Chapter 9: Topics in Hardened Concrete

Introduction

Once concrete has set and hardened, it transitions from a plastic to a rigid material. The hardened state of concrete is the condition in which it serves its structural function. Understanding the behavior of hardened concrete is essential for ensuring its long-term performance, safety, and durability. This chapter explores various physical and mechanical properties of hardened concrete, factors influencing these properties, and methods of testing and evaluation.

9.1 Strength of Hardened Concrete

Concrete strength refers to its capacity to withstand loads without failure. The primary strength characteristics considered are:

9.1.1 Compressive Strength

- **Definition:** Ability to resist axial compressive load.
- **Standard Test:** Cube test (IS: 516), Cylinder test (ASTM C39).
- **Typical Values:** Varies between 15 MPa to 60 MPa for general construction; can exceed 100 MPa for high-strength concrete.
- **Factors Influencing:**
  - Water-cement ratio (w/c ratio)
  - Degree of compaction
  - Curing conditions
  - Age of concrete
  - Type and quality of cement and aggregates

9.1.2 Tensile Strength

- **Definition:** Resistance to axial tensile load.
- **Importance:** Cracking resistance, especially in pavements, dams, and pipes.
- **Tests:**

- Split tensile test
  - Direct tensile test
  - Flexural test (Modulus of Rupture)
- **Typical Value:** ~10% of compressive strength.

9.1.3 Flexural Strength

- **Also known as Modulus of Rupture (fcr)**
- Measures resistance to bending.
- Especially relevant for road slabs and beams.

9.2 Elastic Properties

9.2.1 Modulus of Elasticity (E)

- Indicates the stiffness of concrete.
- **Determined By:** Stress-strain curve from axial compression test.
- **Typical Formula:**

$$E = 5000\sqrt{f_{ck}}\,(\text{MPa})$$

where f_{ck} is characteristic compressive strength.

9.2.2 Poisson's Ratio (μ)

- Ratio of lateral strain to axial strain.
- Typical values: 0.15 – 0.20.

9.3 Creep of Concrete

Definition:

Gradual, time-dependent increase in strain under sustained load.

Mechanism:

Due to viscous flow in the cement gel and micro-cracking at the interfacial transition zone (ITZ).

Factors Affecting Creep:

- Water-cement ratio

- Aggregate type
- Age at loading
- Humidity and temperature
- Stress level

Implications:

- Loss of pre-stress in PSC structures
- Increase in long-term deflections
- Redistribution of internal stresses

9.4 Shrinkage in Concrete

Types of Shrinkage:

1. **Plastic Shrinkage:** Occurs before setting due to rapid water loss.
2. **Drying Shrinkage:** Loss of moisture from hardened concrete to the environment.
3. **Autogenous Shrinkage:** Due to chemical reactions without external moisture loss.
4. **Carbonation Shrinkage:** Caused by reaction with atmospheric CO_2.

Control Measures:

- Proper curing
- Use of shrinkage-reducing admixtures
- Limiting w/c ratio
- Use of low-shrinkage aggregates

9.5 Permeability of Concrete

Definition:

Ease with which fluids (like water or gases) can penetrate concrete.

Significance:

Highly permeable concrete allows ingress of harmful substances (chlorides, sulfates), leading to corrosion and deterioration.

Tests for Permeability:

- Water permeability test
- Rapid chloride permeability test (RCPT – ASTM C1202)

Factors Affecting Permeability:

- Water-cement ratio
- Degree of compaction
- Curing duration
- Use of pozzolanic materials (fly ash, silica fume)

9.6 Durability of Concrete

Definition:

Ability to withstand weathering, chemical attack, abrasion, and other deteriorating processes over its service life.

Major Durability Problems:

- Sulfate attack
- Chloride-induced corrosion
- Alkali-aggregate reaction (AAR)
- Freezing and thawing cycles

Enhancing Durability:

- Low permeability
- Proper cover depth
- Use of blended cements
- Use of waterproofing admixtures

9.7 Thermal Properties of Concrete

Thermal Conductivity:

- Concrete has low thermal conductivity (0.7–1.4 W/m·K), making it suitable for thermal mass applications.

Thermal Expansion:

- Coefficient ranges from 7 to 12 × 10^{-6} /°C.

- Compatibility with steel is essential in RCC.

Heat of Hydration:

- Critical in mass concrete structures to avoid thermal cracking.
- Controlled by using low-heat cement or pozzolanic materials.

9.8 Fire Resistance

- Concrete is inherently fire-resistant due to non-combustibility.
- Spalling may occur due to moisture expansion under high temperatures.
- Siliceous aggregates lose strength earlier than calcareous ones.

9.9 Microstructure of Hardened Concrete

Components:

- **Hydrated Cement Paste (HCP):** Main binding phase.
- **Capillary Pores:** Affect permeability and strength.
- **Transition Zone:** Weak link between aggregate and paste.

Analysis Tools:

- Scanning Electron Microscope (SEM)
- X-Ray Diffraction (XRD)
- Mercury Intrusion Porosimetry (MIP)

9.10 Testing of Hardened Concrete

Destructive Tests:

- Compressive strength test (cube/cylinder)
- Flexural strength test
- Tensile strength test

Non-Destructive Tests (NDT):

- Rebound hammer (Schmidt Hammer)
- Ultrasonic pulse velocity (UPV)
- Core sampling
- Penetration resistance

- Pull-out test

9.11 Surface Hardness and Abrasion Resistance

- Important for pavements and industrial floors.
- Measured using Mohs or Rebound Hammer.
- Depends on w/c ratio, aggregate hardness, and surface finishing.

