Chapter 16: Durability & Permeability – Carbonation, Corrosion, Alkali-Aggregate Reaction

Introduction

Durability and permeability are key performance criteria in assessing the long-term behavior of concrete and other civil engineering materials under varying environmental conditions. Durability refers to the material's capacity to withstand weathering action, chemical attack, abrasion, or any other process of deterioration while maintaining its desired engineering properties. Permeability, on the other hand, is the measure of the ease with which fluids (water, gases, and aggressive chemicals) can pass through concrete, significantly influencing its durability.

This chapter provides an in-depth exploration of the fundamental degradation mechanisms in concrete, including **carbonation**, **steel corrosion**, and **alkali-aggregate reactions (AAR)**, emphasizing the interaction between microstructural properties and long-term performance.

---

1. Durability of Concrete

1.1 Definition

Durability is the ability of a concrete structure to resist deterioration due to environmental conditions, loading, and chemical interactions over its expected lifespan without major loss of strength or serviceability.

1.2 Factors Affecting Durability

- **Environmental exposure**: Marine environments, freeze-thaw cycles, sulfate attack, acidic waters.
- **Permeability**: Highly permeable concrete allows ingress of water, oxygen, CO_2, and other aggressive agents.
- **Material composition**: Cement type, water-cement ratio, aggregate quality.
- **Construction practices**: Curing, compaction, and placement.

- **Crack formation**: Physical and chemical cracking pathways accelerate deterioration.

---

2. Permeability of Concrete

2.1 Definition

Permeability is the capacity of concrete to allow fluids to pass through its microstructure, typically through capillary pores and microcracks.

2.2 Mechanisms of Permeability

- **Capillary suction**: Movement of water through pores by capillary action.
- **Diffusion**: Migration of ions like chloride through pore solution.
- **Permeation**: Pressure-driven flow through the concrete matrix.

2.3 Factors Influencing Permeability

- Water-cement ratio (w/c): Higher w/c ratio → more capillary pores.
- Degree of hydration: Well-hydrated cement paste is denser.
- Curing: Proper curing ensures pore refinement and reduces permeability.
- Supplementary cementitious materials: Use of fly ash, silica fume, and slag improves pore structure.
- Crack width and distribution.

2.4 Test Methods

- Water permeability test (IS 3085)
- Rapid Chloride Penetration Test (ASTM C1202)
- Oxygen permeability index test
- Sorptivity test

---

3. Carbonation of Concrete

3.1 What is Carbonation?

Carbonation is a chemical process in which **carbon dioxide (CO_2)** from the atmosphere reacts with **calcium hydroxide ($Ca(OH)_2$)** in hydrated cement paste to form **calcium carbonate ($CaCO_3$)**.

Reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

3.2 Carbonation Front

The carbonation reaction progresses inward from the concrete surface, forming a "carbonation front" which can be detected by phenolphthalein indicator. The uncarbonated zone turns pink; carbonated areas remain colorless.

3.3 Factors Influencing Carbonation

- **Concrete permeability**: More porous concrete allows faster CO_2 ingress.
- **Relative humidity**: Optimum carbonation occurs at 50–70% RH.
- **CO_2 concentration**: Higher levels accelerate carbonation.
- **Curing and cover depth**: Poor curing and insufficient cover depth accelerate carbonation depth.

3.4 Effects of Carbonation

- Reduction in alkalinity (pH drops from ~12.5 to <9).
- Loss of passive protection layer on reinforcing steel.
- Initiation of **steel corrosion**.
- Shrinkage due to $CaCO_3$ formation → microcracking.

---

4. Corrosion of Reinforcing Steel

4.1 Nature of Corrosion in Concrete

Steel embedded in concrete is naturally protected by the high alkalinity of the cement paste, forming a passive oxide layer. When this passivation is broken, **corrosion** begins, particularly in the presence of moisture, oxygen, and chloride or carbonation.

4.2 Types of Corrosion

- **Uniform corrosion**: Even rusting across surface.
- **Pitting corrosion**: Localized attack forming small pits.
- **Crevice corrosion**: Occurs at poorly compacted areas or voids.
- **Galvanic corrosion**: When two different metals are in contact.

4.3 Causes of Corrosion

- **Carbonation**: Reduces pH and destroys passive layer.
- **Chloride attack**: From de-icing salts or seawater.

- **Oxygen and moisture**: Essential for electrochemical reaction.

4.4 Electrochemical Mechanism

$$\text{Anode:} Fe \rightarrow Fe^{2+¿+2e^{-}¿}$$

$$\text{Cathode:} O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$$

$$\text{Overall:} Fe + \frac{1}{2}O_2 + H_2O \rightarrow Fe¿$$

Rust ($Fe(OH)_2$ and later $Fe_2O_3 \cdot xH_2O$) has greater volume than steel → expansion → cracking and spalling of concrete.

4.5 Detection and Prevention

- **Half-cell potential test**
- **Cover meter and ultrasonic testing**
- **Preventive Measures**:
  - Use of corrosion inhibitors
  - Proper cover depth
  - Use of epoxy-coated or stainless-steel rebars
  - Low permeability concrete
  - Cathodic protection systems

---

5. Alkali-Aggregate Reaction (AAR)

5.1 Introduction

AAR is a chemical reaction between reactive **silica present in some aggregates** and the **alkalis (Na_2O and K_2O)** in cement paste, forming a hygroscopic gel that absorbs water and expands, leading to internal stresses, cracking, and deterioration.

5.2 Types of AAR

- **Alkali-Silica Reaction (ASR)**: Most common form; involves silica-rich aggregates.
- **Alkali-Carbonate Reaction (ACR)**: Involves dolomitic limestone aggregates; rare but severe.

