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Concrete Technology: Materials, Mechanical Behaviour, Durability and Sustainability – A Detailed Review

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ABSTRACT
Concrete is the most widely used construction material globally due to its adaptability, strength, durability, and economic feasibility. Over the last few decades, significant advancements have been made in material science, mix proportioning techniques, durability design, and sustainable construction practices. This review paper presents a comprehensive discussion on constituent materials, hydration mechanisms, fresh and hardened properties, advanced concretes such as Self-Compacting Concrete (SCC), High Performance Concrete (HPC), Fiber Reinforced Concrete (FRC), durability issues, and sustainability aspects. Research developments reported in literature up to May 2016 are critically reviewed.
Keywords: *Concrete Technology, Durability, High Performance Concrete, SCC, Sustainability, Mix Design*

I. INTRODUCTION

Concrete is a composite material composed primarily of cement, aggregates, water, and chemical or mineral admixtures. Its development dates back to ancient civilizations, but modern concrete technology evolved after the invention of Portland cement in the 19th century. With rapid urbanization and infrastructure growth, concrete production has increased enormously. Recent research focuses on improving mechanical performance, extending service life, and reducing environmental impact.

II. MATERIALS USED IN CONCRETE

The performance of concrete depends largely on the characteristics of its constituent materials.

2.1 Cement and Supplementary Cementitious Materials

Ordinary Portland Cement (OPC) is the most commonly used binder. Hydration of cement produces calcium silicate hydrate (C-S-H), which provides strength. Supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag improve durability, reduce permeability, and enhance long-term strength.

2.2 Aggregates

Aggregates constitute about 60–75% of concrete volume. Proper grading reduces voids and enhances density. Aggregate shape, texture, strength, and absorption influence workability and mechanical performance.

2.3 Water and Admixtures

Water initiates hydration reactions. The water-cement ratio significantly affects strength and durability. Chemical admixtures such as superplasticizers, retarders, accelerators, and air-entraining agents modify fresh and hardened properties.

III. HYDRATION MECHANISM AND MICROSTRUCTURE

Hydration is a complex chemical process involving reactions between cement compounds and water. The formation of C-S-H gel and calcium hydroxide governs strength development. Microstructural characteristics such as pore size distribution directly influence permeability and durability.

Main Cement Compounds

The four major clinker phases in ordinary Portland cement:

- C_3S – Tricalcium silicate
- C_2S – Dicalcium silicate
- C_3A – Tricalcium aluminate
- C_4AF – Tetracalcium aluminoferrite

(Shorthand: C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3)

Stages of Hydration (Heat Evolution Curve)

1. Initial Hydrolysis (Minutes)

- Rapid reaction when water contacts cement.
- Dissolution of ions (Ca^{2+}, OH^-, SO_4^{2-}).
- Short heat spike.
- Plastic mix stage.

2. Dormant / Induction Period (1–3 hours)

- Very low reaction rate.
- Concrete remains workable.
- Allows transport, placing, compaction.

3. Acceleration Period (3–10 hours)

- Rapid formation of hydration products.
- Setting occurs (initial + final set).
- Peak heat evolution.
- C_3S hydration dominates.

4. Deceleration Period (10 hours–1 day)

- Hydration slows as products coat particles.
- Strength begins to develop.

5. Steady State / Long-Term Hydration (Days–Years)

- Slow C_2S hydration.
- Continued densification.
- Long-term strength gain.

Main Hydration Reactions

Silicate Hydration (Strength Producing)

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$$

Products:

C–S–H (Calcium silicate hydrate) → main strength phase

CH (Calcium hydroxide) → crystalline, weak

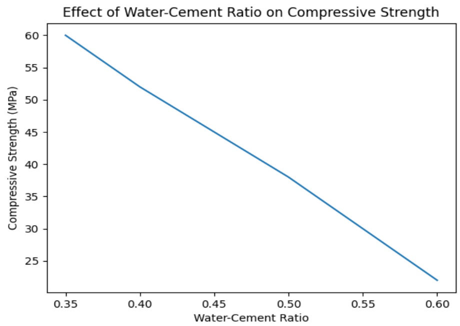
C_2S hydration (later strength):

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$$

IV. FRESH CONCRETE PROPERTIES

Fresh concrete properties include workability, consistency, segregation resistance, and bleeding characteristics. Workability is commonly measured using slump test, compaction factor test, and flow table test.

Chart 1: Effect of Water-Cement Ratio on Strength



V. HARDENED CONCRETE PROPERTIES

Hardened properties include compressive strength, tensile strength, modulus of elasticity, shrinkage, creep, and durability. Compressive strength is the most important parameter for structural design. Tensile strength is significantly lower than compressive strength, hence reinforcement is required in structural applications.

1. Strength Properties

(a) Compressive Strength

- Most important property.
- Measured on cubes or cylinders (7, 28 days).
- Depends on:
  - water–cement ratio
  - degree of hydration
  - curing
  - aggregate quality
- Typical range: **20–60 MPa** (normal concrete).

