less than 40mm or less than the diameter of bars.
2. In case of column of minimum dimension of 200mm or less whose reinforcing bars do not exceed 12mm and a nominal cover of 25mm may be used.
3. For footings a minimum cover should be 50mm.

- **Crack width**

IS 456- 2000 specifies crack width as follows:

1. The surface width of the crack should not in general exceed 0.3mm in members where cracking is not harmful and does not have any serious adverse effect on the durability of the structure.

The structure exposed to the effects of weather or continuously exposed to moisture or in contact with soil or ground water a limit is given as 0.2mm.

For aggressive environment the surface width of cracks should not in general exceed 0.1mm.

INSITU TESTS ON CONCRETE

l. Non Destructive Tests (NDT)

Non Destructive Testing are non-invasive techniques to determine the integrity of a material, component or structure or quantitavely measure some characteristic of an object."

Non-destructive Testing is an easy way to detect or inspect the defects on the surface of the concrete or structure; It is a fast techniques and need not any sort of huge calculation or waiting. Mostly this technique is used in specialist high risk areas such as nuclear and Sea shore structures, gas and oil pipelines.

NDT Advantages

- Access to hidden items — "see through walls"
- Better investigations with NDT
- Rapid accumulation of data
- Generally less expensive than destructive testing
- Minimize interruption of building services
- Evaluation and quality assurance

NDT Disadvantages

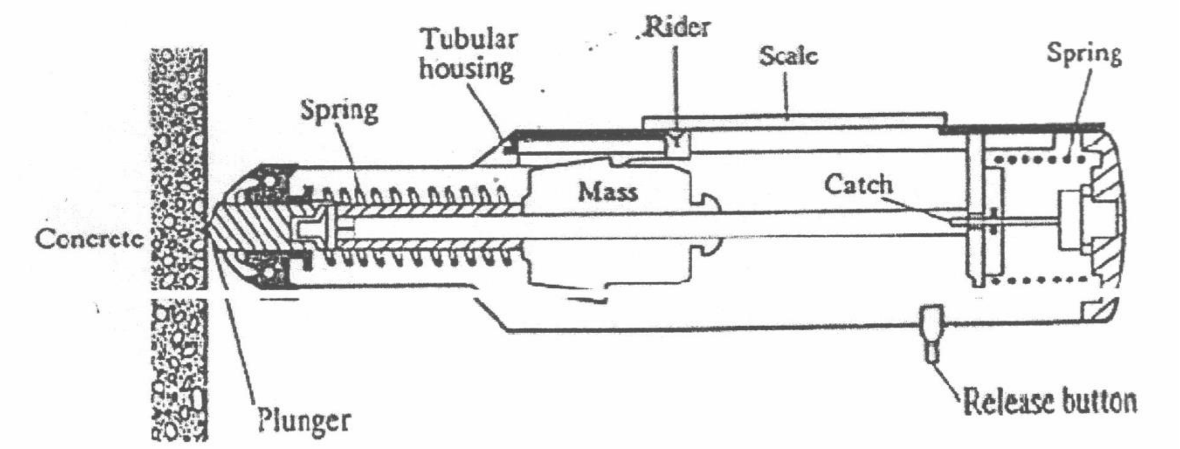
- More than one test method may be required.

- Environmental conditions may effect or distort results.
- Construction details & building components may affect results.
- Some conditions cannot be determined with a reasonable degree of accuracy without destructive testing.

There are a lot of methods involved in non-destructive testing like rebound test,

- Schmidt ReboundHammer
- Coring
- Pullout strength
- Penetration resistance
- Radiography
- Permeability test
- Maturity test
- Carbonation depth
- Break-off test
- Cover meter
- UPV test

Rebound Hammer Determination of Compressive Strength of Hardened Concrete



Scope

- This test method covers the determination of a rebound number of hardened concrete using a spring-driven steel hammer.
- The values stated in inch-pound units are to be regarded as the standard.
- This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Significance and Use

This test method is not intended as the basis for acceptance or rejection of concrete because of the inherent uncertainty in the estimated strength.

