People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
Chadli Bendjedid – El Tarf University
Faculty of Science and Technology
Department of Civil Engineering

Course

Construction Materials

Dr. Guemidi Ismahene

Academic Year: 2025–2026

Presentation

The present handout, entitled **"Construction Materials"**, is primarily intended for second-year Civil Engineering students as an educational support. It is written in a simplified manner to provide a comprehensive working tool and a reference for covering the knowledge required in this field.

This educational material aims to present, concisely, the essential information regarding the raw materials used in the field of civil engineering in general, and more specifically, construction materials.

The handout is organized into four chapters. The first chapter is dedicated to presenting general information on construction materials, particularly their physical, chemical, and mechanical properties.

The second chapter addresses all aspects related to aggregates, including their classification, nature, origin, types, as well as their characteristics and applications in the field of civil engineering.

The third chapter focuses on a detailed study of mineral binders, examining their manufacturing processes, properties, and standardized classifications, with particular emphasis on plasters, limes, and cements.

The final chapter provides an introduction to cementitious matrix materials. It presents, in a concise manner, the concepts related to mortars, including their constituents, compositions, properties, and applications.

Chapter I: General Information
(Properties of Construction Materials)

1. Introduction 01
2. History of Construction Materials 01
3. Classification of construction materials.....03
3.1- Basic materials and composite products.....03
3.2- According to usage.....03
4. Properties of construction materials.....03
4.1- Physical properties 04
4.1.1- Density 04
4.1.2- Porosity and Compactness 06
4.1.2.1- Porosity affects 06
4.1.3- Hygroscopicity (Moisture) 07
4.1.4- Water Absorption Capacity 07
4.1.5- Frost Resistance 07
4.1.6- heat flux 08
4.1.7- Thermal conductivity 08
4.1.8- Thermal resistance 09
4.1.9- Fire resistance 09
4.2- Chemical Properties 09
4.3- Mechanical Properties 10
4.3.1- Compressive strength 10
4.3.2- Tensile Strength 11
4.3.3- Deformation 12
4.3.3.1- Tensile test on a mild steel specimen 12
4.3.4- Shock resistance 13
5. Measurement of Resistance Using Non-Destructive Methods 13
6. Exercise 14

Chapter II: Aggregates

1- Introduction 18
1.1- Definition of Aggregates.....18
2- Classification of Aggregates.....19
2.1- Granularity.....19
2.2- Origin.....19
2.2.1- Natural Aggregate.....19
2.2.2-Artificial Aggregate.....20
2.2.3- Recycled Aggregate.....20
2.3- Shape.....20
2.4- Bulk Density.....21
3- Particle size analysis.....21
3.1-Steps of Particle Size Analysis.....22

3.1.1-The granulometric composition.....23
3.1.2-Calculate the Cumulative Residue.....23
3.2-Fineness Modulus.....25
3.2.1-Correction of the Sand Fineness Modulus.....25
3.3- Uniformity coefficient.....26
3.4- Coefficient of curvature 26
4- Aggregate Cleanliness.....27
4.1-Impurity test.....27
4.1.1- Washing method.....27
4.1.2- Sand equivalent.....27
5- Volumetric Coefficient.....31
5.1- Principle of the test 31
5.2- Equipment required.....32
5.3- Operating Method.....32
5.4- Rolled Aggregates and Crushed Aggregates.....33
5.4.1- Rolled Aggregates.....34
5.4.2- Crushed Aggregates.....34
6- Water absorption.....34
6.1- For gravel [NF P 18- 554].....34
6.2- For sand:[NF P 18- 555].....34
7- Density.....36
7.1- Bulk density 36
7.1.1- Required equipment.....36
7.1.2-Test procedure.....37
7.2- Absolute density.....37
7.2.1- Graduated cylinder method.....37
7.2.2- Pycnometer Method.....38
8- Water content.....39
8.1- Required Equipment.....39
8.2- Operating mode 40
9- Splitting of sand.....40
9.1- Expansion definition.....41
9.2- Materials needed.....41
9.3- Operating mode 41
10- Measurement of the Flakiness Index [NF P 18-561].....42
11- Los Angeles Test [NF P 18-573].....44
12- Micro-Deval Test [NF P 18-572].....45
13- Exercise.....46

Chapter III: Mineral Binders

1- Introduction 50
1.1- Definition of Mineral Binders.....50
1.2- The Evolution of Binder Manufacturing Techniques Used in Construction.....50
2- Classification of Binders.....52
2.1- Air binders.....52

2.2- Hydraulic Binders.....52
3- Plaster.....53
a- Definition.....53
b- Raw Materials.....54
3.1- Plaster manufacturing process 55
3.1.1- Plaster Firing Processes.....56
3.1.2- Rotary kiln.....57
3.2- Classification of plasters.....58
3.2.1- According to the firing temperature.....58
3.2.2- According to the fineness of grinding (their uses).....59
3.2.3- Manufacture of high-strength plaster.....59
3.3- Specific properties of plaster.....60
3.3.1- Grinding fineness.....60
3.3.2- Normal consistency (Souttard mold).....60
3.3.3- Setting Time (Vicat Apparatus).....60
3.3.3.1- Operating Method.....61
3.3.4- Mechanical strength.....62
3.4- The various forms of manufactured plaster.....63
3.4.1- Normal plasters 63
3.4.2- Special plasters.....63
3.4.3- In the medical field.....63
3.4.4- In the field of fine arts.....64
3.5- Characteristics of plaster.....64
3.5.1- Plaster has fire-resistant properties.....64
3.5.2- Plaster acts as a hygrometric regulator.....64
3.5.3- It provides satisfactory sound insulation.....64
3.5.4- Plaster functions as a thermal insulator.....65
4- Air lime.....65
4.1- Quicklime (CaO).....65
4.1.1- Quicklime manufacturing process 65
4.2- Slaked lime.....67
4.3- Classification of limes.....67
4.3.1- Pure, rich, or fat lime.....67
4.3.2- Hydraulic lime.....67
4.3.3- Lean or poor lime.....68
4.4- Their uses.....68
5- Portland cement.....68
5.1- Definition.....68
5.2- The raw materials used in cement manufacturing.....69
5.3- Cement manufacturing process.....70
5.3.1- Wet process.....70
5.3.2- Dry process.....70
5.4- Cement manufacturing process by the dry method.....70
5.4.1- Extraction.....70
5.4.2- Crushing.....71
5.4.3- Raw mix grinding.....71
5.4.4- Firing process.....71
5.4.5- Cooling.....73
5.4.6- Grinding.....73

5.4.7- Cement dispatch.....73
5.5- Clinker.....73
5.6- Hydration phenomenon.....75
5.6.1- Hydrated calcium silicate (CSH).....77
5.6.2- Portlandite [CH].....77
5.6.3- Hydration of C3A.....77
5.6.4- The hydration rate of the main components of cement.....78
5.7- Different types of cement.....79
5.8- Applications of different types of cement.....79
5.9- Properties of Cement.....80
5.9.1- Measurement of cement fineness [NF EN 196-6].....80
5.9.2- Density.....82
5.9.3- Standard Consistency.....82
5.9.4- Shrinkage.....83
5.9.5- Mechanical Properties.....84
5.10- Factors Influencing the Strength of Cement.....85
5.10.1- The chemical composition of the cement.....86
5.10.2-The water-cement ratio (W/C).....86
5.10.3- The degree of fineness of the cement.....86
5.10.4- Curing conditions.....86
5.10.5- Additives and admixtures.....86
5.11- Mineral Additions.....86
5.12- The drawbacks of excessive cement production.....87
5.12.1- Environmental impact.....87
5.12.2- Economic impact.....87
6. Exercises.....88

Chapter IV: Mortars

1- Introduction.....89
2- Definition of Mortar.....89
3- What are the roles of mortar.....89
4- Fundamental Characteristics of Mortar.....90
5- Components of Mortar.....90
5.1- Binders.....90
5.2- Sand.....91
5.3- Water.....91
5.4- Admixtures.....92
5.5-Additives.....93
5.5.1-NaturalPozzolan.....93
5.5.2- Blast Furnace Slag.....94
5.5.3- Silica Fume.....94
6- Classification of Mortars 94
6.1- Nature of the binder.....94
6.1.1- Cement mortars.....94

6.1.2- Lime mortars.....94
6.1.3- Mixed mortars.....94
6.2- Apparent Bulk Density.....95
6.3- Intended Use.....95
6.3.1- Masonry joints.....95
6.3.2-Plasters.....96
7- Main characteristics.....98
7.1- Workability.....98
7.1.1- The shaking table.....98
7.1.2- The LCPC Workability Tester.....99
7.2- Setting Time.....100
7.3- Mechanical Strength.....101
7.3.1-Molds and Specimens.....101
7.3.2-Mortar Preparation.....101
7.3.3- Specimen Preparation and Curing.....102
7.4- Shrinkage and Swelling.....104
8. Exercise.....105

List of Figures

Figure I.1: Civil Engineering Structures and Infrastructure.....01
Figure I.2: Evolution of human dwellings over time.....02
Figure I.3: The Evolution of Construction.....02
Figure I.4: Properties of construction materials.....04
Figure I.5: Relationship between Porosity, Compactness, and Unit Volume.....06
Figure I.6: Types of Mechanical Stresses in Materials.....10
Figure I.7: Mild steel bar with an initial length L0.....12
Figure I.8: Stress-Strain Curve and Material Failure Stages.....13

Figure II.1: Types of aggregates.....18
Figure II.2: Sieves with different mesh sizes.....19
Figure II.3: Angular and rounded aggregates.....20
Figure II.4: The relationship between aggregate size, porosity, and compactness.....21
Figure II.5: Continuous and Discontinuous Grain-Size Curves.....22
Figure II.6: Sieve Analysis Chart for Aggregate Grain-Size Distribution.....23
Figure II.7: Sieve Stack for Aggregate Testing.....24
Figure II.8: Granulometric Curves of Sands and Gravels.....24
Figure II.9: Example of grain-size distribution curves and their coefficients of uniformity and curvature.....26
Figure II.10: Sand equivalent test.....28
Figure II.11: Procedure of the sand equivalent test.....30
Figure II.12: Equipment required.....32
FigureII.13: Real volume of the grains.....33
Figure II.14: the circumscribed spheres corresponding to the Di max.....33
Figure II.15: Aggregate Shapes.....33
Figure II.16: Mould and dame for the water absorption coefficient of the sands.....35
Figure II.17: Representation of bulk, true, and pore volumes in a granular material.....36
Figure II.18: Apparent density test equipment.....37
Figure II.19: Absolute density test equipment.....37
Figure II.20: Pycnometer Test Procedure.....39
Figure II.21: Water content test equipment.....40
Figure II.22: meniscus (water bridge).....41
Figure II.23: three dimensions of an aggregate.....43
Figure II.24: Series of sieves.....44
Figure II.25: Series of slotted grids.....44
Figure II.26: Los Angeles machine.....45
Figure II.27: Micro-Deval Test.....46

Figure III.1: The addition of aggregates to the paste produces mortars and concrete……50
Figure III.2: The clay……51
Figure III.3: Use of Gypsum Plaster by the Ancient Egyptians in Pyramid Construction……51
Figure III.4: Ancient Roman architecture……51
Figure III.5: Industrial cement production plant……52
Figure III.6: Classification of Binders……53
Figure III.7: Hydrated calcium sulfate (gypsum)……53
Figure III.8: Spearhead gypsum and Saccharoidal gypsum……54
Figure III.9: Solubility (in grams of calcium sulfate per kilogram of water)……55
Figure III.10: Different forms of gypsum crystals……55
Figure III.11: Plaster manufacturing process……56
Figure III.12: Autoclave……57
Figure III.13: Rotary kiln……57
Figure III.14: Heating gypsum at a temperature between 110 and 180 °C……58
Figure III.15: Heating gypsum at a temperature between 180 and 250 °C……58
Figure III.16: Heating gypsum at a temperature between 250 and 600 °C……59
Figure III.17: Souttard mold……60
Figure III.18: Vicat Apparatus……61
Figure III.19: Initial setting time……62
Figure III.20: Final setting time……62
Figure III.21 : Medical applications of plaster……63
Figure III.22 : The use of plaster in the field of fine arts……64
Figure III.23: Quicklime manufacturing process……66
Figure III.24: Conceptual illustration of a vertical furnace……66
Figure III.25: Applications of lime in the construction field……68
Figure III.26: Portland cement……69
Figure III.27: Diagram of the cement manufacturing process……69
Figure III.28: Mechanical shovels and bucket excavators……71
Figure III.29: The mode of transport for raw materials……71
Figure III.30: Cement Storage and Packaging……73
Figure III.31: The Clinker……74
Figure III.32: The Cement Manufacturing Process……75
Figure III.33: Exothermic Reaction……76
Figure III.34: SEM observation of the main hydrates: C-S-H and Portlandite....77
Figure III.35: Ettringite……78
Figure III.36: Evolution of the hydration of the main cement constituents over time……78
Figure III.37: The device used to determine the fineness of cement (Blaine Permeability Meter)……81
Figure III.38: Cement fineness test using Blaine's air permeability method……81

Figure III.39: Vicat apparatus equipped with the consistency probe……..83
Figure III.40: Deformation Measurement of Test Specimen with Comparator Apparatus……..84
Figure III.41: Flexural tensile tests and Compression test……..84
Figure III.42: Development of the mechanical strengths of the clinker components……..85
Figure III.43: development of the mechanical strength of standard mortar over time……85
Figure III.44: Arrangement of cement particles with ultrafine powder filling the voids……87
Figure III.45: Source of greenhouse gases……87

Figure IV.1: The mortar……89
Figure IV.2: Essential Roles of Mortar in Construction……90
Figure IV.3: Masonry joints……95
Figure IV.4: Traditional plasters……96
Figure IV.5: Decorative plasters……97
Figure IV.6: Sealing and grouting……97
Figure IV.7: Steel and Polypropylene Fibers Used in Sealing and Grouting Mortars……98
Figure IV.8: The shaking table……99
Figure IV.9: Operating principle of the workability tester……100
Figure IV.10: Vicat device with adjustments……100
Figure IV.11: Prismatic mold of 4 × 4 × 16 cm……101
Figure IV.12: 5-liter mortar mixer……102
Figure IV.13: Flexural strength test apparatus……103
Figure IV.14: Compression testing apparatus……104
Figure IV.15: Measuring shrinkage of mortar……105

List of Tables

Table I.1: Absolute and bulk density of construction materials ……05
Table I.2: Thermal conductivity of construction materials ……09
Table I.3: Compressive strength……11
Table I.4: Tensile Strength……11
Table II.1: Interpretation of Sand Equivalent Test Results ……31
Table II.2: Minimum mass of material needed to determine the water content according to the size of the elements passing through the mesh screen square opening dm……40
Table III.1: Mechanical strength of various types of plaster after 28 days of air curing……62
Table III.2: The thermal conductivity coefficient of some materials ……65
Table III.3: The raw materials used in cement manufacturing……70
Table III.4: Mineralogical composition of Portland cement clinker……74
Table III.5: Chemical composition of clinker……74
Table III.6: Hydration phenomenon over time……76
Table III.7: different types of cement……79
Table III.8: Applications of different types of cement……80
Table IV.1 : Water dosage for CPA 32.5 cement mortars according to sand fineness……91
Table IV.2 : Water dosage for hydraulic lime mortar (rolled sand 0/5 with ≤ 25% fines)……92
Table IV.3: The different types of admixtures and their main effects ……92
Table IV.4: The workability of mortar……99

List of Notifications

$\boldsymbol{\rho_{app}}$**:** Apparent density.

$\boldsymbol{\rho_{abs}}$**:** Absolute density.

P: Porosity

C: Compactness

W: Moisture

$\boldsymbol{m_w}$: The mass of the sample in its wet state.

$\boldsymbol{m_d}$: The dry mass of the sample (after drying in an oven at t= 105°C).

Ab: water absorption capacity

R $_{Frost}$: Frost resistance

$\boldsymbol{\lambda}$**:** Thermal conductivity

$\boldsymbol{R_{th}}$ **:** Thermal resistance

$\boldsymbol{\sigma_c}$**:** Compressive strength

$\boldsymbol{\sigma_t}$**:** Tensile Strength

$\boldsymbol{a_i}$: Partial residue on each sieve

$\boldsymbol{A_i}$: Cumulative residue

FM: Fineness modulus

$\boldsymbol{C_u}$: Uniformity coefficient

$\boldsymbol{C_c}$: Coefficient of curvature

SEv: Visual sand equivalent

Cv: Volumetric coefficient

$\boldsymbol{L_A}$: Los Angeles coefficient

MDE: Micro-Deval coefficient

SS: Cement fineness

C/W: Cement-to-water ratio

1. Introduction:

Construction materials are considered to include all materials used in the construction of reinforced concrete structures or metal constructions, such as buildings (skyscrapers), industrial constructions (factories, warehouses), hydraulic structures (dams), as well as materials used in public works, such as transportation infrastructure (tunnels, roads, railways, airports, etc.).



Figure I.1: Civil Engineering Structures and Infrastructure

2. History of Construction Materials

Sheltering or finding refuge represents one of the essential needs of human beings.



500 000 years ago



1000 years ago



Figure I.2: Evolution of human dwellings over time.

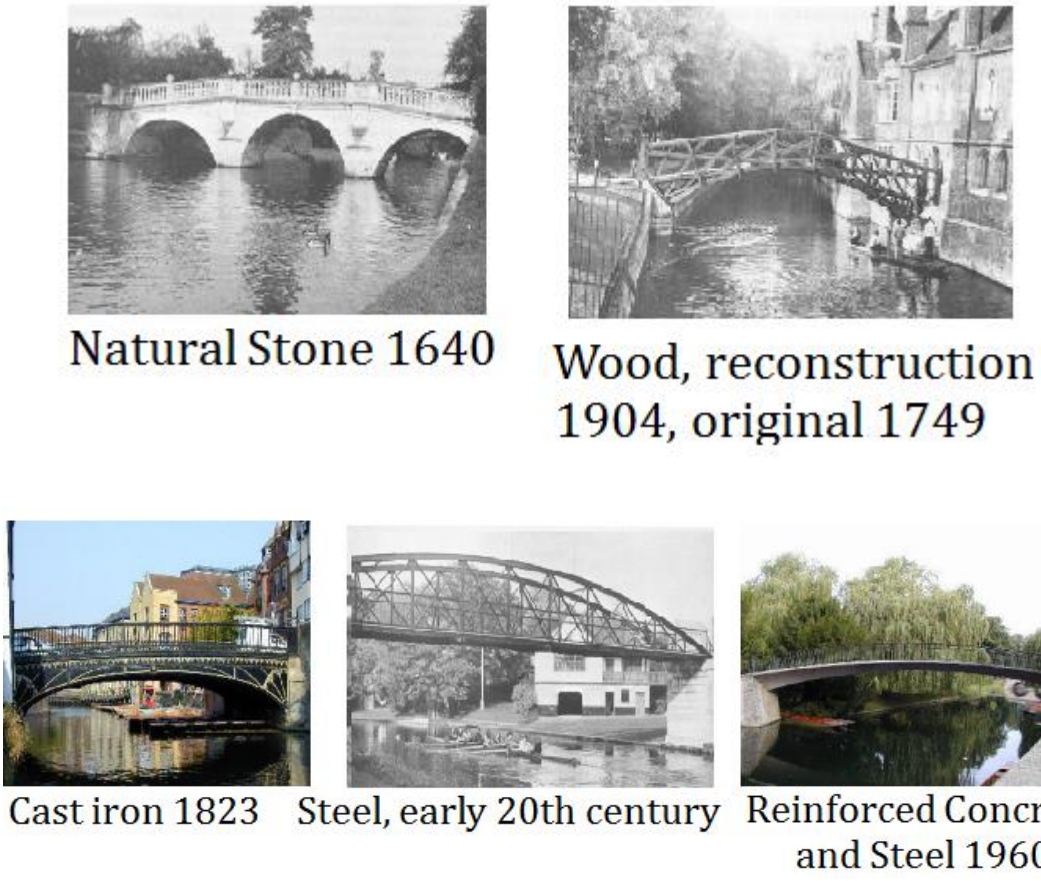


Figure I.3: The Evolution of Construction.

3. Classification of construction materials:

In the field of construction, it has become common to make a distinction between materials:

3.1- Basic materials and composite products:

- Basic materials or raw materials: Clay, stones, wood, limestone, metals, etc.
- Produced materials and composites: Cement (limestone + clay), Hydraulic concrete (aggregates + cement + water), Bituminous concrete (aggregates + bitumen), etc.

3.2- According to usage:

- Structural materials that have the ability to withstand considerable forces and ensure the stability of the structure:
  - Stones
  - Wood
  - Concrete
  - Steel, etc.
- Protective materials that have the property of coating and protecting construction materials:
  - Coatings
  - Paints
  - Bitumen, etc.

4. Properties of construction materials:

The objective of the science of construction materials is to facilitate the optimal selection of construction materials used in the execution of a project, taking into account economic and safety aspects. Any measure used to define a particular

characteristic is referred to as a **property**. Knowledge of material properties allows us to anticipate their ability to withstand different conditions.

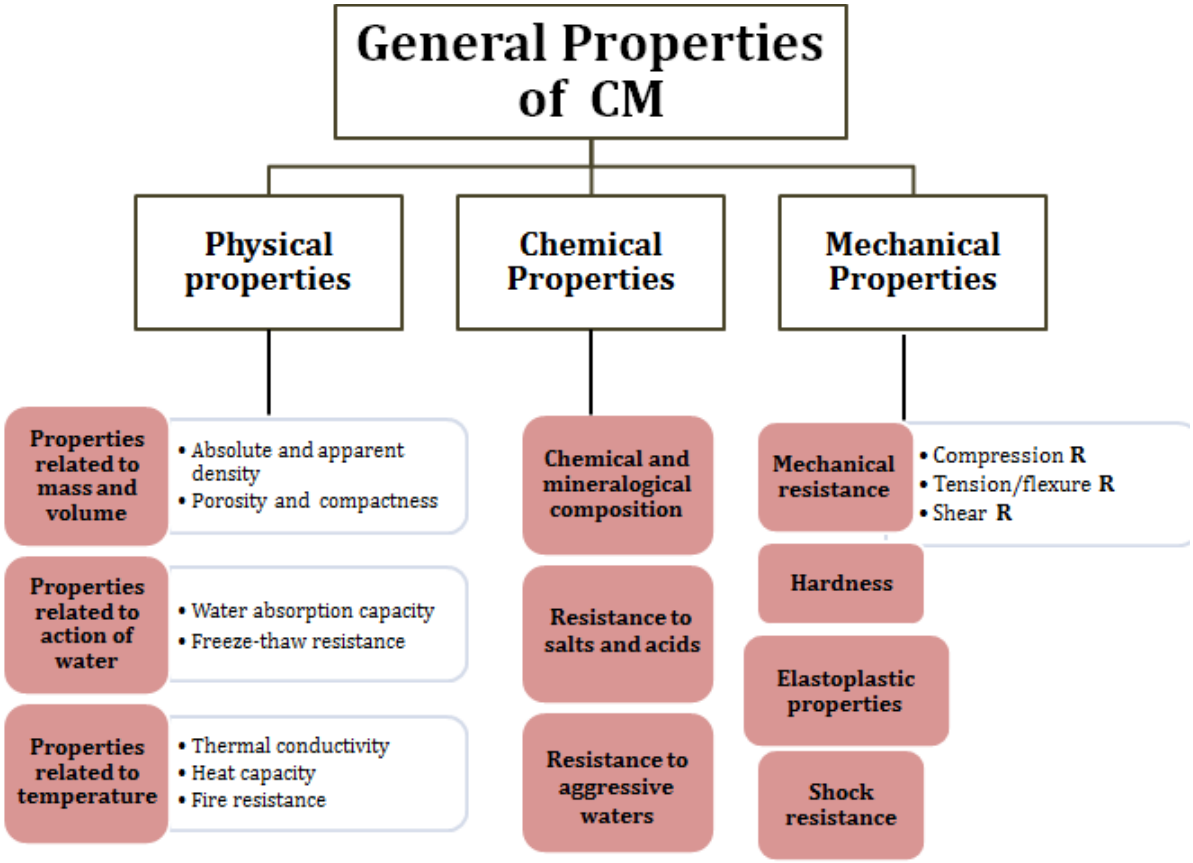


Figure I.4: Properties of construction materials.

