Unit-3

Hardened Concrete: Water / Cement ratio – Abram's Law – Gel/space ratio – Gain of strength of concrete – Maturity concept – Strength in tension and compression – Factors affecting strength – Relation between compression and tensile strength - Curing.
Testing of Hardened Concrete: Compression tests– Tension tests – Factors affecting strength – Flexure tests – Splitting tests – Pull-out test, Non-destructive testing methods – Codal provisions for NDT.

Concept -1

Water-Cement Ratio (W/C Ratio)

- Definition: The ratio of the weight of water to the weight of cement in a concrete mix.
- Formula: W/C ratio $= \frac{\text{Weight of Water}}{\text{Weight of Cement}}$
- IS Code Limit: As per IS 456:2000, the recommended W/C ratio is 0.4 to 0.6 based on concrete grade and exposure conditions.

Why is Water Required in Concrete?

Water plays two critical roles in concrete:

1. **Hydration Process (Chemical Reaction with Cement)**
   - When cement and water mix, a chemical reaction called hydration occurs.
   - Hydration leads to the formation of Calcium Silicate Hydrate (CSH) gel, which gives concrete its strength.
   - The amount of water required for complete hydration of cement is 23% of cement weight.
2. **Formation of CSH Gel (Binding Agent in Concrete)**
   - The CSH gel holds the concrete particles together.
   - Additional 15% of water is required to form a good quality CSH gel.

Thus, the total minimum water required is:

Thus, the total minimum water required is:

$$23\% + 15\% = 38\% \approx 40\%$$

or

$$W/C = 0.4$$

which is the **minimum required water-cement ratio** for complete hydration and gel formation.

What Happens When W/C Ratio is Below 0.4?

1. **Higher Strength**
   - Less water means denser concrete, which increases its compressive strength (ability to bear loads).
2. **Low Workability**
   - Workability means how easy it is to mix, place, and compact concrete.
   - A lower W/C ratio makes the mix stiff and difficult to handle, requiring extra effort in placing and finishing.
3. **Incomplete Hydration**
   - Hydration is the chemical reaction between cement and water that gives concrete its strength.
   - If there is too little water, not all cement reacts properly, reducing long-term strength.
4. **Higher Shrinkage Cracks**
   - Shrinkage occurs when concrete loses moisture after setting.
   - A dry mix with low W/C ratio shrinks more, causing fine cracks on the surface.

What Happens When W/C Ratio is Above 0.6?

1. **Lower Strength**
   - Excess water increases porosity (tiny voids in concrete), making it weaker.
   - This reduces compressive strength, making the structure unsafe for heavy loads.
2. **Higher Permeability**
   - Permeability means how easily water can pass through concrete.
   - More water in the mix leads to more pores, allowing water to seep in, which reduces durability and can cause corrosion in steel reinforcement.
3. **Bleeding and Segregation**
   - Bleeding: When water rises to the surface of fresh concrete, weakening the top layer.
   - Segregation: When cement, sand, and aggregates separate, leading to uneven strength distribution.
4. **Longer Setting Time**
   - Setting time is how long concrete takes to harden and gain strength.
   - Excess water delays this process, increasing construction time and costs.

5. **Cracking**
    - **More water means more shrinkage as it evaporates, leading to cracks in the hardened concrete.**
    - **Cracks reduce the life and durability of the structure.**

Best Practice:

- Use a W/C ratio between 0.4 and 0.6, as recommended by IS codes.
- For high-strength concrete, keep W/C $\leq$ 0.45.
- If low W/C ratio affects workability, use plasticizers or superplasticizers (chemical admixtures that improve workability without adding extra water).

Concept -2

Abrams' Water Cement Ratio Law

Duff Abrams established the W/C ratio law, which correlates the strength of concrete to the W/C ratio. It states:

"With the given concrete ingredients and test conditions, the quantity of mixing water used alone determines the strength of concrete, so long as the concrete mix is workable."

In other words, the law states that the strength of concrete only depends upon the W/C ratio provided the mix is workable.

The limitation of Abrams' law is that the effect of entrapped air on the strength of concrete is ignored, whereas the strength of concrete is greatly affected by the presence of entrapped air.

For example:

- **5% of voids** can lower the strength by as much as **35%**
- **2% of voids** can reduce the strength of concrete by more than **10%**

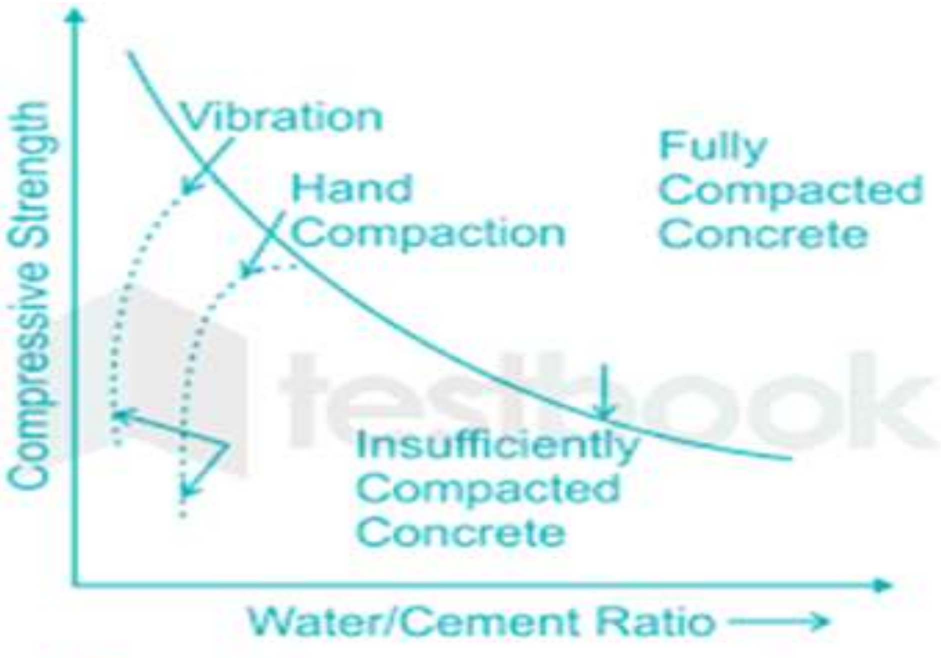
Note: According to Abrams' law, compressive strength is inversely proportional to the water/cement ratio.

Mathematical Representation

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

where,

- **S** = 28 days' compressive strength of concrete
- **x** = water-cement ratio



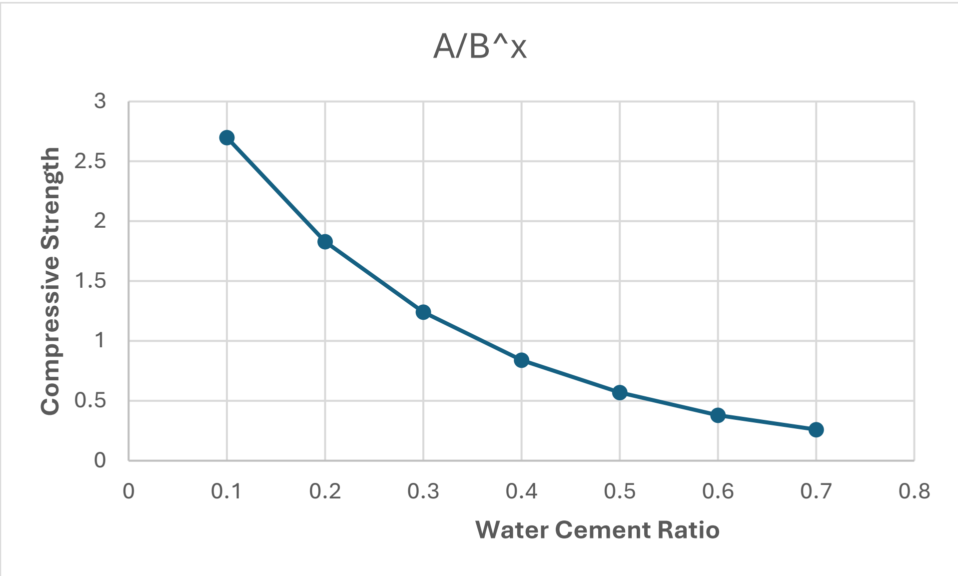
The relation between strength and water/cement ratio of concrete

- **A** and **B** are two empirical constants

A	**B**	**X** **(Water Cement Ratio)**	**B^x**	**A/B^x** **(Compressive Strength)**

Based on these water-cement ratios, find the compressive strength using Abrams' law.

