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Design of Concrete and Masonry Structures

Civil Engineering

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Civil Services Examination

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Design of Concrete and Masonry Structures

01
CHAPTER

Introduction

1.1 Introduction

In design and analysis of reinforced concrete members, which consists of two distinct materials, one of them is concrete which behaves differentially in tension than in compression and the other one is steel which provides ductility to the concrete.

The basic idea we apply to understand the aspects of behaviour of concrete members are:

- Moment will always causes strain to vary linearly with distance from neutral axis.
- Mechanics of materials will allow us to relate stress to strains.
- Section will be in equilibrium.

1.2 Types of Concrete

1.2.1 Plain Concrete

Concrete can be defined as a mass which is made from any cementing material and consists of sand, gravel and water. Mixing of such naturally occurring materials along with a cementing material result in a partial solid mass that can be molded in any shape and form, when wet, and which becomes hard on drying.

Concrete is a highly successful building material and has gained wide popularity because of the following reasons:

1. Concrete is highly durable even under hostile environmental conditions.
2. It can be easily casted into any shape and size.
3. It is relatively cheaper and widely available.

The most important property of concrete is its compression resisting ability i.e. compressive strength, which supersedes any other building material. At present we have concrete grades ranging from 5 MPa to 100 MPa.

The major drawback of concrete is that it cannot resist significant tension. The tensile strength of concrete is about 10% of its compressive strength. Plain concrete is mostly used in mass concrete works (as in dams).

1.2.2 Reinforced Concrete

- Concrete has gained so much importance and popularity because of the development of **reinforced concrete**. Construction of load bearing building elements like beams, slabs etc. is made possible due to the reinforced concrete only. Steel bars embedded in the tension zone of concrete make it able to take tension.

- In reinforced concrete, strain compatibility is assumed to exist i.e. there exists a perfect bond between the concrete and steel bars so that strain in concrete is equal to the strain in steel at the interface of concrete and steel.
- Steel bars embedded in the tension zone of concrete, relive concrete of any tension and takes all tension without separating from concrete.
- Moreover, since the failure of concrete is brittle in nature which takes place without giving any warning, introduction of steel in concrete makes it a ductile material which gives sufficient warning before collapse.
- Now tensile stresses occur either directly (e.g. direct tension, flexural tension) or indirectly (e.g. shear which causes tension along the diagonal planes). Temperature and shrinkage effects may also induce tensile stresses. At all such locations, steel is invariably provided which is in fact inevitable, that passes across the tensile cracks. Insufficient steel causes propagation of cracks which can lead to complete failure.
- Embedding reinforcing bars in compression zone of concrete increases the compressive strength of member (e.g. In columns, doubly reinforced beams etc.).

1.2.3 Prestressed Concrete

Pre-stressed is designed to counteract the external loading to a required extent by developing the internal stresses. It is a high strength concrete with high tensile wires embedded in concrete and tensioned before the application of actual working load. While doing so, the concrete can be compressed to such an extent that when the structure is actually loaded, there is almost no tension developed in the beam section. Prestressed concrete is frequently used where, even a hair line crack is not admissible like, high pressure vessels, pipes, water tanks etc. and at locations which are subjected to fatigue loading like long span bridges or rail sleepers etc.

1.3 Importance of Design Codes in the Design of Structures

These codes are revised periodically based on current research and trends (e.g. IS 456: 1978 and IS 456: 2000). Codes serve the following objectives/purposes:

1. They ensure structural stability/safety by specifying certain minimum design requirements.
2. They make the task of a designer rather simple by making available results in the form of tables and charts.
3. They ensure a consistency in procedures adopted by the various designers in the country.
4. They protect the designer against structural failures that are caused by improper site construction practices i.e. codes have legal sanctity and one can have a stand on the basis of these design codes.