Apparatus

Rebound Hammer — consisting of a spring-loaded steel hammer that when released strikes a steel plunger in contact with the concrete surface. The spring-loaded hammer must travel with a consistent and reproducible velocity. The rebound distance of the steel hammer from the steel plunger is measured on a linear scale attached to the frame of the instrument.

Test Area and Interferences

- Selection of Test Surface — Concrete members to be tested shall be at least 100 mm (4 in) thick and fixed within a structure. Smaller specimens must be rigidly supported. Avoid areas exhibiting honeycombing, scaling, or high porosity. Do not compare test results if the form material against which the concrete was placed is not similar. Troweled surfaces generally exhibit higher rebound numbers than screeded or formed finishes. If possible, test structural slabs from the underside to avoid finished surfaces. Preparation of Test Surface — A test area shall be at least 150 mm (6 in) in diameter. Heavily textured, soft, or surfaces with loose mortar shall be ground flat with the abrasive stone described in Section 4.2. Smooth-formed or troweled surfaces do not have to be ground prior to testing. Do not compare results from ground and unground surfaces.
- Do not test frozen concrete.
- For readings to be compared, the direction of impact, horizontal, downward, upward, or at another angle, must be the same or established correction factors shall be applied to the readings.

- Do not conduct tests directly over reinforcing bars with cover less than 0.75 in (20 mm).

Procedure

Hold the instrument firmly so that the plunger is perpendicular to the test surface. Gradually push the instrument toward the test surface until the hammer impacts. After impact, maintain pressure on the instrument and, if necessary, depress the Read the rebound number on the scale to the nearest whole number and record the rebound number. Take ten readings from each test area. No two impact tests shall be closer together than 25 mm (1 in). Examine the impression made on the surface after impact, and if the impact crushes or breaks through a near-surface air void, disregard the reading and take another reading.

Calculation

Discard readings differing from the average of ten readings by more than six units and determine the average of the remaining readings. If more than two readings differ from the average by six units, discard the entire set of readings and determine rebound numbers at ten new locations within the test area.

2. Ultrasonic pulse velocity method

This test is done to assess the quality of concrete by ultrasonic pulse velocity method as per IS: 13311 (Part 1) — 1992.

The underlying **principle** of this test is

The method consists of measuring the time of travel of an ultrasonic pulse passing through the concrete being tested. Comparatively higher velocity is obtained when concrete quality is good in terms of density, uniformity, homogeneity etc.

- **Procedure to determine strength of hardened concrete by Ultrasonic Pulse Velocity:**

i) Preparing for use: Before switching on the 'V' meter, the transducers should be connected to the sockets marked "TRAN" and "REC". The 'V' meter may be operated with either:

a) the internal battery,

b) An external battery or

c) The A.C line.

ii) Set reference: A reference bar is provided to check the instrument zero. The pulse time for the bar is engraved on it. Apply a smear of grease to the transducer faces before placing it on the opposite ends of the bar. Adjust the 'SET REF' control until the reference bar transit time is obtained on the instrument read-out.

iii) Range selection: For maximum accuracy, it is recommended that the 0.1 microsecond range be selected for path length up to 400mm.

iv) Pulse velocity: Having determined the most suitable test points on the material to be tested, make careful measurement of the path length 'U. Applycouplant to the surfaces of the transducers and press it hard onto the surface of the material. Do not move the transducers while a reading is being taken, as this can generate noise signals and errors in measurements. Continue holding the transducers onto the surface of the material until a consistent reading appears on the display, which is the time in microsecond for the ultrasonic pulse to travel the distance 'U. The mean value of the display readings should be taken when the unit's digit huntsbetween two values.