4.1- Physical properties

Physical properties of materials refer to the intrinsic characteristics that can be measured without altering the chemical composition. These include aspects such as mass, density, thermal conductivity, hardness, strength, etc.

4.1.1- Density

a- Apparent density:

It is the mass of a material per unit of apparent volume (including voids and pores). It is expressed in (g/cm^3; kg/m^3).

$$\boldsymbol{\rho}_{app} = m v_{app} = \frac{m}{V_{app}} \quad \text{(I.1)}$$

$\boldsymbol{\rho}_{app}$**:** Apparent density.

m: Mass of the dry sample.

Vapp: Apparent volume of the sample.

b- Absolute density:

It is the mass of a material per unit of absolute volume of the solid matter (excluding voids and pores). It is expressed in (g/cm^3; kg/m^3).

$$\rho_{abs} = m v_{abs} = \frac{m}{V_{abs}} \quad (I.2)$$

ρ_{abs}**:** Absolute density.

m: Mass of the dry sample.

Vabs: Absolute volume of the sample.

Note: For the same material, $\rho_{abs} > \rho_{app}$.

Table I.1: Absolute and bulk density of construction materials.

construction material	Absolute density (kg/m^3)	Apparent density (kg/m^3)
Sand	2600 - 2700	1450 - 1700
Heavy concrete	2500 – 4000	400 - 2600
Cement	2900 - 3200	1200 - 2100
Limestone	2400 - 2700	2100 - 2700
Wood	1500 - 1600	100 - 1300
Steel	7800 - 7900	7800 - 7900
Plastic materials	900 - 2200	10 - 2200
Glass	2500 - 2900	100 - 2400
Plaster	2300 - 2700	1100 - 1200
Expanded clay	2500 – 2800	800 - 1200

4.1.2- Porosity and Compactness

Porosity is the ratio of the void volume to the total volume of the material.

$$\boldsymbol{P} = \frac{V_{void}}{V_{total}} \times \mathbf{100}(\%) = \left(\frac{V_{total} - V_{abs}}{V_{total}}\right) \times \mathbf{100} = \left(1 - \frac{\rho_{app}}{\rho_{abs}}\right) \times \mathbf{100} \quad \text{(I.3)}$$

Compactness is the ratio of the solid volume to the total volume of the material.

$$\boldsymbol{c} = \frac{V_{solid}}{V_{total}} \times \mathbf{100}(\%) \quad \text{(I.4)}$$

With:

$$V_{solid} = V_{app} - V_{void} \quad \text{(I.5)}$$

Thus:

$$C + P = 1 \quad \text{(I.6)}$$

The void ratio is the ratio of the void volume $\boldsymbol{V_{void}}$ to the solid volume $\boldsymbol{V_{solid}}$.

$$\mathbf{e} = \frac{V_{void}}{V_{solid}} \times \mathbf{100}(\%) \quad \text{(I.7)}$$

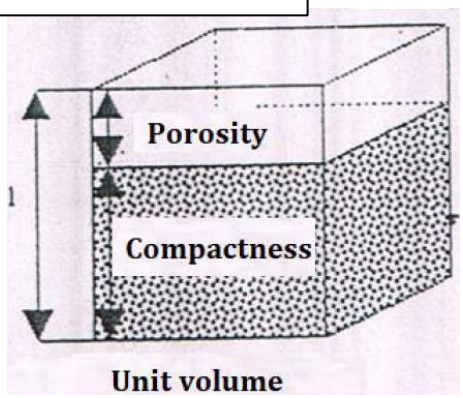


Figure I.5: Relationship between Porosity, Compactness, and Unit Volume.

4.1.2.1- Porosity affects:

- Durability

- Thermal Conductivity

- Frost Resistance

- Mechanical Strength

- Water absorption capacity

4.1.3- Hygroscopicity (Moisture):

It is the ability of a material to absorb the water contained in the surrounding air (moisture), meaning the actual water content of a material retained in its pores. The degree of moisture is influenced by various factors, primarily the environment in which the material is stored, including atmospheric conditions such as wind and temperature, as well as the material's porosity.

In general, moisture is denoted by W and is expressed as a percentage (%). The following formula represents the moisture content of a material:

$$W = \frac{m_w - m_d}{m_d} \times 100(\%) \quad \text{(I.8)}$$

$\boldsymbol{m_w}$: The mass of the sample in its wet state.

$\boldsymbol{m_d}$: The dry mass of the sample (after drying in an oven at t=105°C).

4.1.4- Water Absorption Capacity:

It is the ability of a material fully immersed in water to absorb and retain water. The water absorption capacity mainly depends on the open porosity and is calculated as follows:

$$Ab = \frac{m_{sat} - m_d}{m_d} \times 100(\%) \quad \text{(I.9)}$$

m_d: *The dry mass of the sample* (*after drying in an oven at* t=105°*C*).

m_{sat}: *The mass of the sample saturated in water for* 24 *hours*.

4.1.5- Frost Resistance:

Frost resistance is the ability of a water-saturated material to withstand freeze-thaw cycles without a significant loss of mechanical strength. The following formula represents the frost resistance coefficient:

$$R_{\text{Frost}} = \frac{\sigma_{after\ freeze-thaw\ cycle}}{\sigma_{before\ freeze-thaw\ cycle}} \quad \text{(I.10)}$$

Materials that withstand freeze-thaw cycles must have $R_{\text{Frost}} > 0.75$.

Frost resistance depends on:

- Porosity

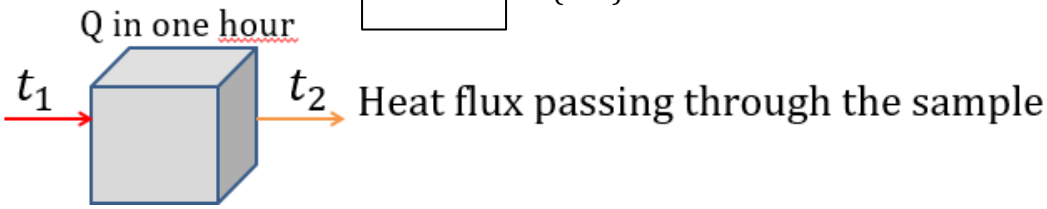
- Pore structure

-The degree of water saturation

4.1.6- heat flux:

The heat flux Φ is the amount of heat Q exchanged per unit of time t and is expressed in watts.

$$\Phi = Q/t \qquad \text{(I.11)}$$



When this heat flux passes through a surface S, we obtain a heat flux density denoted $\boldsymbol{\varphi}$ such that:

$$\boldsymbol{\varphi} = \frac{\Phi}{S} \quad \left(Watt/m^2\right) \qquad \text{(I.12)}$$

4.1.7- Thermal conductivity:

It is the degree of heat transfer through the thickness of a material. A thermal conductivity coefficient is defined as:

$$\lambda = \frac{\Phi . e}{S(t_2 - t_1)} \qquad \text{(I.13)}$$

It is expressed in (Watt/m·°C)

e: thickness of the material (m)

S: the surface where the temperature is applied (m^2)

t_1: initial temperature

t_2: final temperature

Table I.2: Thermal conductivity of construction materials.

Construction material	Thermal conductivity coefficient (W/m.c°)
Aluminium	125 - 230
Normal concrete	1.5 – 2
Natural rock	0.5 - 5
Copper	390
Wood	0.1 – 0.25
Steel	37 - 60
Plastic materials	0.1 – 0.5
Window glass	0.8 – 1.15

4.1.8- Thermal resistance:

Thermal resistance is proportional to the thickness of the material and inversely proportional to the conductivity. It is calculated as follows:

$$R_{th} = \frac{e}{\lambda} \qquad \text{(I.14)}$$

4.1.9- Fire resistance:

Fire resistance refers to the ability of a material to maintain its structural properties and essential characteristics when exposed to high temperatures, without undergoing significant deterioration in strength or major deformations.

4.2- Chemical Properties

The ability of a material to resist the corrosive effects of acids, bases, and saline solutions that can trigger chemical reactions leading to the deterioration of the structure. There is a variety of aggressive environments:

- Inorganic or organic liquids, which, aside from their purely physical effects, primarily act through their acidic or basic nature and the aggressive ions they may contain.

- Gases, whether of natural origin or resulting from air pollution and fermentation processes, commonly include carbon dioxide, sulfur dioxide, nitrogen oxides, hydrogen sulfide, as well as chlorine, bromine, and iodine vapors, along with ammonia.

4.3- Mechanical Properties

The mechanical properties of materials are characterized by their ability to withstand various external stresses such as compression, tension, bending, creep, and impact. They are defined by the maximum breaking stress of a material under an external load (force, weight, etc.). When a force is applied to an element, a set of internal forces arises to balance the external force.

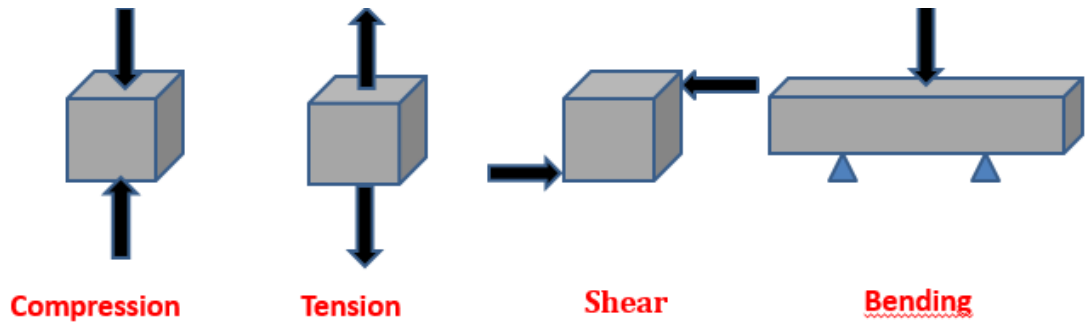
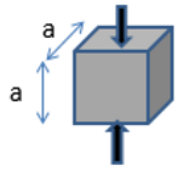
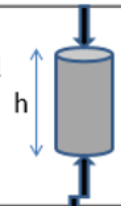
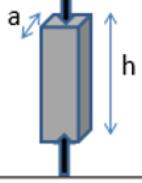


Figure I.6: Types of Mechanical Stresses in Materials.

4.3.1- Compressive strength:

The main property of hardened concrete is its compressive strength. It is measured by crushing a cubic or cylindrical test specimen between two plates of a hydraulic press.

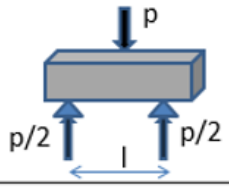
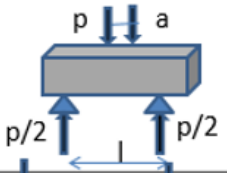
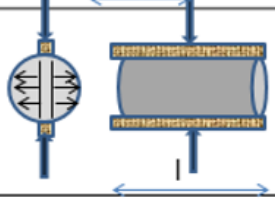
Table I.3: Compressive strength.

Samples	Formula	Size (cm)	Materials
Cubic 	$\sigma_c = \frac{p}{a^2}$ (Kg/cm^2)	5x5x5 10x10x10 15x15x15 20x20x20	Concrete Mortar Stones and Rock
Cylindrical 	$\sigma_c = \frac{4p}{\pi D^2}$ (N/mm^2)	d= 11, h = 22 d= 10, h = 20 d = 16, h = 32	Concrete Mortar Stones and Rock
Prismatic 	$\sigma_c = \frac{p}{a^2}$ (MPa)	a=10, 15, 20 h= 40, 60, 80	Concrete wood

4.3.2- Tensile Strength:

Three types of tensile strength tests can be distinguished, which are presented in the table below.

Table I.4: Tensile Strength.

Type of traction	Formula	Shape
Direct tension	$\sigma_{tr} = \frac{p}{s}$	
Flexural tension (3-point bending)	$\sigma_{tfl} = \frac{3pl}{2bh^2}$	
Flexural tension (4-point bending)	$\sigma_{tfl} = \frac{3p(l-a)}{2bh^2}$	
Splitting tension	$\sigma_{tfend} = \frac{2p}{\pi Dl}$	

4.3.3- Deformation

a- Elastic deformation:

When a loading test is performed and, after unloading, the body returns to the same shape it had before the test, with no residual deformation remaining, it is said that the body exhibits perfectly elastic behavior.

b- Plastic deformation:

A deformation is considered plastic when, after unloading, the material does not return to its original shape and retains permanent deformation. These permanent deformations are also referred to as plastic deformations.

4.3.3.1- Tensile test on a mild steel specimen:

Consider a mild steel bar with an initial length L0 and a constant initial cross-sectional area S0 along its entire length L0 . A tensile force F is applied at each end of the bar. Using a comparator, the elongation ΔL of the specimen can be recorded as a function of the magnitude of the applied force F.

$$\Delta L = L - L0 \quad \text{(I.15)}$$

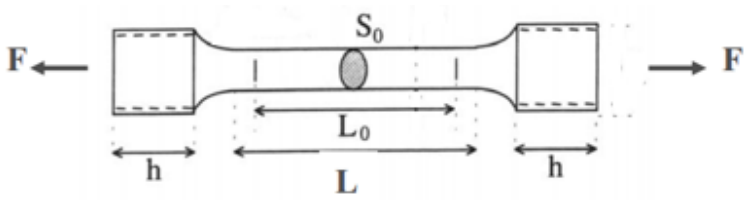


Figure I.7: Mild steel bar with an initial length L0.

To compare the mechanical properties of materials, these properties must be determined independently of the cross-sectional area S 0 and the initial length L 0 of the specimens. Thus, the following are plotted on a graph:

- X-axis: The relative elongation ε.

$$\varepsilon = \frac{\Delta L}{L0} \quad \text{(I.16)}$$

- Y-axis: The stress, σ which is the force per unit area in N/mm^2 or MPa.

$$\sigma = \frac{F}{S0} \quad \text{(I.17)}$$

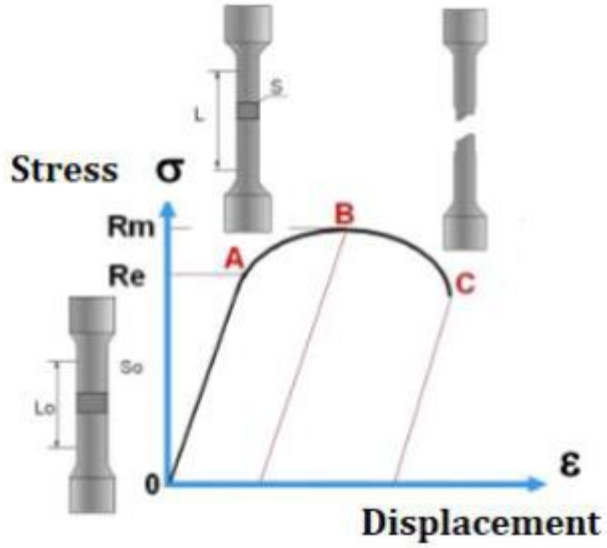


Figure I.8: Stress-Strain Curve and Material Failure Stages

4.3.4- Shock resistance:

This is an essential property for materials used, particularly for flooring and road surfaces. Shock resistance is characterized by the amount of work required to destroy a sample of a given volume and mass (expressed in joules per cubic meter, J/m^3, or joules per kilogram, J/kg).

The shock resistance of construction materials varies depending on several factors, including the nature of the material, its density, composition, and design. Certain materials, such as reinforced concrete and steel, generally have better shock resistance due to their solid structure and ability to absorb kinetic energy. Other materials, such as wood or plastic, may be less resistant to shocks but can be reinforced or designed to improve their impact absorption capacity .

5. Measurement of Resistance Using Non-Destructive Methods

The non-destructive sample testing method is a technique that allows for the rapid assessment of the strength of materials used in structures without the need to extract hardened concrete samples through coring. Generally, a few commonly used approaches exist:

- A device that emits X-rays through the structure is used. By analyzing changes in the speed of the X-rays, it is possible to determine the strength of the materials.

- The **sclerometer** , is used to test the surface hardness of hardened concrete (in structures). The harder the surface, the stronger the concrete, which provides an approximate indication of the strength achieved by the concrete at a given age.

- The use of sonic testing (ultrasounds) involves measuring the speed of sound waves traveling through the concrete. This speed is proportional to the concrete's strength: the higher the speed, the stronger the concrete. Thus, this method provides an estimation of the concrete's strength at a specific stage of its curing process.

6. Exercise :

Exercise 01:

Consider a cubic material with dimensions 7×7×7 cm and a dry mass of m_{sec}=788.9 g, with a total porosity of approximately 25%. After complete immersion in water, the saturated mass is around 857.5 g.

Determine:

- The absolute and apparent density.
- The water absorption capacity.
- The compactness

Solution :

P= 25%

V_{app}= 7×7×7=343cm^3

m_{sec}=788.9g

m_{sat}=857.5g

$\boldsymbol{\rho}_{app}=\frac{m}{V_{app}}=\frac{788.9}{343}=\mathbf{2.3}\ g/cm^3$

$P=(1-\frac{\rho_{app}}{\rho_{abs}})\times\mathbf{100}$ $\frac{25}{100}=(1-\frac{\rho_{app}}{\rho_{abs}})$ $\boldsymbol{\rho}_{abs}=\mathbf{3.067}\ g/cm^3$

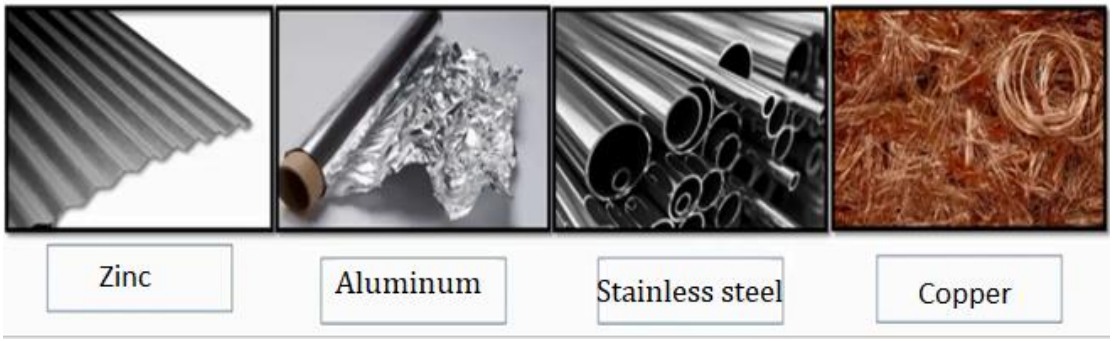
$Ab=\frac{m_{sat}-m_{sec}}{m_{sec}}\times 100=\frac{857.5-788.9}{788.9}\times 100(\%)$

Ab=**8.6956**%

C+P=100% C= **75**%

Exercise 02:

A wall with a surface area of 5 m^2 has a temperature of 700°C on one side and 20°C on the other. Calculate the thermal conductivity and the thickness of the wall for selecting a material that ensures a heat flux density of 300 kW/m^2. The maximum possible thickness is 50 cm, and K = f(T).



Solution :

$$\lambda=\frac{\Phi.e}{S(t_2-t_1)}=\frac{\boldsymbol{\varphi}.e}{(t_2-t_1)}\Rightarrow\frac{\boldsymbol{\lambda}}{\boldsymbol{e}}=\frac{\boldsymbol{\varphi}}{(t_2-t_1)}=\frac{300.10^3}{(700-20)}=441.2Watt/m^2.C^o$$

Finally, we find the maximum thermal conductivity:

$\boldsymbol{\lambda}$ **max** = 441,2 x 0,5=**220.6** Watt/m.C°

We are therefore looking for a material with a thermal conductivity of ≤220.6Watt/m^2·°C.

Copper, aluminum, and zinc are not suitable because their thermal conductivity is higher than 220 W/m^2·°C (at 360°C).

Stainless steel, λ max (360°C) = 20 Watt/m·°C;

Therefore:

$\frac{\lambda}{e} = 441.2 \text{Watt/m}^2.\text{C°} \Rightarrow \frac{20}{e} = 441.2$

e=4,5 cm

Exercise 03 :

A wall with a total thickness of 27 cm is composed of 4 layers:

- Layer 01: e1=10cm ; λ1=0,98 W/m.C°

- Layer 02:e2= ? cm ; λ2=0,23 W/m.C°

- Layer 03: e3=10cm ; λ3=0,98 W/m.C°

- Layer 04: e4=02cm ; λ4=0,25 W/m.C°

1. Calculate the thermal resistance of the wall.

2. If Layer 03 is replaced with a material containing open pores, how will the thermal resistance of the wall change?

Solution :

1/ The total thermal resistance of the wall**:**

$$R_{th} = \frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2} + \frac{e_3}{\lambda_3} + \frac{e_4}{\lambda_4}$$

$$R_{th} = \frac{0,1}{0,98} + \frac{0,05}{0,23} + \frac{0,1}{0,98} + \frac{0,02}{0,25}$$

$$R_{th} = 0,501 \text{ m}^2\text{x °C/w}$$

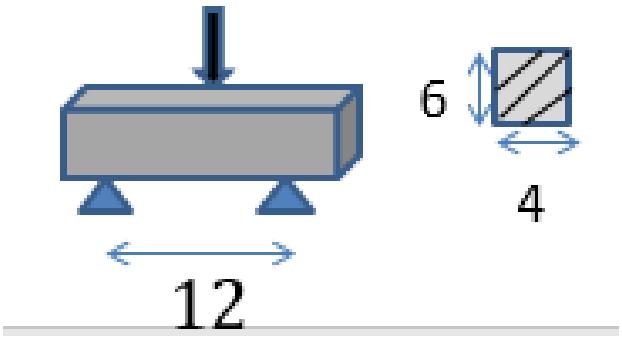
2/ A material with open pores will conduct heat better, so its thermal conductivity will be higher (λ increases). Therefore, if we calculate the new thermal resistance:Rth= Σ $(ei/\lambda i)$

If λ i increases, then R th decreases.