4	50	0.1	1.479	2.70
4	50	0.2	2.187	1.83
4	50	0.3	3.234	1.24
4	50	0.4	4.782	0.84
4	50	0.5	7.071	0.57
4	50	0.6	10.456	0.38
4	50	0.7	15.462	0.26



Concept -3

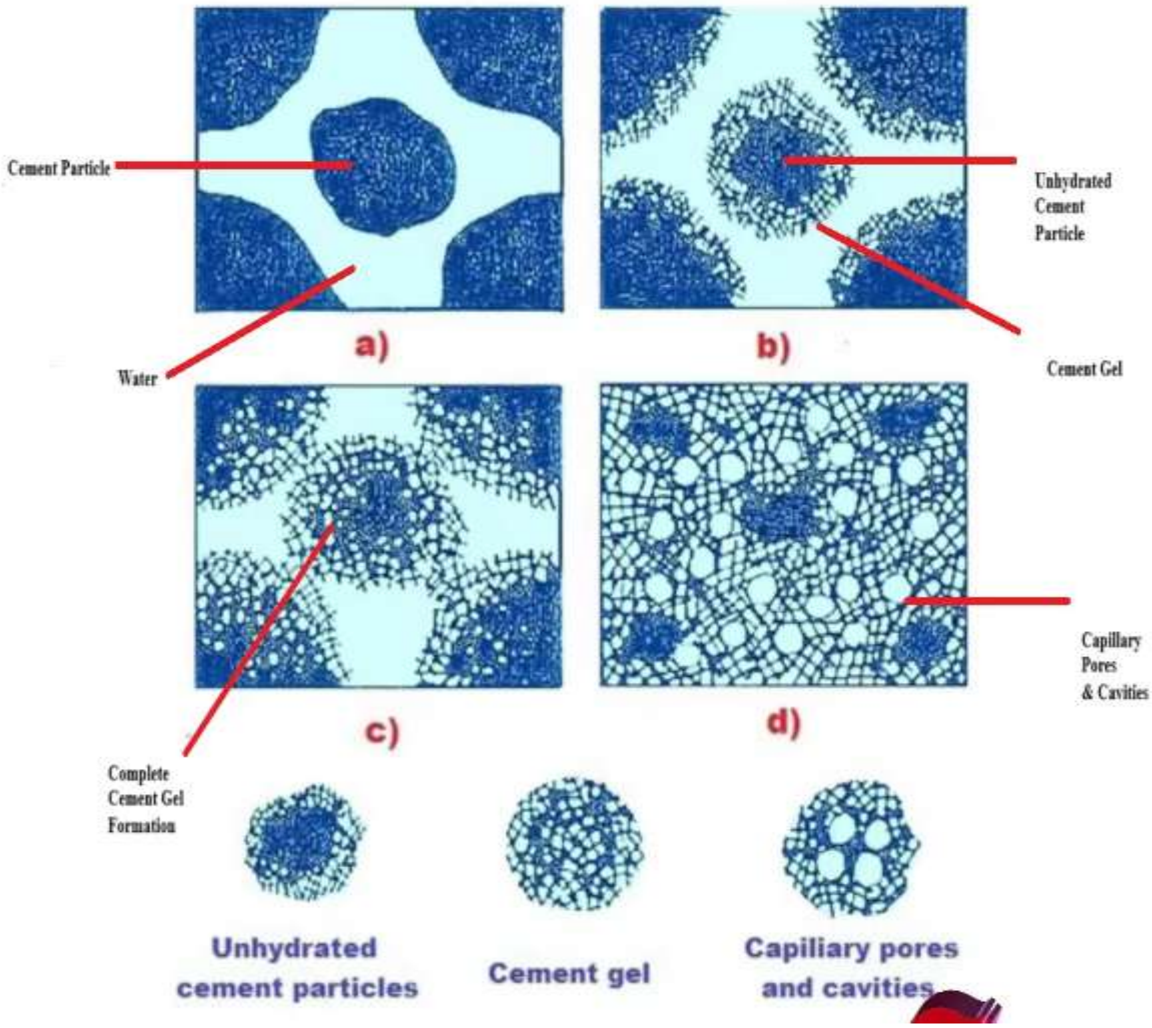
Gel-Space Ratio

The Gel-Space Ratio is the ratio of the volume of hydrated cement paste to the sum of the volumes of hydrated cement and capillary pores.

Key Points:

- The relationship between w/c ratio and strength holds true primarily for the 28-day strength.
- However, the relationship between the Gel-Space Ratio and strength is independent of age.

Abrams' Water/Cement Ratio Law states that the strength of concrete primarily depends on the water/cement (w/c) ratio, provided the mix remains workable but is dipends on lot paprmeters so, to overcome the limitations of this approach, Powers and Brownyard established a correlation between cement strength and the Gel/Space Ratio, offering a more comprehensive understanding of concrete strength development.



For complete hydration:

$$\text{Gel/space ratio} = x = \frac{\text{Volume of gel}}{\text{Space Available}}$$

$$\frac{\text{Volume of Hydrated Product}}{\text{Volume of Hydrated Cement+ Volume of Capillary Pores}}$$

Weight of cement in Volume = Specific volume of cement X Weight of cement

= 0.319 X C

1 ml of Cement Cn form the 2.06 ml of gel upon Hydration

$= \frac{0.319\ X\ 2.06\ X\ C}{0.319 X C + W_0}$

$= \frac{0.657C}{0.319C + W_0}$

For Partial hydration:

$$\text{Gel/space ratio} = x = \frac{0.657C\alpha}{0.319C\alpha + W_0}$$

(1) Question:

Calculate the Gel/Space ratio and theoretical strength of a sample of concrete made with 500g of cement with 0.45 water/cement ratio, on full hydration and at 65% hydration.

Solution:

W/C= 0.4

Volume of Water= 500X0.45 (Specific Gravity of water is 1 so Volume and wight of water will same)

For Full Hydration:

$x = \frac{0.657C}{0.319C + W_o} = \frac{0.657 \times 500}{0.319 \times 500 + 225} = 0.854$

Theoretical Strength $= 240 \times x^3$

$= 240 \times (0.854)^3 = 149.48$ MPa

For Partial Hydration:

$$x = \frac{0.657C\alpha}{0.319C\alpha + W_o} = \frac{0.657 \times 500 \times 0.65}{0.319 \times 500 \times 0.65 + 225} = 0.65$$

$$= 240 \times (0.65)^3 = 65.91 \text{ MPa}$$

Concept -4

Maturity Concept

The maturity concept is based on the understanding that concrete strength development depends not just on time, but also on the temperature it experiences during that time. Think of maturity as a measure of how much "curing progress" concrete has made. If concrete cures at a higher temperature, it gains strength faster. If the temperature is lower, the strength gain is slower. This concept allows engineers to estimate the in-place strength of concrete without breaking test samples every time, which is especially useful on construction sites.

or

Concrete maturity is a measure of how far the curing process has progressed, and it is influenced by both temperature and time. The maturity method is used to estimate the in-place strength of concrete by tracking its temperature history over time. By measuring the maturity at this temperature, construction teams can reliably estimate the strength of the concrete and make informed decisions about when it is safe to proceed with further construction activities, such as removing forms or applying loads.

Maturity Calculation

The **Nurse-Saul equation** is the most used method to calculate the maturity index:

$M(t) = \sum(T_a - T_0) \cdot \Delta t$

- T_a: is the average temperature of the concrete during each time interval.
- T_0: is the **datum temperature**, typically taken as -11°C. Below this value, concrete is assumed **not to gain strength**.
- Δt: is the duration of each time interval (usually in hours).

The result is a **maturity index** in units like **degree-hours (°C·h)** or **degree-days (°C·d)**.
By comparing this maturity index to a **reference curve** developed in lab tests, engineers can predict how much strength the concrete has gained in the field.

Plowman's Coefficients for Maturity Equation

Strength after 28 days at 18°C (maturity of 19800°C·hr) [MPa]	A	B
< 17.5	10	68
17.5 – 35	21	61
35 – 52.5	32	54
52.5 – 70	42	46.5

These coefficients can be used in the maturity strength formula:

$F = A + B \cdot \log_{10}(m \cdot 10^{-3})$

Where:

- F is the % of 28-day strength developed
- m is maturity in °C·hr

The temperature of 18°C (64°F) is often used as a reference point because it is considered a standard temperature for curing concrete. This temperature is used to normalize the maturity calculations, allowing for consistent and comparable results across different projects and conditions

Applications of the Maturity Concept

I. **In-place strength estimation**: Helps estimate the actual strength of concrete in the structure, avoiding delays due to slow lab testing.

II. **Formwork removal timing**: Engineers can safely decide when it's okay to remove molds without damaging the structure.

III. **Post-tensioning**: In pre-stressed concrete, tensioning cables too early can be dangerous; maturity helps determine the right time.

IV. **Traffic opening**: For pavements or bridges, it tells you when it's safe to allow vehicles to pass.

This makes the process **faster, more economical**, and **safer**.

