CIVIL ENGINEERING

Reinforced Cement Concrete & Pre-stressed Concrete

Comprehensive Theory
with Solved Examples *and* Practice Questions

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Introduction

1.1 INTRODUCTION

Concrete is one of the most common building material used for constructing civil engineering structures and is essential in the infrastructure development of any nation. Concrete is used in the construction of various types of structures which include buildings, bridges, piers, chimneys, pavements, dams, hydraulic structures, conveying pipes, liquid retaining tanks/structures, assembly halls, auditorium, swimming pools, bunkers etc. and the list goes on.

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 results in a partial solid mass (when wet) that can be molded in any shape and form and later becomes hard on drying. Concrete is being used as a building material probably from the last 150 years.

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. Thus, the use of plain concrete as a building material is limited to such places where tensile stresses/strains never develop. For example pedestals, mass concreting in dams etc.

1.2.2 Reinforced Concrete

Concrete has gained so much importance and popularity because of the development of **reinforced concrete**. Introducing the reinforcing bars in concrete makes the concrete an excellent composite building material which can resist significant amount of tensile stresses/strains also. 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. 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

Development of prestressed concrete took place along with the reinforced concrete. 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

Different countries have formulated their own codes for laying down the guidelines for the design and construction of structures. These codes came into picture after a collaborative effort of highly experienced structural engineers, construction engineers, academicians and other eminent fellows of respective areas. 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

Due to wide variation in the characteristics of concrete constituents (sand, coarse aggregates etc.), concrete is subjected to considerable variation in strength. Also, due to non-homogeneous nature of concrete, specimens taken from the same mix may give different compressive strengths in tests. This variation can be controlled by strict quality control and quality assurance.

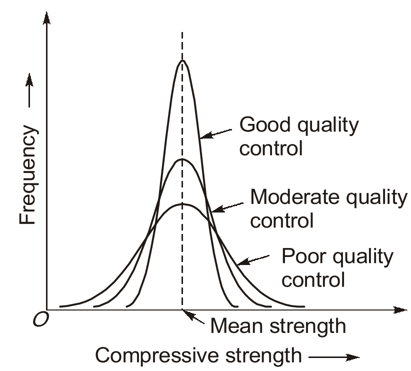

Fig. : Influence of quality control on the frequency distribution of concrete strength

Statistically, the variation in concrete strength is studied in terms of **standard deviation** and/or **coefficient of variation**.

$$\text{Coefficient of variation} = \frac{\text{Standard deviation}}{\text{Mean strength}}$$

Experimentally, it is found that probability distribution of concrete strength (for a particular concrete mix as found out by compressive strength tests in laboratory on a large number of specimens) follows **normal/Gaussian distribution**. The **coefficient of variation varies generally in the range of 0.01 to 0.02**. With higher degree of quality control, this variation can be reduced.

As pointed earlier, 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 (which is applicable for other materials also).

Characteristic Strength is defined as that strength of the material below which not more than 5% of the tests results are expected to fall.

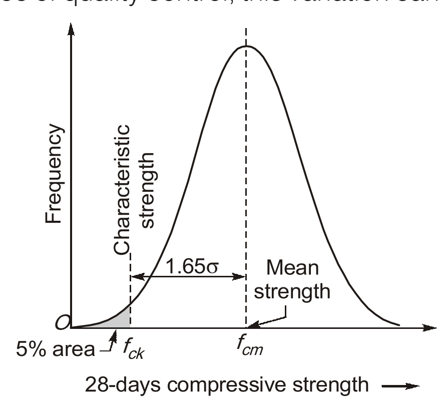

Fig. : Idealised normal distribution of concrete strength

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

where f_{cm} = Mean strength

f_{ck} = Characteristic strength

Thus, mean strength of concrete has to be significantly greater than the characteristic strength of concrete.

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, as shown in table below.