5.3 Mechanism of ASR

1. Hydroxyl ions from pore solution attack reactive silica in aggregates.
2. Formation of alkali-silica gel ($Na_2SiO_3 \cdot nH_2O$).
3. Gel absorbs water and swells.
4. Expansion leads to cracking, spalling, and loss of mechanical integrity.

Simplified reaction:

$$\mathrm{SiO_2}(reactive) + NaOH/KOH \rightarrow Na_2SiO_3 \cdot nH_2O$$

5.4 Symptoms and Effects

- Map (crazing) cracking on surface
- Displacement and warping
- Efflorescence
- Structural distress

5.5 Test Methods

- Mortar bar expansion test (ASTM C1260)
- Concrete prism test (ASTM C1293)
- Petrographic examination (IS 2386 Part 8)

5.6 Preventive Measures

- Use of **non-reactive aggregates** (verified by testing).
- **Low-alkali cement** (Na_2O eq. < 0.6%).
- **Pozzolanic admixtures** like fly ash, silica fume, and slag reduce alkali content and react with available alkalis.
- Control of total alkali loading.
- Use of **lithium-based admixtures**.

---

6. Interaction Between Durability, Permeability & Chemical Attack

- **High permeability** leads to increased exposure of internal components to CO_2, chlorides, and moisture, thereby accelerating carbonation, corrosion, and AAR.
- Proper material selection, mix design, and curing can significantly reduce permeability and improve durability.

- **Durability design** must consider the service environment and ensure sufficient protection against aggressive agents.

---

7. Case Studies on Durability Failures

7.1 Case Study 1: Bridge Deck Corrosion due to Chloride Attack

Location: Coastal highway bridge, Gujarat **Issue:** Severe corrosion observed within 10 years of construction. **Root Cause:**

- High chloride ingress due to poor waterproofing and inadequate concrete cover.
- Water-cement ratio was > 0.55; concrete had high permeability. **Outcome:**
- Corroded rebars led to delamination of cover concrete.
- Bridge required partial demolition and retrofitting using corrosion-resistant rebars.

7.2 Case Study 2: Carbonation in High-Rise Residential Building

Location: Delhi NCR **Issue:** Carbonation depth reached 30 mm within 7 years. **Cause:**

- Low cement content, inadequate curing.
- High relative humidity supported fast carbonation. **Detection:**
- Phenolphthalein test showed no pink coloration in outer layers. **Action Taken:**
- Application of anti-carbonation coatings.
- Surface densifiers used and cover concrete replaced where pH < 9.

---

8. Design Strategies to Improve Durability

8.1 Mix Design Considerations

- **Low Water-Cement Ratio (≤ 0.45)**: Reduces capillary porosity.
- **Pozzolanic Materials**: Fly ash, slag, metakaolin reduce permeability.
- **Air Entrainment**: Improves resistance to freeze-thaw.
- **Use of Plasticizers**: Reduces water demand without affecting workability.

8.2 Structural Detailing

- Adequate **concrete cover** as per IS 456 (minimum 25 mm for mild exposure; 50 mm for severe).
- Use of **bar chairs and spacers** to maintain proper rebar alignment.
- Avoid water accumulation zones in formwork – slope slabs slightly.

8.3 Curing Practices

- Continuous wet curing for at least 7 days (longer for blended cements).
- Use of curing compounds where water curing is impractical.
- Protection from premature drying using wet hessian or polythene sheets.

---

9. Modern Techniques for Durability Enhancement

9.1 Self-Healing Concrete

- Incorporation of **bacteria (e.g., Bacillus sphaericus)** or encapsulated healing agents (sodium silicate, epoxy).
- Cracks up to 0.5 mm can be sealed automatically.
- Enhances life and reduces maintenance.

9.2 Surface Treatments

- **Silane/siloxane sealers**: Repel water and reduce carbonation.
- **Epoxy coatings**: Barrier to chloride and moisture ingress.
- **Mineral densifiers**: React with free lime to form C-S-H gel, reducing permeability.

9.3 Cathodic Protection Systems

- **Sacrificial Anodes**: Zinc or magnesium connected to rebars.
- **Impressed Current Systems**: DC current applied to counteract corrosion.
- Used in marine structures, underground tunnels, and old bridges.

---

10. Durability Specifications in Codes and Standards

10.1 IS:456 – Code of Practice for Plain and Reinforced Concrete

- Exposure-based cover depth, w/c limits, and cement content.

10.2 IS 10262 – Concrete Mix Design

- Mandates durability checks based on exposure conditions.

10.3 IRC SP: 13 & IRC:112

- Guidelines for bridge durability and concrete composition.

10.4 ASTM Standards

- **C1202**: Chloride Ion Penetration
- **C876**: Half-cell potential to assess corrosion
- **C856**: Petrographic analysis of aggregates

---

11. Long-Term Monitoring Techniques

11.1 NDT Methods

- **Ultrasonic Pulse Velocity (UPV)**: Detects internal cracks.
- **Rebound Hammer Test**: Surface hardness.
- **Ground Penetrating Radar (GPR)**: Locates steel and voids.

11.2 Sensors & Smart Monitoring

- **Embedded corrosion sensors** for chloride, pH, temperature.
- **Fiber optic sensors** for strain and crack growth.
- Useful in critical infrastructure like nuclear plants, tunnels, and flyovers.

---

12. Future Research and Innovations

- **Graphene Concrete**: Adds strength and reduces permeability.
- **Carbon-Capture Concrete**: Binds CO_2 from the air during curing.
- **Geopolymer Concrete**: Alkali-activated binders with low carbon footprint and high chemical resistance.
- **AI-Based Predictive Modelling**: Forecasting service life based on real-time data.
