Chapter 11: Hardened Concrete – Destructive Tests: Compressive, Flexural, Tensile, Bond

Introduction

Hardened concrete refers to concrete that has attained its desired mechanical strength and has set and hardened sufficiently to perform structural duties. To assess the performance and safety of concrete in structures, it is essential to test the mechanical properties of hardened concrete using various methods. Destructive testing involves subjecting concrete samples to forces that lead to failure, allowing accurate measurement of their strength characteristics. This chapter explores in depth the major destructive tests used to evaluate hardened concrete: **compressive strength**, **flexural strength**, **tensile strength**, and **bond strength**.

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1. Compressive Strength Test

1.1 Objective

To determine the maximum compressive load a concrete specimen can withstand before failure.

1.2 Importance

- Primary indicator of concrete quality.
- Basis for mix design and quality control.
- Used in structural design specifications.

1.3 Standard Codes

- **IS 516: 1959** – Methods of Tests for Strength of Concrete.
- **ASTM C39/C39M** – Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

1.4 Test Specimens

- Cubes: 150 mm × 150 mm × 150 mm (as per IS standards).
- Cylinders: 150 mm diameter × 300 mm height (as per ASTM).

1.5 Equipment

- Compression testing machine (CTM) with calibrated load gauge or digital display.
- Tamping rod.
- Curing tank.

1.6 Procedure

1. **Casting**: Fresh concrete is placed in moulds in layers and compacted.
2. **Curing**: Specimens are kept in water at 27 ± 2°C for 28 days.
3. **Testing**:
    - Remove specimen from curing tank.
    - Wipe clean and place in CTM.
    - Load is applied at a constant rate until failure.
    - Record the maximum load.

1.7 Calculation

$$\text{Compressive Strength (f_c)} = \frac{\text{Maximum Load (P)}}{\text{Cross-sectional Area (A)}}$$

- Units: N/mm^2 or MPa

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2. Flexural Strength Test

2.1 Objective

To measure the tensile strength of concrete under bending, known as modulus of rupture.

2.2 Importance

- Relevant for pavements, slabs, and beams.
- Reflects the ability of concrete to resist cracking.

2.3 Standard Codes

- **IS 516: 1959**
- **ASTM C78/C78M** – Standard Test Method for Flexural Strength of Concrete.

2.4 Test Specimens

- Beam size: 100 mm × 100 mm × 500 mm or 150 mm × 150 mm × 700 mm.

2.5 Equipment

- Flexural testing machine (can be a modified CTM).
- Loading setup: third-point or center-point loading.
- Steel support rollers and loading rollers.

2.6 Procedure

1. Prepare and cure beam specimens as per standards.
2. Remove from curing, clean and place on support rollers.
3. Apply load at specified points:
   - **Center-point loading**: One load at mid-span.
   - **Third-point loading**: Two loads at one-third span.
4. Apply load gradually until failure.
5. Measure distance between supports (L), width (b), and depth (d).

2.7 Calculation

For third-point loading:

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

For center-point loading:

$$f_r = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot d^2}$$

Where:

- f_r = modulus of rupture (N/mm²)
- P = failure load (N)
- L = span length (mm)
- b = specimen width (mm)
- d = specimen depth (mm)

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3. Tensile Strength Test (Split Cylinder Test)

3.1 Objective

To determine the tensile strength of concrete indirectly using the split tensile method.

3.2 Importance

- Direct tensile testing is difficult due to gripping issues.
- Helps assess cracking behavior in concrete.

3.3 Standard Codes

- **IS 5816: 1999** – Splitting Tensile Strength of Concrete Method.
- **ASTM C496/C496M**

3.4 Test Specimens

- Cylindrical specimen: 150 mm diameter × 300 mm height.

3.5 Equipment

- CTM with horizontal loading platens.
- Plywood strips for load distribution.

3.6 Procedure

1. Place the cylinder horizontally between platens.
2. Thin plywood strips are placed between specimen and platens.
3. Apply compressive load along the vertical diameter.
4. Load causes splitting due to tensile stresses.
5. Record the maximum load at failure.

3.7 Calculation

$$f_t = \frac{2P}{\pi \cdot d \cdot l}$$

Where:

- f_t = split tensile strength (N/mm^2)
- P = failure load (N)
- d = diameter of cylinder (mm)
- l = length of cylinder (mm)

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4. Bond Strength Test (Pull-out Test)

4.1 Objective

To evaluate the bond between concrete and reinforcement.

4.2 Importance

- Critical for load transfer between steel and concrete.
- Affects anchorage and development length in structural design.

4.3 Types of Bond

- **Adhesion**: Initial grip between cement paste and steel.
- **Friction**: Resistance due to surface roughness.
- **Mechanical interlock**: Caused by ribs/deformations on bars.

4.4 Standard Codes

- **IS 2770 (Part 1): 1967** – Method of test for bond in reinforced concrete.

4.5 Test Specimens

- Cylindrical or cubical concrete specimen with embedded steel bar (usually 12 mm dia, 100–150 mm embedment length).

4.6 Equipment

- Universal Testing Machine (UTM) or Pull-out test setup.
- Dial gauge or extensometer for slip measurement.

4.7 Procedure

1. Embed a deformed steel bar centrally in a concrete cube or cylinder.
2. Cure for 28 days.
3. Place in testing setup and apply tensile force on the bar.
4. Measure slip and load at various intervals.
5. Record the maximum load at which bond failure occurs.