Table : *Grades of Concrete (Clause 6.1, 9.2.2, 15.1.1 and 36.1)*

Group (1)	Grade Designation (2)	Specified Characteristic Compressive Strength of 150 mm Cube at 28 Days in N/mm^2 (3)
Ordinary Concrete	M10 M15 M20	10 15 20
Standard Concrete	M25 M30 M35 M40 M45 M50 M55 M60	25 30 35 40 45 50 55 60
High Srength Concrete	M65 M70 M75 M80 M85 M90 M95 M100	65 70 75 80 85 90 95 100

Notes :
1. In the designation of concrete mix *M* refers to the mix and the number to the specified compressive strength of 150 mm size cube at 28 days, expressed in N/mm^2.
2. For concrete of compressive strength greater than M60, design parameters given in the standard code may not be applicable and the values may be obtained from specialized literatures and experimental results.

1.6 DURABILITY OF CONCRETE

A durable concrete is one that performs satisfactorily in the working environment during its anticipated exposure conditions during service life. The materials and mix proportions specified and used should be such as to maintain its integrity and, if applicable, to protect embedded metal from corrosion.

One of the main characteristics influencing the durability of concrete is its permeability to the ingress of water, oxygen, carbon dioxide, chloride, sulphate and other potentially deleterious substances. Impermeability is governed by the constituents and workmanship used in making the concrete. With normal-weight aggregates a suitably low permeability is achieved by having an adequate cement content, sufficiently low free water/cement ratio, by ensuring complete compaction of the concrete, and by adequate curing.

The factors influencing durability include :

(a) the environment;

(b) the cover to embedded steel;

(c) the type and quality of constituent materials;

(d) the cement content and water/cement ratio of the concrete;

(e) workmanship, to obtain full compaction and efficient curing; and

(f) the shape and size of the member.

The degree of exposure anticipated for the concrete during its service life together with other relevant factors relating to mix composition, workmanship, design and detailing should be considered.

1.6.1 Methods to Increase the Durability of Concrete

By reducing the permeability of concrete in following ways:

1. Use of high strength concrete
2. By proper curing of concrete
3. By having a low water cement ratio
4. Using improved quality of admixtures
5. By having the maximum possible compaction of concrete
6. By the use of well graded, dense aggregates
7. By minimizing the possibility of cracks at the design phase itself

By providing protection to reinforcing steel in following ways:

1. By providing adequate clear cover to reinforcing steel as per relevant stipulations of IS codes.
2. Using coated steel or suitable corrosion resistant steel.
3. By preventing the corrosion of steel by the methods like sacrificial protection etc.
4. By the use of suitable corrosion resistant cement.
5. Avoid use of alkali reactive aggregates.
6. By preventing ponding on roof slabs and on other concrete surfaces by proper drainage of water.
7. By having a proper control on chloride and sulphate content in the concrete mix.

1.6.2 Environmental Exposure Conditions

The general environment to which the concrete will be exposed during its working life is classified into five levels of severity, that is, mild, moderate, severe, very severe and extreme as described in table.

***Table :** Environmental Exposure Conditions*
(Clauses 8.2.2.1 and 35.3.2)

Sl.No.	Environment	Exposure Conditions
(i)	Mild	Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal area.
(ii)	Moderate	Concrete surfaces sheltered from severe rain or freezing whilst wet. Concrete exposed to condensation and rain. Concrete continuously under water. Concrete in contact or buried under non-aggressive soil/ground water. Concrete surfaces sheltered from saturated salt air in coastal area.
(iii)	Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation. Concrete completely immersed in sea water. Concrete exposed to coastal environment.
(iv)	Very severe	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet. Concrete in contact with or buried under aggressive sub-soil/ground water.
(v)	Extreme	Surface of members in tidal zone. Members in direct contact with liquid/solid aggressive chemicals.

1.7 CONCRETE MIX DESIGN

Design of concrete mix for a particular grade of concrete involves proper 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).