Key Benefits

- **Real-time monitoring**: Sensors inside the concrete transmit temperature data to calculate maturity and predict strength on the go.
- **Fewer destructive tests**: Reduces the need to cast and break cubes/cylinders.
- **Better construction planning**: Helps schedule work more efficiently, especially in **cold** or **hot** weather.
- **Increased safety**: Ensures that structural elements are only loaded when they are strong enough.

Question: 1

Question:
A laboratory experiment conducted on a particular concrete mix showed a strength of 40 MPa for fully matured concrete. For an identical concrete placed in the field, the temperature is maintained at an average of 10°C. The concrete will be subjected to a stripping stress of 35 MPa.

(i) Is it safe to remove the formwork at 15 days when the average curing temperature is 10°C, considering the concrete will be subjected to a stripping stress of 35 MPa?

(ii) Estimate the age at which the formwork can be safely removed if the concrete is continuously cured at 10°C.

(iii) What average temperature is required so that the formwork can be safely removed at 15 days?

Solution

(i)

Given Data

- If it Fully matured concrete strength or Target mean strength, $f_{28} = 40$ MPa
- Age = 15 days = 15 × 24 = 360 hours
- Average temperature = 10°C
- Reference temperature, $T_0 = -11°C$ (Plowman's standard)
- Stripping stress = 35 MPa (at which we can remove formwork)

Note:

So only we can remove strength is more than the 35 Mpa so Need to find: Is the strength at 15 days ≥ 35 MPa?

Calculate Maturity:

Maturity (°C.hr) $= \sum(T - T_0) \cdot \Delta t = \big(10 - (-11)\big) \cdot 360 = 21 \cdot 360 = 7560$ °C.hr

Use Plowman's Equation

$F = A + B \cdot \log_{10}(m \cdot 10^{-3})$

- Maturity, $m = 7560$
- $m \cdot 10^{-3} = 7.56$
- Strength at 28 days = 40 MPa (From the table, this falls in **35–52.5 MPa** range) Use **A = 32**, **B = 54**

$F = 32 + 54 \cdot \log_{10}(7.56)$ $\log_{10}(7.56) \approx 0.878$ $F = 32 + 54 \cdot 0.878 = 32 + 47.41 = 79.41\%$

Estimate Strength

Strength at 15 days $= \frac{F}{100} \cdot f_{28} = \frac{79.41}{100} \cdot 40 = 31.76$ MPa

- Strength at 15 days = **31.76 MPa**
- Required (stripping) strength = **35 MPa**

No, it is NOT safe to remove the formwork at 15 days under these conditions.

(ii)

Given Data:

- Target strength: **35 MPa**
- 28-day strength: **40 MPa**

- So, required % strength: $\frac{35}{40} \times 100 = 87.5\%$
- By using Plowman's equation:

  $F = A + B \cdot \log_{10}(m \cdot 10^{-3})$

  With:

    - A = 32
    - B = 54
    - F = 87.5%

Solve for maturity (m)

Start from:

$87.5 = 32 + 54 \cdot \log_{10}(m \cdot 10^{-3})$

$87.5 - 32 = 54 \cdot \log_{10}(m \cdot 10^{-3})$

$55.5 = 54 \cdot \log_{10}(m \cdot 10^{-3})$

$\log_{10}(m \cdot 10^{-3}) = \frac{55.5}{54} \approx 1.028$

m≈10,670

$M = (T - T_0) \cdot t \Rightarrow t = \frac{M}{T-T_0} = \frac{10{,}670}{21} \approx 508.1 \text{ hours} = 21.17 \text{ days}$

So we can **safely remove formwork after ≈ 21.2 days**
if the concrete is cured continuously at **10°C** and the required stripping stress is **35 MPa**.

(iii)

Given Values:

- Required strength = **35 MPa**
- 28-day strength = **40 MPa**
- Required time = **15 days** $= 15 \times 24 = 360 \text{ hours}$
- Datum temperature T_0 = **–11°C**
- Target strength: **35 MPa**
- 28-day strength: **40 MPa**
- So, required % strength: $\frac{35}{40} \times 100 = 87.5\%$
- By using Plowman's equation:

$F = A + B \cdot \log_{10}(m \cdot 10^{-3})$

With:

- A = 32
- B = 54
- F = 87.5%

Solve for maturity (m)

$87.5 = 32 + 54 \cdot \log_{10}(m \cdot 10^{-3})$

$87.5 - 32 = 54 \cdot \log_{10}(m \cdot 10^{-3})$

$55.5 = 54 \cdot \log_{10}(m \cdot 10^{-3})$

$\log_{10}(m \cdot 10^{-3}) = \frac{55.5}{54} \approx 1.028$

m≈10,670

Calculate Required Average Temperature

Using the maturity formula:

$M = (T_{\text{avg}} - T_0) \cdot t$

Rearranging to solve for T_{avg}:

$T_{\text{avg}} = \frac{M}{t} + T_0$

Substituting the known values:

$T_{\text{avg}} = \frac{10{,}670}{360} + (-11)\ T_{\text{avg}} = 29.64 - 11\ T_{\text{avg}} \approx 18.64°\text{C}$

To safely remove the formwork at **15 days**, the concrete would need to be cured at an **average temperature of approximately 18.6°C**.

Concept -5

Compressive Strength of Concrete

Compressive strength is defined as the capacity of hardened concrete to resist axial compressive loads without failure. It is the most critical parameter used to classify concrete grades (M20, M25, M30, etc.). It directly influences the design and durability of load-bearing structural elements like columns, foundations, and walls. Higher compressive strength ensures resistance to crushing under service loads.

As per **IS 516:1959**, the compressive strength test is performed using cube specimens of 150 mm × 150 mm × 150 mm size.

Apparatus Required

Compression Testing Machine

The testing machine may be of any reliable type, of sufficient capacity for the tests and capable of applying the load at the specified rate. The permissible error shall be not greater than ± 2 percent of the maximum load.

Moulds/ Cubes for Testing

The mould shall be of 150 mm size conforming to IS: 10086-1982.

The cubes are cast, cured (typically 28 days), and subjected to axial loading at 140 kg/cm²/min until failure in a compression testing machine (CTM). The formula used is:

$$f_{ck} = \frac{P}{A}$$

Where:

- f_{ck}: Compressive strength (MPa)
- P: Ultimate load (N)
- A: Loaded area (mm²)

Strength Development (Assuming M30 Grade Concrete)

Age	% Strength	Compressive Strength (MPa)
1 Day	16%	4.8
3 Days	40%	12.0
7 Days	65%	19.5
14 Days	90%	27.0
28 Days	99%	29.7

Factors Affecting Compressive Strength

V. **Water-Cement Ratio (W/C):**
Lower W/C ratio leads to higher strength due to less porosity and better cement gel formation. E.g., 0.4 W/C gives stronger concrete than 0.6.

VI. **Cement Type and Quality:**
Rapid hardening cement or PPC may enhance early strength. Fineness and C3S content influence the hydration rate.

VII. **Curing Conditions:**
Inadequate curing leads to incomplete hydration, causing lower strength. Steam curing accelerates early strength for precast elements.

VIII. **Aggregate Properties:**
Angular, strong aggregates increase interlock and strength. Weak or flaky aggregates reduce compressive performance.

IX. **Mix Proportions:**
A rich mix with proper grading improves the paste-aggregate bond, reducing voids.

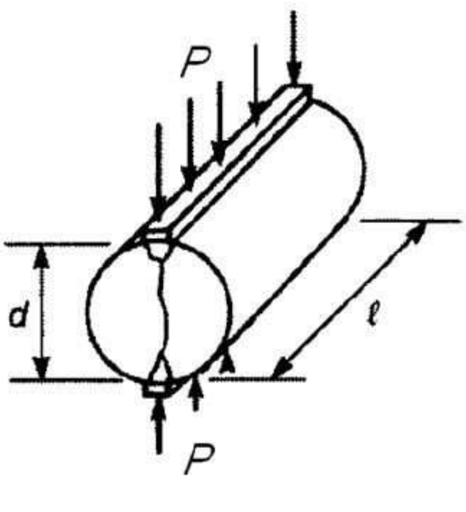
X. **Compaction and Workmanship:**
Poor compaction leaves air voids and honeycombing, severely reducing strength.