Exercise 04:

Consider two specimens: A cubic specimen with dimensions 10×10×10 cm, subjected to compression, which failed under a load of P = 30 tf. A prismatic specimen with dimensions 4×6×16 cm, subjected to a three-point bending tensile test, with a failure load of 5 kN and a support span of 12 cm.

Calculate Rc (compressive strength) and Rtf (tensile strength in bending).



Solution :

$\sigma_c = \frac{P}{S} = \frac{30 \times 10^4}{100 \times 100} =$ **30** Mpa

$\sigma_{tf} = \frac{3pl}{2bh^2} = \frac{3 \times 5 \times 10^3 \times 120}{2 \times 40 \times 60^2} =$ **6.25**MPa

1. Introduction:

1.1- Definition of Aggregates:

An "aggregate" is an inert material consisting of a collection of grains with sizes ranging from 0 mm to 125 mm, intended to be bound together by cement paste.

Aggregates are granular materials of natural, artificial, or recycled origin, such as sand, gravel, crushed stone, or materials obtained from the recycling of construction waste. They constitute one of the fundamental components of construction materials, particularly concrete and mortar, in which they generally represent the largest volumetric fraction.

Their role is not limited to simple filling; they significantly contribute to the mechanical properties (compressive strength, stiffness), physical properties (density, porosity), and durability (resistance to freeze–thaw cycles, wear, and chemical attack) of structures. The quality, mineralogical nature, grading, and cleanliness of aggregates directly influence the final performance of the material in which they are incorporated. Therefore, the selection and control of aggregate characteristics are essential to ensure the quality, stability, and durability of construction structures.



Figure II.1: Types of aggregates.

2. Classification of Aggregates

Aggregates are classified based on their:

2.1- Granularity:

Determined by particle size analysis using standardized sieves. They are distinguished by "d" and "D," which represent the smallest and largest grain sizes, respectively. They are referred to as d/D or 0/D. The dimensions d and D are selected from the following series:

0 —0,063 — 0,08 — 0,1 —0,125 — 0,16 — 0,2 —0,25 — 0,315 — 0,4 —0,5 — 0,63 — 0,8 —1 — 1,25 —1,6 —2 — 2,5 — 3,15 —4 — 5 — 6,3 —8 — 10 — 12,5 — 14 —16 — 20 — 25 —31,5 — 40 — 50 —63— 80 — 100 —125 mm.



Figure II.2: Sieves with different mesh sizes.

2.2- Origin:

2.2.1- Natural Aggregate: Derived from loose rocks or solid rock formations. Natural aggregates are classified into two categories:

a- Quarry aggregates: Obtained by crushing and screening.

b- Alluvial aggregates: Includes sea sand, river sand, and dune sand.

2.2.2-Artificial Aggregate:

Several types of artificial aggregates can be used for specific applications:

a- Industrial by-products:

The most commonly used are crushed crystallized slag and granulated blast furnace slag. These aggregates are mainly used in road concrete.

b- Lightweight Aggregates:

The most commonly used are expanded clay, expanded shale, and expanded slag. They are used to produce both structural concrete and concrete with good thermal insulation properties.

c-Heavy Aggregates:

These aggregates are characterized by their high density (ferrous waste). Heavy aggregates are mainly used for the production of heavy concrete.

2.2.3- Recycled Aggregate:

These are materials obtained from the demolition of existing concrete structures.

2.3- Shape:

Aggregates can be angular or rounded, depending on their origin and processing. Angular aggregates have sharp edges and irregular surfaces, providing better interlocking and higher mechanical strength in concrete. Rounded aggregates, often found in riverbeds or beaches, have smooth surfaces that improve workability but may reduce the internal bonding of concrete. The shape of aggregates significantly affects the workability, strength, and durability of construction materials, making it an important factor to consider in mix design.



Figure II.3: Angular and rounded aggregates.

2.4- Bulk Density:

-Lightweight aggregate with an apparent bulk density of less than 1800 kg/m^3.

- Heavyweight aggregate with an apparent bulk density of greater than 1800 kg/m^3.

3. Particle size analysis:

Why do we perform particle size analysis?

Particle size analysis plays a decisive role in the composition of concrete. Indeed, it is interested in determining the size of the grains and it also determines the proportions of grains of the same size (% by weight). The proportion of each grain size must be selected to minimize porosity (maximize compaction). Particle size analysis is the best method to illustrate the distribution of grains according to their size.

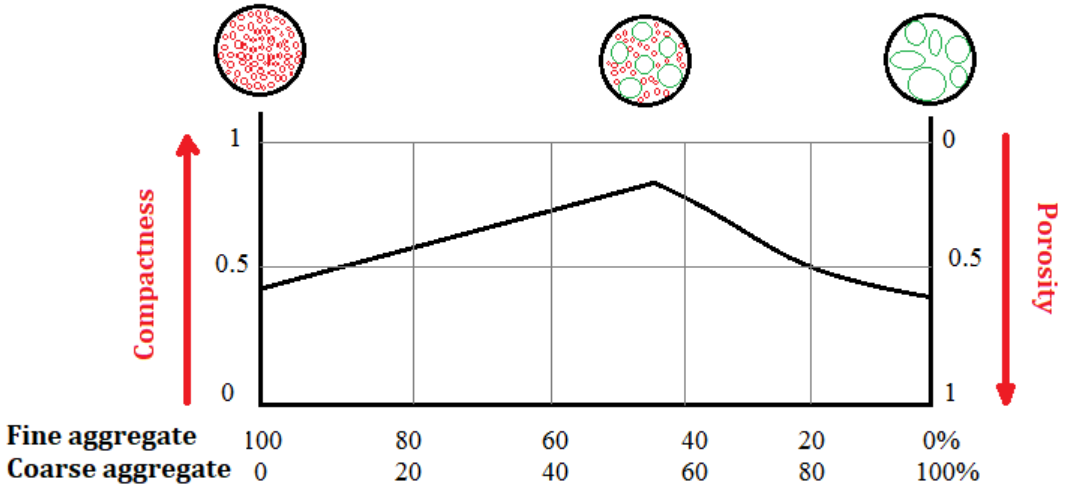


Figure II.4: The relationship between aggregate size, porosity, and compactness.

The continuity or discontinuity of the granulometry also influences the compaction. The presence of a plateau indicates the absence of a granular class.

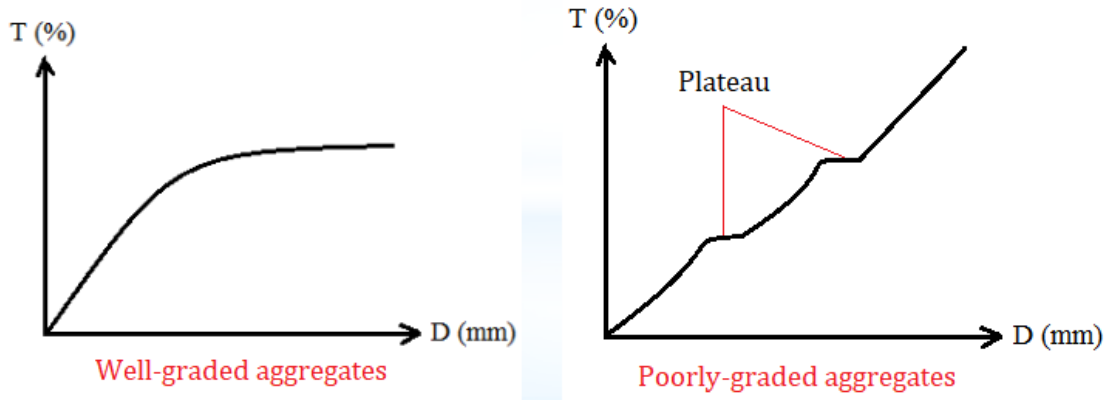


Figure II.5: Continuous and Discontinuous Grain-Size Curves

3.1-Steps of Particle Size Analysis:

- A sample with weight P of an aggregate; this mass must be greater than 0.2 D, with M expressed in kilograms and D is the largest dimension specified in millimetres . This mass is placed in the top sieve of a series of sieves arranged in descending order of mesh size (with the largest at the top and the smallest at the bottom). After vibrating the sieve series, the grains of the sample separate based on their sizes, and each sieve retains a portion, called the partial residue of the sieve.

The cumulative (total) residue of a sieve is the sum of all the partial residues of the sieves located above it.

$$Residue\ \% = \frac{Cumulative\ residue\ weight}{Sample\ weight} \times 100 \qquad \text{(II.1)}$$

$$Sieving\ \% = 100 - Residue\ \% \qquad \text{(II.2)}$$

a- For sand: the analysis is done by sieving using the following standardized sieve series: 6.3 – 5 – 3.15 – 2.5 – 1.25 – 0.63 – 0.315 – 0.16 – 0.08 mm.

b-For coarse aggregates: the analysis is done by sieving using the following standardized sieve series: 125 – 80 – 63 – 50 – 40 – 31.5 – 25 – 20 – 16 – 12.5 – 8 – 6.3 mm.

3.1.1-The granulometric composition:

The granulometric composition is represented by a curve where the ordinate represents the cumulative residue in percentage or the Sieving in percentage, and the abscissa corresponds to the sieve sizes.

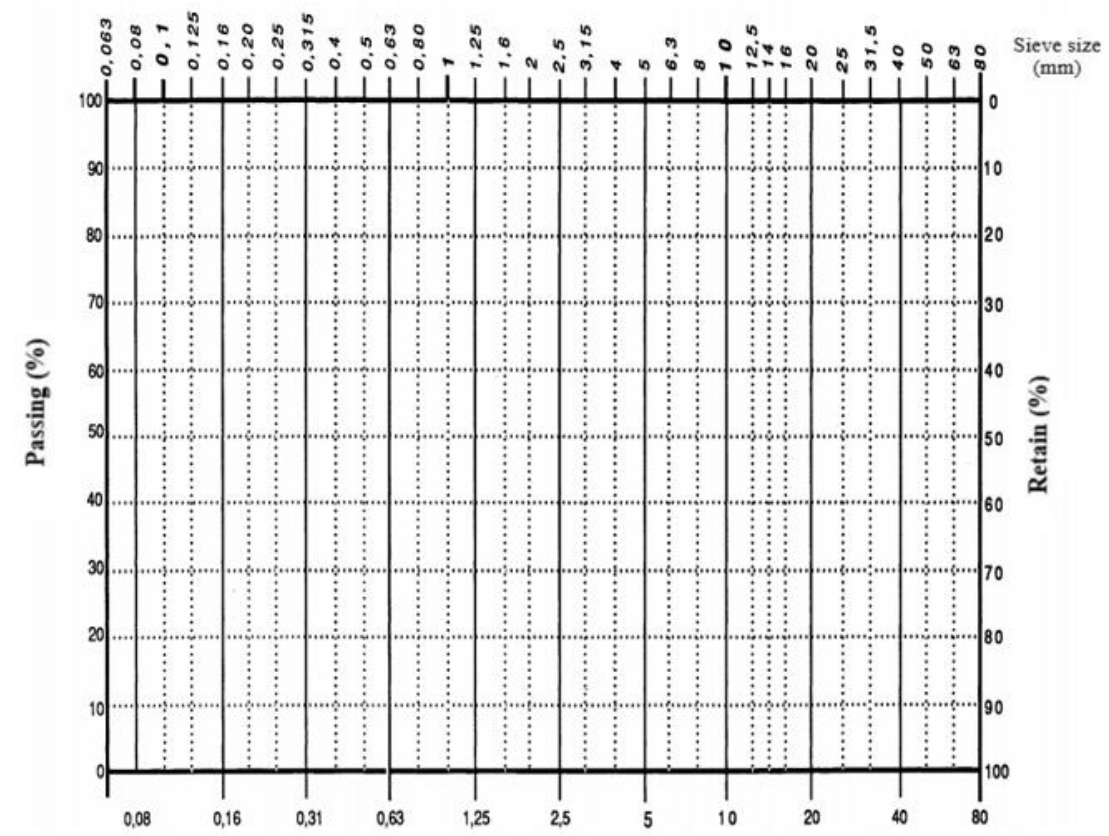


Figure II.6: Sieve Analysis Chart for Aggregate Grain-Size Distribution.

3.1.2-Calculate the Cumulative Residue:

- Determine the mass of residues on each sieve (mi (g)).

- Calculate the partial residue on each sieve.

- Calculate the cumulative residue.

$$a_i = \frac{m_i}{m_T} \times 100 \qquad \text{(II.3)}$$

$$A_i = \sum_{i=max}^{i=i} a_i \qquad \text{(II.4)}$$

$$T_i = 100 - A_i \qquad \text{(II.5)}$$



Figure II.7: Sieve Stack for Aggregate Testing

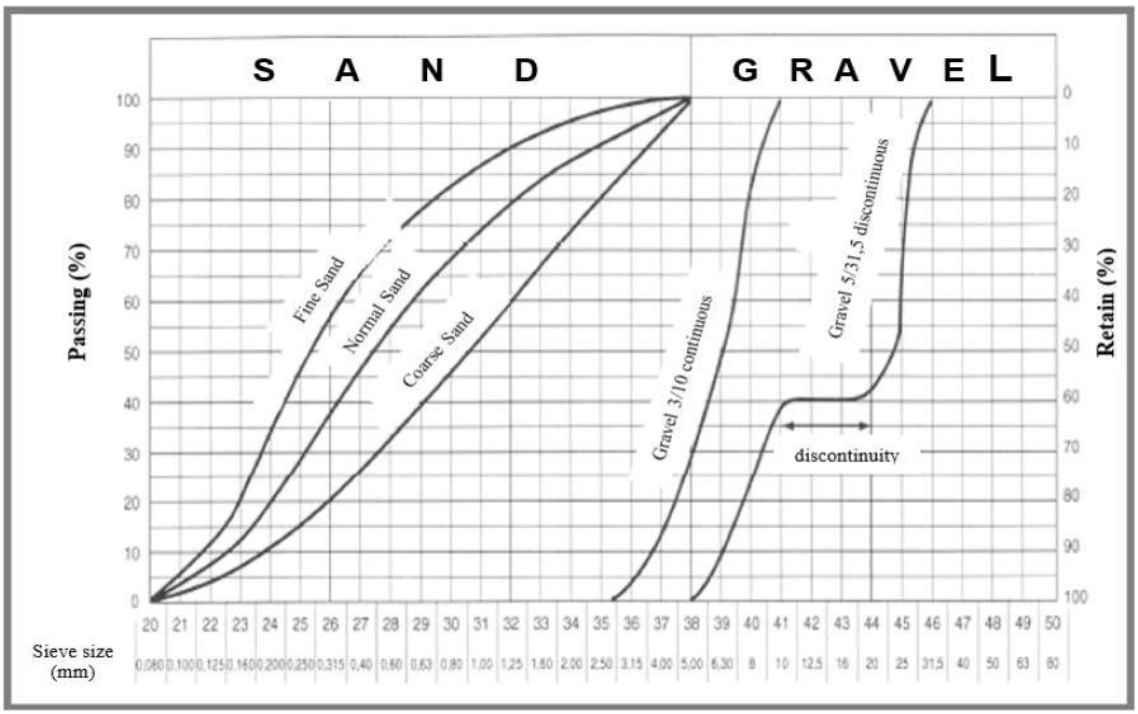


Figure II.8: Granulometric Curves of Sands and Gravels.

3.2-Fineness Modulus:

The fineness modulus is a coefficient used to characterize the proportion of fine particles in an aggregate. The fineness modulus of sand is equal to 1/100 of the sum of the cumulative residues, expressed as percentages, on the following sieves: 0.16 – 0.315 – 0.63 – 1.25 – 2.5 – 5 mm.

$$FM = \frac{A_5 + A_{2.5} + A_{1.25} + A_{0.63} + A_{0.315} + A_{0.16}}{100} \qquad \text{(II.6)}$$

- **Slightly too fine sand**: [1.80 - 2.20]
- **Preferred sand**: [2.20 - 2.80] (satisfactory workability and good strength with limited risk of segregation)
- **Slightly too coarse sand**: [2.80 à 3.20]

3.2.1-Correction of the Sand Fineness Modulus:

The correction of sand can be carried out experimentally by gradually mixing the main sand with the added sand until a blend with the desired characteristics for concrete is obtained. However, knowing the fineness modulus (FM) of the component sands and the target FM allows the problem to be solved directly using Abrams' rule.

- A coarse sand S1 with a fineness modulus FM1

- A fine sand S2 with a fineness modulus FM2

- The desired sand S with a fineness modulus FM

The proportions of sands S1 and S2 will be as follows:

$$\%S_1 = \frac{FM - FM_2}{FM_1 - FM_2} \qquad \text{(II.7)}$$

$$\%S_2 = \frac{FM_1 - FM}{FM_1 - FM_2} \qquad \text{(II.8)}$$

3.3- Uniformity coefficient:

The uniformity coefficient defines the spread of a particle size curve. is given by

$$C_u = \frac{D_{60}}{D_{10}} \qquad \text{(II.9)}$$

With: D60: the effective diameter corresponds to the cumulative sieve 60%.

D10: the effective diameter corresponds to the cumulative sieve 10%.

Cu =1 $\Rightarrow$ particle size has a single size

1 < Cu ≤ 2 $\Rightarrow$ Very uniform grain-size distribution

2 < Cu ≤ 5 $\Rightarrow$ uniform grain-size distribution.

5< Cu ≤20 $\Rightarrow$ Poorly graded grain-size distribution.

20 < Cu $\Rightarrow$ very wide grain-size distribution

3.4- Coefficient of curvature :

It is used to quantify the distribution of particles in a particle size curve. It is given as:

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \qquad \text{(II.10)}$$

Cu > 2 → spread particle size distribution. Cu < 2 → uniform or close particle size distribution.

1 < Cc < 3 → well-graded material (continuity is well distributed). Cc < 1 or Cc > 3 → poorly graded material (continuity is poorly distributed). Well-graded materials → denser materials.

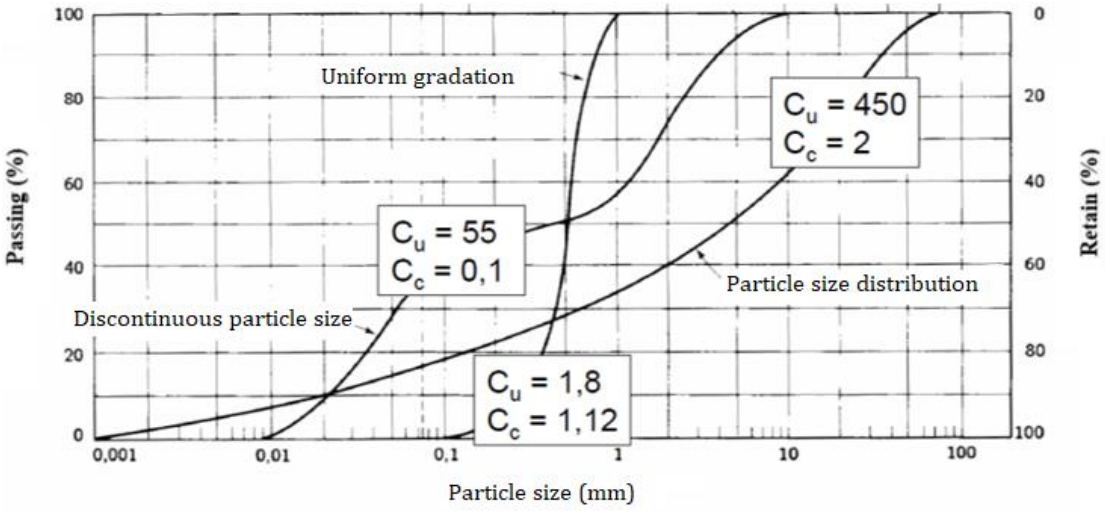


Figure II.9: Example of grain-size distribution curves and their coefficients of uniformity and curvature

4. Aggregate Cleanliness:

All aggregates contain a certain amount of impurities, which may be vegetal, clayey, or plastic. In general, the impurity percentage should not exceed 1.5%, as it negatively affects the essential properties of concrete, such as strength, impermeability, and durability.

4.1-Impurity test:

4.1.1- Washing method:

The test consists of washing a dry aggregate sample ($m_{before\ washing}$) with water through a 0.08 mm sieve in order to remove fine particles. Then, the washed sample is dried in an oven until a constant mass is reached. Finally, the sample is weighed after washing (m_{clean}). To calculate the percentage of impurities, the following formula is used:

$$\%Imp = \frac{m_{before\ washing} - m_{clean}}{m_{clean}} \times 100 \quad \text{(II.11)}$$

$m_{before\ washing}$: mass of the raw sample.

m_{clean} : mass of the sample after washing and drying.

4.1.2- Sand equivalent:

The sand equivalent test, used to measure the cleanliness of a sand used in the composition of concretes, consists of separating the fine elements of a sand. In general, the cleanliness of aggregates must be checked because the use of polluted aggregates causes a decrease in mechanical strengths and an increase in shrinkage. The excess of fines requires a higher water dosage and the lack of fines causes the segregation of concrete (low compactness).

The test is carried out on the fraction of an aggregate passing through a 5mm square mesh sieve. The sample is washed according to a standardized process and allowed to stand, after 20 minutes h1 and h2 are measured.

h1: only clean sand

h2: clean sand + fine elements

The height h2 is measured visually (SE at sight) or using a piston (SE piston).

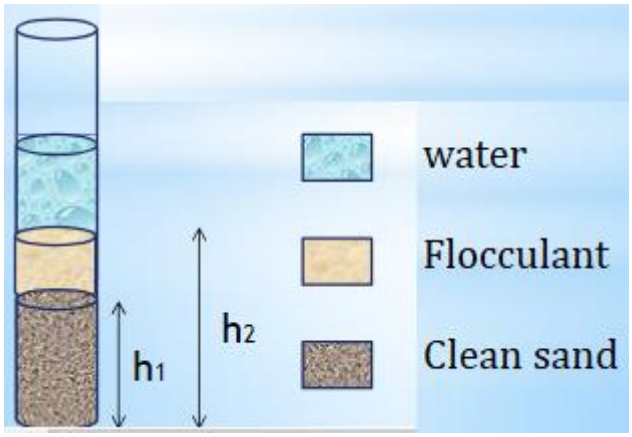


Figure II.10: Sand equivalent test

a- Materials used:

-Sand sample: A 2mm mesh sieved sand sample with a moisture content of less than 2% and a temperature of (23±3) ℃. [The wet mass of the sample = 120× (1+w) in g].

-The washing solution: this solution separates the fine clay elements and causes flocculation, which is composed of:

- calcium chloride
- 480±5g glycerin
- 12 to 13 g of aqueous formaldehyde solution
- in 5 liters of distilled water

b- Equipment required

-A 2mm mesh sieve

- A 1g Precision scales .