1.7.1 Nominal Mix Design

Concrete mix design is a process that needs experience. Earlier, concrete mixes were specified in terms of fixed ratios like 1:2:4, 1:1.5:3 and so on for cement, sand and coarse aggregates respectively (by mass or by volume). This is a very rough method of concrete mix design which often gives wrong translations of concrete grades like M15, M20, M25, M30 etc.

Table : 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

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.

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).

1.7.2 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**.

1.8 STEPS INVOLVED IN MIX DESIGN OF CONCRETE AS PER IS RECOMMENDATION

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

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

where, σ is the standard deviation that depends on quality control as listed in Table 8 of IS 456: 2000. The same table has been reproduced here.

Table : Standard deviation for various concrete grades

Concrete Grade	Assumed Standard Deviation (N/mm^2)
M10	3.5
M15	
M20	4
M25	
M30	5
M35	
M40	
M45	
M50	
M55	
M60	

Step 2 : Determine the water-cement ratio based on 28 days strength of cement and the mean target strength of concrete. This ratio must not exceed the limits specified in Table 5 of IS 456: 2000 part of which is reproduced here.

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.

Table : Minimum cement content and maximum water cement ratio based on exposure condition

Exposure Condition	Minimum cement content (in kg/m^3)	Maximum free water cement ratio	Minimum grade of concrete
Mild	300	0.55	M20
Moderate	300	0.50	M25
Severe	320	0.45	M30
Very Severe	340	0.45	M35
Extreme	360	0.40	M40

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.

NOTE : Clause 8.2.4.2 of 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 masses of cement, fine aggregates (sand) and coarse aggregates respectively and ρ_c, ρ_{FA} and ρ_{CA} denotes the mass densities 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.

1.9 SAMPLING OF DESIGNED CONCRETE MIX (AS PER IS 456 : 2000)

1. Samples from fresh concrete are taken as per IS 1199 and cube specimen is tested after 28 days of casting and curing as per IS 516.
2. The sampling procedure adopted must ensure that each concrete batch shall have a reasonable chance of being tested.
3. The minimum frequency of sampling of concrete of each grade shall be in accordance with the following :

Quantity of Concrete in the Work, m^3	Number of Samples
1 – 5	1
6 – 15	2
16 – 30	3
31 – 50	4
51 and above	4 plus one additional sample for each additional 50 m^3 or part thereof

4. Three test specimens are made for each sample for testing at 28 days.
5. The test results of the sample is the average of the strength of three specimens.
6. The individual variation should not be more than ±15% of the average otherwise the test result of sample are considered invalid.

1.10 ACCEPTANCE CRITERIA (AS PER IS 456 : 2000)

1.10.1 Compressive Strength

The concrete shall be deemed to comply with the strength requirements when both the following conditions are met :

(a) The mean strength determined from any group of four non-overlapping consecutive test results complies with the appropriate limits in column 2 of Table given below.

(b) Any individual test result complies with the appropriate limits in column 3 of Table given below.

Table : 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 or above	$\geq f_{ck}$ + 0.825 × Established standard deviation (rounded off to nearest 0.5 N/mm^2) or f_{ck} + 3 N/mm^2, whichever is greater	$\geq f_{ck}$-3 N/mm^2

NOTE: For concrete of quantity upto 30 m^3, the mean of test results of all such samples shall be f_{ck} + 4 N/mm^2, minimum and the requirement of individual test result shall be f_{ck} – 2 N/mm^2. However, when the number of sample is only one, the requirement shall be f_{ck} + 4 N/mm^2, minimum.

1.10.2 Flexural Strength

When both the following conditions are met, the concrete complies with the specified flexural strength.

(a) The mean strength determined from any group of four consecutive test results exceeds the specified characteristic strength by at least 0.3 N/mm^2.

(b) The strength determined from any test result is not less than the specified characteristic strength less 0.3 N/mm^2.

1.11 TESTING OF CONCRETE

In case of doubt regarding the grade of concrete used, either due to poor workmanship or based on results of cube strength tests, compressive strength tests of concrete on the basis of core test and/or load test may be carried out.