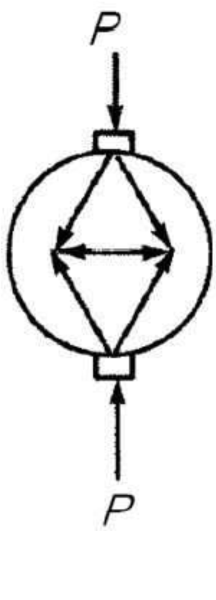
Practical Applications

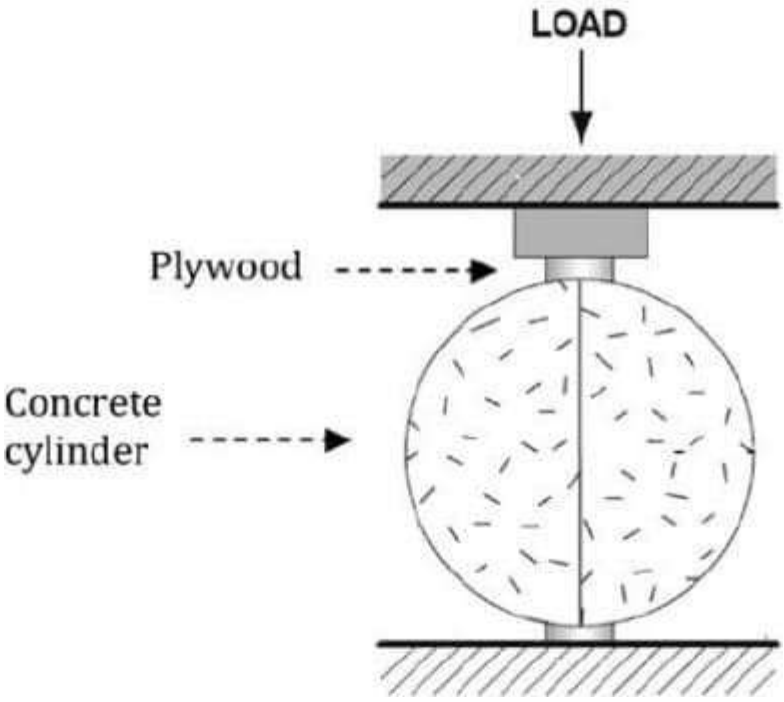
- **Structural Design:** Basis for selecting grade in columns, beams, and foundations.
- **Quality Control:** Ensures site concrete matches design expectations.
- **Formwork Removal Schedule:** Early strength benchmarks (e.g., 65% in 7 days) help plan construction timelines.
- **Precast Members:** Ensures handling safety before transportation.

Compressive strength is the backbone of concrete performance and governs the entire structural integrity. Ensuring proper mix design, curing, and testing ensures a durable and safe concrete structure.

Split Tensile Strength of Concrete







The tensile strength of concrete is one of the basic and important properties which greatly affect the extent and size of cracking in structures. Moreover, the concrete is very weak in tension due to its brittle nature. Hence. it is not expected to resist the direct tension. So, concrete develops cracks when tensile forces exceed its tensile strength. Therefore, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack. Furthermore, splitting tensile strength test on concrete cylinder is a method to determine the tensile strength of concrete. As per **IS 5816:1999**, the test is conducted using **cylindrical specimens** (150 mm diameter × 300 mm height).

The specimen is placed horizontally in a CTM. Load is applied along the vertical diameter, inducing tensile stress across the horizontal diameter.

$$f_{ct} = \frac{2P}{\pi d L}$$

Where:

- P: Load at failure
- d, L: Diameter and length of the specimen

Split Tensile Strength (Approx. 10% of Compressive Strength)

Age	Compressive (MPa)	Split Tensile (MPa)
1 Day	4.8	0.48
3 Days	12.0	1.20
7 Days	19.5	1.95
14 Days	27.0	2.70
28 Days	29.7	2.97

Factors Affecting Split Tensile Strength

I. **Aggregate Type and Shape:**
Angular aggregates increase interlock and tensile capacity. Rounded aggregates lead to lower strength.

II. **Cement Content:**
Higher cement content generally improves paste bonding and tensile resistance.

III. **Curing Quality:**
Poor curing leads to surface cracks and premature failure in tension zones.

IV. **Specimen Defects:**
Air voids, cracks, and segregation reduce tensile strength significantly.

V. **Mix Homogeneity:**
Uniformly mixed concrete ensures balanced load distribution during testing.

Practical Applications

- **Crack Control Design:**
  Used to evaluate crack resistance in slabs, tanks, and pipes.
- **Pavement Engineering:**
  Helps in thickness design and durability assessments.
- **Quality Checks for Precast Structures:**
  Important for assessing handling and transportation resistance.
- **Finite Element Modeling Inputs:**
  Required for simulations in tension zones of structural analysis.

Split tensile strength is critical for understanding and designing concrete structures subjected to tensile stresses. It complements compressive strength by providing insights into cracking behavior and durability.

Flexural Strength of Concrete

Flexural strength of Concrete, also known as **Modulus of rupture,** is an indirect measure of the tensile strength of unreinforced concrete. Modulus of rupture can also be defined as the measure of the extreme fibre stresses when a member is subjected to bending. Apart from external loading, tensile stresses can also be caused by warping, corrosion of steel, drying shrinkage and temperature gradient. Concrete is strong in compression but weak in tension because of which the flexural strength accounts for only 10% to 20% of the compressive strength.

IS 516:1959 describes the flexural test using a **beam specimen (100 mm × 100 mm × 500 mm)**.

A beam is simply supported and loaded at third points. The bottom experiences tension, causing flexural cracking.

$$f_{cr} = \frac{P \cdot L}{b \cdot d^2}$$

Where:

- P: Load at failure
- L: Span length
- b, d: Width and depth of the beam

Flexural Strength (Approx. 15% of Compressive Strength)

Age	Compressive (MPa)	Flexural Strength (MPa)
1 Day	4.8	0.72
3 Days	12.0	1.80
7 Days	19.5	2.93
14 Days	27.0	4.05
28 Days	29.7	4.45

Factors Affecting Flexural Strength

I. **Surface Cracks and Defects:**
Micro-cracks formed during setting act as stress concentrators and reduce rupture strength.

II. **Aggregate-Paste Bonding:**
Poor bonding leads to failure at lower loads. Strong ITZ (Interfacial Transition Zone) enhances strength.

III. **Beam Size and Support Conditions:**
Incorrect loading positions or support spacing alters moment and stress distribution.

IV. **Curing Conditions:**
Insufficient curing causes shrinkage cracks that weaken flexural behavior.

V. **Loading Rate:**
Fast loading may result in brittle failure, affecting accurate measurement.

Practical Applications

- **Roads and Runways:**
  Governs pavement design thickness under wheel loadings.

- **Beams and Slabs:**
  Flexural stress governs reinforcement sizing and spacing.

- **Precast Lintels and Panels:**
  Helps in ensuring flexural integrity during transport and installation.

- **Machine Foundations:**
  Resists cyclic flexural loads induced by dynamic machinery.

Flexural strength is crucial in designing structural elements under bending action. It ensures long-term crack resistance and serviceability under flexural loads, especially in unreinforced or lightly reinforced sections.

Final Summary Table (Strength Development for M30 Concrete)

Age	Compressive (MPa)	Split Tensile (MPa)	Flexural (MPa)
1 Day	4.8	0.48	0.72
3 Days	12.0	1.20	1.80
7 Days	19.5	1.95	2.93
14 Days	27.0	2.70	4.05
28 Days	29.7	2.97	4.45

Concept -6

Relationship between Compressive strength, split tensile, flexural strength

Split Tensile Strength of Concrete

Formula (IS 456:2000):

$$f_{ct} = 0.56\sqrt{f_{ck}}$$

This empirical relation gives the **characteristic split tensile strength** f_{ct} in MPa, based on the **characteristic compressive strength** f_{ck}. Since direct tensile strength testing is complex, this formula allows engineers to estimate tensile capacity using compressive strength data.

- It is derived from extensive experimental correlations.
- Useful in design of concrete structures where **crack control**, **reinforcement detailing**, and **serviceability limits** are important.
- Commonly used for **pavements**, **retaining walls**, **pipes**, and **liquid tanks**.

◇ 2. Flexural Strength (Modulus of Rupture)

Formula (IS 456:2000):

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

This formula estimates the **modulus of rupture** or **flexural strength** f_{cr}, which is the concrete's resistance to bending. It is important for design and analysis of **slabs**, **beams**, **bridge decks**, and **rigid pavements**.

- Flexural strength is higher than split tensile strength due to the combined stress state in bending.
- This formula is especially useful in **pavement and slab design**, where bending (rather than direct compression) governs the failure mode.
- It reflects the **tensile performance** in the tension zone of flexural members.

Summary Table of IS 456:2000 Empirical Formulas

Property	IS Code Formula	Application
Split Tensile Strength	$f_{ct} = 0.56\sqrt{f_{ck}}$	Crack control, rebar design
Flexural Strength	$f_{cr} = 0.7\sqrt{f_{ck}}$	Pavement, slab, beam design

Important Notes:

- These formulas are valid for **normal-weight concrete** up to **M60 grade**.
- The compressive strength f_{ck} should be in **MPa**.
- They are **conservative approximations** for use in design if **actual test results are not available**.
- Always refer to **actual test values** when available for more accurate structural analysis, especially in **prestressed** or **high-performance concrete**.

