Chapter 1: Cement – Production and Composition

1.1 Introduction

Cement is the backbone of modern construction, acting as the binding material in concrete and mortar. Its importance in civil engineering is unparalleled, as it plays a key role in infrastructure development—roads, bridges, buildings, dams, and more. The properties of cement significantly influence the strength and durability of concrete, making it essential for engineers to understand its manufacturing process and chemical composition in depth.

1.2 Types of Cement Used in Construction

Although Ordinary Portland Cement (OPC) is the most widely used, several types of cement exist, including:

- **OPC (Ordinary Portland Cement)** – Grades 33, 43, 53
- **PPC (Portland Pozzolana Cement)**
- **PSC (Portland Slag Cement)**
- **Rapid Hardening Cement**
- **Low Heat Cement**
- **Sulphate Resisting Cement**
- **White Cement**
- **Coloured Cement**
- **Expansive Cement**

This chapter focuses primarily on OPC, especially its production and composition.

1.3 Raw Materials Used in Cement Manufacturing

Cement production begins with raw materials that contain the main oxide components:

Material	Constituents	Purpose
Limestone	$CaCO_3$ (Calcium Carbonate)	Provides lime (CaO)
Clay/Shale	Silica, Alumina, Iron oxide	Provides SiO_2, Al_2O_3, Fe_2O_3
Laterite	Iron oxide and alumina	Supplementary source of Fe_2O_3 and Al_2O_3
Gypsum	$CaSO_4 \cdot 2H_2O$	Regulates setting time
Corrective materials	Bauxite, sand, iron ore	Used to correct deficiencies in raw mix

1.4 Manufacturing Process of Cement

The manufacturing of cement can be divided into **two main processes**:

1.4.1 Wet Process (Obsolete in India)

In the wet process:

- Raw materials are mixed with water to form a slurry.
- This slurry is fed into rotary kilns.
- High fuel consumption is a major disadvantage.

> **Note:** Due to high energy consumption and environmental concerns, the wet process is now rarely used.

1.4.2 Dry Process (Modern and Efficient)

The dry process is widely used in contemporary cement plants. It involves the following stages:

1.4.2.1 Crushing and Grinding

- Limestone and clay are extracted from quarries and crushed into small pieces.
- These are then ground to a fine powder in ball mills or vertical roller mills.

1.4.2.2 Proportioning and Blending

- The raw materials are proportioned using gravimetric or volumetric feeders.
- Proper blending ensures uniform chemical composition in the final product.

1.4.2.3 Preheating

- The raw meal is passed through a series of cyclonic preheaters.
- Heat from kiln gases is used to preheat the meal to about 800°C.

1.4.2.4 Calcination

- At around 900°C, calcium carbonate ($CaCO_3$) decomposes to calcium oxide (CaO) and carbon dioxide (CO_2).

$$CaCO_3 \rightarrow CaO + CO_2 \uparrow$$

1.4.2.5 Clinker Formation in Rotary Kiln

- The most critical stage, occurring at 1450°C.
- Chemical reactions occur to form **clinker nodules**:

  Major reactions:

  - Formation of C_3S (Alite) and C_2S (Belite)
  - Reaction of alumina and iron oxide with lime to form C_3A and C_4AF

1.4.2.6 Cooling of Clinker

- Hot clinker is cooled rapidly using air in **grate coolers**.
- Rapid cooling preserves the desired mineral forms.

1.4.2.7 Grinding with Gypsum

- Clinker is mixed with 3–5% gypsum and ground into a fine powder in ball mills.
- Gypsum controls the setting time by moderating the hydration of tricalcium aluminate (C_3A).

1.4.2.8 Storage and Packaging

- The final product (cement) is stored in **silos**.
- It is packed in bags (usually 50 kg) or supplied in bulk through tankers.

1.5 Chemical Composition of OPC

Cement primarily consists of the following **oxides**:

Oxide	Chemical Formula	Approximate % in OPC
Lime	CaO	60–67%
Silica	SiO_2	17–25%
Alumina	Al_2O_3	3–8%
Iron Oxide	Fe_2O_3	0.5–6%
Magnesia	MgO	0.1–4%
Sulphur Trioxide	SO_3	1–3%
Alkalis	Na_2O, K_2O	0.2–1.3%

1.6 Bogue's Compounds

The above oxides combine during kiln burning to form **four main compounds**, known as **Bogue's compounds**:

Compound	Abbreviation	Chemical Formula	Role in Cement
Tricalcium Silicate	C_3S	$3CaO \cdot SiO_2$	Early strength (initial 7 days)
Dicalcium Silicate	C_2S	$2CaO \cdot SiO_2$	Later strength (after 7 days)
Tricalcium Aluminate	C_3A	$3CaO \cdot Al_2O_3$	Fast reaction, contributes to early setting
Tetracalcium Aluminoferrite	C_4AF	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	Imparts grey colour, low strength contribution

1.7 Heat of Hydration

When cement is mixed with water, **exothermic chemical reactions** occur. This is called **heat of hydration**.

Key Reactions:

- $C_3S + H_2O \rightarrow$ C-S-H (Calcium Silicate Hydrate) + $Ca(OH)_2$ + heat

- $C_2S + H_2O \rightarrow$ C-S-H + $Ca(OH)_2$ (less heat than C_3S)
- C_3A + gypsum + $H_2O \rightarrow$ Ettringite (expansive)

The heat generated is critical in massive concrete structures like dams, where **temperature rise may cause cracks**.