1.11.1 Core Test

IS code recommendations for core tests are as follows :

(i) Cores shall be prepared and tested as described in IS 516 and minimum 3 cores should be tested.

(ii) Concrete in the member represented by a core test shall be considered acceptable if the average equivalent cube strength of the cores is equal to at least 85 per cent of the cube strength of the grade of concrete specified for the corresponding age and no individual core has a strength less than 75 percent.

(iii) If core test result do not satisfy above requirements or in case where core test is not done, load test may be resorted to.

1.11.2 Load Test

IS code recommendations of load tests for flexural members are as follows:

(i) Load tests should be carried out as soon as possible after expiry of 28 days from the time of placing of concrete.

(ii) The structure should be subjected to a load equal to full dead load of the structure plus 1.25 times the imposed load for a period of 24 hours and then the imposed load shall be removed.

(iii) The deflection due to imposed load only shall be recorded. If within 24 hours of removal of the imposed load the structure does not recover at least 75 percent of the deflection under superimposed load, the test may be repeated after a lapse of 72 hour. If the recovery is less than 80 percent, the structure shall be deemed to be unacceptable.

EXAMPLE : 1.1 Find the quantities of cement, sand and coarse aggregates in 1 m^3 of concrete for a mix proportion of 1 : 1.15 : 2.5 (by volume). The water cement ratio required is 0.56 (by weight).

Bulk density of cement = 1500 kg/m^3

Bulk density of sand = 1780 kg/m^3

Bulk density of coarse aggregates = 1650 kg/m^3

Assume volume of entrained air per cubic meter of concrete as 3%.

Specific gravity of cement = 3.15

Specific gravity of sand = 2.65

Specific gravity of coarse aggregates = 2.3

Solution :

Mix proportion is 1 : 1.15 : 2.5 (by volume)

Let volume of cement per m^3 of concrete = x m^3

$\therefore$ Volume of cement : FA : CA = $x : 1.15x : 2.5x$ (m^3)

(Volume includes air volume enclosed also)

Also, Water-cement ratio = 0.56

$$\Rightarrow \quad \frac{\text{Mass of water}}{\text{Mass of cement}} = 0.56$$

Now, bulk density of cement, γ_c = 1500 kg/m^3

Bulk density of sand, γ_{FA} = 1780 kg/m^3

Bulk density of coarse aggregates,

γ_{CA} = 1650 kg/m^3

$\therefore$ x m^3 of cement $\equiv$ $1500x$ kg of cement

$1.15x$ m^3 of sand $\equiv$ $1780(1.15x)$ kg of sand

$2.5x$ m^3 of coarse aggregates $\equiv$ 1650(2.5x) kg of coarse aggregates

and Mass of water = 0.56 times of mass of cement

= 0.56 (1500 x) kg of water per m^3 of concrete

$$\therefore \text{Volume of water} = \frac{0.56(1500\,x)}{1000}\text{m}^3 \qquad (\because \gamma_w = 1000 \text{ kg/m}^3)$$

Given: Volume of air = 0.03 m^3 per m^3 of concrete

$\therefore$ Volume of concrete = Vol. of cement + Vol. of sand + Vol. of coarse aggregates + Vol. of air + Vol. of water

$$\Rightarrow 1 = \frac{1500\,x}{3.15\times1000} + \frac{1780(1.15\,x)}{2.65\times1000} + \frac{1650(2.5\,x)}{2.3\times1000} + 0.03 + \frac{0.56(1500\,x)}{1000}$$

$$\Rightarrow 0.97 = 0.4762x + 0.7725x + 1.793x + 0.84x$$

$$\Rightarrow x = 0.25$$

$\therefore$ Weight of cement = $1500x = 375$ kg

Weight of sand = $1780(1.15x) = 511.75$ kg

Weight of coarse aggregates

= $1650(2.5x) = 1031.25$ kg

Weight of water = $0.56(1500x) = 210$ kg

1.12 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.