Example (For M30 Concrete):

- $f_{ck} = 30$ MPa

$f_{ct} = 0.56\sqrt{30} \approx 0.56 \times 5.48 \approx 3.07$ Mpa

$f_{cr} = 0.7\sqrt{30} \approx 0.7 \times 5.48 \approx 3.84$ MPa

The IS 456:2000 empirical formulas provide a practical and standardized way to estimate **tensile and flexural strengths** from the more easily obtainable **compressive strength**. These relationships are essential in the **design, analysis, and quality assurance** of concrete structures, especially when full testing of all parameters is not feasible.

Concept -7

Factors affecting compressive strength

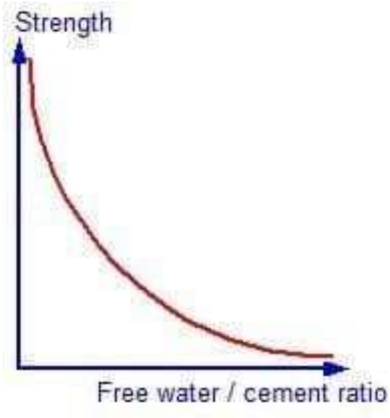
Concrete strength is affected by many factors, such as quality of raw materials, water/cement ratio, coarse/fine aggregate ratio, age of concrete, compaction of concrete, temperature, relative humidity and curing of concrete.

Quality of Raw Materials

Cement: Provided the cement conforms with the appropriate standard and it has been stored correctly (i.e. in dry conditions), it should be suitable for use in concrete.
Aggregates: Quality of aggregates, its size, shape, texture, strength etc determines the strength of concrete. The presence of salts (chlorides and sulphates), silt and clay also reduce the strength of concrete.
Water: frequently the quality of the water is covered by a clause stating “. The water should be fit for drinking.”. This criterion though is not absolute and reference should be made to respective codes for testing of water construction purpose.

Water / Cement Ratio

The relation between water cement ratio and strength of concrete is shown in the plot as shown below:



The higher the water/cement ratio, the greater the initial spacing between the cement grains and the greater the volume of residual voids not filled by hydration products. There is one thing missing on the graph. For a given cement content, the workability of the concrete is reduced if the water/cement ratio is reduced. A lower water cement ratio means less water, or more cement and lower workability. However, if the workability becomes too low the concrete becomes difficult to compact and the strength reduces. For a given set of materials and environment conditions, the strength at any age depends only on the water-cement ratio, providing full compaction can be achieved.

Coarse / fine aggregate ratio

Following points should be noted for coarse/fine aggregate ratio:

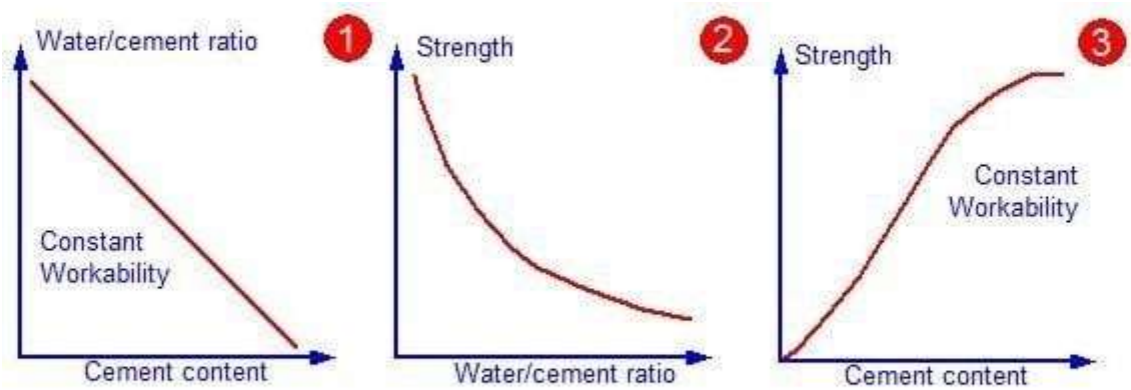
- If the proportion of fines is increased in relation to the coarse aggregate, the overall aggregate surface area will increase.
- If the surface area of the aggregate has increased, the water demand will also increase.
- Assuming the water demand has increased, the water cement ratio will increase.
- Since the water cement ratio has increased, the compressive strength will decrease.

Aggregate / Cement Ratio

Following points must be noted for aggregate cement ratio:

- If the volume remains the same and the proportion of cement in relation to that of sand is increased the surface area of the solid will increase.
- If the surface area of the solids has increased, the water demand will stay the same for the constant workability.
- Assuming an increase in cement content for no increase in water demand, the water cement ratio will decrease.
- If the water cement ratio reduces, the strength of the concrete will increase.

The influence of cement content on workability and strength is an important one to remember and can be summarized as follows:



1. For a given workability an increase in the proportion of cement in a mix has little effect on the water demand and results in a reduction in the water/cement ratio.
2. The reduction in water/cement ratio leads to an increase in strength of concrete.
3. Therefore, for a given workability an increase in the cement content results in an increase in strength of concrete.

Age of concrete

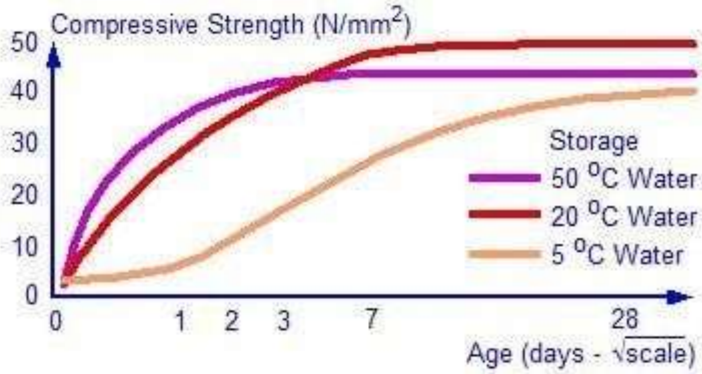
The degree of hydration is synonymous with the age of concrete provided the concrete has not been allowed to dry out or the temperature is too low. In theory, provided the concrete is not allowed to dry out, then it will always be increasing albeit at an ever reducing rate. For convenience and for most practical applications, it is generally accepted that the majority of the strength has been achieved by 28 days.

Compaction of concrete

Any entrapped air resulting from inadequate compaction of the plastic concrete will lead to a reduction in strength. If there was 10% trapped air in the concrete, the strength will fall down in the range of 30 to 40%.

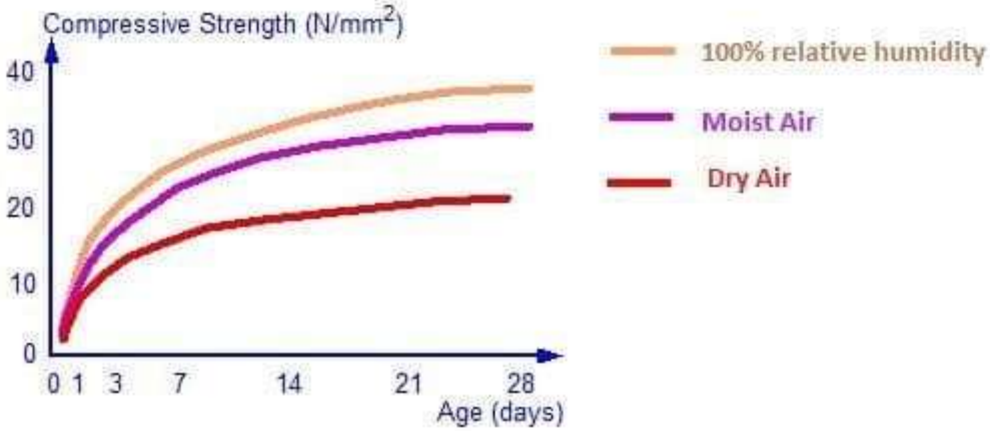
Temperature

The rate of hydration reaction is temperature dependent. If the temperature increases the reaction also increases. This means that the concrete kept at higher temperature will gain strength more quickly than a similar concrete kept at a lower temperature. However, the final strength of the concrete kept at the higher temperature will be lower. This is because the physical form of the hardened cement paste is less well-structured and more porous when hydration proceeds at faster rate. This is an important point to remember because temperature has a similar but more pronounced detrimental effect on permeability of the concrete.



Relative humidity

If the concrete is allowed to dry out, the hydration reaction will stop. The hydration reaction cannot proceed without moisture. The three curves show the strength development of similar concretes exposed to different conditions.



Curing

Curing is a crucial step in concrete construction that ensures proper hydration of cement particles, which is essential for the development of strength, durability, and long-term performance. Without adequate curing, the concrete may not achieve its designed compressive strength and could become more susceptible to cracking and surface defects. Curing maintains the required moisture and temperature in the concrete for a specific period, allowing the chemical process of hydration to continue effectively.

Nondestructive test

Non-Destructive Testing (NDT) of Concrete – 10 Marks Answer

Non-Destructive Testing (NDT) refers to a set of techniques used to evaluate the **mechanical and physical properties** of concrete structures **without damaging** or altering the material. These methods allow engineers to check **strength, durability, surface hardness, internal flaws, and uniformity** in structures that are either under construction or already in service.