1.8 Role of Gypsum in Cement

Without gypsum, cement would set almost immediately upon adding water. Gypsum acts as a **retarder**:

- It **delays the hydration of C_3A**, controlling the setting time.
- Typically, **3–5% gypsum** is added during grinding.

1.9 Quality Control in Cement Manufacturing

- **Raw Material Testing:** Chemical and physical properties of raw materials are tested regularly.
- **Clinker Quality:** Clinker composition is monitored to maintain the required C_3S and C_2S content.
- **Final Product Testing:** The cement is tested for:
    - Fineness (Blaine's air permeability test)
    - Setting time (initial and final)
    - Soundness (Le Chatelier test)
    - Compressive strength (standard mortar cube)

1.10 Environmental Concerns and Innovations

Cement manufacturing contributes significantly to **CO_2 emissions** due to:

- Calcination of limestone
- Combustion of fossil fuels in kilns

Modern Innovations:

- **Blended cements** (with fly ash, slag)
- **Carbon capture and storage (CCS)**

- **Alternative fuels** (biomass, waste-derived fuels)
- **Low-clinker cements** for sustainability

1.11 Indian Standards Related to Cement

To ensure quality and uniformity, cement production and testing are governed by **Bureau of Indian Standards (BIS)** specifications. The key IS codes include:

Standard	Title
IS 269	Ordinary Portland Cement, 33 Grade
IS 8112	Ordinary Portland Cement, 43 Grade
IS 12269	Ordinary Portland Cement, 53 Grade
IS 1489 (Part 1 & 2)	Portland Pozzolana Cement (fly ash-based and calcined clay-based)
IS 455	Portland Slag Cement
IS 3812	Fly Ash for use in cement and concrete
IS 4031 (Parts 1 to 15)	Methods of physical tests for hydraulic cement
IS 4032	Methods of chemical analysis of hydraulic cement
IS 650	Standard sand for testing of cement
IS 8042	White Portland Cement

These standards specify:

- Fineness (specific surface area)
- Compressive strength requirements
- Setting time ranges
- Soundness limits
- Chemical composition limits (e.g., $MgO < 6\%$, $SO_3 < 3\%$)

1.12 Cement Testing in Laboratories

To maintain uniform performance, several **standard laboratory tests** are conducted:

1.12.1 Fineness Test

- Measured using **Blaine's air permeability apparatus** or sieve analysis.
- Greater fineness → higher surface area → faster hydration → early strength.

1.12.2 Consistency Test

- Determines the water content required for normal consistency using **Vicat's apparatus**.
- Important for other setting time and soundness tests.

1.12.3 Setting Time Test

- **Initial setting time**: Time taken to lose plasticity (minimum 30 minutes as per IS code).
- **Final setting time**: Time to complete hardening (max 600 minutes).

1.12.4 Soundness Test

- Measures volume stability using **Le Chatelier's apparatus**.
- Ensures cement does not expand excessively after setting.

1.12.5 Compressive Strength Test

- Conducted on mortar cubes (1:3 cement:sand ratio).
- Cured in water for 3, 7, and 28 days.
- Minimum strength for OPC 53 grade = 53 MPa (after 28 days).

1.13 Storage of Cement

Improper storage leads to **moisture absorption**, lump formation, and loss of strength.

Guidelines for Safe Storage:

- Store in airtight, moisture-free warehouses.
- Stack cement bags **not more than 10 bags high**.
- Place on raised wooden platforms at least 150 mm above the floor.
- Maintain FIFO (First In, First Out) usage principle.

- Avoid storing cement for more than **3 months** if not sealed.

1.14 Adulteration and Shelf Life of Cement

Cement may lose strength if:

- It is adulterated with excessive fly ash or sand.
- It absorbs atmospheric moisture.
- It is used beyond its **shelf life (3 months ideally)**.

Field checks for **lumpy bags**, poor flowability, or color changes can help detect deteriorated cement.

1.15 Innovations in Cement Technology

Modern civil engineering demands sustainable, performance-enhanced cement products. Several innovations have emerged:

1.15.1 Green Cement

- Lower carbon footprint.
- Manufactured using **alkali-activated binders**, **geopolymers**, or **limestone calcined clay cement (LC^3)**.

1.15.2 Nano-Modified Cement

- Nanoparticles (e.g., nano-silica) are added to improve strength, reduce porosity, and accelerate hydration.

1.15.3 Self-Healing Cement

- Embedded bacteria or capsules release minerals to seal cracks upon contact with water.

1.15.4 Photocatalytic Cement

- Contains **titanium dioxide (TiO_2)** which breaks down pollutants when exposed to sunlight (used in facades and pavements).

1.16 Cement Industry in India – An Overview

India is the **second-largest producer of cement in the world**, with a production capacity exceeding **500 million tonnes per annum (MTPA)**.

Key Industry Highlights:

- Major players: Ultratech, ACC, Ambuja, Dalmia, Shree Cement, Ramco, JK Cement.
- Energy-intensive industry with a high environmental footprint.
- Shift toward blended and eco-friendly cement.

Cement Zones in India:

- **North Zone**: Rajasthan, Haryana
- **South Zone**: Tamil Nadu, Andhra Pradesh, Telangana
- **East Zone**: Odisha, Chhattisgarh
- **West Zone**: Gujarat, Maharashtra

1.17 Future Trends in Cement Manufacturing

- **Carbon-Neutral Production**: Net-zero cement manufacturing targets for 2050.
- **Waste Utilization**: Use of industrial by-products like red mud, copper slag, and marble dust.
- **Digital Cement Plants**: AI, IoT, and real-time analytics for process optimization.
- **3D Printing with Cementitious Materials**: For modular, customizable construction with minimal waste.