1.3.1 Basic Indian Standard Codes for Structural Design

Some of the basic Indian Standard codes for reinforced concrete published by the BIS (Bureau of Indian Standards) are:

1. IS 456: 2000 Plain and reinforced concrete-Code of practice.
2. IS 875: 1987 (Part-I to V) Code of practice for design loads.
3. IS 1893: 2002 Criteria for earthquake resistant design of structures.
4. IS 13920: 1993 Ductile detailing of reinforced concrete structures subjected to seismic forces.

1.4 Characteristic Strength of Concrete

1.4.1 Standard Deviation

- The strength of similar concrete varies in different testing because no material is homogenous.

- Frequency density = $\dfrac{\text{No. of samples in an interval}}{\text{Total no. of samples}}$
- For most of the engineering material, probability is symmetrical about mean and such a curve is called **Normal Probability Distribution Curve**.

Mean strength, $f_t = \dfrac{\Sigma f}{n}$

f = strength of individual sample, η = no. of samples

$$\sigma = \sqrt{\frac{\Sigma\left(f - f_t\right)^2}{n}}$$

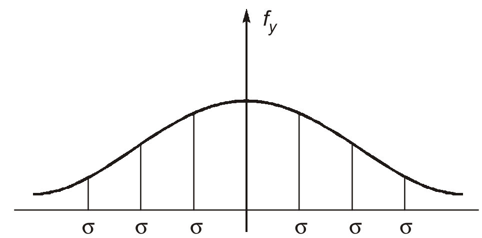

Fig. 1.1

$f - f_t$ = deviation from mean, σ = standard deviation

- If value of σ is very large, then it denotes the poor quality control.
- If value of σ is very small, then it denotes the high quality control.

According to clause 9.2.4.1 as per IS-456:

- The total number of test samples required to constitute an acceptable record for calculation of standard deviation shall not be less than 30. Attempts should be made to obtain 30 samples, as early as possible.
- When sufficient test results for a particular grade of concrete are not available, the value of standard deviation given in Table 1.1 may be assumed for design as mixture.

Table 1.1: Standard deviation for various concrete grades

<table>
<tr><th>Concrete Grade</th><th>Assumed Standard Deviation (N/mm^2)</th></tr>
<tr><td>M10</td><td rowspan="2">3.5</td></tr>
<tr><td>M15</td></tr>
<tr><td>M20</td><td rowspan="2">4</td></tr>
<tr><td>M25</td></tr>
<tr><td>M30</td><td rowspan="6">5</td></tr>
<tr><td>M35</td></tr>
<tr><td>M40</td></tr>
<tr><td>M45</td></tr>
<tr><td>M50</td></tr>
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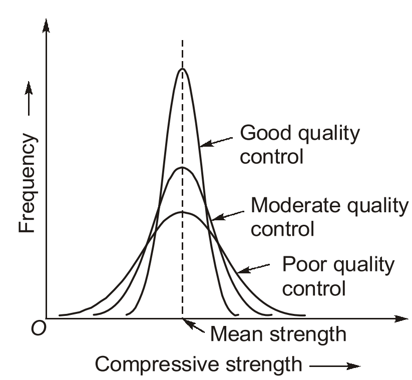

Fig.1.2 Influence of quality control on the frequency distribution of concrete strength

NOTE

- For no. of test samples ≥ 30, $\sigma = \sqrt{\dfrac{\Sigma\left(f - f_t\right)^2}{n}}$
- For no. of test samples ≤ 30, $\sigma = \sqrt{\dfrac{\Sigma\left(f - f_t\right)^2}{n-1}}$

1.4.2 Characteristic Strength

DO YOU KNOW ?

- **Characteristic Strength** is defined as that strength of the material below which not more than 5% of the tests results are expected to fall. This is shown in the Figure 1.3.
- Due to significant variation in the compressive strength of concrete (tested on concrete cube/cylinder specimens), it is quite essential to ensure that a certain minimum strength of concrete can always be obtained from a given mix. This is obtained by defining **Characteristic Strength** of concrete.