Objectives of NDT:

VI. **To assess in-situ strength:** When cube test results are unavailable or suspect, NDT offers indirect strength estimation.

VII. **To detect internal flaws:** Such as cracks, honeycombing, voids, and delaminations.

VIII. **To evaluate concrete uniformity and workmanship:** Especially for large pours or precast elements.

IX. **To support repair/retrofit decisions:** NDT provides key data for assessing the extent of deterioration.

X. **To monitor durability:** Especially in aging infrastructure like bridges, dams, and high-rise buildings.

Advantages of NDT:

- **Non-invasive:** Testing does not damage the concrete surface or structure.
- **Time-saving and cost-effective:** Faster than cutting cores or loading specimens.
- **Portable equipment:** Rebound hammers and UPV testers can be used easily on-site.
- **Useful for quality assurance:** Especially in precast industries and large-scale construction projects.

IS Codal Provisions:

IS Code	**Description**
IS 13311 (Part 1): 1992	Details method for **Ultrasonic Pulse Velocity (UPV)** to check internal uniformity
IS 13311 (Part 2): 1992	Covers **Rebound Hammer and Pullout Tests** for surface hardness and in-place strength
IS 516 (Part 5/Sec 1): 2018	Updated procedure for **UPV testing** – replaces older methods with modern accuracy standards
IS 456:2000 (Clause 17)	Allows NDT methods for **acceptance of concrete** in case of dispute or absence of cube tests
IS 4926:2003	RMC guidelines recommend NDT for **quality verification**

Common NDT Methods in Concrete (with Purpose and IS Code):

Test Name	Purpose	IS Code
Rebound Hammer	Surface hardness & estimated strength	IS 13311 (Part 2): 1992
UPV (Pulse Velocity)	Uniformity, cracks, and void detection	IS 13311 (Part 1): 1992 / IS 516
Pullout Test	In-place compressive strength (semi-NDT)	IS 13311 (Part 2): 1992
Core Extraction (Semi-NDT)	Accurate in-situ compressive strength	IS 516:1959
Cover Meter	Rebar location and cover thickness	IS 13311 (Part 1): 1992

General Procedure for NDT:

XI. **Select the suitable method** based on the objective: strength, flaws, or durability.

XII. **Prepare the surface** (cleaning, leveling).

XIII. **Calibrate the equipment** using standard samples or manufacturer charts.

XIV. **Conduct multiple readings** (usually minimum 10 per location).

XV. **Interpret the data** using IS codal curves or strength correlations.

XVI. **Report and decide** whether the structure is safe or needs repair.

Factors Affecting NDT Results:

Test Type	Key Influencing Factors
Rebound Hammer	Surface moisture, orientation, carbonation, aggregate type, surface roughness
UPV	Moisture content, cracks/voids, temperature, aggregate quality, coupling quality
Pullout Test	Insert geometry, concrete maturity, bond strength, aggregate interlock

Applications of NDT in Field:

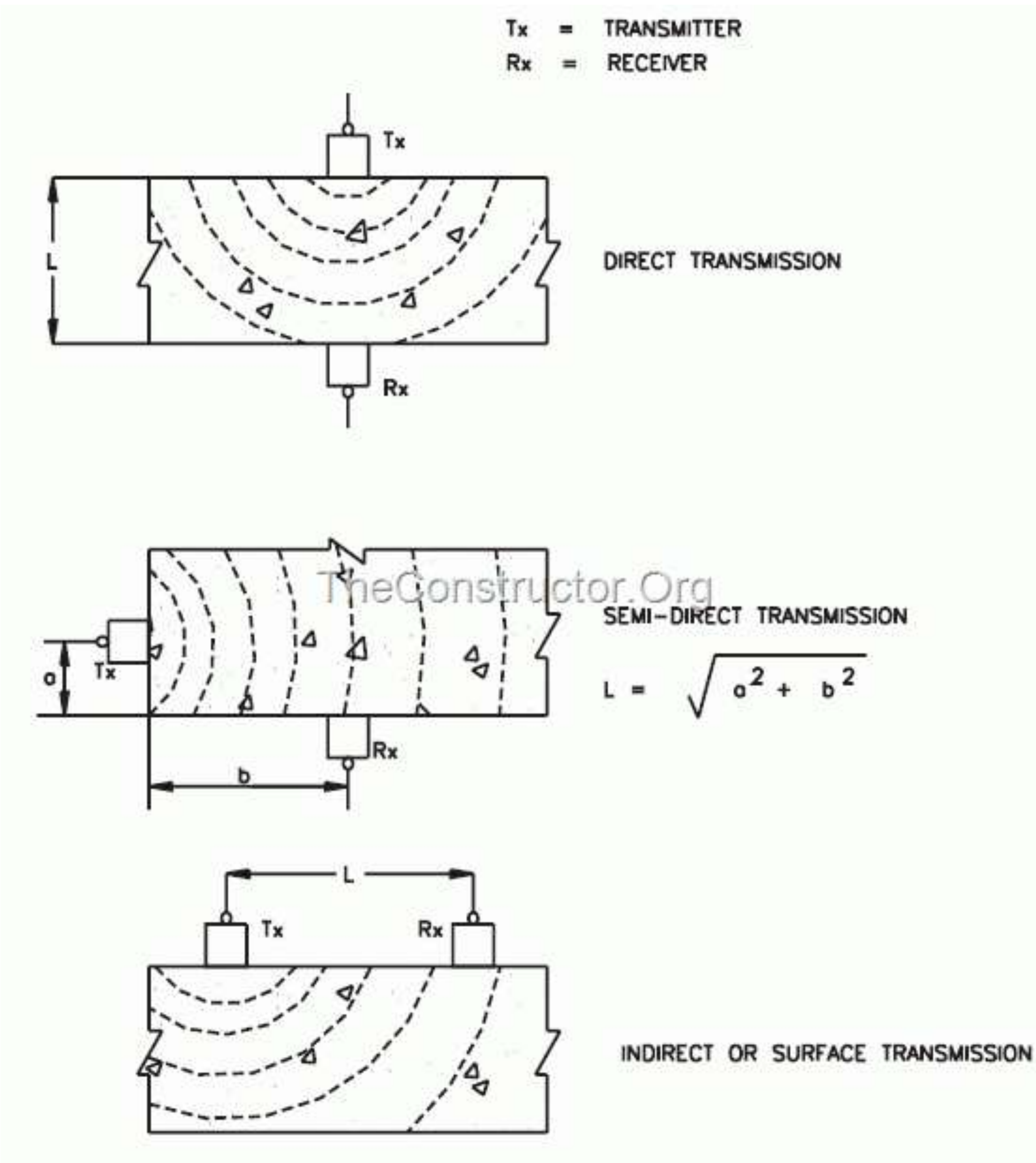
- **Quality assurance:** Ensuring correct concrete strength in new buildings.
- **Bridge inspections:** Evaluate aged or corroded concrete without dismantling.
- **Precast element checking:** Verifies strength before lifting or dispatch.
- **Before retrofitting:** Understand structure's condition before design changes.
- **Comparative studies:** Test different structural zones for uniformity or localized deterioration.

Limitations of NDT:

- **Indirect measurement:** Most NDT tests only give indirect strength estimates.
- **Influenced by surface condition:** Surface damage or carbonation can skew results.
- **Calibration needed:** Results need correlation with core test data for reliability.
- **Combination often required:** Using multiple NDT methods gives more accurate insights.

Non-Destructive Testing is a critical tool in modern civil engineering for assessing the **health, strength, and uniformity** of concrete structures **without damaging them**. When used as per **IS codal provisions** like IS 13311 and IS 516, NDT methods ensure safe design verification, structural safety evaluation, and cost-effective quality control, especially in large-scale and aging infrastructure.

Ultrasonic Testing of Concrete for Compressive Strength



Ultrasonic Pulse Velocity (UPV) is a **non-destructive test (NDT)** used to evaluate the **quality, uniformity, and integrity** of concrete by measuring the **velocity of high-frequency sound waves** passing through it. It helps detect internal defects such as **cracks, voids, honeycombing**, and determines the concrete's **modulus of elasticity and strength indirectly**.

The UPV test is governed by **IS 516 Part 5 Section 1 (2018)** and earlier referred to in **IS 13311 (Part 1): 1992 – Non-destructive testing of concrete – Method of test – Ultrasonic pulse velocity**.