- A funnel

- A stopwatch

-Transparent plastic specimens, with two reference lines 100 and 380mm, (D_{int}= 32mm, H= 430mm)

-Rubber stopper fits on the test piece

-A 5 liter bottle (washing solution), placed 1 meter above the work table

-A stirring machine

-A washer tube connected to the vial with a shut-off valve

-A tared piston of 1 Kg

-A metal ruler of 500mm in length

c- Procedure :

1-Fill the test tube with the washing solution until the first stroke

2-Spill the sample into the test tube using a funnel

3-Eliminate air bubbles and let stand for 10 minutes

4-Stopper the test piece and secure it correctly in the stirring machine and shake it for 30 seconds

5-Rinse the stopper and the walls of the test tube with the washing solution using the washer tube

6-Fill the test tube with the scrubber tube. To wash the sand, simply lower the washer tube and slowly raise it into the mass of sand so that the fines rise to the surface. When the liquid level reaches the second line, the tap is closed.

7-Let sit for 20 minutes.

8-Display the heights h_1 and h_2, but measuring h_1 is not always easy, which leads to a more accurate measurement (use the piston)

9 - Slowly lower the piston into the test tube, the sleeve resting on the upper edge of the test tube and immobilized in contact with the sand, measure h_1'.

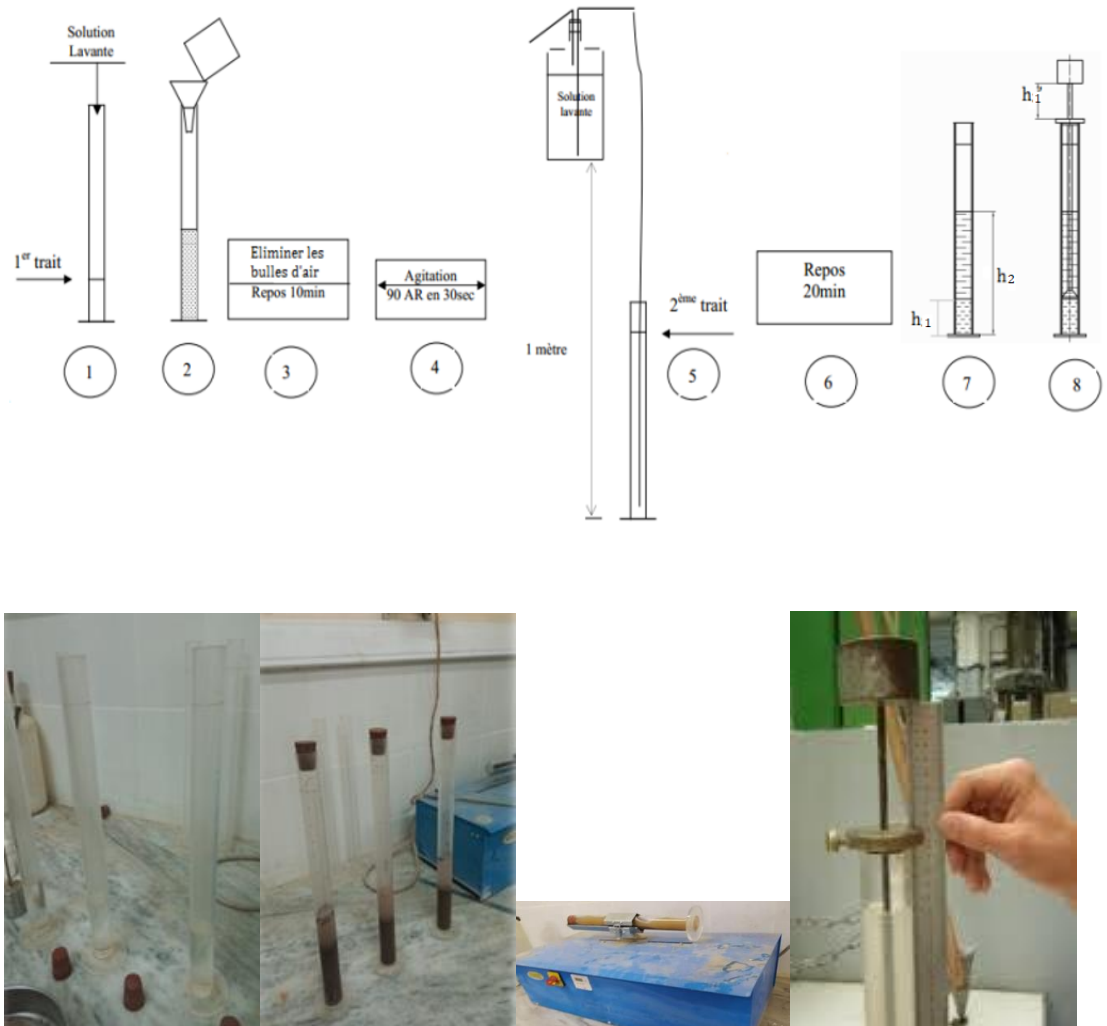


Figure II.11: Procedure of the sand equivalent test

10- Determine the coefficient of the visual sand equivalent and piston sand equivalent:

$$SEv = \frac{h_1}{h_2} \times 100 \qquad \text{(II.12)}$$

$$SEp = \frac{h_1'}{h_2} \times 100 \qquad \text{(II.13)}$$

The table below presents the values recommended by the standard (NF P 18-598) to determine the nature and quality of the sand.

Table II.1: Interpretation of Sand Equivalent Test Results.

Sand Equivalent (SE)	**Natur**	**Sand Quality**
SE<60	Clayey Sand	Risk of shrinkage or swelling, to be rejected for high-quality concrete.
60<SE<70	Slightly Clayey Sand	Acceptable cleanliness for high-quality concrete
70<SE<80	Clean Sand	Perfectly suitable for high-quality concrete.
SE>80	Very clean sand	Risk of causing a plasticity defect.

5. Volumetric Coefficient:

The grains of gravel are distinguished by their shapes: spherical, cubic, or elongated. The volumetric coefficient provides a precise idea of the shape of the considered element. For a grain, it is the ratio between the volume Vi of the grain and the volume V of the circumscribed sphere with diameter D (where D is the largest dimension of the grain).

5.1- Principle of the test

The test consists of taking a sample of gravel and determining the maximum diameter (Di max) of each grain in the sample. In addition, it is necessary to perform the calculations of the volume of the circumscribed spheres corresponding to the Di max. Next, it is advisable to fill a test tube with a volume of water and to introduce the sample into the test tube, taking care to remove the air bubbles. Thereafter, locate the value of the new volume corresponding to the total volume of the grains (V) and finally, determine the volumetric coefficient (Cv) of the gravel.

5.2- Equipment required

Balance

5mm sieve

Graduated cylinder

Calliper



Figure II.12: Equipment required

5.3- Operating Method:

1. Dry a sample of the gravel (ex:12.5/25 mm) to be studied
2. Sieve the gravel through a 5mm sieve and keep only the reject
3. Weigh the sample
4. Measure the Di max of each grain using a caliper
5. Perform the calculations of the volume of the circumscribed spheres corresponding to the Di max
6. Fill a test tube with a volume of water and note the value (V1)
7. Introduce the sample into the test tube, taking care to remove the air bubbles, then identify the value of the new volume (V2)
8. Determine the volumetric coefficient Cv of the gravel

$$C_v = \frac{\sum v}{\sum \pi \frac{D_i^3}{6}} \qquad \text{(II.14)}$$

Real volume of the grains:

$$\sum v = V_2 - V_1 \qquad \text{(II.15)}$$

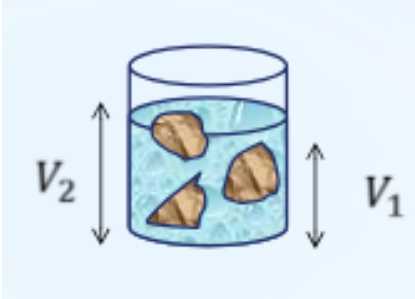


Figure II.13: Real volume of the grains

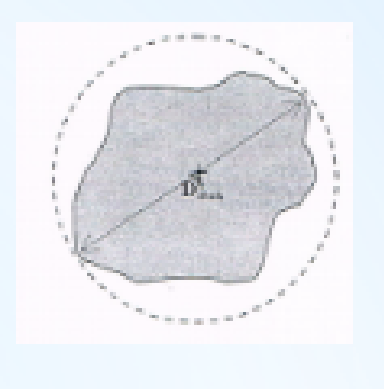


Figure II.14: the circumscribed spheres corresponding to the Di max

When the volume coefficient is low, the aggregate has a number of flats, chips and needles. When the coefficient is high, the aggregate is said to be cubic or rounded.

- If Cv is close to 1: The shape of the aggregates is more or less rounded or cubic.

- If Cv is much less than 1: The aggregates are angular or flattened.



Figure II.15: Aggregate Shapes

5.4- Rolled Aggregates and Crushed Aggregates:

A decision between these two categories of aggregates may arise for the user, and it is often quite difficult to draw definitive conclusions.

5.4.1- Rolled Aggregates:

They are easier to place, do not require significant compaction efforts since they slide easily between the reinforcements, and are particularly suitable for reinforced concrete.

5.4.2- Crushed Aggregates:

These lead to rigid concrete that is difficult to place. However, they adhere well to the cement paste and give the concrete greater strength, particularly in tension.

6. Water absorption:

Some granular materials may have internal porosity that is detrimental, especially to the thaw resistance of concretes. Indeed, at low temperature, the water included in the aggregate causes the concrete to burst.

The water absorption coefficient of an aggregate Ab is defined as the ratio of the increase in the mass of the sample caused by partial water soaking, to the dry mass of the sample. This partial imbibition is obtained by immersing the sample in water for 24 hours at 20° C, at atmospheric pressure.

6.1- For gravel [NF P 18- 554]

- Weigh a mass M of the gravel.
- Dry the sample in an oven at 105°C ± 5°C to constant mass.
- Allow it to cool and weigh; M_d.
- Place the gravel sample in water for 24 hours at 20°C at atmospheric pressure.
- Remove water from the surface of the aggregates using a cloth.
- Weigh the soaked sample Ma.

6.2- For sand:[NF P 18- 555]

- Weigh the mass sample M.

- Dry the sample in an oven at 105°C ± 5°C to constant mass.
- Allow it to cool and weigh; M_d.
- Immerse the sample in water for 24 hours at 20°C at atmospheric pressure.
- To remove excess water, spread the on a flat, non-absorbent surface and expose the sand to a flow of warm air.
- Continue the operation until the sample approaches the free flow state.
- Fill a portion of partially dried sand in a mold to the top.
- Slightly groom the surface 25 times and remove the mold vertically.
- If the surface moisture remains, the sample keeps the shape of the mold, then continue drying until the groomed sample collapses at the time of demolding, so we have reached the dry surface soaked state.
- Weigh the entire sample, Ma.

$$Ab = \frac{M_a - M_d}{M_d} \times 100 \qquad \text{(II.16)}$$

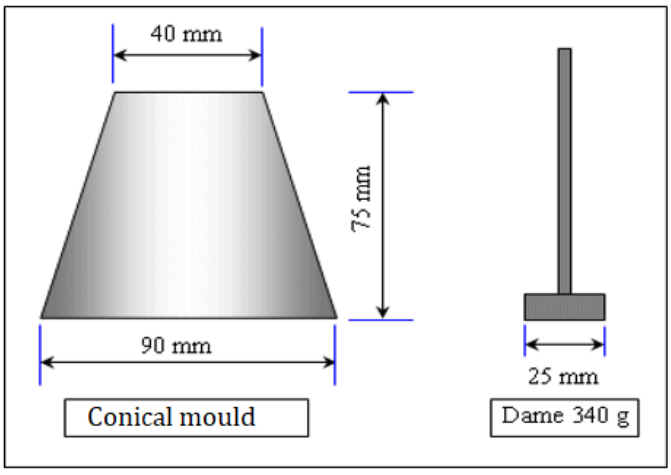


Figure II.16: Mould and dame for the water absorption coefficient of the sands.

7. Density:

It allows the determination, within a given volume, of the weight of any sample. It is an indirect measurement used on construction sites as a means of controlling the quantities of constituents. It establishes the relationship between the mass and the volume of a granular fraction, thereby making it possible to obtain an optimal concrete mix composition.

7.1- Bulk density :

Bulk density is defined as the ratio of the dry mass of the sample to the volume occupied by the solid material, including the voids between the grains.

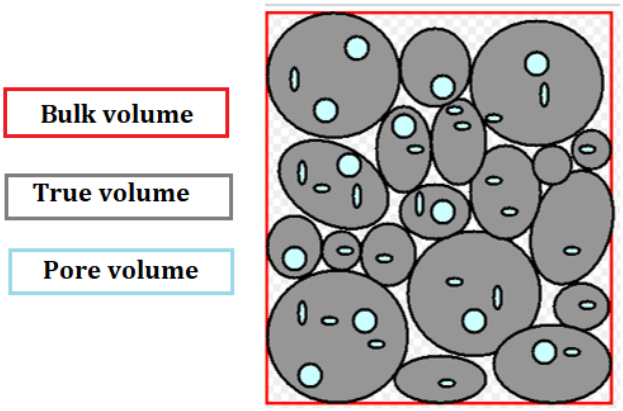


Figure II.17: Representation of bulk, true, and pore volumes in a granular material.

7.1.1- Required equipment:

-Precision balance with 0.1 g accuracy

-Container of known volume

-Straightedge (striking-off ruler)

-Funnel mounted on a tripod





Figure II.18: Apparent density test equipment.

7.1.2-Test procedure:

- Determine the volume of the container (V), if it is not known.

- Place the container on the balance and tare its mass.

- Pour the sample into the container using the funnel until it is filled (the distance between the funnel outlet and the rim of the container is 10 cm).

- Level off the top surface of the container using a metal straightedge.

- Weigh the contents of the container (M).

Therefore, the bulk density is given by the following formula:

$$M_{app} = \frac{m}{V_{app}} \quad (g/cm^3) \qquad \text{(II.17)}$$

7.2- Absolute density:

It is the mass of a sample per unit volume, without taking into account the voids, whether they are within or between the grains.

7.2.1- Graduated cylinder method:

a- Required equipment:

- Precision balance (0.1 g)

- Graduated cylinder





Figure II.19: Absolute density test equipment.

b- Test procedure:

- Weigh a mass (M).

- Fill the graduated cylinder with a volume of water (V1).

- Pour the sample into the cylinder.

- Record the new volume (V2).

The absolute density is given by the following formula:

$$M_{abs} = \frac{m}{V_2 - V_1} \quad (g/cm^3) \qquad \text{(II.18)}$$

7.2.2- Pycnometer Method:

a- Procedure

- Weigh a quantity of dry aggregate (300 g of sand) to determine its bulk density.

- Weigh the empty pycnometer with its stopper (m1).

-Introduce the material into the pycnometer and weigh it with the stopper (m2).

- Fill the pycnometer flask with distilled water and then remove air bubbles by applying a vacuum or by boiling.

- Fill the pycnometer with distilled water up to the mark and then weigh it with the stopper (m3).

- Empty the pycnometer and clean it.

- Fill the pycnometer with distilled water up to the mark and then weigh it with the stopper (m4).

- Calculate the absolute density using the following formula:

$$M_{abs} = \rho_{abs} = \frac{\rho_w \times (m_2 - m_1)}{(m_4 + m_2 - m_1 - m_3)} \qquad \text{(II.19)}$$

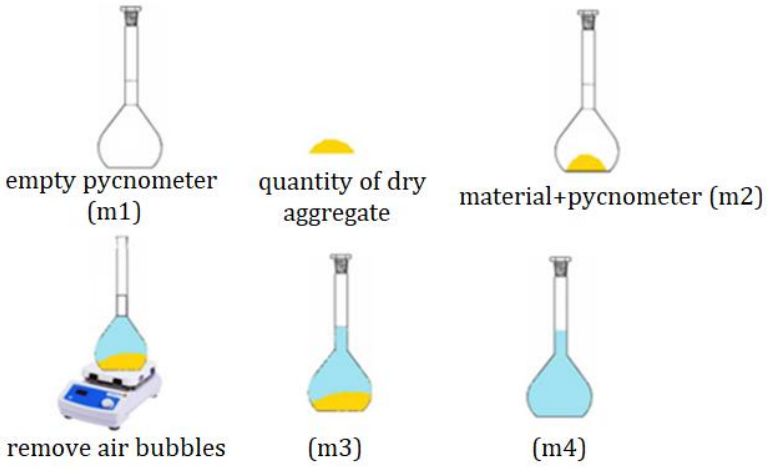


Figure II.20: Pycnometer Test Procedure.

8. Water content:

Water content is the mass proportion of water contained in a soil sample (sand), expressed as the ratio between the mass of water and the total mass of the sample, usually in percentage. This parameter is essential in soil characterization, as it influences the physical behavior and mechanical properties of the material.

It is defined as the ratio of the mass of water evaporated during drying at 105 °C to the mass of dry material, expressed as a percentage (%).

$$W=\frac{P_W}{P_d}\times 100 \qquad \text{(II.20)}$$

$\boldsymbol{P_W}$: the mass of water contained in the sample.

$\boldsymbol{P_d}$: the mass of the solid grains (the mass of the dry material).

8.1- Required Equipment:

- A drying oven (temperature: 105°C).
- A precision balance (accuracy: 0.1 g).
- Containers made of material resistant to heat and moisture.



Figure II.21: Water content test equipment.

8.2- Operating mode :

1/ Weigh a sample m (wet state), this mass is chosen according to the size of the elements it contains, it must be greater than or equal to the values in table II.2.

Table II.2: Minimum mass of material needed to determine the water content according to the size of the elements passing through the mesh screen square opening dm.

d_m (mm)	1	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80
m (kg)	0.2	0.3	0.4	0.5	0.8	1.2	2	3	5	8	12	20	30	50

2/ Place the sample in an oven at 105° C until a constant mass (dry material) is obtained.

3/ After 24 hours, weigh the dry sample m_d .

4/ Determine the water content w by the following formula:

$$W(\%) = \frac{m - m_d}{m_d} \times 100 \qquad \text{(II.21)}$$

9. Splitting of sand

The majority of sites that manufacture concretes in situ, their granular materials used are not always protected from the weather (open storage), that is why we notice a very variable humidity of sand that disturbs on the one hand their volumetric dosage and on the other hand the amount of water contained in fresh concrete. Therefore, a volumetric dosage of wet sands leads to a lack of solid matter (fine elements) and an excess of water detrimental to the manufacture of concrete. The objective is therefore to determine this gap with a view to filling it during the preparation of the mixture.

9.1- Expansion definition:

For low humidity, at the interface of two sand particles, the humidity is in the form of a water bridge (meniscus), which creates attractive forces between the wet particles. When the amount of water increases , the size of the bridge increases, the force of attraction will gradually be replaced by a force of repulsion and it seems that the sand swells; this phenomenon is called **bulking**.

This test consists in measuring the variation in the apparent density of a sand sample as a function of the gradual increase in its water content (w).

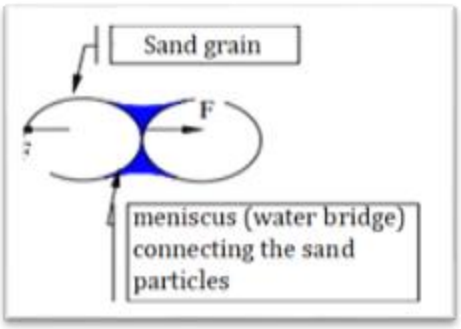


Figure II.22: meniscus (water bridge)

9.2- Materials needed:

- Precision balance

- A container with a volume of 1 liter.

- A metal ruler.

- A funnel

- One hand scoops for filling.

- A spatula.

- Plastic bins.

9.3- Operating mode :

1 / Prepare in a basin a mass of dry sand (previously dried in an oven), M1 = 2000 g with W = 0%.

2/ Fill without tamping a 01 liter container with a funnel and shave with a metal ruler.

3/ Weigh the contents of the container m0.

4/ Determine the apparent density of dry sand.

$$\rho_0 = \frac{m_0}{V} \quad \text{(II.22)}$$

5/ Pour the sand contained in the 01 liter container into the basin.

6/ Add 2% water, or 40 g of water, to the 2000 g of dry sand and mix with a spatula.

7/ Fill without tamping the 01 liter container and shave using a metal ruler.

8/ Weigh the contents of the container m1.

9/Determine the bulk density ρ1 for W = 2%.

$$\rho_1 = \frac{m_1}{V} \quad \text{(II.23)}$$

10/ Repeat the operation by varying the water content by 2% between 0 and 20%. The

Expansion is the variation in apparent volume according to the water content.

$$\text{Expansion coefficient} = \frac{(V_h - V_d)}{V_d} = \frac{V_h}{V_d} - 1 = \frac{\rho_d(1+\omega)}{\rho_h} - 1 \quad \text{(II.24)}$$

With:

V_h: apparent volume of wet sand.

V_d: apparent volume of dry sand.

10. Measurement of the Flakiness Index [NF P 18-561]:

The production of concrete requires the use of aggregates with a fairly compact shape. The measurement of the flakiness index (A) characterizes the shape of the

aggregates. The shape of a particle is defined by three main dimensions (Figure II.23):

- **Length (L)**: the greatest distance between a pair of parallel tangent planes.
- **Thickness (E)**: the smallest distance between a pair of parallel tangent planes.
- **Size (G)**: the dimension of the smallest square mesh through which the particle can pass.

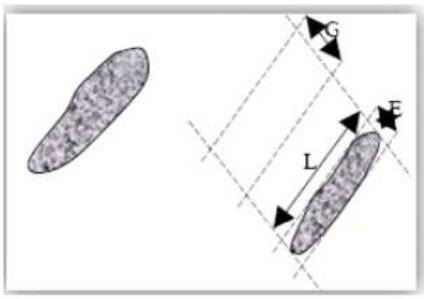


Figure II.23: three dimensions of an aggregate.

The flakiness index (A) is obtained by performing a double sieve analysis (Figure II.24 and Figure II.25), using successively, and on the same aggregate sample:

- a series of standardized square-mesh sieves, with mesh openings of: 50 – 40 – 31.5 – 25 – 20 – 16 – 14 – 12.5 – 10 – 8 – 6.3 – 5 and 4 mm.
- a series of slot sieves consisting of parallel cylindrical bars fixed in a square frame. The internal spacings of the bars are respectively: 50 –31.5 – 25 – 20 – 16 – 12.5 – 10 – 8 – 6.3 – 5 – 4 – 3.15 and 2.5 mm.



Figure II.24: Series of sieves.



Figure II.25: Series of slotted grids.

First, weigh and retain separately all the particles of fraction d_1/D. Then, sieve each size class d_1/D_1 using a slotted grid with spacing $E = D_1/2$. Finally, weigh the particles passing through each slot.

For a given size class d_1/D_i, a partial flakiness index can be defined as follows:

$$A_i = \frac{m_i}{M_i} \times 100 \quad \text{(II.25)}$$

$\mathbf{M_i}$: mass of each size class d_1/D_1, in grams.

$\boldsymbol{m_i}$: mass of particles of each size class d_1/D passing through the corresponding grid.

The overall flakiness index A is obtained by combining the partial values determined for each size class (Eq. III.6), satisfying the condition $G/E > 1.58$:

$$A = \frac{\sum m_i}{\sum M_i} \times 100 \quad \text{(II.26)}$$

The higher A increases ➜ the quality of the aggregates in concrete decreases.