Table 1.2: Characteristic compressive strength compliance requirement (as per Cl. 16.1 and 16.3 of IS 456: 2000)

Specified Grade	Mean of the Group of 4 Non-Overlapping Consecutive Test Results in N/mm^2	Individual Test Results in N/mm^2
M15	$\geq f_{ck}$ + 0.825 × Established standard deviation (rounded off to nearest 0.5 N/mm^2) **or** f_{ck} + 3 N/mm^2, whichever is greater	f_{ck}–3 N/mm^2
M20 or above	$\geq f_{ck}$ + 0.825 × Established standard deviation (rounded off to nearest 0.5 N/mm^2) **or** f_{ck} + 4 N/mm^2, whichever is greater	f_{ck}–4 N/mm^2

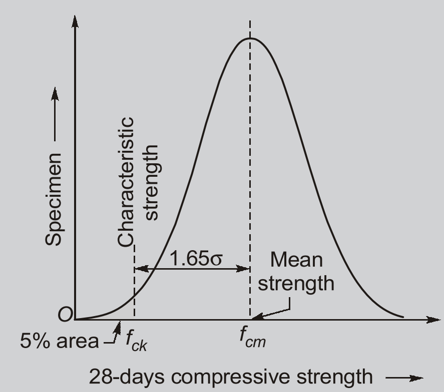

Fig. 1.3 Idealised normal distribution of concrete strength

1.5 Grade of Concrete

- The desired properties of concrete are its compressive strength, tensile strength, shear strength, bond strength, density, durability, impermeability etc. Among these properties, the most important property is the compressive strength of concrete. This is measured by standard tests on concrete cube/cylinder specimens. Many other properties of concrete can be inferred from its compressive strength.
- The grade of concrete is expressed in terms of its characteristic compressive strength (of 150 mm cube at 28 days) expressed in N/mm^2 or MPa. e.g. Different grades of concrete are M20, M25, M30, M40 and so on.

Table 1.3 Minimum grade of concrete based on exposure conditions as per IS: 456

Exposure Condition	Minimum Concrete Grade
Mild	M20
Moderate	M25
Severe	M30
Very Severe	M35
Extreme	M40

- Strength of concrete in uniaxial compression is determined by loading standard test tube (150 mm size) to failure in compression testing machine.
- Strength of the cube is average of three specimen of a sample.
- Individual variation should not be more than ±15% of average if variation is more, test results of the sample are invalid.

1.6 Concrete Mix Design

Design of concrete mix for a particular grade of concrete involves economical selection of relative proportions of cement, sand and coarse aggregates. While designing a concrete mix, it is always tried to obtain a minimum strength which is equal to characteristic strength of concrete but concrete must also have the desired workability (when fresh/green), impermeability and durability (in hardened state). **Table 1.4** depicts the various grades of concrete based on concrete mix design. Concrete mix design is classified as nominal mix design and the design mix.

Table 1.4 Various grades of concrete as per IS 456 : 2000

Concrete Grade	Type of Concrete
M10	Ordinary grade concrete
M15	
M20	
M25 - M55	Standard grade concrete
M60 - M100	High Strength concrete

Note: Provision of IS 456: 2000 do not apply to grades of concrete M60 and above.

1.6.1 Nominal Mix Design

IS 456: 2000 provides a more precise nominal mix proportions for M5, M7.5, M10, M15 and M20 grades of concrete in terms of total mass of aggregates, proportions of fine to coarse aggregates and volume of water to be used per 50 kg (i.e. 1 bag) of cement (which is in volume equal to **34.5 liters**). Nominal mix concrete can only be used in ordinary concrete constructions involving concrete grade not higher than M20. For higher grades of concrete, design mix concrete is adopted.

