Chapter 13: Hardened Concrete – Failure Mechanism, Stress-Strain Behavior, Creep & Shrinkage

Introduction

Hardened concrete refers to the state of concrete after it has gained sufficient strength through hydration and has set completely. Understanding the behavior of hardened concrete is essential for analyzing structural performance, durability, serviceability, and failure characteristics. This chapter dives into the key aspects of hardened concrete, specifically focusing on **failure mechanisms**, **stress-strain behavior**, **creep**, and **shrinkage**. Each of these phenomena plays a vital role in determining how concrete structures respond to loading and environmental conditions over time.

1. Failure Mechanism in Hardened Concrete

Concrete failure can occur due to various factors and manifests in different modes, depending on the loading conditions, material properties, and environmental influences. The primary failure mechanisms in hardened concrete include:

1.1. Tensile Failure

- Concrete is inherently weak in tension.
- Cracking initiates when the tensile stress exceeds the tensile strength (typically 1/10 of its compressive strength).
- Tensile failure is often brittle with minimal warning.
- Cracks usually develop perpendicular to the direction of the tensile force.

1.2. Compressive Failure

- Most structural members are designed to withstand compressive loads.
- Compressive failure in concrete is characterized by:
    - Initial microcracking.
    - Progressive crack coalescence.

    - Sudden crushing with possible spalling of concrete.
- The failure surface is typically inclined at 30° to 45° (shear plane) relative to the loading axis.

1.3. Shear Failure

- Shear failure is common in beams and occurs along a plane where internal shear stresses exceed the concrete's shear capacity.
- It is brittle in nature and usually follows diagonal cracking patterns.
- Inadequate shear reinforcement may exacerbate this failure.

1.4. Flexural Failure

- Occurs in beams subjected to bending.
- Initiates in the tension zone (bottom fibers in simply supported beams).
- Flexural cracks form perpendicular to the beam axis and propagate upwards.
- If reinforcement is inadequate, brittle failure can occur; if over-reinforced, crushing in compression zone dominates.

1.5. Fatigue Failure

- Concrete subjected to repeated or cyclic loading may fail even if stresses are below its ultimate strength.
- Fatigue life depends on stress range, loading frequency, and the number of cycles.
- Microcracks accumulate over time leading to eventual fracture.

1.6. Durability-Based Failure

- Includes failure due to environmental effects like corrosion of reinforcement, freeze-thaw action, sulfate attack, alkali-silica reaction, etc.
- These mechanisms weaken the internal matrix, reducing strength and accelerating physical damage.

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2. Stress-Strain Behavior of Hardened Concrete

The stress-strain behavior of concrete under axial loading is non-linear and varies in tension and compression. The relationship helps in understanding the deformability and energy absorption capacity of concrete.

2.1. Stress-Strain Curve in Compression

Key Characteristics:

- Initially linear up to about 30–40% of ultimate compressive strength.
- Curve becomes non-linear as microcracks develop.
- Peak point represents **ultimate compressive strength (fc)**.
- Post-peak, the curve descends steeply (brittle failure).

Typical Parameters:

- **Modulus of Elasticity (Ec):** Initial slope of the curve; varies with strength and aggregate type.
- **Ultimate Strain (εcu):** Strain at failure, typically around 0.0035 for normal concrete.

Graph Description:

- X-axis: Strain (ε), Y-axis: Stress (σ).
- Steep linear rise, curving gradually to the peak, followed by a steep drop.

2.2. Stress-Strain Curve in Tension

- Linear till the **tensile strength (ft)** is reached.
- Cracking occurs suddenly.
- After cracking, stress drops sharply to zero — indicating brittle nature.
- No significant post-cracking load capacity.

2.3. Influence of Aggregate and Mix Design

- Denser aggregates increase Ec and compressive strength.
- Higher water-cement ratio flattens the curve (more ductile but weaker).
- Use of admixtures and supplementary cementitious materials alters the shape of the stress-strain curve.

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3. Creep in Hardened Concrete

3.1. Definition

Creep is the time-dependent increase in strain under sustained load. It occurs even when the stress level is constant, particularly in compression.

3.2. Mechanism

- Caused by viscous flow and microcrack development in the cement paste.
- Influenced by water content, temperature, humidity, and loading history.

3.3. Stages of Creep

1. **Instantaneous Strain:** Immediate deformation upon loading.
2. **Primary Creep:** Rapid strain increase immediately after loading.
3. **Secondary Creep:** Slower, steady strain development.
4. **Tertiary Creep:** Accelerated strain leading to failure (rare in structures).

3.4. Factors Influencing Creep

- **Stress level:** Higher stress = higher creep.
- **Age of concrete:** Younger concrete creeps more.
- **Humidity:** Lower humidity = higher creep.
- **Temperature:** Higher temperature accelerates creep.
- **Mix design:** Higher paste content = more creep.

3.5. Effects of Creep

- **Loss of prestress** in prestressed concrete.
- **Deflection** in beams and slabs over time.
- **Redistribution of internal stresses**.
- **Stress relaxation** in statically indeterminate structures.

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4. Shrinkage in Hardened Concrete

4.1. Definition

Shrinkage is the reduction in volume of concrete due to moisture loss and other physicochemical reactions. Unlike creep, shrinkage occurs even in the absence of external load.

4.2. Types of Shrinkage

a. Plastic Shrinkage:

- Occurs within few hours of placing.
- Caused by rapid evaporation of surface water.
- Results in surface cracking.

b. Drying Shrinkage:

- Most common type.
- Due to moisture loss from hardened concrete.
- Significant in the first few months after curing.

c. Autogenous Shrinkage:

- Results from internal chemical reactions.
- Prominent in low water-cement ratio mixes.

d. Carbonation Shrinkage:

- Due to reaction between CO_2 and calcium hydroxide.
- Occurs at the surface over long periods.