11. Los Angeles Test [NF P 18-573]:

This test is used to determine the resistance of aggregates to fragmentation by impact. The test consists of measuring the quantity of elements smaller than 1.6 mm produced by subjecting the aggregates to impacts from standardized steel

balls in the Los Angeles machine (Figure II.26), with 500 to 1000 rotations. The number of rotations depends on the aggregate size classes used.

The Los Angeles coefficient is defined as:

$$L_A = \frac{m}{M} \times 100 \qquad \text{(II.27)}$$

- m: mass of elements smaller than 1.6 mm.
- M: initial mass (5000 g)



Figure II.26: Los Angeles machine.

12. Micro-Deval Test [NF P 18-572]:

The purpose of this test is to measure the resistance of materials to wear by friction. The principle of the Micro-Deval test is similar to that of the Los Angeles test, but with a lighter charge (steel balls) of 10 mm diameter and a rotation duration of 2 hours at a speed of 100 rotations per minute (Figure II.27).

The Micro-Deval coefficient (MDE) is defined by:

$$MDE = \frac{m}{M} \times 100 \qquad \text{(II.28)}$$

- **m**: mass of elements smaller than 1.6 mm
- **M**: initial mass (500 g)




Figure II.27: Micro-Deval Test.

13. Exercise:

Exercise 01:

Given two different sands:

A coarse sand S1 with a fineness modulus FM1 = 3.9A fine sand S2 with a fineness modulus FM2 = 1.8We are looking for a sand with satisfactory workability, good strength, and a fineness modulus FM = 2.4.

How can we proceed?

Solution:

The proportions of sands S1 and S2 will be as follows:

$$\%S_1 = \frac{2.4 - 1.8}{3.9 - 1.8} = 0.29$$

$$\boldsymbol{S_1 = 29\%}$$

$$\%S_2 = \frac{3.9 - 2.4}{3.9 - 1.8} = 0.71$$

$$\boldsymbol{S_2 = 0.71\%}$$

Exercise 02:

The results of the granulometric analysis test of a material are presented in the table below.

sieve mesh size in mm	cumulative percent passing by weight(g)
8	2000
5	1900
2.5	1720
1.25	1300
0.63	860
0.315	500
0.16	200
0.08	40

1- What is the purpose of the granulometric curve?

2- Calculate the sieving percentages for all diameters and determine the residue for each diameter.

3- Plot the granulometric curve (sieving curve).

4- Calculate FM, Cu, Cc.

5- Comment on the granulometric curve and determine the granular class and nature of this material.

Solution:

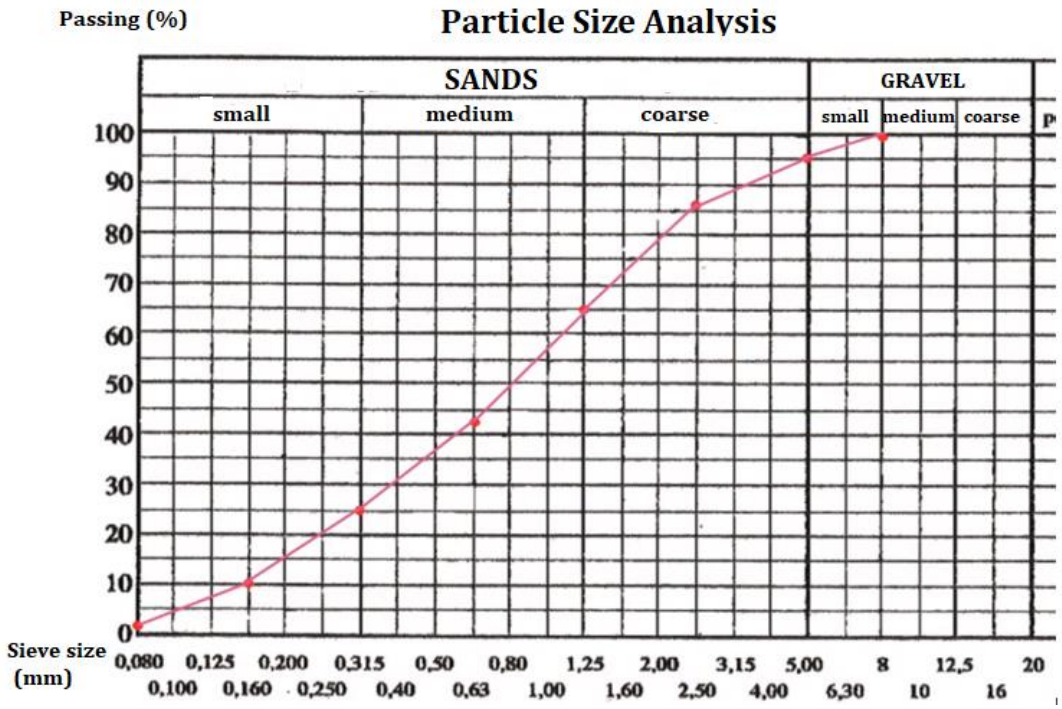
1- The particle size distribution curve allows us to identify the type of material, as well as its gradation class and nature.

2- The percentage passing for all sieve sizes and the retained percentage for each size :

sieve mesh size in mm	cumulative percent passing by weight(g)	%passing	% retained
8	2000	100	0
5	1900	95	5

2.5	1720	86	14
1.25	1300	65	35
0.63	860	43	57
0.315	500	25	75
0.16	200	10	90
0.08	40	2	98

3- Plot the granulometric curve (sieving curve).



4- Calculate FM, Cu, Cc:

$$FM = \frac{A_5 + A_{2.5} + A_{1.25} + A_{0.63} + A_{0.315} + A_{0.16}}{100} = \frac{5 + 14 + 35 + 57 + 75 + 90}{100}$$

$$\boldsymbol{FM = 2.76}$$

$$C_u = \frac{D_{60}}{D_{10}} = \frac{1.125}{0.16} = 7.03$$

$$\boldsymbol{C_u = 7.03}$$

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} = \frac{(0.4)^2}{0.16 \times 1.125} = 0.9$$

$$C_c = 0.9$$

5- The particle size distribution curve is continuous, and the nature of this material is sand, since most of its particle size range lies between 0 and 5 mm.

1. Introduction:

1.1- Definition of Mineral Binders:

Mineral binders are finely ground inorganic materials that, when combined with water, undergo physical and chemical transformations to form a cohesive and adhesive paste. This paste initially exhibits plasticity, allowing it to be shaped or applied, and then progressively hardens through processes such as hydration or crystallization, ultimately developing strength and durability over time.

When aggregates such as sand and gravel are incorporated into this paste, the resulting mixtures are known as mortars (when using fine aggregates) and concrete (when combining both fine and coarse aggregates). These composite materials are widely used in construction due to their versatility, mechanical strength, and long-term stability.



Figure III.1: The addition of aggregates to the paste produces mortars and concrete.

1.2- The Evolution of Binder Manufacturing Techniques Used in Construction:

During prehistoric times and the early stages of Antiquity, clay was used as a binding agent to assemble stones.



Figure III.2: The clay.

The ancient Egyptians (during the construction of the pyramids) used a plaster obtained by heating gypsum.

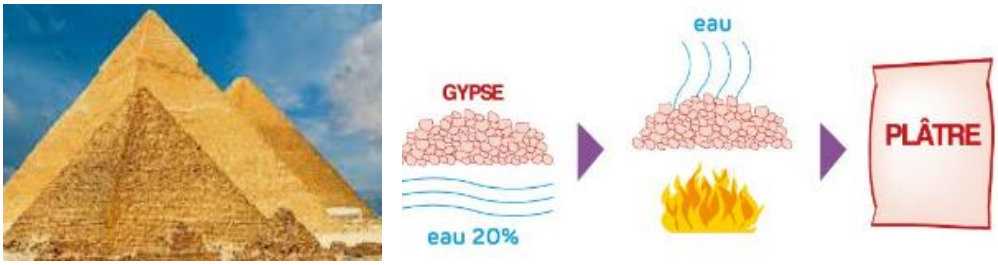


Figure III.3: Use of Gypsum Plaster by the Ancient Egyptians in Pyramid Construction.

The Greeks, followed by the Romans, used lime obtained by calcining (heating) limestone. Later, they improved this binder by adding volcanic ash from the region of Pozzuoli (pozzolana), which led to the creation of Roman cement.



Figure III.4: Ancient Roman architecture.

In 1817, the French engineer Louis Vicat, followed in the early 1824s by the Scotsman Aspdin, named the cement they produced "Portland" because it had characteristics similar to the stone from that region.

DUPONT and DEMARQUE established the first cement factory using a vertical kiln in 1846. Further advancements were made possible with the introduction of rotary kilns around 1880.

In 1870, producing one ton of clinker, which is the basis of cement, took 40 hours, whereas today it takes about 3 minutes.



Figure III.5: Industrial cement production plant.

2. Classification of Binders:

There are two types of mineral binders:

2.1- Air binders:

Air binders are materials that, once mixed with water, form a plastic paste that can only harden and remain stable when exposed to air. Moreover, air binders are soluble in water.

2.2- Hydraulic Binders:

Hydraulic binders are substances capable of hardening and maintaining their strength both when exposed to air and when submerged in water. The durability of their strength is influenced by the chemical composition of their environment.

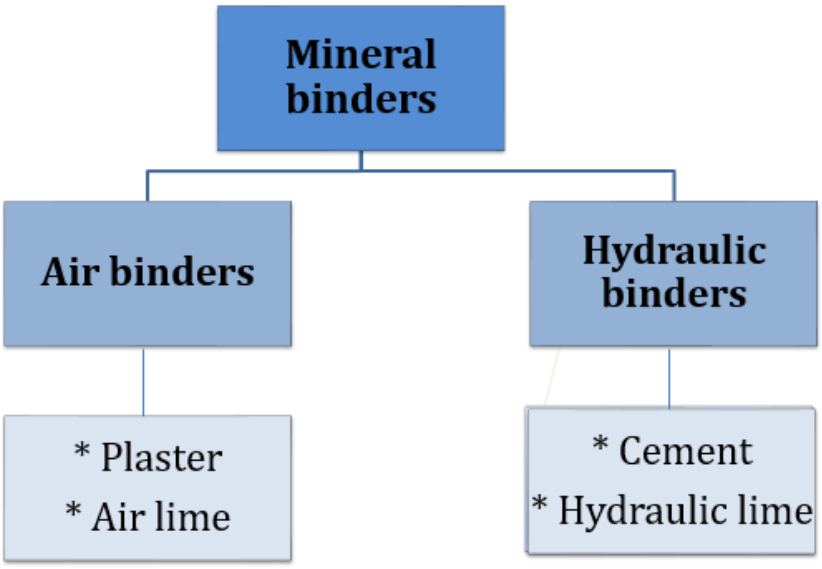


Figure III.6: Classification of Binders.

3. Plaster:

a- Definition:

Plaster is an air binder; it is made of hydrated calcium sulfate ($CaSO_4 \cdot 2H_2O$), also known as **gypsum**, which undergoes partial or complete dehydration through heating. Gypsum is white in color when it is pure.

Plaster has remarkable physical characteristics, including:

- Fire resistance
- Moisture resistance
- Decorative appeal
- Thermal and acoustic insulation



Figure III.7: Hydrated calcium sulfate (gypsum).

b- Raw Materials:

Gypsum and Anhydrite, the two forms of calcium sulfate.

Calcium sulfate is found in nature primarily in the following two forms:

– Hydrated, with two water molecules per molecule of calcium sulfate: this is gypsum, $CaSO_4 \cdot 2H_2O$

–Anhydrous: this is anhydrite, $CaSO_4$

It can also be found, under specific geological conditions, in a hydrated form with a fraction of a water molecule per molecule of calcium sulfate ($CaSO_4 \cdot ½H_2O$): this is bassanite, which is metastable under normal conditions and occurs in small quantities (less than 1%).

The physicochemical characteristics of gypsum are:

• Chemical formula: $CaSO_4 \cdot 2H_2O$

• Density: 2.32 g/cm^3

• Crystal system: Monoclinic

• Hardness (Mohs scale): 1.5 to 2 depending on the orientation of the crystal face



Figure III.8: Spearhead gypsum & Saccharoidal gypsum

• Solubility (in grams of calcium sulfate per kilogram of water):
– at 3 °C: 1.81
– at 20 °C: 2.04
– at 38 °C: 2.10 (maximum solubility)
– at 100 °C: 1.69

Gypsum's solubility is significantly higher in saltwater (seawater).

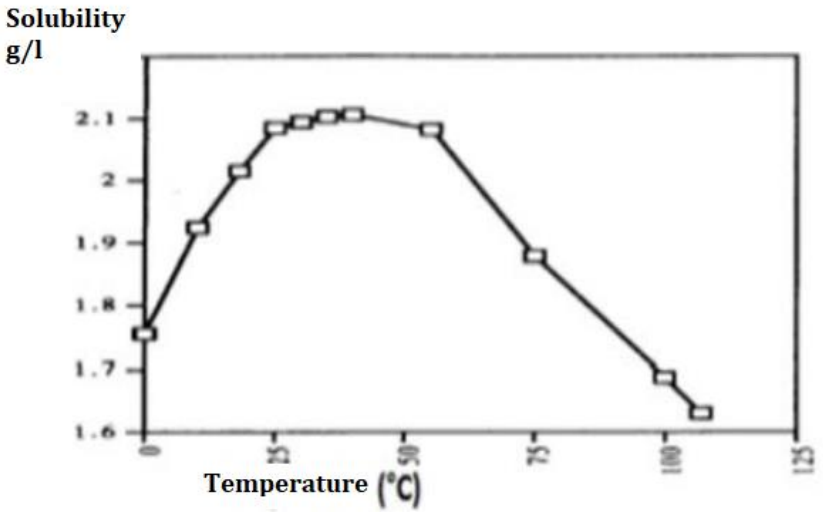


Figure III.9: Solubility (in grams of calcium sulfate per kilogram of water)



Figure III.10: Different forms of gypsum crystals.

3.1- Plaster manufacturing process :

The flowchart below shows the steps in the manufacturing of plaster.

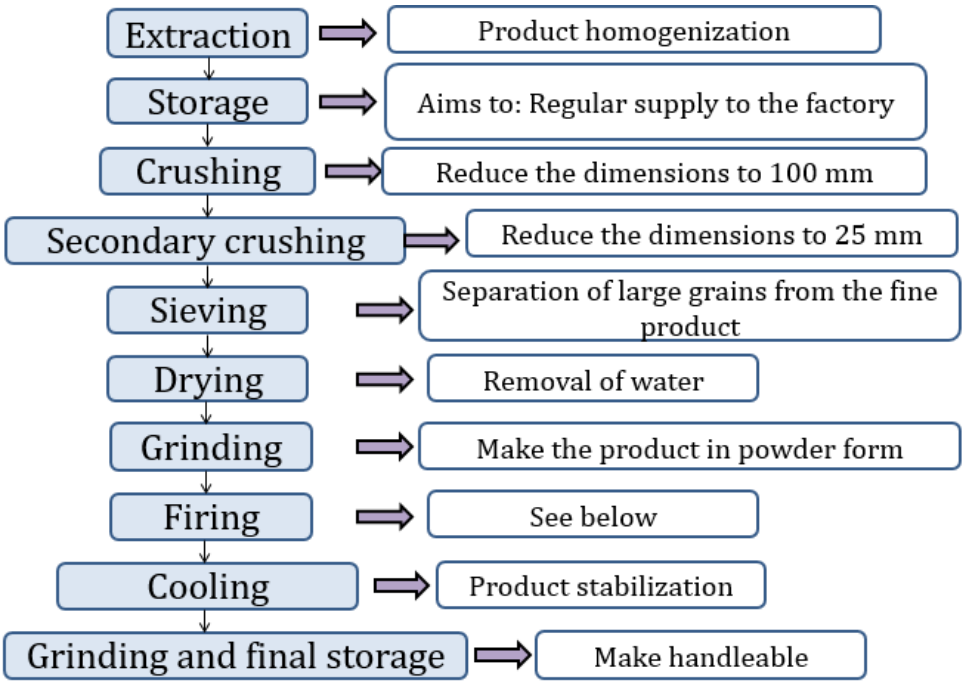


Figure III.11: Plaster manufacturing process.

3.1.1- Plaster Firing Processes:

Plaster firing can be carried out using two processes: the dry process or the wet process.

a- Dry process:

This method is predominantly used for plaster production. The firing takes place under atmospheric pressure or low steam pressure. At temperatures below 180°C, it produces β-hemihydrate ($CaSO_4 \cdot 0.5H_2O$). At temperatures above 350°C, it produces anhydrite II ($CaSO_4$), also known as overburnt plaster.

b- Wet process:

This method produces α-hemihydrate. The firing takes place in a saturated steam atmosphere, either in autoclaves or in a saline solution. In autoclaves, gypsum is heated under steam pressure ranging from 2 to 7 bars for several hours. The α-hemihydrate is then extracted and dried with hot air.In a saline solution, powdered gypsum is cooked in a solution containing various salts (such as calcium chloride, magnesium salts, etc.). The resulting α-hemihydrate is then filtered, washed, and dried.

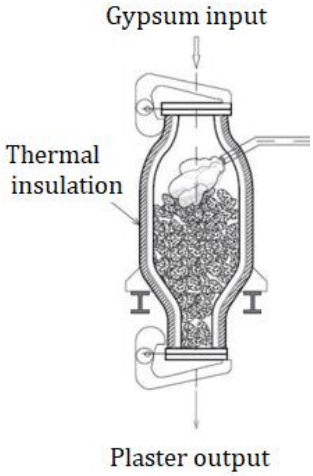


Figure III.12: Autoclave.

3.1.2- Rotary kiln:

Indirectly heated rotary kilns are cylinders equipped with heating tubes through which a fluid (gas, steam, or oil) circulates. The gypsum, ground to a maximum particle size of 2 mm, passes through them in the opposite direction to the heat transfer fluid and is cooked by indirect contact.

When natural gypsum is used, a combined drying and grinding unit is installed upstream. The dehydration gases are treated by filtration after calcination. The use of refractory tubes enables the kiln to produce a range of plaster grades by precisely controlling temperature and residence time, while maintaining high energy efficiency. These kilns are typically designed with lengths ranging from 10 m to 25 m, corresponding to production capacities between 1 t/h and 40 t/h.



Figure III.13: Rotary kiln.

3.2- Classification of plasters:

The classification is based on two factors:

3.2.1- According to the firing temperature:

- Firing at a temperature between 110 – 180°C:

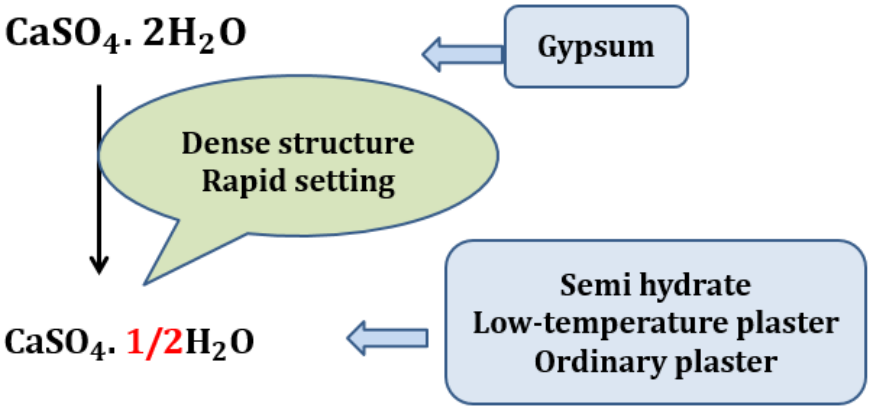


Figure III.14: Heating gypsum at a temperature between 110 and 180 °C.

- Firing at a temperature between 180 – 250°C:

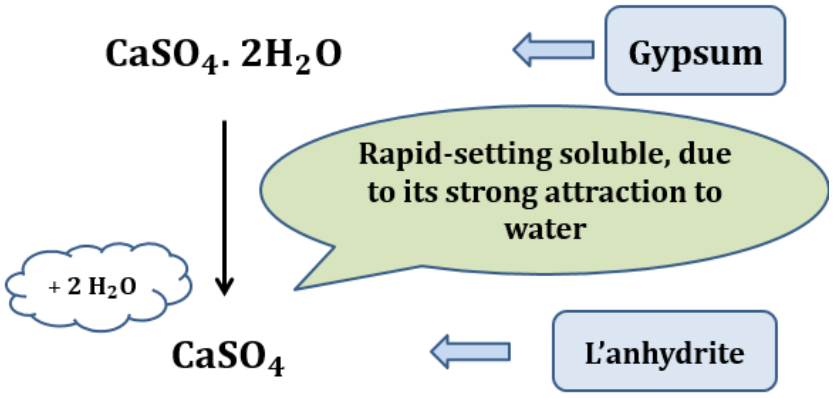


Figure III.15: Heating gypsum at a temperature between 180 and 250 °C.

- Firing at a temperature between 250 – 600°C :

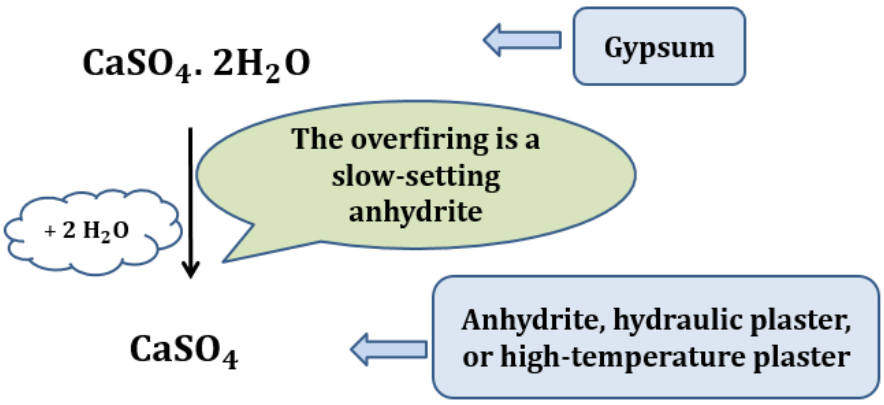


Figure III.16: Heating gypsum at a temperature between 250 and 600 °C.

- Firing at a temperature of **1100°C** results in a plaster of **high hardness.**

3.2.2- According to the fineness of grinding (their uses):

a- Coarse construction plaster (PGC):

The percentage of material passing through a 0.315 mm sieve is about 60 to 65%. It is used for the prefabrication of plaster elements (solid, perforated boards, and panels) for partitions, ceilings, etc.

b- Fine construction plaster (PFC):

The percentage of material passing through a 0.315 mm sieve is greater than 80%. It is used for final coatings, sealants, and moldings.

c- Special and molding plasters:

It is used in interior decoration and in the industry.

3.2.3- Manufacture of high-strength plaster:

Ordinary plaster, which is mainly composed of β-hemihydrate, requires a very large amount of water (60 to 65%) for mixing. The excess water, that is, the water beyond the amount needed for hydration, evaporates, forming pores. As a result, the plaster has a porosity of up to 40%, leading to low strength.

When gypsum is fired with steam under a pressure of 0.3 to 3 MPa, α-hemihydrate plaster is obtained. Its crystals are larger, which requires less mixing water (40 to 45%). Upon hardening, it produces a less porous plaster

with a compressive strength that can reach 15 to 40 MPa after 7 days. This is known as high-strength plaster.The production of this plaster is minimal, and its use is reserved for making molds in metallurgy.