Principle of the Test:

- UPV works on the principle that **ultrasonic waves travel faster** in **denser and defect-free concrete**, and **slower** in concrete containing **cracks, voids, or weak zones**.
- A pulse of ultrasonic frequency (usually 40 to 54 kHz) is generated and made to pass through the concrete.
- The **time taken** for the pulse to travel a known distance is measured.
- The velocity V is calculated by:

$$V = \frac{L}{T}$$

Where:

- V = Pulse velocity (m/s)
- L = Path length between transducers (m)
- T = Time taken by pulse to travel (s)

Test Setup and Procedure:

- **Equipment:** UPV tester with transmitter and receiver (transducers), coupling gel, and time-measuring device.
- **Test Methods:**
    a. **Direct transmission:** Transducers placed on opposite sides (most accurate)
    b. **Semi-direct:** Transducers placed at right angles
    c. **Indirect (surface):** Both transducers on the same face (least sensitive but commonly used)

- **Procedure:**
  - Clean the concrete surface.
  - Apply coupling gel to ensure signal transmission.
  - Place the transducers and record the time for the pulse to travel.
  - Repeat for multiple points and record average readings.

Interpretation of Results (as per IS 13311 Part 1: 1992):

Pulse Velocity (km/s)	Concrete Quality
> 4.5	Excellent
3.5 – 4.5	Good
3.0 – 3.5	Doubtful (needs further tests)
< 3.0	Poor

Factors Affecting Ultrasonic Pulse Velocity (UPV) Test

Moisture Content of Concrete

- Wet concrete shows slightly higher velocity due to better acoustic transmission.

Concrete Density

- Denser concrete transmits ultrasonic pulses faster.

Aggregate Type and Size

- Heavier, well-graded aggregates improve velocity; lightweight aggregates reduce it.

Presence of Cracks or Voids

- Defects disrupt wave path, reducing pulse velocity.

Temperature of Concrete

- Very high or low temperatures affect pulse speed; standard correction is needed.

Surface Roughness and Coupling

- Poor surface contact or improper coupling gel causes signal loss or distortion.

Path Length and Geometry

- Longer paths or indirect transmission reduce accuracy.

Reinforcement in Path

- Steel bars may reflect or alter wave travel and give misleading results.

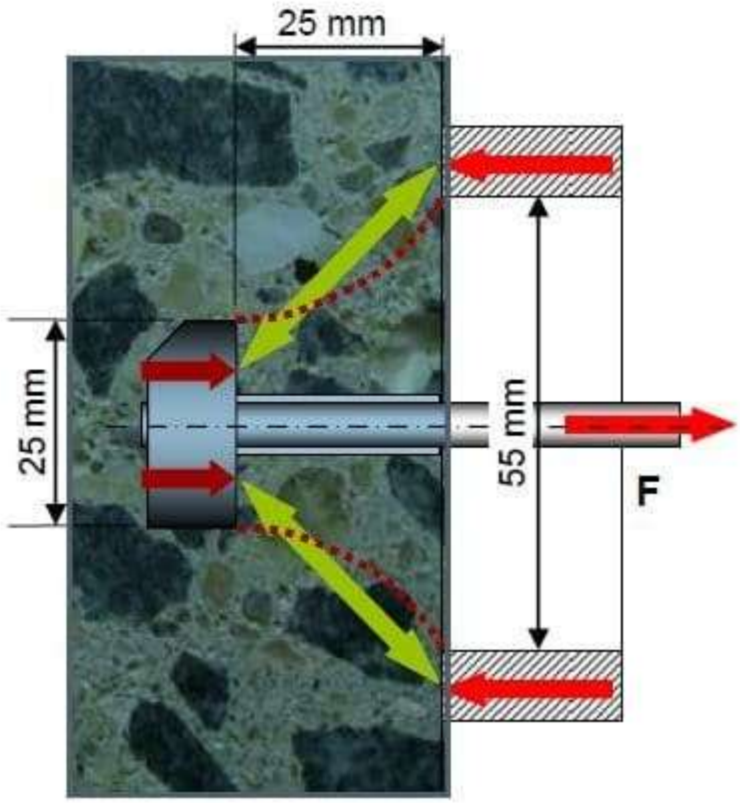
Applications of UPV Test:

- **Assessing Concrete Quality in Existing Structures:**
  Evaluates uniformity and identifies weak zones without damaging the structure.
- **Detecting Internal Defects:**
  Finds honeycombing, delaminations, cracks, and segregation in concrete.
- **Estimating In-Situ Strength (indirectly):**
  Combined with rebound hammer data or correlation curves.
- **Quality Control in Precast Elements:**
  Ensures strength and homogeneity before acceptance.
- **Long-Term Durability Assessments:**
  Used to monitor changes in structural integrity over time.

Ultrasonic Pulse Velocity is a vital **non-destructive technique** that ensures **concrete integrity and quality assurance** in both new and existing structures. It provides **quick, reliable, and repeatable results** that help engineers make informed decisions without damaging the concrete, making it indispensable in modern civil engineering practices.

Pullout Test on Hardened Concrete

The **pullout test** is a **semi-destructive method** used to estimate the **in-situ compressive strength** of hardened concrete. It involves **pulling out a specially embedded metal insert** (typically a bolt or rod) from the concrete and measuring the force required to extract it. This force is then correlated to compressive strength. Pullout tests are particularly useful when standard cube/cylinder samples are unavailable or where actual in-place strength is to be determined.



- **IS 13311 (Part 2): 1992** – *Non-destructive testing of concrete – Method of test – Part 2: Pullout test*
- Also referred in guidelines like **ACI 347** and **ASTM C900** for international practices.

Principle of the Test:

The test is based on the **mechanical interlock** and **bond between the concrete and the metal insert**. As the embedded insert is pulled out, a **cone-shaped portion of concrete** surrounding it is also pulled out. The **pullout force** needed to cause failure is directly related to the **compressive strength** of concrete around the insert.

Test Setup and Procedure:

- **Specimen:** The test can be done:
  - On specially cast concrete samples
  - On in-place structures using pre-inserted or post-installed devices

- **Equipment:** Pullout test equipment includes a loading frame, hydraulic jack, load measuring device, and embedded pullout insert.

Steps:

XVII. A metal insert is embedded in the fresh concrete (e.g., 25 mm deep, with an enlarged head or disc).

XVIII. After the concrete hardens (usually 28 days), the insert is pulled vertically using a hydraulic jack.

XIX. The **maximum load (P)** at failure is recorded.

XX. The load is converted to **compressive strength** using calibration curves.

Pullout Strength – Estimation Formula:

Though there is no universal formula, the typical relation is:

$$f_{ck} = k \cdot P^n$$

Where:

- f_{ck} = Estimated compressive strength (MPa)
- P = Pullout load (N)
- k, n = Constants obtained from calibration with standard specimens

The relation depends on insert geometry and concrete properties.

Factors Affecting Pullout Test Results:

Concrete Strength and Maturity

- Higher strength concrete resists pullout better; age significantly affects results.

Type and Shape of Insert

- Larger or rough-surfaced inserts develop more bond and higher pullout loads.

Embedment Depth

- Deeper embedment leads to greater cone resistance and higher pullout force.

Aggregate Interlock and Size

- Larger and angular aggregates improve mechanical interlock, affecting pullout cone strength.

Concrete Curing and Moisture

- Proper curing enhances bond strength; poor curing reduces it.

Surface Conditions and Microcracks

- Surface defects or cracks reduce bond strength and pullout load.

Loading Rate

- Faster pullout rates can yield erratic results; uniform rate is essential.

Calibration Accuracy

- Test must be calibrated with standard cubes for meaningful strength correlation.

Applications of Pullout Test:

- **In-Situ Strength Estimation:**
  Used where standard cube or core testing is not possible.
- **Structural Assessment:**
  Helps verify whether hardened concrete has achieved design strength.
- **Quality Assurance in Repair Projects:**
  Useful in evaluating bond strength of repair mortars.
- **Calibration of NDT Tools:**
  Can help correlate rebound hammer and UPV results with true strength.
- **Precast Element Evaluation:**
  Checks early-age strength before lifting or transporting precast members.

Limitations:

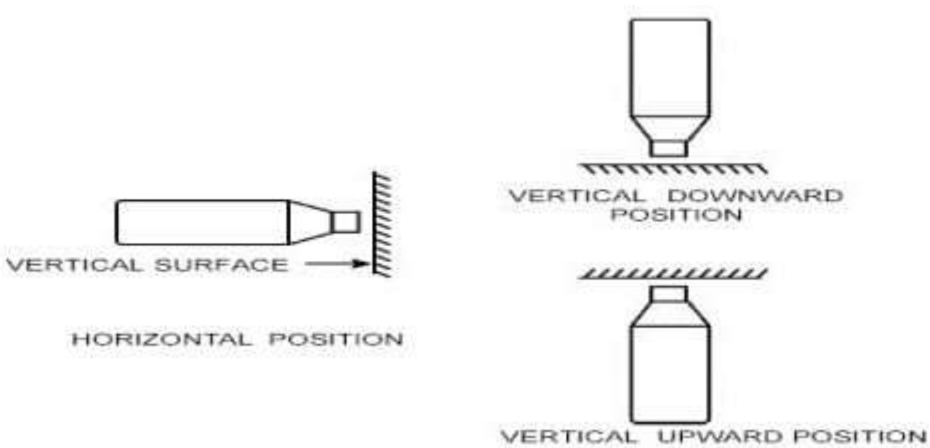
- **Partial Damage to Surface:**
  Though semi-destructive, it leaves a cone-shaped hole in concrete.
- **Requires Calibration:**
  Must be calibrated against standard cube strengths for meaningful interpretation.