Table 1.5 Proportions of nominal mix concrete as per IS 456: 2000

Concrete Grade	Weight of FA and CA in 50 kg of cement	FA:CA	Weight of water (in kg) per 50 kg (1 bag) of cement
M5	800	Generally 1:2 but subject to an upper limit of 1:1.5 and a lower limit of 1:2.5	60
M7.5	625		45
M10	480		34
M15	330		32
M20	250		30

***FA** : Fine Aggregate, **CA** : Coarse Aggregate*

Traditional nominal mix of 1 : 2 : 4 (cement : sand : coarse aggregate, by weight) with 33 grade of OPC conforms approximately to M15 concrete grade. This nominal mix with higher grades of cement (43, 53 grades) yields higher grades of concrete (M 20 and above).

1.6.2 Design Mix Concrete

Design mix concrete is based on the principles of "mix design" and is always preferred over nominal mix of concrete. It yields concrete of desired quality and is more economical than the nominal mix. The IS recommendations of the mix design are given in **IS 10262: 1982** and **SP 23: 1982**.

1.7 Steps Involved in Mix Design of Concrete as per IS Recommendation

Step 1. Determine the mean target strength (f_m) from the desired characteristic strength (f_{ck}) as:

$$f_m = f_{ck} + 1.65\sigma$$

where, σ is the standard deviation that depends on quality control as listed in Table 8 of IS 456: 2000. σ is calculated from previous records or may be assumed.

Step 2. Determine the water-cement ratio based on 28 days strength of cement and the mean target strength of concrete. The water cement ratio can be taken from the charts available as shown in Fig. 1.4. This ratio must not exceed the limits specified in Table 5 of IS 456: 2000 part of which is reproduced here as **Table 1.6**.

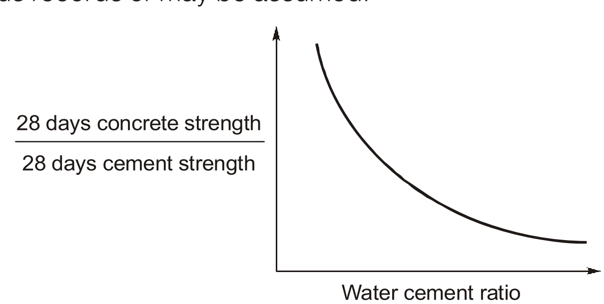

Fig. 1.4

Step 3. Determine the water content based on requirements of workability. Select the type of proportion of fine and coarse aggregate (by mass) based on aggregate grading and type. Water requirement is usually in the range of 170-200 litres per cubic metre of concrete (without admixtures) and ratio of fine and coarse aggregates is generally taken as 1:1.5, 1:2, or 1:2.5.

Step 4. Determine the cement content (in kg/m^3) as:

$$\text{Cement Content} = \frac{\text{Water content}}{\text{Water-cement ratio}}$$

Cement content should not be less than that specified in Tables 4 and 5 of IS 456: 2000 for durability considerations.

Do you know? IS 456: 2000 restricts the use of cement beyond 450 kg/m^3 in order to control shrinkage and thermal cracks.

Step 5. Determine the masses of coarse and fine aggregates based on absolute volume principle as:

$$\frac{C}{\rho_c} + \frac{FA}{\rho_{FA}} + \frac{CA}{\rho_{CA}} + V_W + V_a = 1$$

Here *C*, *FA* and *CA* denotes the mass of cement, fine aggregates (sand) and coarse aggregates respectively and ρ_c, ρ_{FA} and ρ_{CA} denotes the mass density of cement, fine aggregates (sand) and coarse aggregates respectively.

V_w = Volume of water and V_a = Volume of air voids.

Step 6. Determine the weight of ingredients per batch based on capacity of the concrete mixer.

1.8 Behaviour of Concrete under Uniaxial Compression

Strength of concrete is determined by the compressive strength test on a standard 150 mm concrete cube in a compression testing machine as per **IS 516: 1959**. The test specimens are generally tested after 28 days of casting and continuous curing. The loading is **strain-controlled** and load is generally applied at a uniform **strain rate of 0.001 mm/mm/minute**. The maximum stress attained in this loading process is called as **cube strength** of concrete.