3.3- Specific properties of plaster:

3.3.1- Grinding fineness:

The test involves sieving a plaster sample (m_t) through a 0.4 mm sieve, then weighing the residue (m r). Finally, the grinding fineness is calculated using the formula:

$$Fm=\frac{m_r}{m_t} \times 100 \qquad \text{(III.1)}$$

3.3.2- Normal consistency (Souttard mold):

The test involves determining the amount of water required to prepare a paste with normal consistency (workability). This is done by measuring the spread diameter of a plaster cast, which should be equal to 12 cm.



Figure III.17: Souttard mold.

3.3.3- Setting Time (Vicat Apparatus):

Setting is defined as the transition from a fluid state to a solid state. The setting time of plaster varies depending on several factors, such as the type of plaster used, humidity, ambient temperature, and the amount of water added during mixing.

The setting time test consists of determining the working times of the plaster paste. These are defined as follows :

a- Initial setting time:

This is the time interval between the start of mixing and the moment when the paste begins to lose its plasticity.

b- Final setting time:

This is the point at which the paste has completely lost its plasticity.

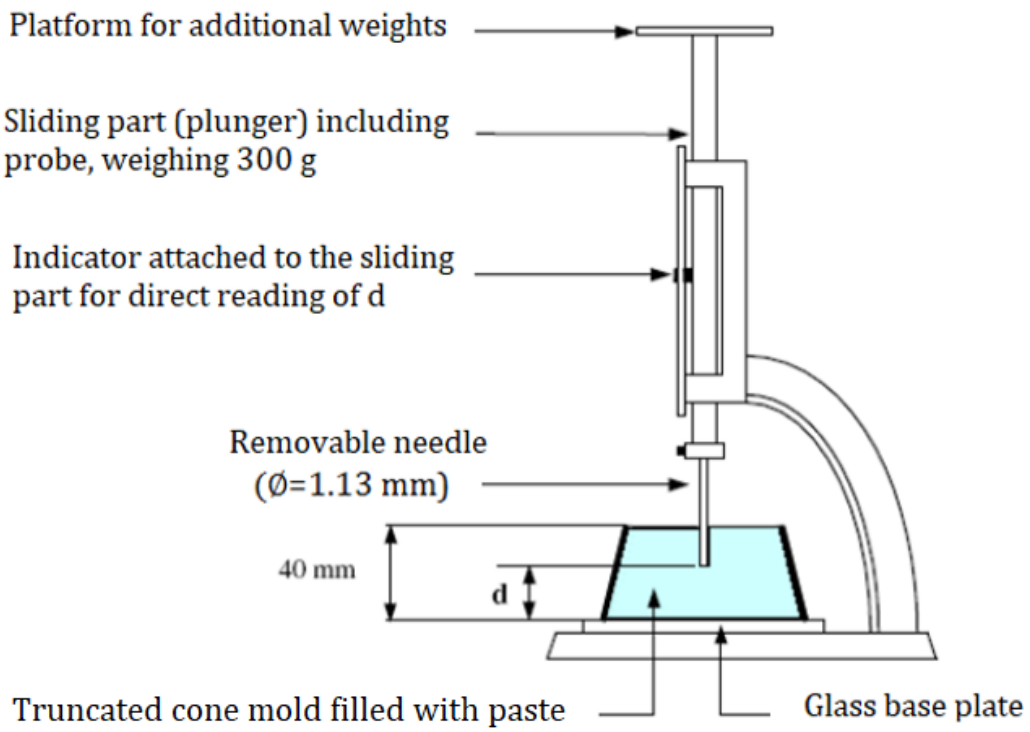


Figure III.18: Vicat Apparatus.

3.3.3.1- Operating Method:

- Prepare a paste using 400 g of plaster and an appropriate amount of water.

- After 1 minute and 30 seconds of mixing, fill the Vicat mold.

- Place the needle in contact with the paste, then release it and allow it to penetrate by gravity for 30 seconds.

- Measure the depth of penetration.

- **Initial setting time:** corresponds to the time interval between the start of mixing and the moment when the needle stops 1 mm from the bottom of the mold.

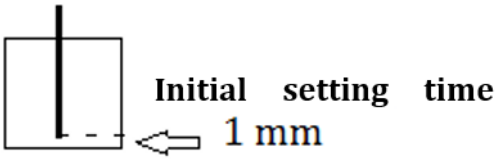


Figure III.19: Initial setting time.

- **Final setting time:** Corresponds to the time interval between the start of mixing and the point at which the needle penetrates only 1 mm into the paste.

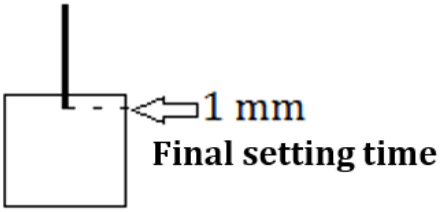


Figure III.20: Final setting time.

3.3.4- Mechanical strength:

The strength of plaster varies depending on its composition, nature, and fineness. The approximate compressive and tensile strengths obtained for different types of plaster stored in air for 28 days after mixing, under conditions of average humidity, are summarized in the table below:

Table III.1: Mechanical strength of various types of plaster after 28 days of air curing.

Désignation	Mixing water in %	Strength at 28days in MPa	
		Compressive	Tensile
Molding plaster	75	5,0	1,8
Fine plaster	75	4,5	1,5
Coarse plaster	60	5,5	1,2
Tile plaster	60	6,0	1,6
Alum plaster	35	15,0	4,0

3.4- The various forms of manufactured plaster:

3.4.1- Normal plasters :



- Moulding plaster
- Construction plasters:
- Fine plaster
- Coarse plaster
- Partition block plaster





3.4.2- Special plasters:

- Alum plaster
- Floor plaster



3.4.3- In the medical field:

In medicine, this term also refers to a support and immobilization device that is molded directly onto the patient, whether on a limb, part of a limb, or a joint in the case of a bone fracture.



Figure III.21 : Medical applications of plaster.

3.4.4- In the field of fine arts:

This refers to a plaster model of a work that is planned to be created in a more valuable material.



Figure III.22 : The use of plaster in the field of fine arts.

3.5- Characteristics of plaster:

3.5.1- Plaster has fire-resistant properties:

Due to its chemically bound water content of 20% when hardened, plaster is fire-resistant. Its dehydration requires a large amount of heat:

- A 10 mm layer of plaster provides 30 minutes of protection at a temperature of 800 °C.
- A 30 mm layer of plaster offers 40 minutes of protection at a temperature of 1100 °C.

3.5.2- Plaster acts as a hygrometric regulator:

As a porous material, plaster absorbs and releases moisture, provided it is not covered with a waterproof paint.

3.5.3- It provides satisfactory sound insulation:

A partition coated with plaster on both sides can absorb up to 48 decibels.

3.5.4- Plaster functions as a thermal insulator:

The thermal conductivity coefficients of materials can be compared in the table below:

Table III.2: The thermal conductivity coefficient of some materials.

Materials	Cellular plaster	Plaster render	Concrete	Red brick
λ (w / m C°)	0.10	0.16	0.87	0.60

Plaster remains essential due to the solutions it offers in terms of comfort, safety, aesthetics, and cost-effectiveness.

4. Air lime:

Lime, mainly composed of calcium oxide or hydroxide, gradually hardens in air through the action of ambient carbon dioxide. The hardening of air lime occurs only under dry air conditions.

4.1- Quicklime (CaO):

Is produced by heating pure limestone ($CaCO_3$) at a firing temperature ranging from 800 to 1000°C, in a process called calcination. This transformation triggers a chemical reaction in which the limestone decomposes into quicklime (CaO) and carbon dioxide (CO_2). This reaction results in a weight loss of approximately 45%, corresponding to the release of carbon dioxide.

$$CaCO_3 \xrightarrow{800 \text{ à } 1000°C} CaO + CO_2$$

4.1.1- Quicklime manufacturing process :

The flowchart below shows the steps in the manufacturing of quicklime:

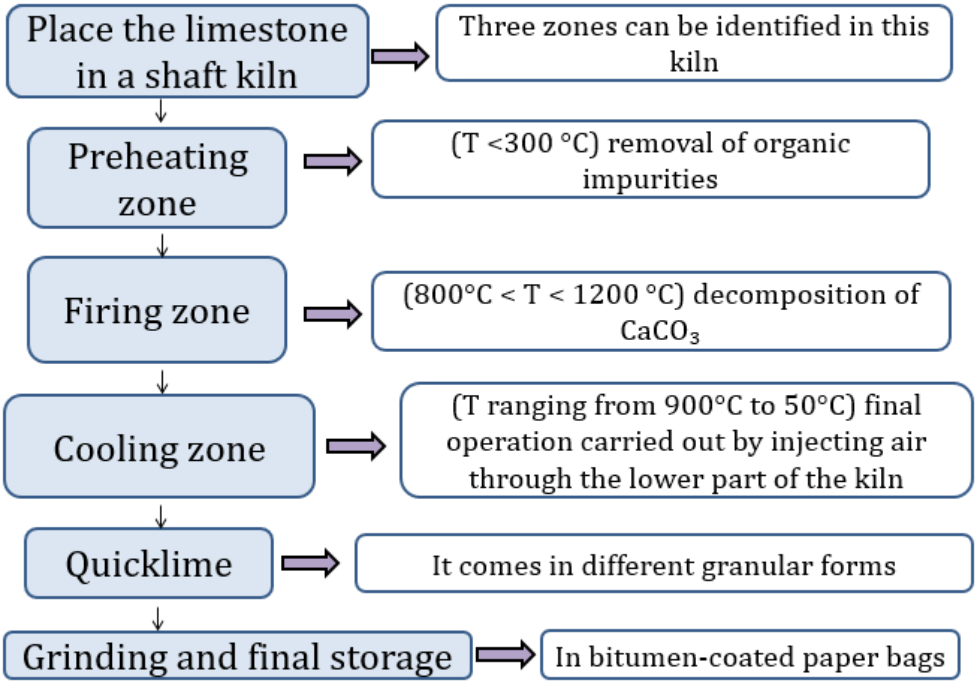


Figure III.23: Quicklime manufacturing process.

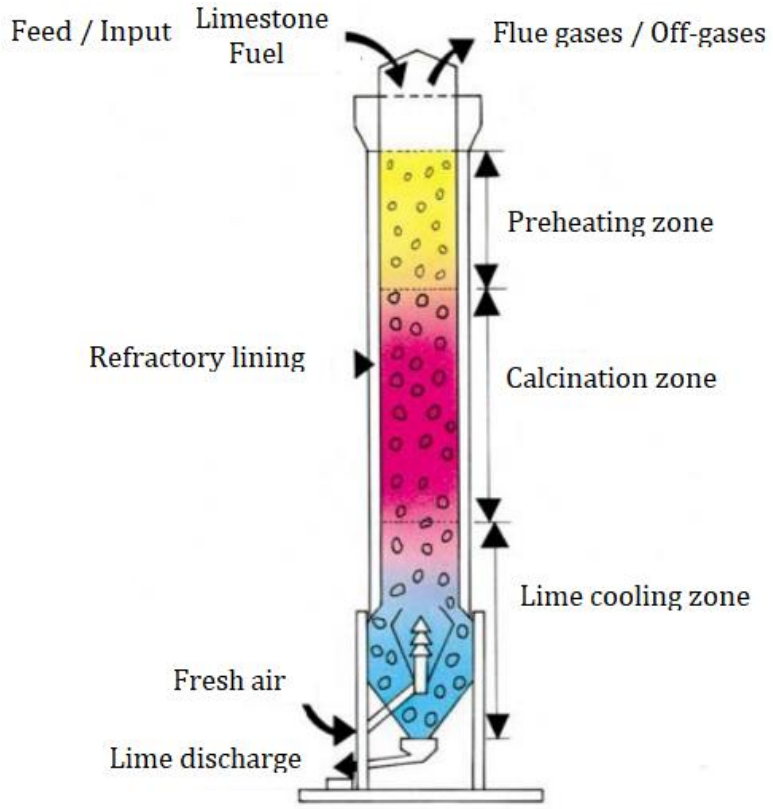
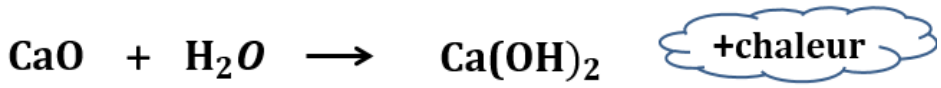


Figure III.24: Conceptual illustration of a vertical furnace.

4.2- Slaked lime:

Also known as air lime, it is mainly composed of calcium hydroxide ($Ca(OH)_2$) and is obtained by the controlled slaking of quicklime. The transformation of quicklime (CaO) into slaked lime ($Ca(OH)_2$) occurs by the addition of water (H_2O). This slaking process is accompanied by a significant release of heat.



The hardening of air lime only occurs under dry air conditions and is achieved through carbonation. The carbonation reaction of air lime is described as follows:



4.3- Classification of limes:

Lime is classified based on its calcium oxide (CaO) content and clay impurities, and is divided into three main categories:

4.3.1- Pure, rich, or fat lime:

It contains more than 95% CaO and less than 5% MgO. Obtained by calcining pure limestone, it is soft and hydrates quickly, forming a fine powder of $Ca(OH)_2$ with a strong release of heat. It hardens slowly in air by absorbing CO_2 from the atmosphere. It is used in the manufacture of mortar, whitewash, concrete, and in the metallurgical industry.

4.3.2- Hydraulic lime: Contains limestone with 5 to 30% clay. It hardens in the presence of water thanks to the silicates, aluminates, and ferrites formed during firing. Depending on the clay content, it can be:

- Weakly hydraulic (5–10% clay): for less important structures in damp areas.
- Moderately hydraulic (10–20% clay): for more robust constructions.

- Highly hydraulic (20–30% clay): used for durable structures exposed to moisture.

4.3.3- Lean or poor lime:

Contains 80 to 85% CaO + MgO and 10 to 40% insoluble impurities (sand, stone). Its hardening is slow, and it does not increase in volume. It produces a lower-quality mortar, suitable for less demanding structures.

Each type of lime has specific properties, such as the speed of slaking, hardening, color, and is used according to the construction requirements.

4.4- Their uses:

Air lime is used for:

-The preparation of masonry mortars and plasters.

-The production of artificial stones.

-The production of paints.



Figure III.25: Applications of lime in the construction field.

5. Portland cement

5.1- Definition:

Cement, as a hydraulic binder, is the main component of concrete. It comes in the form of a fine powder, typically gray, obtained by grinding clinker with specific additives.



Figure III.26: Portland cement.

Clinker, a product of the firing and cooling of a carefully homogenized and proportioned mixture of limestone and clay, is primarily composed of CaO combined with SiO2, Al2O3, and Fe2O3. This composition is designed to adjust the material's properties to meet construction needs. Additives such as blast furnace slag, natural pozzolana, silica fume, and ground limestone are incorporated to improve the properties of cement and concrete, addressing various issues encountered during the construction of structures.

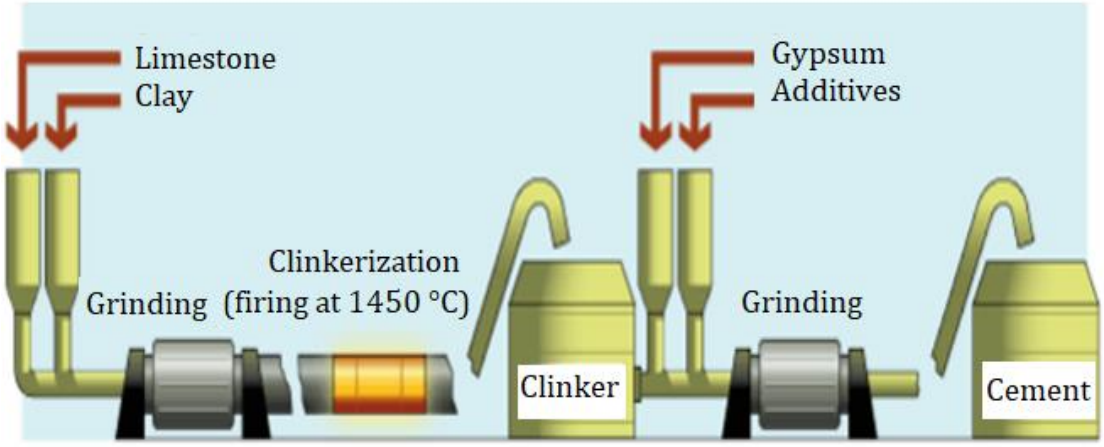


Figure III.27: Diagram of the cement manufacturing process.

5.2- The raw materials used in cement manufacturing:

The raw materials used in cement manufacturing are mainly limestone and clay. Limestone provides the necessary calcium, while clay supplies silica, alumina, and iron.

Table III.3: The raw materials used in cement manufacturing.

Materials	Chemical composition	Nature of rocks	Proportions (%)
Limestone	CaCO3	Sedimentary	70 - 80
Marl	CaCO3+Argile	Sedimentary	-
Clay	$Al_2O_32.SiO_2n.H_2O$	Sedimentary	20 - 25
Gypsum	$CaSO_4.2H_2O$	Sedimentary	2 - 5
Iron ore	Fe_2O_3	Metamorphic	3 - 5

5.3- Cement manufacturing process:

There are two main methods for producing Portland cement:

5.3.1- Wet process:

This method is chosen when the raw materials have a moisture content higher than 15% (the raw materials are ground and mixed in the presence of water). This method is more environmentally friendly, generates less dust, but is less economical. The kiln used is quite long, over 200 meters.

5.3.2- Dry process:

This method is chosen when the raw materials have a moisture content below 15% (the raw materials are ground, mixed, and fired dry). This method is less environmentally friendly but more economical. The kiln is relatively short, less than 100 meters.

5.4- Cement manufacturing process by the dry method:

5.4.1- Extraction: The raw materials are extracted from open-pit quarries located near the plant to facilitate transport and reduce operating costs. Limestone is extracted using explosives, while clay is directly extracted using mechanical shovels or bucket excavators, due to its soft and crumbly nature, which makes it easier to extract than the harder limestone.




Figure III.28: Mechanical shovels and bucket excavators.

5.4.2- Crushing:

Stone blocks, reaching a maximum size of one meter, undergo a crushing process (both primary and secondary) at the quarry site to reduce them to sizes of 50 or 100 mm, making transportation to the plant easier.

The mode of transport for raw materials depends on the distance between the quarries and the plant and can be carried out by conveyor belt, trucks, or rail wagons.





Figure III.29: The mode of transport for raw materials.

5.4.3- Raw mix grinding:

The raw mix is dried and ground simultaneously in a combined grinding and drying unit. The resulting powder, known as raw meal, has a fineness of around 100 to 200 µm and is then stored in two separate silos: the first is referred to as the "low-grade silo," while the second is called the "high-grade silo.

5.4.4- Firing process:

The homogeneous raw meal is fed directly into the rotary kiln, which is continuously heated.

- **Stages of firing:**

a- Evaporation of water at 100°C.

b- Release of chemically combined water from the clay at 450°C.

$$Al_2O_3 2.SiO_2 2.H_2O \xrightarrow{450°C} Al_2O_3 2.SiO_2 + H_2O$$

c- Decomposition of clay into simple oxides:

$$Al_2O_3 2.SiO_2 \xrightarrow{700°C} Al_2O_3 + 2.SiO_2$$

d- Complete dissociation of calcium carbonate at 900°C:

$$CaCO_3 \xrightarrow{900°C} CaO + CO2$$

e- Combination of the lime obtained with the clay component at a temperature of 1450°C to form the 4 constituent minerals of clinker:

$$2CaO + 3(CaO.Al_2O_3) \xrightarrow{900°C} 5.CaO.Al_2O_3 \xrightarrow{1000°C} [C_3A]\ 3.CaO.Al_2O_3$$

$$CaO + CaO.Fe_2O_3 \xrightarrow{900°C} 2.CaO.Fe_2O_3$$

$$2.CaO + CaO.Fe_2O_3 + CaO.Al_2O_3 \xrightarrow{1000°C} [C_4AF]\ 4.CaO.Al_2O_3.Fe_2O_3$$

$$2.CaO + SiO_2 \xrightarrow{1200°C} [C_2S]\ 2.CaOSiO_2$$

$$CaO + 2.CaOSiO_2 \xrightarrow{1450°C} [C_3S]\ 3.CaOSiO_2$$

5.4.5- Cooling:

After firing, the material undergoes rapid cooling to prevent the transformation of C2S β into C2S γ. Then, the clinker is reduced into granules with a diameter ranging from 0 to 40 mm using a hammer crusher.

5.4.6- Grinding:

At this stage, the setting regulator (gypsum) is added in the appropriate dosage, along with other possible additives such as blast furnace slag, natural pozzolana, silica fume, fly ash, etc. The mixture is ground until a Blaine fineness between 3000 and 3500 cm^2/g is achieved.

5.4.7- Cement dispatch:

The cement produced is stored in silos and then packed into 50 kg bags.



Figure III.30: Cement Storage and Packaging.

5.5- Clinker:

Portland clinker is a hydraulic material that must contain at least two-thirds by mass of calcium silicates (C3S) and (C2S), with the remaining third consisting of aluminum oxide (Al2O3), iron oxide (Fe2O3), and other oxides. The (CaO/SiO2) ratio must not be less than 2. The proportion of magnesium oxide must not exceed 5% by mass.



Figure III.31: The Clinker.

The table below shows the typical average mineralogical composition of Portland cement clinker:

Table III.4: Mineralogical composition of Portland cement clinker.

Constituent	Cement Chemist Notation	Chemical Formula	Mass (%) of Phases in Clinker
Tricalcium silicate (Alite)	C_3S	Ca_3SiO_5	60–65%
Dicalcium silicate (Belite)	C_2S	Ca_2SiO_4	10–20%
Tricalcium aluminate	C_3A	$Ca_3Al_2O_6$	8–12%
Tetracalcium aluminoferrite	C_4AF	$Ca_4Al_2Fe_2O_{10}$	8–10%

The table below shows the chemical composition of clinker:

Table III.5: Chemical composition of clinker.