Pulse velocity= (Path length/Travel time)

v) Separation of transducer leads: It is advisable to prevent the two transducer leads from coming into close contact with each other when the transit time measurements are being taken. If this is not done, the receiver lead might pick-up unwanted signals from the transmitter lead and this would result in an incorrect display of the transit time.

- **Interpretation of Results**

The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks and segregation, etc,indicative of the level of workmanship employed, can thus be assessed using the guidelines given below, which have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.

Pulse velocity	Concrete quality
Above 4.5 km/sec	Excellent
3.5 to 4.5 km/sec	Good
3.0 to 3.5 km/sec	Medium
Below 3.0	Doubtful

Methods of testing:

There are three methods of testing the concrete depending upon the placement of the transducers;

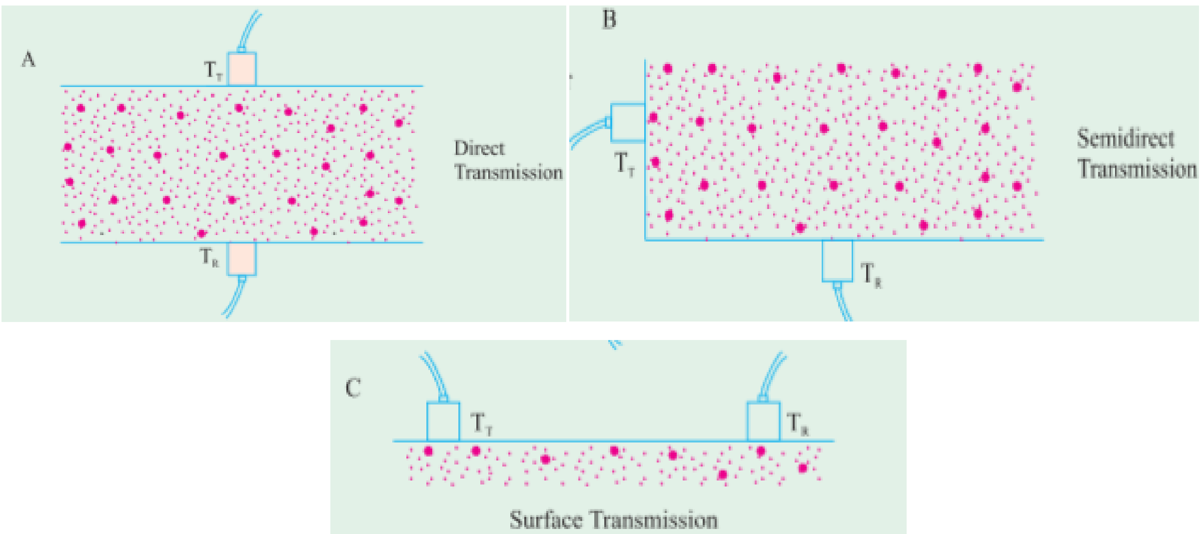
- **Direct Method:**

  If the two transducers are placed in such a way that one is placed at one end and other at the other end throughout the member it is direct method

- **Indirect method**

  In this method both transducers are place on the same surface of concrete and the receiver receives the pulse coming after striking the concrete molecules

- **Semi-direct method:** It is mostly used for corners of concrete members



- **Apparatus Required:**

  Electrical Pulse Generator, Transducer, Amplifier Electronic Timing Device

- **Advantages and Disadvantages of the Ultrasonic Pulse Velocity Test:**

As far as the advantage of the ultrasonic pulse velocity is concerned; it has high penetrating power which ensure very easy measurement even for the very deep concrete members; it is highly sensitive thus giving accurate results; easy to use for estimating the size. Shape and nature of flaws in the concrete member;