Do you know? In USA, instead of 150 mm cubes, standard test cylinders of height to diameter ratio of 2. e.g.150 mm diameter and 300 mm height cylinders are used. **Cylinder strength comes out to be lower than the cube strength of concrete** for the same quality of concrete.

1.9 Behaviour of Concrete in Tension

Concrete is quite weak in tension and is not supposed to designed to take any direct tension. But tensile stresses occur in concrete due to flexure, shear, shrinkage and temperature stresses etc. Pure shear causes tension on diagonal planes for which sufficient knowledge of direct tensile strength of concrete is important for assessing the shear strength of beams with unreinforced webs. For assessing the moment at first crack, the knowledge of flexural tensile strength of concrete is necessary. The direct tensile strength of concrete is about 7 to 15% of the compressive strength of concrete.

It is difficult to have direct tension test on concrete as it requires pure axial tensile stress free from any secondary stresses and misalignment in the tension testing machine. Thus indirect tension tests are performed using **flexure test** or **cylinder splitting test**.

1.9.1 Modulus of Rupture (Flexural Strength of Concrete)

- Tensile strength of concrete in flexure is called flexural strength.
- While performing flexure test, a standard simply supported plain concrete beam of square or rectangular section is used, which is subjected to two points loading until failure, for a linear stress distribution

across the section, the theoretical maximum tensile stress which is developed in the extreme fiber is called Modulus of Rupture (f_{cr}) of concrete.

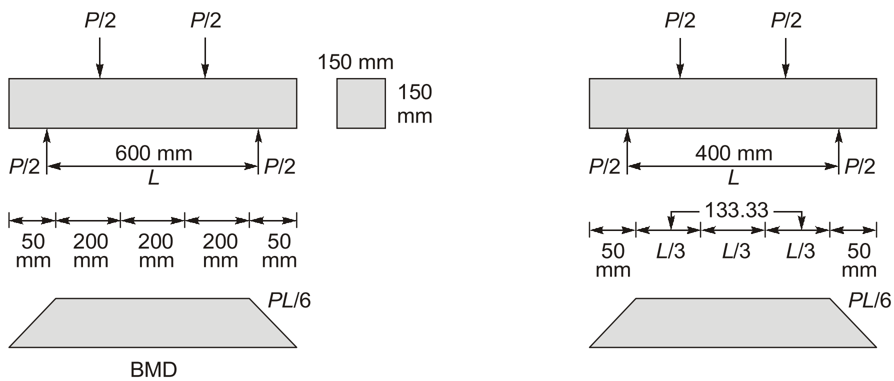

Fig. 1.5

where P is in kN and L is length in 'm'.

$$\frac{M}{Z} = \frac{P \times 400 \times 6 \times 10^3}{6 \times 100 \times 100^2} \text{ N/mm}^2 \text{ ...[For } 100 \times 100 \times 500 \text{ mm specimen]}$$

NOTE: Assuming linear stress-strain curve and contribution of steel area to be negligible.

$$f_{cr} = \frac{M}{Z} = 0.4 \text{ P N/mm}^2$$

Since, stress-strain curve is not linear, So, as per IS code

$$f_{cr} = 0.7\sqrt{f_{ck}}$$

where, f_{cr}, is the modulus of rupture in N/mm^2 and f_{ck} is the characteristic strength of concrete in N/mm^2.

Flexural strength is used to determine the onset of cranking or loading at which cracking starts in a structure.

1.9.2 Splitting Tensile Strength of Concrete

Owing to limitations of direct tensile strength test of concrete, cylinder splitting test is performed which gives more uniform results. In this test, a standard plain concrete cylinder (as used in compression test) is loaded on its sides along a diameter. Failure occurs by splitting of the cylinder along the plane of loading. This type of loading produces a uniform tensile stress across the plane of loading.