Oxide	Lime	Silica	Alumina	Iron Oxide	Magnesia	Potash	Soda	Sulfur Trioxide
Formula	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3
Content (%)	60–69	18–24	4–8	1–8	0.0–5.0	0–2	0–2	≤ 3.50

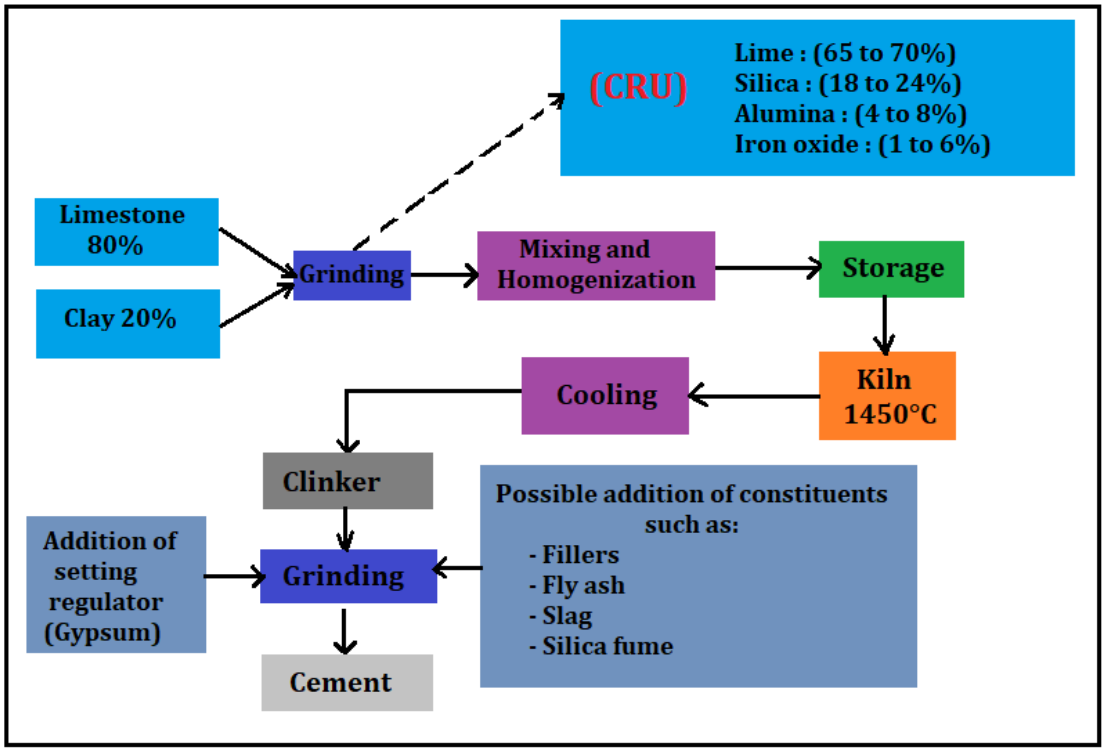


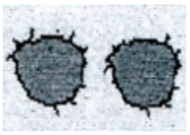
Figure III.32: The Cement Manufacturing Process

5.6- Hydration phenomenon:

The components of cement are indeed hydraulic, meaning they chemically react with water. Hydration is the process by which this chemical reaction occurs, leading to the setting and hardening of the cement. Setting takes place in the first few hours after mixing and is characterized by the loss of plasticity in the cement paste. Hardening, which continues over time, is marked by an increase in the material's strength and can take several years.

Changes observed in the hydration reaction over time and evolution of the composition of the cement paste.

Table III.6: Hydration phenomenon over time.

				
0 minute	From 1 to 5 minutes.	From 5 to 30 minutes.	From 30 minutes to 2 hours.	From 2 hours and beyond.
Anhydrous cement grains	Introduction of water and mixing. Immediate formation of hydrate crystals at the surface of the grains.	Dormant period. Hydration continues, but at a slow rate as long as there is enough gypsum remaining.	Setting begins: Gypsum is consumed, which accelerates hydration. Hydrate bridges start to form, connecting the grains to each other.	End of setting: The grains are all bonded together. The continuation of hydration leads to the onset of hardening.

Hydration reactions release heat, making them **exothermic**. The intensity of this heat varies depending on the types of cement and the setting rate. The resulting hydrates include:

- Hydrated calcium silicates
- Portlandite
- Ettringite

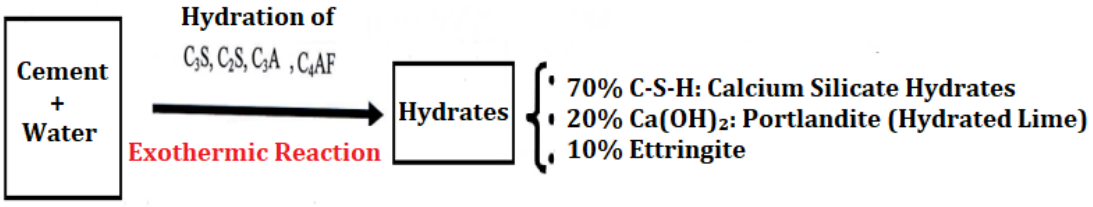


Figure III.33: Exothermic Reaction.

During the reaction of C3S, two products are formed: calcium hydroxide, known as Portlandite (Ca(OH)2), and a gel of hydrated calcium silicate, CSH.

5.6.1- Hydrated calcium silicate (CSH):

The composition of the gel varies throughout the hydration process, which is also influenced by the water/cement (W/C) ratio and the curing temperature. The product of the reaction is referred to as CSH without specifying its composition. The CSH produced at room temperature is generally amorphous, but when formed during the hydration of Portland cement at high temperatures, it may exhibit a crystalline structure.

5.6.2- Portlandite [CH]:

It crystallizes in the hexagonal system in the form of plates or small hexagonal crystals that form clusters. These crystals are easily cleavable along their preferred growth plane. It is soluble in water, and its density is 2,34 .



Figure III.34: SEM observation of the main hydrates: C-S-H and Portlandite.

5.6.3- Hydration of C3A:

The very high reaction rate of C3A leads to the rapid setting of Portland cement pastes, which causes problems when working with concrete made from ordinary Portland cement (OPC). To regulate this reaction, the addition of gypsum ($CaSO_4.2H_2O$ or $C\hat{S}H_2$) is carefully controlled, which delays setting. This delay is due to the formation of an ettringite shell around the C3A grains, thereby isolating the anhydrous grain.

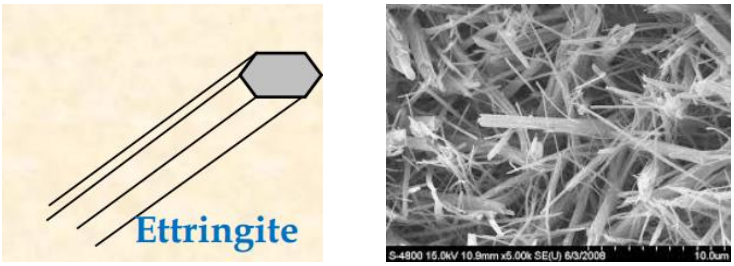


Figure III.35: Ettringite.

Hydration of C_3S:

$$2(3CaO.SiO_2) + 6H_2O \longrightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2 + Q$$

Hydration of βC_2S:

$$2(2CaO.SiO_2) + 4H_2O \longrightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2 + Q$$

Hydration of C_3A:

$$3CaO.Al_2O_3 + 6\ H_2O \longrightarrow 3CaO.Al_2O_3.6H_2O + Q$$

Hydration of C_4AF:

$$4CaO.Al_2O_3.Fe_2O_3 + 2CaO.H_2O + 10H_2O \longrightarrow 3CaO.Al_2O_3.6H_2O + 3CaO.Fe_2O_3.6H_2O + Q$$

5.6.4- The hydration rate of the main components of cement:

The higher the hydration rate of a mineral, the more quickly its strength increases.

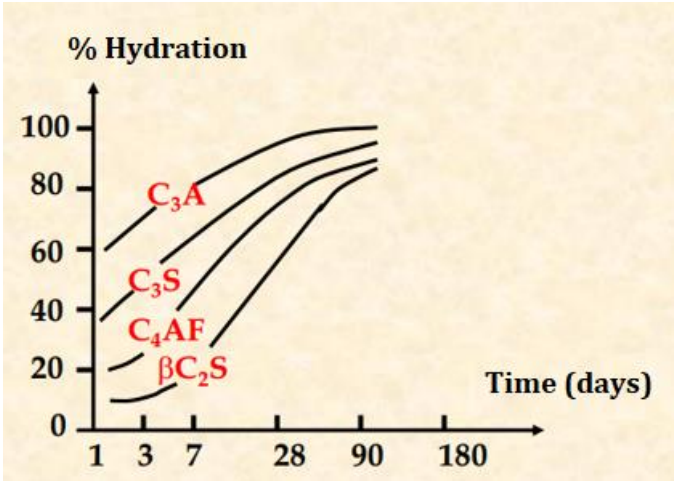


Figure III.36: Evolution of the hydration of the main cement constituents over time.

5.7- Different types of cement:

The table below shows the different types of cement.

Table III.7: different types of cement.

Types of cements	Notation	clinker	Other constituents	Minor constituants
Portland cement	CPA – CEM I (32.5-42.5 - 52.5)	>95	/	0-5 gypsum
portland cement Compound	CPJ – CEM II A (32.5 - 42.5) CPJ - CEM II B (32.5 - 42.5)	80 – 94 65 – 79	6 – 20 % 21 à 35% slag, pozzolan, limestone, Fly Ash,	0-5 gypsum
Blast furance cement	CHF – CEM III A CHF – CEM III B CHF – CEM III c	35 – 64 20 – 34 5 – 19	36 – 65 % 66 – 80 % 81 – 95 % Granulated slag	0-5 gypsum
Pozzolanic cement	CPZ – CEM IV A CPZ – CEM IV B	65 – 90 45 – 64	10 – 35 % 36 – 55 % de natural pozzolan	0-5 gypsum
Slag and Ash cement	CLC – CEM V A CLC – CEM V B	40 – 65 20 - 39	18 – 30 % Slag and fly 18 – 30% ash 31 - 50 % Slag and 31 - 50 % fly Ash	0-5 gypsum

5.8- Applications of different types of cement:

The table below shows the applications of different types of cement.

Table III.8: Applications of different types of cement.

Types of cements	Area of use
CPA – CEM I	All common works in reinforced concrete or prestressed concrete, whether in the air, in the ground, or in water. This concrete requires high short-term strength.
CPJ – CEM II A CPJ - CEM II B	All common works in reinforced concrete or prestressed concrete, whether in the air, in the ground, or in water. Moderate resistance to aggressive waters.
CHF – CEM III A CHF – CEM III B CHF – CEM III c	Massive structures (piers of civil engineering works, retaining walls, dams). Reinforced concrete works in an aggressive environment. Underground works. Maritime works, particularly in ports or reservoirs. Very good resistance to the aggressive environment.
CPZ – CEM IV A CPZ – CEM IV B	All reinforced concrete or prestressed concrete works in an aggressive environment. Large-scale works. Very good resistance to aggressive waters.
CLC – CEM V A CLC – CEM V B	Marine works. Foundation works. Massive works. Structure exposed to aggressive waters.

5.9- Properties of Cement:

5.9.1- Measurement of cement fineness [NF EN 196-6]:

The principle of this test involves passing a specified amount of air through a compacted bed of cement under defined conditions, measuring the passage time, and deducing the specific surface by applying an empirical formula. The device used to determine the grinding fineness of the cement is called the 'Blaine Permeability Meter.'

$$SS = \frac{K}{\rho} \times \frac{\sqrt{P^3}}{1-P} \times \frac{\sqrt{t}}{\sqrt{0.1\eta}} \qquad \text{(III.2)}$$

K: constant of the device

P: porosity of the cement layer (taken as 0.5)

t: air flow time between two markers (2 – 3)

ρ: absolute density of the cement (g/cm^3)

η: viscosity of air at the test temperature

The fineness of the cement plays a crucial role during mixing; the larger the surface area of cement in contact with water, the faster and more complete the hydration process.

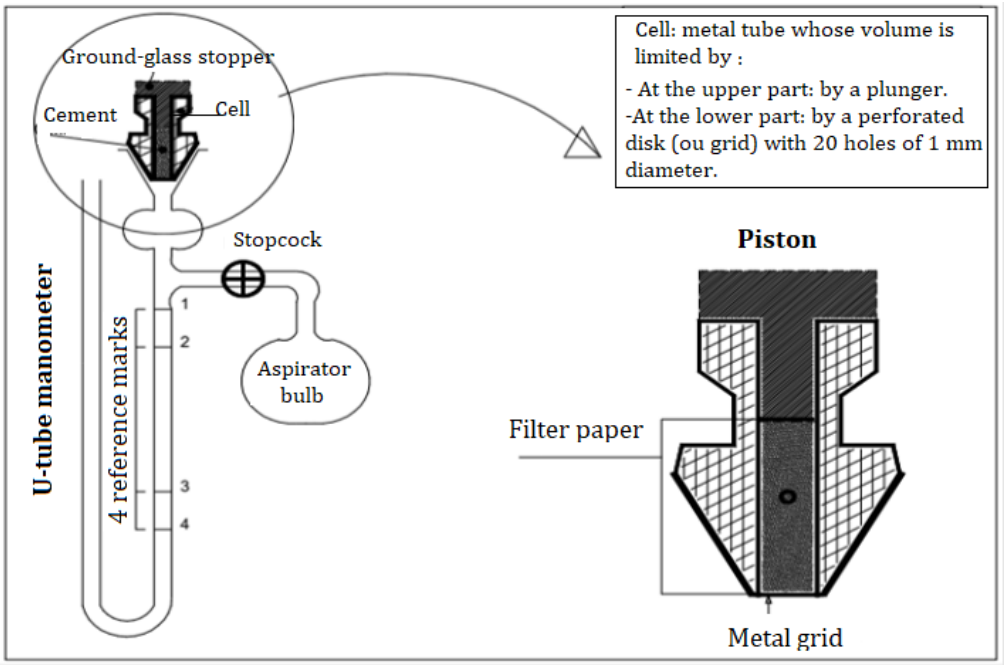


Figure III.37: The device used to determine the fineness of cement (Blaine Permeability Meter).

In general, the specific surface of cement ranges from 2800 to 5000 cm^2/g.

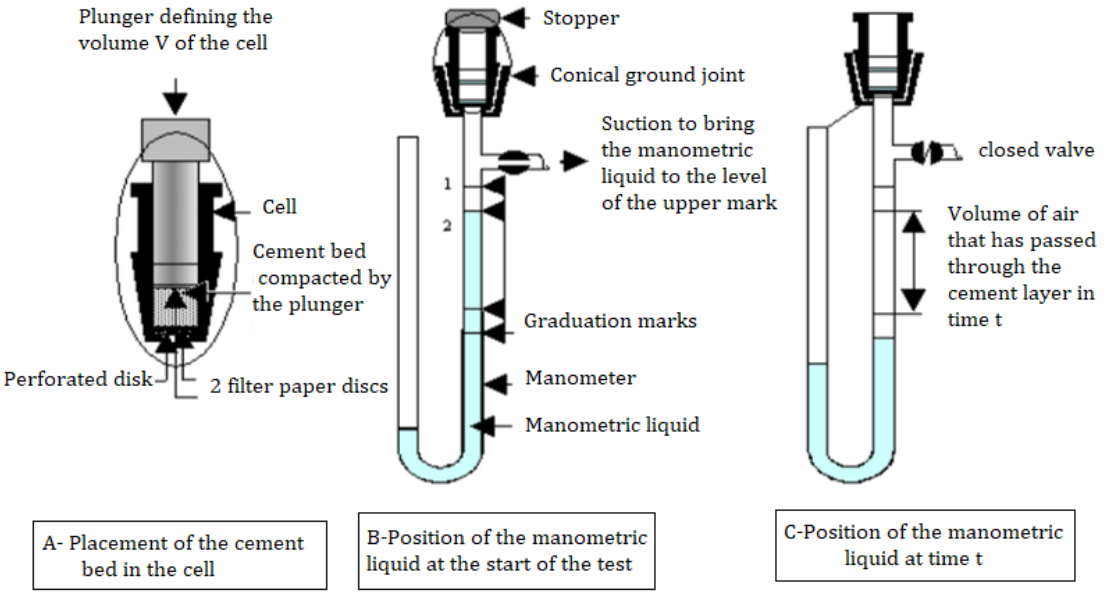


Figure III.38: Cement fineness test using Blaine's air permeability method.

5.9.2- Density:

Density is the ratio between the mass and the volume of a material. The bulk density of cement is approximately 0.8 to 1.2 g/cm^3. The absolute density of cement is approximately 2.9 to 3.1 g/cm^3.

5.9.3- Standard Consistency:

The consistency of cement refers to the amount of water required to mix with the powder in order to obtain a plastic paste with what is considered normal consistency.

- **Setting Test of Cement Paste [NF EN 196-3]:**

This test consists of the following steps:

- Weigh 500 g of cement and place it into the mixing bowl. The selected amount of water is added to the cement within a time frame of 5 to 10 seconds.

- Start the mixer at low speed for 90 seconds. Stop the machine for 15 seconds and, using a small trowel, gather the paste sticking to the bowl and extending beyond the mixing area. Restart the machine for another 90 seconds at low speed.

- The paste is then quickly placed into the conical mold set on a glass plate, without excessive tamping or vibration. The excess paste is removed by a back-and-forth motion using a trowel held perpendicular to the top surface of the mold. Then the entire assembly is placed on the Vicat apparatus base plate.

- Four minutes after the start of mixing, the needle is brought into contact with the top surface of the sample (conical mold) and released without force. The needle then penetrates into the paste.

- When the needle is immobilized (or after a 30-second wait), the distance “d” between the tip of the needle and the base plate is measured. This distance “d” characterizes the consistency of the tested paste.

  - If “d” = 6 mm ± 1 mm, the consistency of the tested paste is said to be standard (standard consistency).

- If "d" does not reach this value, the test must be repeated with a different water-to-cement ratio until the desired consistency value is achieved.

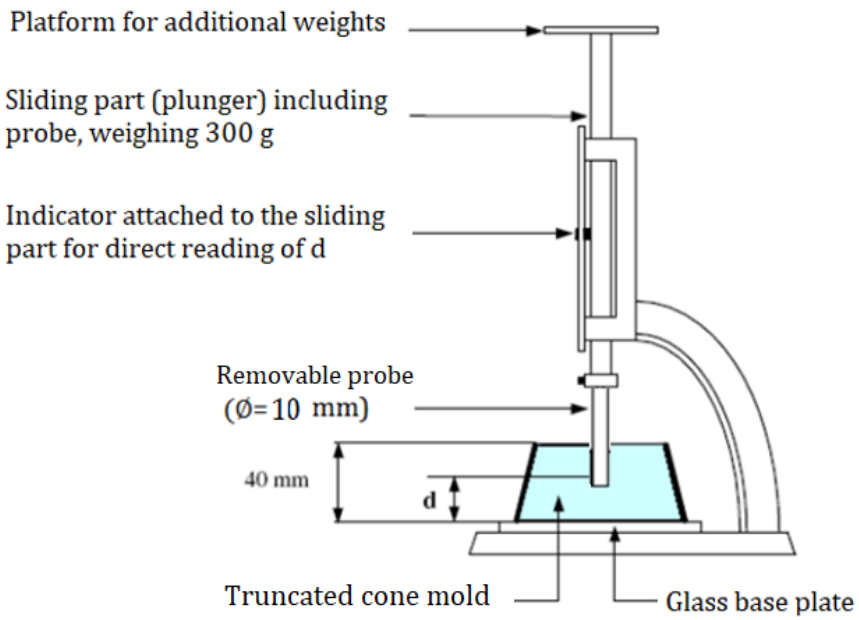


Figure III.39: Vicat apparatus equipped with the consistency probe.

5.9.4- Shrinkage:

Shrinkage is defined as the reduction in the apparent volume of a material; it is evaluated using specimens with dimensions of 4×4×16 cm, which are kept at a temperature of 20 °C and under controlled relative humidity conditions.

$$\varepsilon = \frac{\Delta l}{l_0} \qquad \text{(III.3)}$$

ε ≈ 800 to 1000 µm/m

l_0: initial length.

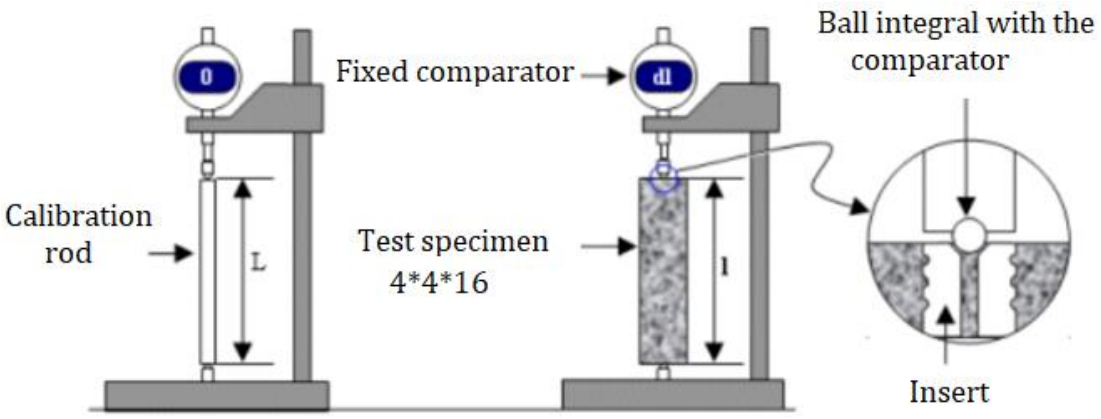


Figure III.40: Deformation Measurement of Test Specimen with Comparator Apparatus.

5.9.5- Mechanical Properties:

Based on the European standard NF EN 196-1, flexural tests are carried out on prismatic specimens (4×4×16 cm) made of standard mortar at 28 days of age. The half-prisms obtained after flexural failure are then broken in compression.



Figure III.41: Flexural tensile tests and Compression test.

The strength of the mortar is then considered representative of the cement's strength. The graph below shows the development of the mechanical strengths of the clinker components.

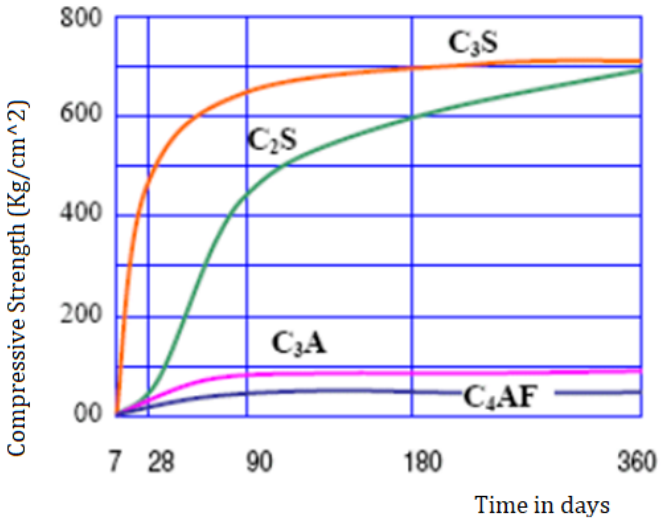


Figure III.42: Development of the mechanical strengths of the clinker components.

The figure below shows the development of the mechanical strength of standard mortar over time.