9.12 Volume Changes and Cracking

Causes of Volume Changes:

- Moisture movement
- Thermal expansion
- Chemical reactions
- External loading

Types of Cracks:

- Structural (due to overloads)
- Non-structural (shrinkage, temperature)
- Plastic and drying cracks

Control:

- Joints, reinforcements
- Controlled curing
- Use of fibers

9.13 Chemical Attack on Concrete

Concrete is vulnerable to various aggressive chemical environments that deteriorate its matrix and reduce its durability.

9.13.1 Sulfate Attack

- **Sources:** Groundwater, sewage, industrial waste.
- **Effect:** Formation of expansive products like ettringite and gypsum causing cracking and expansion.

- **Types:**
  - External Sulfate Attack (ESA)
  - Internal Sulfate Attack (ISA)
- **Prevention:**
  - Use sulfate-resistant cement (SRC)
  - Reduce permeability
  - Adequate cover and compaction

9.13.2 Acid Attack

- **Mechanism:** Acids react with calcium hydroxide and C-S-H gel, forming soluble calcium salts.
- **Examples:** H_2SO_4, HCl, HNO_3, acetic acid.
- **Symptoms:** Surface erosion, loss of mass, exposure of aggregates.
- **Protection:**
  - Protective coatings
  - Use of pozzolans to reduce free lime content
  - Silica fume and fly ash improve acid resistance

9.13.3 Alkali-Aggregate Reaction (AAR)

- **Includes:**
  - Alkali-Silica Reaction (ASR): most common
  - Alkali-Carbonate Reaction (ACR)
- **Effect:** Expansion and cracking due to reactive aggregates.
- **Control Measures:**
  - Use of non-reactive aggregates
  - Use of lithium salts or pozzolanic materials
  - Low-alkali cement

9.14 Carbonation of Concrete

Process:

- Reaction between atmospheric CO_2 and calcium hydroxide ($Ca(OH)_2$) in concrete.
- Forms calcium carbonate ($CaCO_3$), reducing pH of concrete from ~12.5 to <9.

Impact:

- Reduced alkalinity removes protection of reinforcement against corrosion.
- Cracking and spalling near reinforcement.

Testing:

- Phenolphthalein indicator test: Turns pink in non-carbonated zones.

Control Measures:

- Adequate cover thickness
- Dense, impermeable concrete
- Surface sealers or paints

9.15 Corrosion of Reinforcement in Concrete

Causes:

- Ingress of chlorides (from sea water, de-icing salts)
- Carbonation-induced pH drop
- Moisture and oxygen presence

Mechanism:

- Electrochemical cell formation between anodic and cathodic regions
- Formation of rust which has 2–6 times the volume of steel → causes cracking and spalling

Types:

- Uniform corrosion
- Pitting corrosion

Protection Strategies:

- Use of corrosion inhibitors
- Epoxy-coated or galvanized bars

- Cathodic protection systems
- Corrosion-resistant steel (CRS)
- Adequate concrete cover and low permeability

9.16 Fiber Reinforced Concrete (FRC)

Definition:

Concrete containing fibrous materials to increase structural integrity.

Common Fibers:

- Steel fibers
- Glass fibers (GFRC)
- Polypropylene fibers
- Carbon fibers
- Natural fibers (coir, sisal)

Benefits:

- Improved toughness and energy absorption
- Reduced crack propagation
- Enhanced impact resistance
- Increased ductility

Applications:

- Pavements, tunnels, airport runways
- Shotcrete applications
- Industrial flooring

9.17 High-Performance Concrete (HPC) and Ultra-High Performance Concrete (UHPC)

High-Performance Concrete (HPC):

- **Definition:** Concrete with enhanced performance attributes – strength, durability, workability, and resistance to aggressive environments.

- **Key Materials:**

    - Silica fume, fly ash, GGBS
    - Superplasticizers
- **Typical Strength:** 60–100 MPa

Ultra-High Performance Concrete (UHPC):

- **Definition:** Steel fiber-reinforced concrete with compressive strength >150 MPa.
- **Properties:**
    - Densified microstructure
    - Very low porosity
    - Self-compacting
- **Used For:** Precast segments, defense applications, high-rise structures

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9.18 Self-Compacting Concrete (SCC)

Definition:

Concrete that flows under its own weight without the need for mechanical vibration.

Characteristics:

- High flowability
- Stability (no segregation)
- High passing ability

Advantages:

- Faster placement
- Better surface finish
- Reduced labor and noise
- Suitable for congested reinforcement zones

Typical Mix Components:

- High-range water reducers
- Viscosity modifying agents
- Fine fillers (like fly ash or limestone powder)

9.19 Recycled Aggregate Concrete (RAC)

Definition:

Concrete made using crushed concrete waste as aggregate.

Advantages:

- Reduces construction waste
- Environmentally sustainable
- Saves natural resources

Challenges:

- Higher water absorption
- Lower density and strength
- Requires quality control and processing

Use Cases:

- Non-structural applications
- Pavements and base layers
- Blended in limited proportions in structural concrete

9.20 Testing Advanced Properties of Hardened Concrete

9.20.1 Petrographic Analysis

- Microscopic examination of concrete's composition and deterioration.
- Helps in diagnosing causes of cracking or failures.

9.20.2 Thermogravimetric Analysis (TGA)

- Measures mass change with temperature to assess hydration products.

9.20.3 Differential Scanning Calorimetry (DSC)

- Determines exothermic and endothermic reactions in hydrated cement paste.

9.20.4 X-Ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR)

- Used to identify crystalline and amorphous phases.
- Characterizes hydration and deterioration mechanisms.