Chapter 15: Durability & Permeability – Gas & Fluid Transport, Cracking Causes

Introduction

Durability and permeability are two critical parameters in assessing the long-term performance of civil engineering materials, especially concrete and masonry. Durability ensures the material retains its required engineering properties throughout the design life under given environmental exposures. Permeability, on the other hand, controls how easily fluids or gases can move through the material, directly affecting its resistance to various forms of deterioration, such as corrosion, freeze-thaw cycles, and chemical attacks.

This chapter examines in detail the transport mechanisms of gases and fluids through concrete, the physical and chemical causes of cracking, and how these factors collectively affect the structural integrity and lifespan of a construction material.

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1. Durability of Construction Materials

Durability is defined as the ability of a material to withstand environmental attack and maintain its desired engineering properties over its intended service life without significant degradation.

Factors Influencing Durability

- **Environmental Exposure**: Sulfate attack, carbonation, chloride ingress, freeze-thaw cycles.
- **Material Quality**: Water-cement ratio, curing, aggregate properties.
- **Design & Detailing**: Cover depth, jointing, reinforcement placement.
- **Workmanship**: Compaction, finishing, curing practices.
- **Maintenance Practices**: Timely inspection, repair, protection against further damage.

Durability Mechanisms

- **Physical mechanisms**: Abrasion, freeze-thaw damage, thermal stresses.

- **Chemical mechanisms**: Corrosion of steel reinforcement, alkali-aggregate reaction (AAR), sulfate attack, carbonation.

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2. Permeability in Concrete

Permeability refers to the capacity of a material to allow fluids (liquids or gases) to pass through its pore system. For concrete, permeability is a key indicator of its resistance to aggressive agents such as chlorides, sulfates, carbon dioxide, and water.

Types of Transport Mechanisms

i. Permeation

- The movement of fluids under pressure through the pore system.
- Governed by **Darcy's Law**:

$$Q = \frac{k A \Delta h}{L}$$

  where:

  - Q: discharge,
  - k: permeability coefficient,
  - A: cross-sectional area,
  - Δh: hydraulic head,
  - L: length of the flow path.

ii. Diffusion

- Movement of ions or molecules due to concentration gradients.
- Relevant for gases like CO_2 or chloride ions entering concrete.

iii. Capillary Suction (Absorption)

- Suction of water due to surface tension in the capillaries.
- Common when concrete is exposed to water intermittently.

iv. Wick Action

- Occurs when water moves along reinforcement or interfaces due to pressure or gravity.

Factors Affecting Permeability

- **Water-Cement Ratio (w/c)**: Lower w/c ratios reduce capillary pores.
- **Curing**: Proper curing leads to better hydration and reduced porosity.

- **Air Voids**: Entrapped air increases permeability; entrained air (when controlled) may help in freeze-thaw resistance.
- **Aggregate Quality**: Good quality aggregates reduce porosity.
- **Admixtures**: Silica fume, fly ash, and GGBS refine pore structure and lower permeability.

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3. Gas and Fluid Transport in Concrete

Transport phenomena through concrete are primarily governed by the **porosity and pore connectivity** of the cement matrix.

i. Gas Transport

- **Carbonation**: CO_2 diffuses into concrete and reacts with $Ca(OH)_2$ to form $CaCO_3$, reducing pH and promoting corrosion.
- **Oxygen Ingress**: Oxygen reaches steel reinforcement, aiding corrosion if moisture and chlorides are present.

ii. Fluid Transport

- **Water Penetration**: Occurs via capillary pores or cracks.
- **Chloride Ingress**: Primary cause of reinforcement corrosion, especially in coastal or de-icing salt environments.
- **Sulfate Attack**: Waterborne sulfates react with hydrated cement compounds, leading to expansion and cracking.

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4. Cracking in Concrete

Cracks are physical manifestations of internal stresses or material weaknesses. They serve as direct pathways for aggressive agents, increasing permeability and reducing durability.

i. Classification of Cracks

- **Structural Cracks**: Due to load, settlement, thermal movement.
- **Non-structural Cracks**: Due to shrinkage, poor workmanship, environmental effects.

ii. Causes of Cracking

a. Plastic Shrinkage

- Occurs in fresh concrete due to rapid surface drying.
- Results in shallow cracks, often appearing within a few hours of placing.

b. Drying Shrinkage

- Long-term evaporation of moisture from hardened concrete causes contraction.
- Leads to distributed fine cracks on the surface.

c. Thermal Cracking

- Results from temperature differentials, especially in mass concrete.
- Heat of hydration and ambient temperature changes are key drivers.

d. Creep and Load-Induced Cracks

- Sustained loading causes deformation and possible cracking due to stress relaxation.

e. Corrosion-Induced Cracking

- Expansion of corroding steel reinforcement generates internal tensile stresses in concrete, causing it to crack and spall.

f. Alkali-Aggregate Reaction (AAR)

- Alkalis in cement react with reactive aggregates, forming expansive gel.
- Cracks appear in random patterns with exudation of gel in severe cases.

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5. Testing for Durability and Permeability

a. Water Permeability Test (IS 3085)

- Measures depth and rate of water penetration under pressure.
- Used to classify concrete as impermeable or permeable.

b. Rapid Chloride Permeability Test (RCPT – ASTM C1202)

- Measures total charge passed (Coulombs) to assess chloride ion permeability.

c. Oxygen Permeability Index (OPI)

- Used to evaluate the ease with which oxygen diffuses through concrete, a factor in corrosion risk.

d. Sorptivity Test

- Measures the rate of capillary suction of water.

e. Carbonation Depth Test (Phenolphthalein Indicator)

- Used to detect the depth of carbonation in hardened concrete.