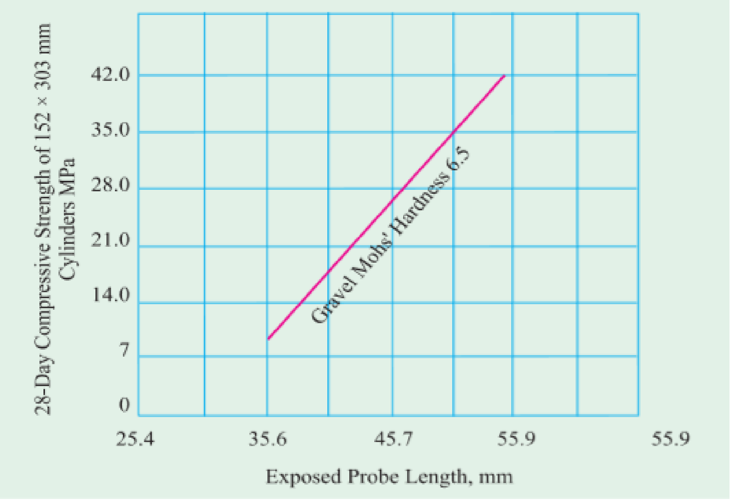
But this method also have some **limitations** like; manual operation of the instrument requires careful attention by experienced technicians; if the surface is irregular it is difficult to estimate accurately the pulse velocity; test objects must be water resistant.

- **Penetration Test:**

The Windsor probe is generally considered to be the best means of testing penetration. Equipment consists of a powder-actuated gun or driver, hardened alloy probes, loaded cartridges, a depth gauge for measuring penetration of probes and other related equipment. A probe, diameter 0.25 in. (6.5 mm) and length 3.125 in. (8.0 cm), is driven into the concrete by means of a precision powder charge. Depth of penetration provides an indication of the compressive strength of the concrete. Although calibration charts are provided by the manufacturer, the instrument should be calibrated for type of concrete and type and size of aggregate used.