- **Not Suitable for Finished Structures:**
  Typically used in early construction phases or non-critical areas.

The pullout test is a **valuable semi-destructive technique** to assess the in-place strength of concrete. It bridges the gap between fully destructive methods (like core cutting) and non-destructive tests (like rebound hammer or UPV). When properly calibrated and executed as per **IS 13311 (Part 2): 1992**, it provides reliable data for decision-making in structural evaluations and quality control.

The **Rebound Hammer Test** is a **non-destructive testing (NDT)** method used to assess the **surface hardness and estimated compressive strength** of hardened concrete. It is simple, quick, and widely used for **in-situ evaluation** of concrete quality and uniformity without damaging the structure.

IS 13311 (Part 2): 1992 – Non-destructive testing of concrete – Method of test – Part 2: Rebound Hammer Test



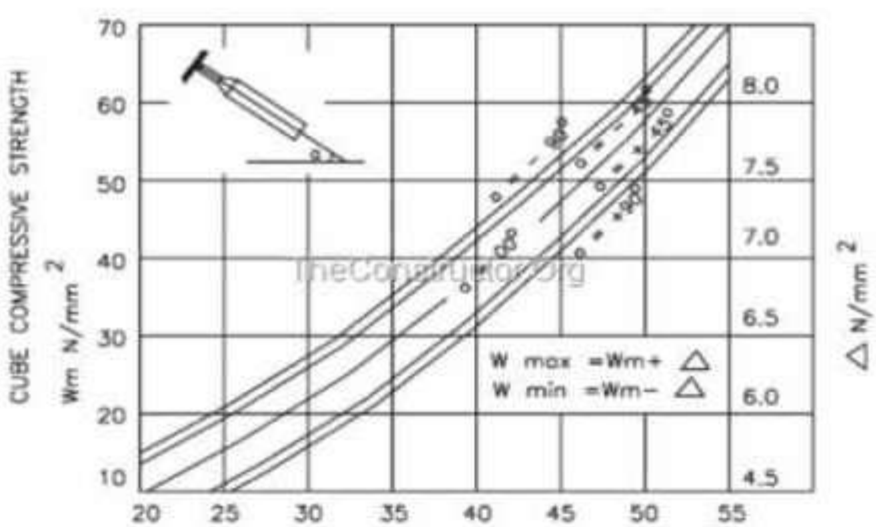
Principle of the Test:

The test is based on the principle that **the rebound of an elastic mass** depends on the **surface hardness** of the material it strikes. When the plunger of the rebound hammer is pressed against a concrete surface, a spring-driven mass impacts it. The **rebound distance** (called **rebound**

number or rebound index) is measured and correlated with **compressive strength** using calibration charts.

Equipment and Procedure:

- **Equipment:** Schmidt Rebound Hammer (spring-controlled with a plunger and rebound scale).
- **Test Surface:** Clean, dry, smooth surface of concrete (horizontal, vertical, or overhead).
- **Procedure:**
    a. Ensure the concrete surface is clean and free of dust or loose particles.
    b. Hold the hammer perpendicular to the surface.
    c. Press the plunger firmly against the surface until the hammer strikes.
    d. Record the rebound number from the scale.
    e. Take a **minimum of 10 readings** at each test location and use the **average value**.
    f. Use the rebound number to estimate compressive strength from the manufacturer's chart or IS chart.



Interpretation of Rebound Number (IS 13311 Part 2: 1992):

Rebound Number	Concrete Quality
> 40	Very Good (Hard surface)
30 – 40	Good
20 – 30	Fair
< 20	Poor/Weak or Unsound Concrete

Note: For accurate strength estimation, use **correlation curves** based on actual concrete calibration.

Factors Affecting Rebound Hammer Results:

Surface Hardness

- The test measures surface hardness; weaker surface zones give lower readings.

Moisture Content

- Wet surfaces reduce rebound number; dry surfaces give higher values.

Age of Concrete

- Early-age concrete has lower rebound values; strength increases with age.

Orientation of Test

- Vertical upward readings are lower than horizontal due to gravity effects.

Aggregate Type and Size

- Hard aggregates like granite increase rebound number.

Surface Texture and Roughness

- Rough or textured surfaces reduce accuracy; smooth, even surfaces are preferred.

Carbonation of Surface Layer

- Carbonation increases surface hardness, falsely increasing rebound number.

Operator Handling and Angle

- Improper handling or testing at an angle gives inconsistent values.

Applications of Rebound Hammer Test:

- **Quick field evaluation of concrete quality** in buildings, bridges, and pavements.
- **Uniformity check** across different members or areas.
- **Quality control in precast concrete** and structural repairs.
- **Verification of compressive strength** when cube test data is missing.
- **Comparative strength assessment** between new and old concrete.

Limitations:

- Measures **only surface hardness**, not internal strength.
- Requires **correlation with standard compressive test data** for strength estimation.
- Not suitable for very rough, textured, or curved surfaces.
- Not reliable for **lightweight concrete** or **low-strength concrete** below 15 MPa.

The **Rebound Hammer Test** is a **simple, portable, and quick non-destructive method** for evaluating surface hardness and indirectly estimating compressive strength of concrete. While not a replacement for cube or core tests, it is extremely valuable for **initial assessments, comparative studies**, and **quality checks** in the field. Following **IS 13311 (Part 2): 1992** ensures standardization and reliability of test results.

Relationship Between Compressive Strength, UPV, Rebound Hammer, and Pullout Test

Compressive Strength – The Reference Parameter

- Compressive strength (f_{ck}) is the most important mechanical property of concrete.
- NDT methods like **UPV**, **Rebound Hammer**, and **Pullout Test** do **not directly measure** compressive strength but provide **empirical correlations** based on experimental calibration.

Relationship with Rebound Hammer Test

☑ ***IS Code**: IS 13311 (Part 2): 1992*

- The rebound hammer measures the **surface hardness** of concrete.
- The rebound number (**R**) is **empirically related** to compressive strength through **calibration curves**.
- **Relation (typical empirical form):**

$$f_{ck} = a \cdot R + b$$

Where:

- f_{ck}: Estimated compressive strength (MPa)
- R: Rebound number
- a, b: Empirical constants (from calibration with cube strength)

🔎 **Note**: Surface carbonation, moisture, and aggregate type affect R value.

Relationship with Ultrasonic Pulse Velocity (UPV)

☑ ***IS Code**: IS 13311 (Part 1): 1992*

☑ ***Revised Procedure**: IS 516 (Part 5/Sec 1): 2018*

- UPV measures the **speed of ultrasonic waves** through concrete.
- Denser and well-bonded concrete yields **higher velocity**.
- **Relation (empirical):**

$$f_{ck} = k \cdot V^n$$

Where:

- f_{ck}: Compressive strength (MPa)
- V: Pulse velocity (km/s)

- k, n: Constants depending on aggregate type and curing

Relationship with Pullout Test

☑ ***IS Code**: IS 13311 (Part 2): 1992*

- Measures the **force required to pull out an embedded insert** from concrete.
- Stronger concrete offers more resistance.
- **Relation (empirical):**

$$f_{ck} = c \cdot P^n$$

Where:

- f_{ck}: Compressive strength (MPa)
- P: Pullout load (N)
- c, n: Empirical constants (from laboratory calibration)

Comparative Strength Correlation Table

Test	Measured Quantity	Relation to Compressive Strength	Accuracy Level
Rebound Hammer	Surface hardness (R)	$f_{ck} = aR + b$	Moderate (surface-only)
Ultrasonic Pulse Velocity	Wave speed (V, in km/s)	$f_{ck} = kV^n$	Good for uniformity
Pullout Test	Pullout force (P)	$f_{ck} = cP^n$	High (near true strength)

Practical Use and Combined Methods

- **Rebound Hammer + UPV:** Used together to estimate compressive strength more accurately (combined methods reduce errors).
- **Pullout Test:** Preferred when destructive core testing is not feasible but strength estimation is critical (e.g., prestressed elements).
- **Calibration Needed:** All relations are **empirical** and need **site-specific or material-specific calibration** using standard cube/cylinder strength data.

NDT methods such as **Rebound Hammer**, **UPV**, and **Pullout** do not give direct compressive strength but provide **correlated estimates**. These correlations depend on **calibration constants** and are influenced by **material, environmental, and surface conditions**. Used together, they provide a reliable and non-invasive way to evaluate the in-situ condition of concrete.