The splitting tensile strength (f_{ct}) is obtained as:

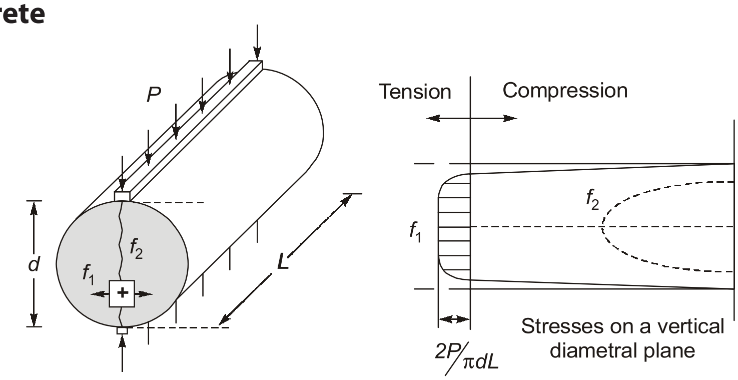

Fig. 1.6 Cylinder splitting test for tensile strength concrete cylinder diameter (150 mm) (300 mm length)

$$f_{ct} = \frac{2P}{\pi dL}$$

f_{ct} = splitting tensile strength = 0.66 f_{ck} or 2/3 f_{ck}

where, f_{cr} is modulus of rupture.

direct tensile strength = (0.5 – 0.625) f_{cr}

Where, P is the maximum load applied at failure, d is the diameter of the cylinder specimen, L is the length of the cylinder specimen.

1.10 Modulus of Elasticity of Concrete

- Concrete is not a truly elastic material i.e. it cannot regain its original shape from the deformed shape after removal of loading. It is not only **inelastic**, it is **non-linear** also i.e. stress – strain relationship is not linear. Thus, conventional elastic constants (like modulus of elasticity, Poisson's ratio etc.) cannot be defined for a non-linear, inelastic material like concrete. **Even though we have to define these constants for concrete in order to make possible the analysis of structures which are in fact based on linear elastic analysis.**
- In situations, where long term effects of loading on the structure are negligible like wind or earthquake loading, we define **initial tangent modulus** which is in fact a measure of **dynamic modulus of elasticity** of concrete. In the usual linear static analysis, we define **static modulus of elasticity**. When loads on the structure are of long duration (dead and live loads), the long term effects of **creep decreases the effective modulus of elasticity of concrete**.

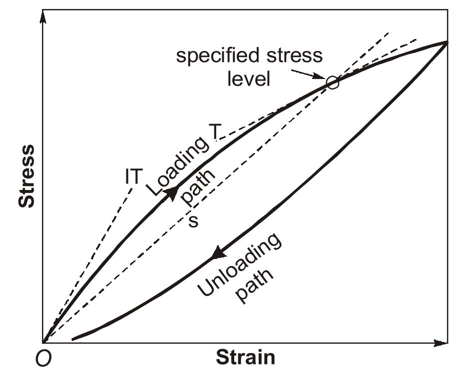

Fig. 1.7 Various descriptions of modulus of elasticity of concrete
(*IT* = Initial tangent, *T* = tangents, *s* = secant)

- It is difficult to separate the long term strains due to creep and shrinkage from short term elastic strains. Thus, while estimating deflection of reinforced concrete beam, the total deflection is assumed to be the sum of instantaneous elastic deflection (due to loads) and long term deflections due to creep and shrinkage. Short term static modulus of elasticity of concrete (E_c) is used in computing the instantaneous elastic deflection.
- Secant modulus at a stress level of about 1/3rd the cube strength of concrete is generally found acceptable in expressing the average value of E_c under the usual service load conditions.
- As per **IS 456: 2000**, short term static modulus of elasticity of concrete (E_c, in MPa) is given in terms of characteristic strength of concrete as:

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

- Modulus of elasticity is primarily influenced by the elastic properties of aggregate and to a linear extent by the conditions of curing, age of concrete, mix proportion and type of cement.