REMEMBER 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.

1.12.1 Influence of Specimen Size on Strength of Concrete

Height to width ratio of the specimen and the cross sectional dimensions of the specimen affects the compressive strength (maximum stress attained) obtained from compression testing machine.

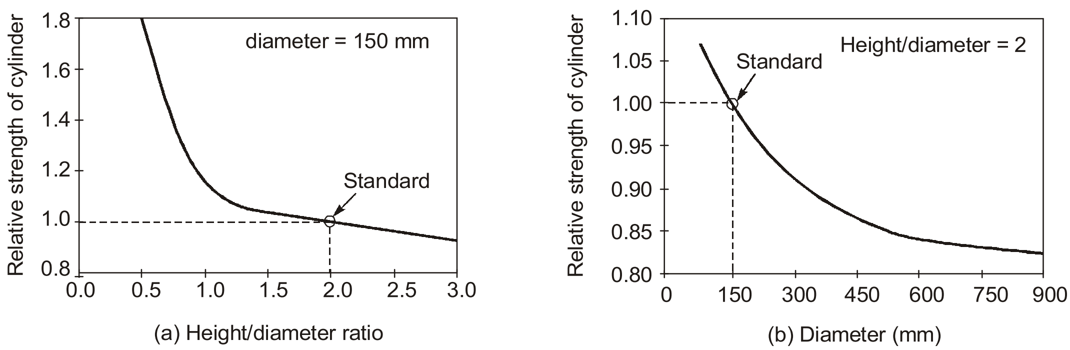

Fig. : Influence of (a) height/diameter ratio and (b) diameter on cylinder strength

In case of cylindrical test specimen of 150 mm diameter and height to diameter ratio of 2, the compressive strength of the concrete specimen increases to about 80% as the height/diameter ratio is reduced from 2 to 0.5. With the same height/diameter ratio being equal to 2, the strength decreases by about 17% as the diameter of the cylindrical specimen is increased from 150 mm to 900 mm.

The loading plates and the top/bottom surface of the concrete specimen offers some frictional resistance called as platen restraint which introduces shear stress at the top and bottom surfaces of the specimen and this effect diminishes as the distance between the platen surfaces increases.

For this reason, standard concrete cube (height/diameter ratio equal to 1) specimen gives higher compressive strength than the cylindrical specimen (height/diameter ratio equal to 2).

REMEMBER: Cube strength of concrete is nearly 1.25 times the cylinder strength.

1.12.2 Stress Strain Curve of Concrete in Compression

Typical stress-strain curves of concrete obtained from standard uniaxial compression test are shown in figure. These stress strain curves of concrete for various grades are somewhat linear in the initial phase of loading. The non-linearity in the curve becomes quite significant when the stress in concrete reaches to about one third to one half of the maximum value.

For concrete, the maximum stress is reached at a strain which is approximately equal to 0.002, beyond which an increase in strain is accompanied by a decrease in stress. Usually at failure, the strain in concrete ranges from 0.003 to 0.005.

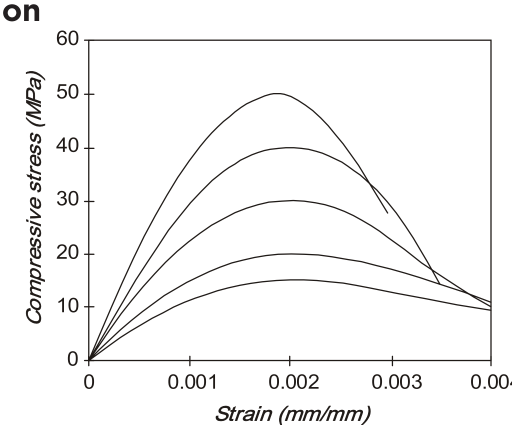

Fig. : Typical stress-strain curves of concrete in compression

1.13 BEHAVIOUR OF CONCRETE IN TENSION

Concrete is quite weak in tension and is not supposed to and also not 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.