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6. Improving Durability and Reducing Permeability

- **Use of Pozzolanic Admixtures**: Silica fume, fly ash, GGBS reduce pore size and connectivity.
- **Proper Curing**: Ensures adequate hydration and reduces surface porosity.
- **Low Water-Cement Ratio**: Leads to denser and more durable concrete.
- **Use of Water-Proofing Agents**: Integral water-proofing compounds enhance resistance.
- **Surface Coatings & Sealers**: Acrylics, epoxies, or silanes to limit ingress of aggressive agents.
- **Adequate Cover to Reinforcement**: Prevents rapid ingress of harmful gases or liquids.

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7. Relationship Between Durability and Permeability

There is a **direct correlation** between permeability and durability:

- Lower permeability usually means better durability.
- Permeability accelerates degradation processes like corrosion and sulfate attack.
- Durability design must include permeability control through material selection, mix design, and detailing.

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8. Role of Microstructure in Durability and Permeability

8.1 Microstructure of Hardened Cement Paste

The hardened cement paste comprises:

- **Capillary pores** (large, connected pores – 10 nm to several μm)
- **Gel pores** (very fine pores within C-S-H structure – <10 nm)
- **Unhydrated cement grains**

- **Crystalline products** like $Ca(OH)_2$, ettringite, etc.

The microstructure directly controls:

- Strength
- Permeability
- Durability
- Shrinkage and creep

A dense, well-hydrated microstructure resists ingress of fluids and gases, ensuring longer durability.

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9. Durability Design Considerations in Structural Engineering

9.1 Durability Design Philosophy (IS 456:2000 & IS 1343)

Design for durability includes:

- Selecting suitable **exposure class**
- Specifying **minimum cement content and maximum w/c ratio**
- Ensuring **minimum cover to reinforcement**
- Choosing proper **curing period**
- Selecting **durable aggregates**

9.2 Exposure Classifications (as per IS 456:2000)

Exposure Condition	Example Locations	w/c Max	Min Cement (kg/m^3)	Cover to Reinforcement
Mild	Indoors, dry zone	0.55	300	20 mm
Moderate	Coastal plains	0.50	300	30 mm
Severe	Coastal splash zones	0.45	320	45 mm
Very Severe	Marine splash	0.45	340	50 mm

Exposure Condition	Example Locations	w/c Max	Min Cement (kg/m^3)	Cover to Reinforcement
Extreme	Direct contact with sea water	0.40	360	75 mm

10. Durability Enhancing Materials and Techniques

10.1 Mineral Admixtures

- **Fly Ash**: Reduces permeability, increases long-term strength.
- **Silica Fume**: Highly effective in refining pores; best for high-performance concrete (HPC).
- **Ground Granulated Blast Furnace Slag (GGBS)**: Increases resistance to sulfate and chloride attack.

10.2 Chemical Admixtures

- **Water reducers/superplasticizers**: Lower water demand.
- **Corrosion inhibitors**: Reduce reinforcement corrosion rate.
- **Integral waterproofing agents**: Fill pores and capillaries internally.

10.3 Coatings & Surface Treatments

- **Epoxy coatings**: Strong barrier to chemical and water ingress.
- **Acrylic sealers**: UV-resistant; prevent carbonation.
- **Silanes/Siloxanes**: Penetrating hydrophobic agents for facades.

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11. Cracks and Their Role in Accelerating Permeability

Cracks, even micro-cracks invisible to the eye, can drastically increase permeability by connecting the internal pore network to the surface.

11.1 Crack Width and Durability

- Cracks > **0.3 mm** can allow direct ingress of harmful ions.
- IS 456 recommends controlling surface crack widths within **0.2 mm** in aggressive environments.

- Cracks can increase:
  - Chloride ingress up to **10x**
  - Carbonation depth
  - Corrosion initiation time

11.2 Crack-Healing Phenomena

In some cases, concrete exhibits **autogenous healing**, where calcium hydroxide and unreacted cement hydrate and seal small cracks.

- Occurs best in moist conditions
- Works effectively for cracks < **0.1 mm**

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12. Durability Testing in Real-Time Projects

12.1 Core Sampling

- Concrete cores extracted from structures are tested for:
  - Compressive strength
  - Carbonation depth
  - Chloride content profile
  - Water absorption

12.2 NDT (Non-Destructive Testing) Techniques

Test Type	Purpose
Rebound Hammer Test	Surface hardness (indicative strength)
Ultrasonic Pulse Velocity	Detect internal cracks and homogeneity
Half-cell Potential	Detect corrosion activity in rebar
Ground Penetrating Radar	Map rebar placement and concrete cover

13. Case Studies: Failures Due to Poor Durability

13.1 Coastal Bridge (Chloride Attack)

- Premature corrosion of reinforcement due to inadequate cover and poor concrete quality.
- Chloride permeability was >4000 Coulombs (ASTM C1202 – High Risk).

13.2 High-Rise Building (Carbonation)

- Carbonation depth reached the reinforcement layer in 6 years due to insufficient curing and poor surface quality.
- pH reduced to <9; corrosion started.

13.3 Industrial Floor (Sulfate Attack)

- Exposure to chemicals without protective lining.
- Ettringite formation caused expansion and cracking.

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14. Recent Advances in Enhancing Durability

14.1 Self-Healing Concrete

- Contains bacteria (e.g., *Bacillus pasteurii*) or encapsulated agents that precipitate $CaCO_3$ to seal cracks.
- Increases service life with minimal maintenance.

14.2 Nano-Modified Concrete

- Nanoparticles (nano-SiO_2, TiO_2) refine pore structure and enhance hydration.
- Improves impermeability and resistance to degradation.

14.3 Ultra High Performance Concrete (UHPC)

- Very low permeability due to extremely dense microstructure.
- Used in long-span bridges, marine structures, and nuclear facilities.