Key relation:
Lower w/c ratio → higher strength.

(b) Tensile Strength

- Concrete is weak in tension.
- ≈ 8–12% of compressive strength.
- Measured by:
  - split cylinder test
  - direct tension (rare)

(c) Flexural Strength (Modulus of Rupture)

- Resistance to bending.
- Important for pavements, slabs.
- ≈ 10–20% of compressive strength.

2. Elastic Properties

(a) Modulus of Elasticity (E)

- Stiffness of concrete.
- Depends mainly on aggregate stiffness.
- Typical: **20–40 GPa**.

Higher strength → higher modulus.

(b) Poisson's Ratio

- Lateral strain / longitudinal strain.
- Typical: **0.15–0.20**.

3. Time-Dependent Deformations

(a) Creep

- Gradual increase in strain under sustained load.
- Occurs due to viscous flow of C–S–H gel.
- Influenced by:
    - humidity
    - stress level
    - age at loading
    - w/c ratio

Effects:

- deflection increase
- prestress loss
- stress redistribution

(b) Shrinkage

Volume reduction without load.

Types:

- Plastic shrinkage (early)
- Drying shrinkage
- Autogenous shrinkage
- Carbonation shrinkage

Causes: moisture loss, hydration.

Effects: cracking.

4. Durability Properties

(a) Permeability

- Ease of fluid penetration.
- Controlled by capillary pores.
- Low permeability → durable concrete.

(b) Water Absorption

- Indicates pore connectivity.
- Higher absorption → weaker durability.

(c) Resistance to Chemical Attack

Concrete may deteriorate due to:

- sulfates
- acids
- seawater
- carbonation

Dense microstructure improves resistance.

(d) Freeze–Thaw Resistance

- Important in cold climates.
- Water in pores expands on freezing.
- Air entrainment improves resistance.

5. Density and Porosity

Density

- Normal concrete: **2400 kg/m³**
- Lightweight: 300–1850 kg/m³
- Heavyweight: up to 4000 kg/m³

Porosity

- Volume of voids.
- Higher porosity → lower strength & durability.

6. Abrasion and Wear Resistance

- Important for floors, pavements, hydraulic structures.
- Improves with:
  - hard aggregates
  - high strength
  - proper curing

7. Thermal Properties

- Coefficient of thermal expansion:
  8–12 × 10^{-6} /°C
- Thermal conductivity depends on density.
- Affects cracking in temperature changes.

8. Bond Strength with Steel

- Adhesion between concrete and reinforcement.
- Essential for reinforced concrete action.
- Influenced by:
  - concrete strength
  - bar surface
  - cover
  - confinement

Factors Affecting Hardened Concrete Properties

- Water–cement ratio
- Cement type
- Aggregate type & grading
- Curing conditions
- Age of concrete
- Admixtures
- Compaction

Microstructure–Property Link (Key Concept)

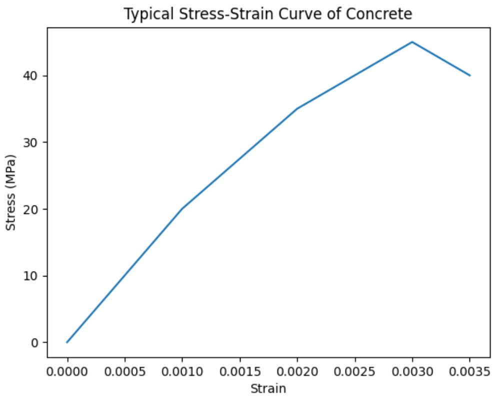
Denser hydration products + fewer capillary pores →
✔ higher strength
✔ lower permeability
✔ better durability

Exam-Ready Summary

Hardened concrete properties include:

- Strength (compressive, tensile, flexural)
- Elastic properties (modulus, Poisson's ratio)
- Creep and shrinkage
- Durability (permeability, chemical resistance)
- Density and porosity
- Abrasion resistance
- Thermal properties
- Bond with steel

Figure 1: Typical Stress-Strain Curve of Concrete



VI. ADVANCED CONCRETE TECHNOLOGIES

Self-Compacting Concrete (SCC) flows under its own weight without vibration. High Performance Concrete (HPC) provides superior mechanical and durability properties. Fiber Reinforced Concrete (FRC) enhances crack resistance and toughness.

VII. DURABILITY OF CONCRETE

Durability problems include chloride ingress, sulphate attack, carbonation, alkali-silica reaction, freeze-thaw cycles, creep, and shrinkage. Proper mix design and curing significantly improve durability performance.

VIII. SUSTAINABILITY AND ENVIRONMENTAL ASPECTS

The cement industry contributes significantly to global CO2 emissions. Use of SCMs, recycled aggregates, and optimized mix design reduces environmental impact. Life-cycle assessment is increasingly used for sustainable evaluation.

IX. CONCLUSION

Concrete technology has evolved considerably with advancements in material science and durability design. Future developments are expected to focus on sustainability, performance optimization, and smart materials.

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