4.3. Factors Affecting Shrinkage

- **Water-cement ratio:** Higher w/c = more shrinkage.
- **Aggregate content and type:** More aggregate = less shrinkage.
- **Curing method:** Proper curing reduces shrinkage.
- **Environmental conditions:** Low humidity and high temperature increase shrinkage.

4.4. Effects of Shrinkage

- **Cracking:** Especially in restrained conditions (e.g., slabs).
- **Loss of serviceability:** Affects alignment and surface finish.
- **Loss of bond:** Can reduce reinforcement-concrete bond strength.

4.5. Shrinkage Cracking: Mechanism and Risk Areas

Shrinkage does not always result in visible damage. However, when **movement is restrained** — either externally (e.g., by foundation, reinforcement, or adjacent structural elements) or internally (e.g., differential drying) — cracks can form.

Cracking Mechanism:

- Restraint introduces **tensile stress** in the concrete as it tries to shrink.
- If tensile stress exceeds the tensile strength of concrete, **cracks form**.
- Typically, these cracks are:
  - **Random or map-like** on slabs and pavements.
  - **Parallel and spaced** regularly in walls or beams.
  - **Surface-wide microcracks** in high-shrinkage pastes.

High-Risk Zones:

- Slabs-on-grade.
- Long retaining walls.

- Tunnel linings.
- Precast members with low reinforcement.
- Concrete exposed to sun and wind during curing.

4.6. Mitigation of Shrinkage and Shrinkage Cracking

Engineers and contractors adopt various strategies to **minimize shrinkage** and **control cracking**, enhancing long-term durability and aesthetics.

a. Mix Design Optimization:

- Use **low water-cement ratio** (<0.5).
- Add **shrinkage-reducing admixtures (SRA)**.
- Replace part of cement with **fly ash or slag** to reduce heat and self-desiccation.
- Use well-graded **aggregates** in higher proportion to minimize paste volume.

b. Curing Techniques:

- Begin curing **immediately after finishing**.
- Use **wet coverings, fogging, or sprinkling** for moist curing.
- Apply **curing compounds** (liquid membranes) on exposed surfaces.
- **Extended curing** (at least 7–14 days) for large structures.

c. Structural Detailing:

- Provide adequate **reinforcement** to resist tensile stresses.
- Use **control joints or contraction joints** in slabs and walls at proper intervals.
- Provide **expansion joints** in long structures.
- Ensure **smooth transitions** between new and existing concrete.

4.7. Testing Methods for Creep and Shrinkage

Proper characterization of creep and shrinkage is essential for prediction models and quality control.

a. Shrinkage Testing (IS 1199 / ASTM C157):

- **Drying Shrinkage:** Standard prism (e.g., 75×75×285 mm) is measured for length change over 28, 56, 90 days.

- **Autogenous Shrinkage:** Specimens are sealed and monitored for volume change.
- **Plastic Shrinkage Test:** Measures cracking susceptibility under controlled drying conditions.

b. Creep Testing (IS 516 / ASTM C512):

- Cylindrical specimens are subjected to **constant axial compressive stress** (usually 30-40% of compressive strength).
- **Strain gauges or extensometers** measure deformation over time.
- Simultaneous control specimens are kept unloaded to isolate creep from shrinkage.

4.8. Modeling Creep and Shrinkage in Design

Modern structural codes require engineers to **account for time-dependent deformations** in long-term deflection and stress analysis.

Key Models and Standards:

- **ACI 209R** – Prediction models for creep and shrinkage.
- **CEB-FIP Model Code** – European design guidelines.
- **IS 456:2000** – Indian code provisions for creep coefficient and shrinkage strain.
- **Eurocode 2** – Time functions for creep, shrinkage, and modulus of elasticity.

Creep Coefficient (φ):

- Defined as:

$$\phi(t,t_0)=\frac{\varepsilon_{cr}(t,t_0)}{\varepsilon_e(t_0)}$$

  where:

  - ε_{cr} = creep strain,
  - ε_e = elastic strain at loading.

Total Strain Equation (under sustained load):

$$\varepsilon_{total}(t)=\varepsilon_e+\varepsilon_{cr}(t)+\varepsilon_{sh}(t)$$

Where:

- ε_e = Immediate elastic strain,
- $\varepsilon_{cr}(t)$ = Creep strain,

- $\varepsilon_{sh}(t)$ = Shrinkage strain.

These equations help in **deflection prediction** and **serviceability checks** in beams, slabs, and tall structures.

4.9. Real-World Engineering Considerations

Engineers must evaluate site conditions, environmental exposure, and structural function to balance performance and cost.

Precast vs. Cast-In-Situ:

- Precast members must control shrinkage and creep due to **storage, transport, and erection loads**.
- In cast-in-place elements, **long-term differential shrinkage** between old and new concrete is critical.

Tall Buildings and Bridges:

- Long columns and bridge piers suffer **differential creep**, leading to misalignment.
- Post-tensioned bridges must account for **loss of prestress due to creep and shrinkage**.

Mass Concrete:

- Shrinkage cracking is minimized by **temperature control**, **low heat cement**, and **mass placement planning**.

4.10. Research Trends and Innovations

- **Engineered Cementitious Composites (ECC):** Exhibit microcracking and self-healing.
- **Use of nanomaterials** (e.g., nano-silica) to control shrinkage and improve packing density.
- **3D printed concrete** — new methods are being developed to predict shrinkage and deformation during printing.
- **Machine learning models** are now used to **predict shrinkage and creep** using big data from field and lab tests.