4.8 Calculation

$$\tau_b = \frac{P}{\pi \cdot d \cdot l}$$

Where:

- τ_b = average bond stress (N/mm²)

- P = maximum load (N)
- d = diameter of reinforcing bar (mm)
- l = embedded length of bar (mm)

Additional Notes on Test Execution and Interpretation

- **Curing Conditions**: Improper curing affects all test results significantly. Standard curing is essential for valid comparisons.
- **Rate of Loading**: Tests should be conducted at a constant, specified loading rate as per code to avoid false strengths.
- **Failure Mode Analysis**: Crack patterns and failure types (shear, tension, compression) provide additional insight into concrete behavior.
- **Repeatability and Number of Samples**: Minimum three specimens are tested to ensure reliability, and the average value is considered.

4.9 Interpretation of Bond Strength Results

Bond strength results are used not only to assess anchorage adequacy but also to evaluate:

- The **compatibility between bar surface characteristics** (plain vs deformed) and the surrounding concrete.
- The **effect of concrete grade** and **water-cement ratio** on the bonding.
- The impact of **bar position** during casting (top or bottom bars can have different bond strengths due to settlement and bleeding).
- The effectiveness of **curing and compaction** methods.

Typical Observations:

- Higher-grade concrete generally improves bond strength.
- Poor compaction leads to air voids near bars, reducing contact area.
- Corrosion or dirty bars reduce adhesion and frictional resistance.
- Inadequate cover or improper alignment during casting reduces bond efficiency.

4.10 Factors Influencing Destructive Test Results

The outcomes of destructive tests are influenced by various controllable and uncontrollable factors:

1. Mix Proportioning

- Cement content, water-cement ratio, and aggregate type directly affect strength development.

2. Curing Duration and Conditions

- Insufficient curing leads to incomplete hydration, lowering strength.
- Wet curing is superior to air curing.

3. Age of Concrete

- Strength gain is time-dependent. Typically, concrete attains:
  - ~70% strength at 7 days.
  - ~100% strength at 28 days.
  - Slow gain up to 90 days or more depending on mix.

4. Specimen Size and Shape

- Larger specimens may yield slightly lower strength due to internal flaws.
- Cube vs cylinder testing differences due to stress distribution and aspect ratio.

5. Loading Rate

- A rapid load application may result in higher apparent strength due to inertia.
- Standard codes specify slow and steady application.

6. Temperature and Humidity

- High temperature accelerates hydration but may cause shrinkage cracks.
- Cold temperature slows strength development.

4.11 Limitations of Destructive Tests

Despite being accurate and widely adopted, destructive tests have some inherent limitations:

- **Irreversible**: The specimen is destroyed during the test.
- **Not applicable in-situ**: Usually conducted on lab specimens, not on-site.
- **Limited sample representation**: A few test specimens may not represent the entire batch or structure.
- **Labor and time-intensive**: Requires careful specimen preparation, curing, and testing.

4.12 Quality Control and Acceptance Criteria

Destructive tests form the foundation of concrete **quality assurance**. Based on test results:

- The concrete is either accepted, rejected, or subjected to further investigation.
- Acceptance criteria are typically defined in:
    - **IS 456: 2000**, Clause 16
    - **ACI 318**, for international projects

Example: As per IS 456:2000

- The **average of 3 cubes** at 28 days must be ≥ characteristic strength.
- **Individual cube** must not be less than **characteristic strength – 4 MPa** for M20–M25.

4.13 Comparative Table of Destructive Tests

Test	Property Measured	Specimen Type	Key Formula	Application
Compressive Strength	Crushing Resistance	Cube / Cylinder	$f_c = \frac{P}{A}$	Structural capacity, mix design
Flexural Strength	Modulus of Rupture	Beam	$f_r = \frac{P \cdot L}{b \cdot d^2}$	Pavements, slabs
Tensile Strength	Indirect Tensile Strength	Cylinder	$f_t = \frac{2P}{\pi \cdot d \cdot l}$	Cracking resistance

Test	Property Measured	Specimen Type	Key Formula	Application
Bond Strength	Pull-out Bond	Cube/ Cylinder with bar	$\tau_b = \frac{P}{\pi \cdot d \cdot l}$	Bar anchorage, development length

4.14 Best Practices for Reliable Test Results

To ensure consistency and accuracy in destructive testing:

- Use calibrated and well-maintained testing machines.
- Follow **national/international standards** strictly.
- Cast and cure specimens carefully and label them properly.
- Perform tests at **standard temperature** (27 ± 2°C) and humidity conditions.
- Discard any specimen with visible flaws, honeycombing, or damage.
- Document failure types (brittle, ductile, sudden, progressive).

4.15 Integration with Structural Design and Safety

Results from destructive testing directly impact:

- **Load calculations**: Designing for axial, flexural, and tensile forces.
- **Safety margins**: Ensuring strength exceeds demand by required factors of safety.
- **Retrofit decisions**: Identifying areas requiring strengthening.
- **Material certification**: Batch approval in large-scale construction.

Concrete's **compressive strength** is the **foundation** of all structural designs. However, as cracks often originate from tensile stresses, **flexural and tensile tests** are equally important. **Bond strength** ensures the composite action of RCC is maintained.