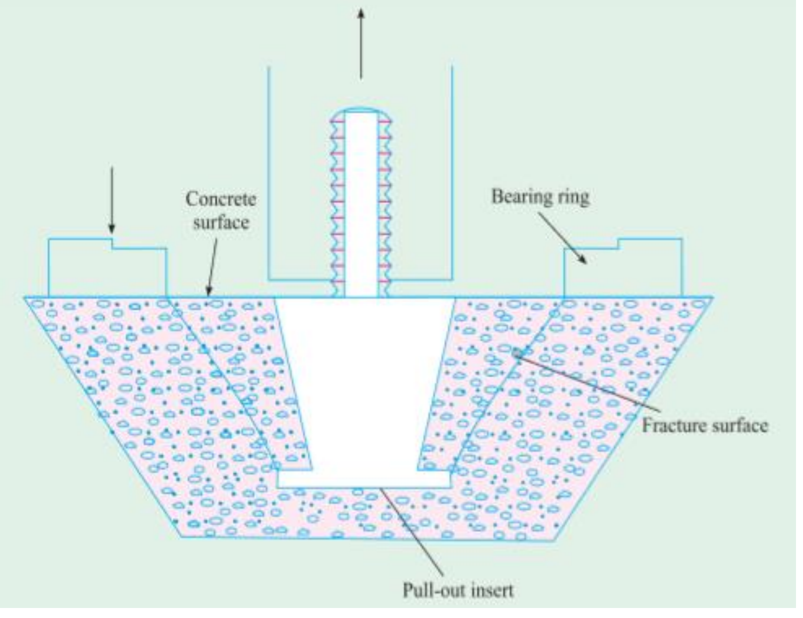
- **Limitations and Advantages:**

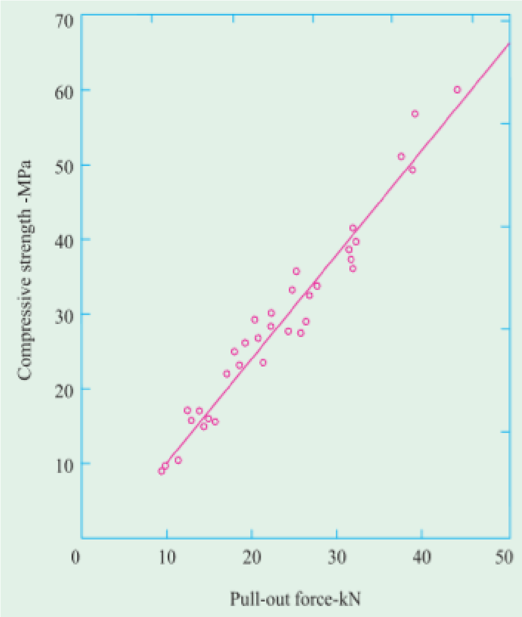
The probe test produces quite variable results and should not be expected to give accurate values of concrete strength. It has, however, the potential for providing a quick means of checking quality and maturity of in situ concrete. It also provides a means of assessing strength development with curing. The test is essentially non-destructive, since concrete and structural members can be tested in situ, with only minor patching of holes on exposed faces.



- **Pull Out Test**

A pull-out test measures, with a special ram, the force required to pull from the concrete a specially shaped steel rod whose enlarged end has been cast into the concrete to a depth of 3 in. (7.6 cm). The concrete is simultaneously in tension and in shear, but the force required to pull the concrete out can be related to its compressive strength. The pull-out technique can thus measure quantitatively the in-situ strength of concrete when proper correlations have been made. It has been found, over a wide range of strengths, that pull-out strengths have a coefficient of variation comparable to that of compressive strength.





- **Limitations and Advantages:**

Although pullout tests do not measure the interior strength of mass concrete, theydo give information on the maturity and development of strength of a representative part of it. Such tests have the advantage of measuring quantitatively the strength of concrete in place. Their main disadvantage is that they have to be planned in advance and pull-out assemblies set into the formwork before the concrete is placed. The pull-out, of course, creates some minor damage. The test can be non-destructive, however, if a minimum pull-out force is applied that stops short of failure but makes certain that a minimum strength has been reached. This is information of distinct value in determining when forms can be removed safely.

- **Core extraction:**

While Rebound Hammer, CAPO/Pullout, Windsor probe and ultrasonic pulse velocitytests give indirect evidence of concrete quality, a more direct assessment on strength can be made by core sampling and testing. Cores are usually cut by means of a rotary cutting tool with diamond bits. In this manner, a cylindrical specimen is obtained usually with its ends being uneven, parallel and square and sometimes with embedded pieces of reinforcement. The cores are visually described and photographed, giving specific attention to compaction, distribution of aggregates, presence of steel etc. the core should then be soaked in water, capped with molten sulphur to make its ends plane, parallel, at right angle and then tested in compression in a moist condition. The core samples can also be used for the following:

- Strength and density determination
- Depth of carbonation of concrete
- Chemical analysis
- Water/gas permeability
- Petrographic analysis
- Chloride permeability test

The strength of a test specimen depends on its shape, proportions and size. The influence of height/diameter (H/D) ratio on the recorded strength of cylinder is and stablished fact. Strength of core has to be related to the standard cylinder strengths, i.e. for H/D ratio of 2. Thus core should be preferably having this ration near to 2. For values of H/D less than 1, between 1 and 2, a correction factor has to be applied. Cores with H/D ratio less than 1 yield unreliable results and BS 1881: Part-4:1970 prescribes a minimum value as 0.95. The same standard specifies the use of 150mm or 100mm cores. However cores as small as 50mm are also permitted in the standards. Very small diameter cores exhibit more variability in results than larger diameter cores, hence their use is generally not recommended. The general rule adopted for fixing the core size, besides the H/D ratio, is the nominal size of stone aggregate and the dia should be not less than 3 times the maximum size of stone aggregate. For diameter of core less than 3 times the size of the stone aggregate, an increased number of cores have to be tested.