  Long term modulus of elasticity including creep

$$E_{ce} = \frac{E_c}{1+\theta}$$

E_c = short term modulus of elasticity,

$$\theta = \text{creep coefficient} = \frac{\text{Ultimate creep strain}}{\text{Elastic strain at the age of loading}}$$

Table 1.6

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

1.11 Creep of Concrete

When concrete is subjected to sustained compressive loading for a longer duration its deformation keeps on increasing continuously, even though the stress level is not altered. Time dependent component of total strain is called **Creep**.

Creep of concrete is covered in more detail in forthcoming chapters. At present, it is worth to note that creep of concrete have the following ill effects on concrete structures:

1. It increases the deflections of certain concrete elements like beams and slabs.
2. It increases the deflection of very long / slender columns.

3. It slowly transfers the load from concrete to reinforcing steel over a period of time.
4. It causes loss of prestress in prestressed concrete members.

1.12 Effect of Duration of Loading on Stress Strain Curve

The standard compression test gets over within 10 minutes with loading being applied at a uniform strain rate of 0.001 mm/mm/minute. When load is applied at a faster strain rate (as impact loading), the modulus of elasticity and strength of concrete increase but the failure strain decreases. When the load is applied at a slower rate (duration greater than 10 minutes to as long as 1 year or more) then there is a slight decrease in the modulus of elasticity and significant increase in the failure strain.

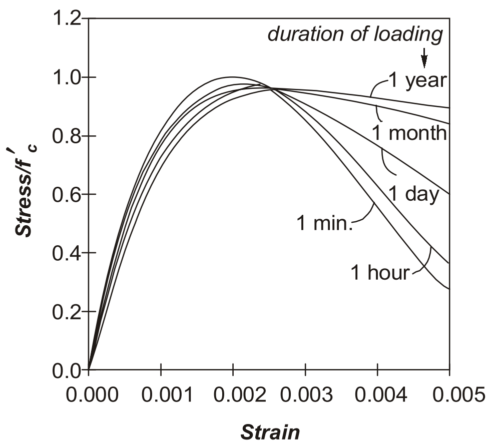

Fig.1.8 Influence of duration of loading (strain-controlled) on the stress-strain curve of concrete

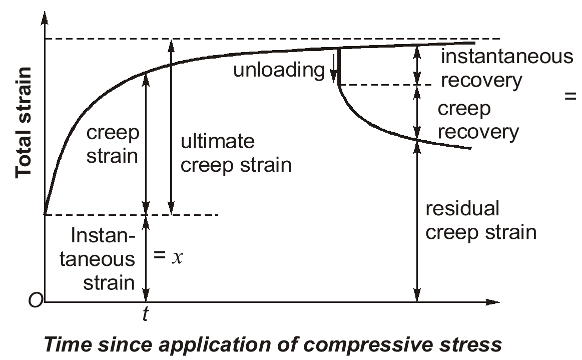

Fig.1.9 Typical strain-time curve for concrete in uniaxial compression

Following factors influence the creep of concrete:

1. High cement content increases the creep of concrete.
2. High water-cement ratio increases creep of concrete.
3. Creep increases when aggregate content is low.
4. It increases when air entrainment is high in concrete.
5. Low relative humidity increases creep.
6. Small size/thickness of members show large amount of creep.
7. Early loading of concrete members increases creep.
8. Long term sustained loading increases creep of concrete.

Long term sustained loading on concrete at a constant stress results in creep strains and a decrease in the compressive strength of concrete.

1.13 Compressive Strength of Concrete in the Design of Structures

The compressive strength of concrete in an actual structure cannot be exactly same as compressive strength obtained by uniaxial compression test in laboratory even for the samples obtained from the concrete mix which is used in actual construction. This is because of the effect of loading duration, member sizes and strain gradient.

The maximum strength of concrete is taken as 0.85 times the specified cylinder strength for the design of RCC members (for both in compression and flexure/bending). This comes out to be approximately equal to 0.67 times the characteristic cube strength. IS 456: 2000 also limits the failure strain to 0.002 in direct compression and 0.0035 in flexure.

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