Following are the factors which affect the compressive strength of extracted concrete cores:

- **Size of stone aggregate:** If the ratio of diameter of core to maximum size of stone aggregate is less than 3, a reduction in strength is reported. For concrete with 20mm size aggregate, 50mm dia core has been tested to give 10% lower results than with 10mm dia cores.
- **Presence of transverse reinforcement steel:** It is reported that the presence of transverse steel causes a 5 to 15% reduction in compressive strength of core. The effect of

embedded steel is higher on stronger concrete and as its location moves away from ends, i.e. towards the middle. However presence of steel parallel to the axis of the core is not desirable.

- **H/D ratio:** This has been already discussed above. However its value should be minimum 0.95 and maximum 2. Higher ratio would cause a reduction in strength.

- **Age of concrete:** No age allowance is recommended by the Concrete Society as some evidence is reported to suggest that in-situ concrete gains little strength after 28 days. Whereas others suggest that under average conditions, the increase over 28 days' strength is 10% after 3 months, 15% after 6 months. Hence it is not easy to deal the effect of age on core strength.

- **Strength of concrete:** The effect in reducing the core strength appears to be higher in stronger concretes and reduction has been reported as 15% for 40 MPa concrete. However a reduction of 5 to 7% is considered reasonable.
- **Drilling operations:** The strength of cores is generally less than that of standard cylinders, partly as a consequence of disturbance due to vibrations during drilling operations. Whatever best precautions are taken during drilling, there is always a risk of slight damage.

- **Site conditions v/s standard specimens:** Because site curing is invariably inferior to curing prescribed for standard specimens, the in-situ core strength is invariably lower than the standard specimens taken and tested during concreting operations.

REVIEW QUESTIONS

1. Explain the influence of water/cement ratio on the strength of the concrete
2. Explain how the compressive and tensile strength of the concrete is determined?
3. What do you mean by non-destructive testing of concrete? Explain any one of them
4. What are the factors that influence the strength of the concrete?
5. Explain the different types of shrinkage that takes place in concrete?
6. Write a note on creep and shrinkage of concrete
7. Define tensile strength of concrete? How is it related with the tensile strength of the concrete? (Dec 13)
8. Define
   (i) Flexural Strength
   (ii) Compressive strength
   (iii) Split tensile strength
9. Explain the relation between the modulus of elasticity and compressive strength of Concrete.

10. Write a short notes on factors effecting (i) creep (ii) shrinkage
11. What are the factors contributing to cracks in concrete?
12. Explain the significance of durability of concrete in its life time and what are the factors affecting durability of concrete.

13. Explain the factors affecting the strength of hardened concrete
14. Explain (i) Aggregate cement bond strength (ii) Flexural strength of concrete
15. Explain the factors effecting modulus of elasticity of concrete and relation between modulus of elasticity and strength
16. List and explain the factors affecting durability of concrete?
17. Explain chloride, sulfate and freeze and thaw attack on concrete and its effect on durability of concrete?
18. Depict the interplay of factors influencing concrete strength, preferably through a simplified flow chart
19. Establish a relationship between (i) compressive strength and tensile strength (ii) Cube strength and cylinder strengths.
20. Strength of a fully mature concrete is 30MPa. Find the strength of concrete at an age of 7 days when cured at an average temperature of 25°C during day (12 Hours) and 10°C during night (12hours). Use the relation for strength at Maturity as percentage of strength at full maturity, when A=21 B= 61 corresponding to strength at full maturity, express as

$$A + B\log_{10}\left(\frac{Maturity}{1000}\right),$$

21. Explain elastic behavior of concrete and the relationship between modulus of elasticity and strength

22. Distinguish between (i) Creep and Shrinkage (ii) Plastic shrinkage and drying shrinkage.

23. If the volume of the paste is 40 % of the total volume and E_p and E_a are 2, 00,000 and 3, 20,000kg/cm^2. What is the modulus of elasticity of concrete.
24. Define durability? How concrete is made durable against (i) Sulphate attack (ii) freezing and thawing (iii) Corrosion of steel
25. Why the permeability of mortar or concrete is higher than the corresponding cement paste?