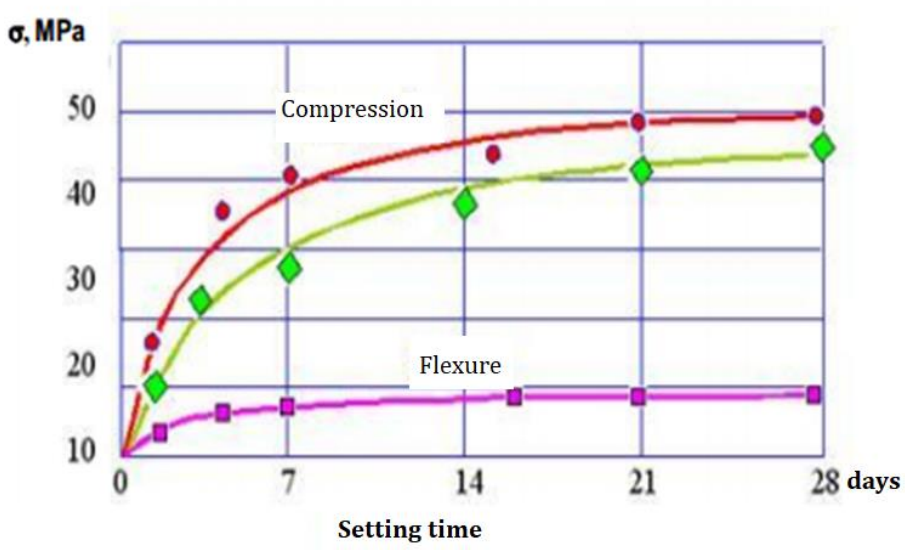


Figure III.43: development of the mechanical strength of standard mortar over time.

5.10- Factors Influencing the Strength of Cement:

Indeed, the strength of cement depends on several factors. Among these factors are:

5.10.1- The chemical composition of the cement:

The proportions of the different components of the cement, such as clinker and additives, influence its strength.

5.10.2-The water-cement ratio (W/C): The ratio between the amount of water and the amount of cement used in the mix plays a crucial role in the final strength of the material. A lower water/cement ratio tends to produce stronger concrete.

5.10.3- The degree of fineness of the cement: The size of the cement particles, also called fineness, affects its reactivity and thus its strength. Finer cement generally has higher strength due to its larger specific surface area.

5.10.4- Curing conditions: Temperature, humidity, and curing duration all influence the strength of the cement. Optimal curing conditions can lead to better strength in the final material.

5.10.5- Additives and admixtures: The addition of specific additives and admixtures can alter the properties of the cement, including its strength.

5.11- Mineral Additions

Ground granulated blast-furnace slag, fly ash, pozzolans, and silica fume, whether used as cement components or as additions in concrete, are generally beneficial to the chemical resistance of concrete. This is partly because they reduce the overall alkalinity of the material by consuming the lime released during the hydration of C3S and C2S silicates, and partly due to their positive effect on the concrete's microstructure.

The figure below shows the role of ultra-fine materials and cement in the compactness of concrete.

These are fine particles which, when added in amounts around 10% of the cement weight, enhance the performance and durability of concrete due to their physicochemical properties (fly ash, slag, fillers, etc.).

Silica fume, or microsilica, is the most commonly used. It consists of amorphous silicon oxides in the form of microspheres with a diameter of about 0.1 µm, a very high specific surface area, and strong pozzolanic activity.

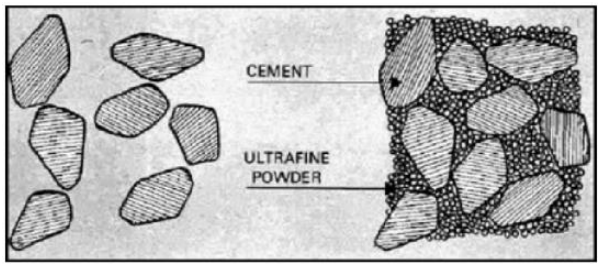


Figure III.44: Arrangement of cement particles with ultrafine powder filling the voids

5.12- The drawbacks of excessive cement production:

5.12.1- Environmental impact:

Cement manufacturing releases significant amounts of carbon dioxide. It is a major source of greenhouse gases, accounting for approximately 8% of total global CO_2 emissions.

5.12.2- Economic impact:

The energy required for cement production must also be taken into account. As an indicative example, the average annual energy consumption of cement plants in Algeria (1 billion kWh, 7 billion therms) is equivalent to the annual electricity consumption of a city with 750,000 to 800,000 inhabitants (9700 kWh per capita).

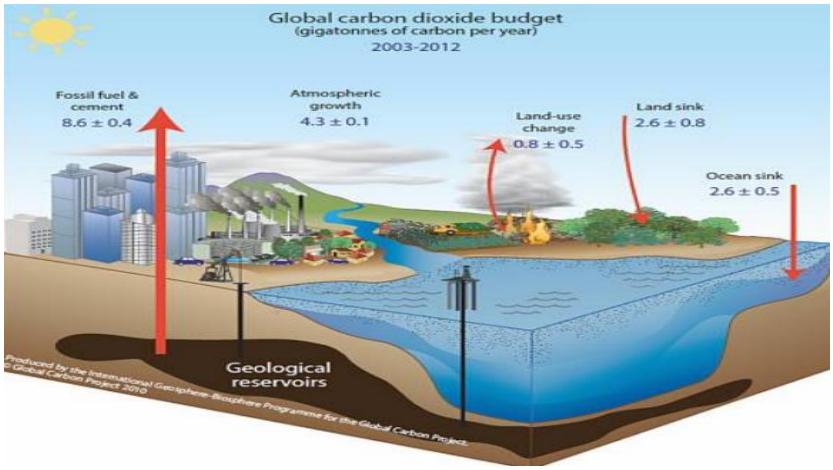


Figure III.45: Source of greenhouse gases.

Theoretically, the electrical consumption of cement plants is distributed as follows [Cetim 2001]:

- Raw material preparation: 30% (crushing – raw grinding)
- Clinker production: 30% (kiln – auxiliary equipment)

Cement production: 40% (cement grinding)

6. Exercises

Exercise 01:

During a cement test, the following results are obtained:

Initial setting time: 10 h 20 min

Final setting time: 12 h 05 min

Calculate the setting time.

Solution:

12 h 05 min - 10 h 20 min = 1 h 45 min.

Therefore, the duration between the initial and final setting times is 1 h 45 min.

Exercise 02:

To produce a mortar, 500 kg of cement is used. The water-to-cement ratio (W/C) is equal to 0.50.

The sand used has a water content of 6%, and its dry mass is 1500 kg.

Determine:

1- The total amount of water corresponding to the W/C ratio.

2- The amount of water already contained in the sand.

3- The additional amount of water to be added to the mixture.

Solution:

1. Theoretical total amount of water:

$$m_w = 0.50 \times 500 = 250 \text{ kg}$$

2. Amount of water contained in the sand:

$$m_{w\ (sand)} = 1500 \times \frac{6}{100}$$

$$m_{w\ (sand)} = 90 \text{ kg}$$

3. Amount of water to be added:

$$m_w \text{ (added)} = 250 - 90 = 160 \text{ kg}$$

Therefore, 160 kg of water must be added to the mixer, since 90 kg of water is already supplied by the moisture contained in the sand.

1. Introduction:

Mortar is a material capable of meeting various requirements in the field of construction. Its primary role is to bind masonry elements together to form a single unit. In addition, mortar separates the elements and fills all cavities and cracks to ensure a uniform contact surface, which helps prevent the infiltration of rainwater.



Figure IV.1: The mortar.

2. Definition of Mortar:

Mortar is a construction material used to bind together masonry elements such as bricks, concrete blocks, stones, etc. It is generally composed of a mixture of a binder (such as cement or lime), sand, water, and possibly additives and admixtures to improve its properties. Mortar is applied between the joints of construction elements to hold them together and ensure their structural stability.

3. What are the roles of mortar?

Mortar serves several important functions in construction:

- Ensure bonding and cohesion between masonry elements, meaning the overall integrity and unity of the structure.
- Protect constructions against moisture:
    - By forming wearing screeds for concrete flooring.
    - In the form of plaster/render coatings.
    - In the form of waterproof barriers.

- Manufacture of various molded elements.
- Strengthening certain soil foundations through injection techniques.



Figure IV.2: Essential Roles of Mortar in Construction.

4. Fundamental Characteristics of Mortar:

- **Waterproofing:** It must be impermeable to ensure maximum sealing of masonry joints and coatings.
- **Compressive strength:** It should be dense (with minimal voids) to prevent water infiltration into the structure.
- **Adhesion:** It must bond well to materials to ensure effective load transfer.
- **Resistance to corrosive agents:** It should withstand aggressive substances present in the atmosphere or in contaminated soil.
- **Workability:** It must be easy to handle and apply so that workers can place it under the best conditions.

5. Components of Mortar:

5.1- Binders:

Generally, cement and lime are used. Their selection and dosage depend on the type of structure to be built as well as its environmental conditions. For example,

a waterproofing mortar will have a higher binder content than a mortar used for building a wall. The use of lime in mortar makes it more workable, but it also leads to a reduction in strength.

5.2- Sand:

Rounded sands of siliceous or silico-calcareous nature, as well as crushed sands, can be used. However, it is preferable to choose rounded grains, as angular grains make mortars more rigid and more difficult to work with. The particle size of sand typically ranges from 0.08 mm to 5 mm. Excessive fineness can lead to reduced strength and increased shrinkage. An inappropriate choice of sand can have harmful effects on the mortar.

5.3- Water:

The amount of mixing water depends on several factors, including:

- The intended use of the mortar
- The proportion and type of binder
- The specific surface area
- The moisture content of the sand upon delivery to the site
- The quality of the sand, particularly its porosity and shape
- The grain size

Table IV.1 : Water dosage for CPA 32.5 cement mortars according to sand fineness.

Mortar with CPA 32.5 cement, dosed at	**250 Kg**	**450 Kg**	**650 Kg**
Required water, with coarse or medium sand.	150 Liters	200 Liters	230 Liters
Required water: with very fine sand.	240 Liters	270 Liters	300 Liters

Table IV.2 : Water dosage for hydraulic lime mortar (rolled sand 0/5 with ≤ 25% fines).

Hydraulic lime mortar, highly dosed at:	**250 Kg**	**350 Kg**	**450 Kg**
Required water quantity for rolled sand of class 0/5 containing up to 25% fine particles.	200 Liters	260 Liters	300 Liters

5.4- Admixtures:

Admixtures are chemical substances used to modify certain properties of concrete and mortar. They are added to the mix in small proportions. Mortars can include various types of admixtures:

Table IV.3: The different types of admixtures and their main effects.

Admixture	Standard	Main Effects
Water-reducing plasticizer	NF P 18-336	At the same consistency, it allows a reduction in water dosage, and at a constant water dosage, it allows an increase in Abrams cone slump.
Superplasticizer – high water-reducer	P 18 - 330	Its definition is identical to that of a water-reducing plasticizer, but the reduction in water dosage and the increase in cone slump are more pronounced.
Air-entraining agent	NF P 18-338	It enables the formation, during mixing, of a uniform network of small air bubbles that remain in the hardened concrete.
Setting accelerator	NF P 18-331	It accelerates the initial setting, that is, the moment when fresh concrete changes from a plastic

		to a rigid state. The setting time is measured on normal mortar (pr. NF P 15-431).
Hardening accelerator	NF P 18-332	It accelerates the short-term strength development of concrete. Both chlorinated and non-chlorinated admixtures also apply to hardening accelerators (standard NF P 18-332, admixtures for concrete, mortar, and grout: non-chlorinated hardening accelerators).
Setting retarder	NF P337	It delays the initial setting and extends the plastic state, during which the concrete is moldable.
Water repellent / Hydrophobic agent	EN 480-5	It reduces the capillary absorption of hardened concrete. Capillary absorption is measured according to the draft European standard prEN 480-5.

5.5-Additives:

Additives are components incorporated into mortars, usually in the form of fine powders that react chemically.

5.5.1-NaturalPozzolan:

According to ASTM standards, pozzolans are primarily composed of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). The remaining fraction contains various other oxides as well as a percentage of lime (CaO). They are generally red or black in color. Pozzolan is defined as a silico-aluminous material that, although it does not possess binding properties on its own, chemically reacts with calcium hydroxide ($Ca(OH)_2$) at room temperature when in the form of a very fine

powder and in the presence of moisture, forming compounds with binding properties.

5.5.2- Blast Furnace Slag:

Blast furnace slag aggregates are produced by a rapid cooling process of molten slag resulting from the smelting of iron ore in a blast furnace.

5.5.3- Silica Fume:

Silica fume is a fine powder composed primarily of silica particles (>90%) with a very high specific surface area, reaching 220,000 cm^2/g. Silica is a mineral compound found in many common materials such as sand, quartz, and granite. When these materials are handled or processed, fine silica particles can be released into the air as dust. This powdered product has a silvery color.

6. Classification of Mortars :

Mortars can be classified according to various criteria:

6.1- Nature of the binder:

6.1.1- Cement mortars:

The binder consists exclusively of cement. These mortars are preferred when the goal is to achieve high mechanical strength, good waterproofing, or when they are intended for use in humid environments.

6.1.2- Lime mortars:

The binder used is lime. These mortars are highly plastic, making them more workable, but they have low strength.

6.1.3- Mixed mortars:

The binder consists of a mixture of cement and lime. The choice of the cement-to-lime ratio depends on the primary property sought, whether it is plasticity or

mechanical strength. These mortars are characterized by good workability while still providing adequate mechanical strength.

6.2- Apparent Bulk Density:

Ordinary mortars: Mortars with an apparent bulk density ($\rho_a$pp) ≥ 1500 kg/m^3 are made from natural rounded or crushed sands.

Lightweight mortars: Mortars with an apparent bulk density ($\rho_a$pp) ≤ 1500 kg/m^3 are made using lightweight sands.

6.3- Intended Use:

6.3.1- Masonry joints:

The mix proportions for laying mortars vary widely. The most common mix is 50 kg of cement for 150 liters of sand. The type of sand used should be coarse for pointing rubble stone joints and medium for constructing walls with bricks or concrete blocks. This mortar must have sufficient mechanical properties to ensure load transfer and adequate density to guarantee waterproofing.



Figure IV.3: Masonry joints.

6.3.2-Plasters:

a- Traditional plasters:

Traditional plasters are made of cement, lime, or a mixture of cement and lime for exterior work, and of plaster and air lime for interior work. They serve two main functions: to protect the structural work by making it waterproof and water-repellent, while also contributing to the aesthetic appearance and color of the façades.



Figure IV.4: Traditional plasters.

b- Decorative plasters :

These mortars must have both good workability and guaranteed mechanical strength. The choice of binder depends on the material to which the mortar will be applied:

- Grey, white, or colored cement is used for standard concrete and lightweight concrete.
- Grey, white, colored cement or lime is used for Siporex (aerated concrete) bricks.

To give a shiny appearance to the finishing layer of a decorative mortar, 1% mica or 10% crushed glass is added to its composition, along with natural or artificial pigments as colorants.



Figure IV.5: Decorative plasters.

c- Sealing and grouting:

These mortars have multiple uses: the positioning of industrial equipment, the sealing of posts and inspection chambers, beams, doors, windows, street furniture, and signage elements, as well as sealing work in marine environments.



Figure IV.6: Sealing and grouting.

- Sealing and grouting mortars are composed of high-grade cement (classes 52.5 and 42.5), generally rapid-hardening (R), and very clean sand (preferably rounded) with a maximum size of 2 to 3 mm; various admixtures and, if necessary, steel or polypropylene fibers.



Figure IV.7: Steel and Polypropylene Fibers Used in Sealing and Grouting Mortars.

Binder dosages are generally high (600 to 700 kg per 1 m^3 of sand). The water content must be adjusted according to the desired consistency, with a water/cement ratio (W/C) between 0.40 and 0.50.

7. Main characteristics:

Mortars are primarily distinguished by their workability, setting time, mechanical strength, and deformations, particularly shrinkage and swelling.

7.1- Workability:

The workability of a mortar is assessed using various devices, the most common of which are:

7.1.1- The shaking table:

After the mortar is placed and removed from a conical mold, it is subjected to 15 shocks over 15 seconds. The diameter of the resulting disc is then measured (Figure IV.8). The spread, expressed as a percentage, is calculated using the formula:

$$E=\frac{D_f-D_i}{D_i}\times 100(\%) \qquad \text{(IV.1)}$$

D_i: Initial diameter

D_f: Final diameter

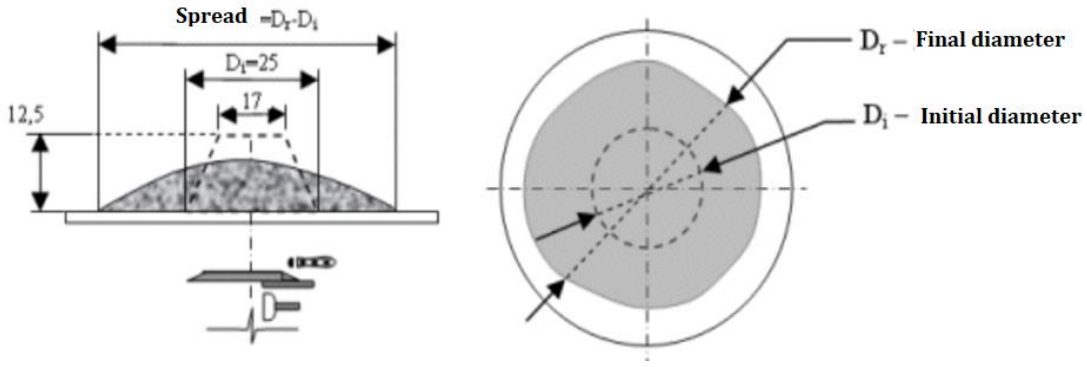


Figure IV.8: The shaking table.

Table IV.4: The workability of mortar.

Workability	Spread on the Table (%)
Very stiff	10 – 30
Stiff	30 – 60
Normal (plastic)	60 – 80
Soft (very plastic)	80 – 100
Very soft to liquid	>100

7.1.2- The LCPC Workability Tester:

It consists of a parallelepiped mold with a movable wall and a vibrator (Figure IV.9). The test principle involves, after removing the movable wall, measuring the time required for the mortar under vibration to reach a mark engraved on the inner face of the mold.

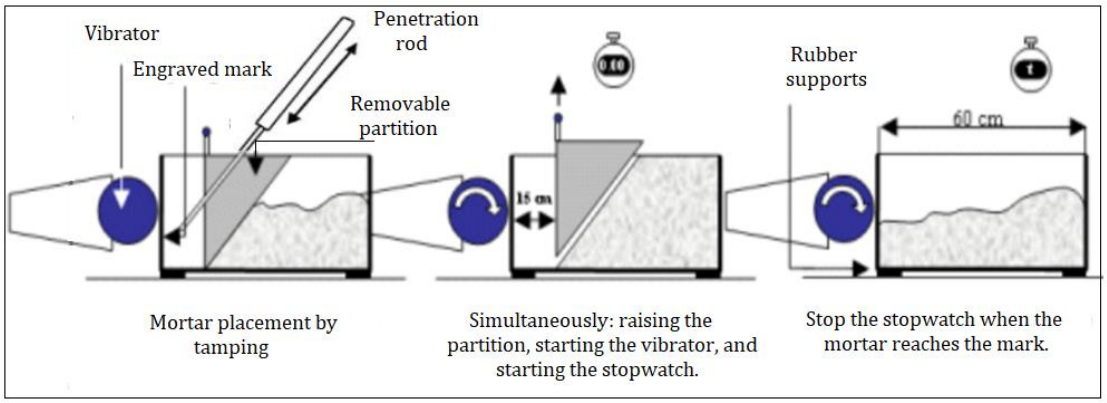


Figure IV.9: Operating principle of the workability tester

7.2- Setting Time:

The setting time is usually measured on a pure cement paste of normal consistency (24 to 30% water) using the Vicat apparatus.

It is also possible to determine the setting time of a mortar (normal) using the same device, by placing a 700-gram surcharge on the upper plate. The penetrating needle weighs 1000 grams.

- **Initial setting time:** the moment when the needle stops **2.5 mm from the bottom** of the mold (corresponding to the size of the largest sand grains).
- **Final setting time:** the moment when the needle stops **2.5 mm from the top** of the mortar.

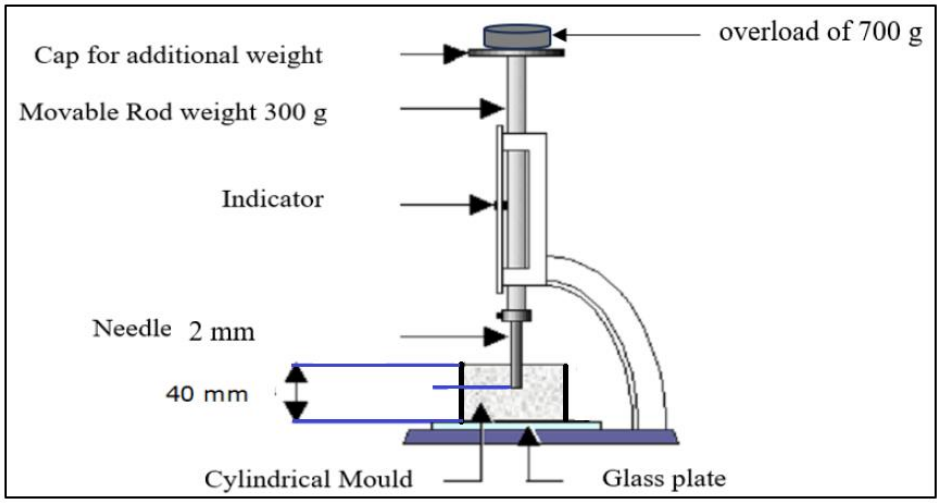


Figure IV.10: Vicat device with adjustments

7.3- Mechanical Strength:

Tests are carried out on prismatic specimens measuring 4 × 4 × 16 cm, kept in water at 20 °C. The specimens are first tested in flexural tension and then in compression.

The strength of mortars (as in the case of concrete) depends on numerous factors:

- Type and dosage of cement;
- Cement-to-water ratio (C/W);
- Particle size distribution and type of sand;
- Mixing energy and placement method;
- Duration and conditions of curing.

7.3.1-Molds and Specimens

The mold must have three compartments, allowing the simultaneous casting of three prismatic specimens measuring 4 × 4 × 16 cm.



Figure IV.11: Prismatic mold of 4 × 4 × 16 cm.

7.3.2-Mortar Preparation:

The composition of the standardized mortar for a batch of three prismatic specimens (4 × 4 × 16 cm) is as follows:

Standard sand: 1350 ± 5 g

Binder (cement): 450 ± 2 g

Water: 225 ± 1 g

The materials should be mixed using a vertical-axis mortar mixer with a capacity of 5 liters.



Figure IV.12: 5-liter mortar mixer.

7.3.3- Specimen Preparation and Curing:

The molds are oiled, and the mortar is cast immediately after preparation, then mechanically compacted using a shaking table. The specimens, covered with a plastic film, are stored in the open air of the laboratory.

After 24 hours, the specimens are demolded and immersed in water at a temperature of 20 °C ± 1 °C until the specified testing age (2, 7, or 28 days).

a- Flexural Strength:

The flexural strength (Figure IV.13) is given by the following expression:

$$\sigma_f = \frac{1.5 \times F_f \times l}{b^3} \qquad \text{(IV.2)}$$

where:

- σ_f: flexural strength [N/mm^2]
- b: side of the square cross-section of the prism [mm]
- F_f: Load applied at the center of the prism at failure [N]
- l: distance between supports [mm]





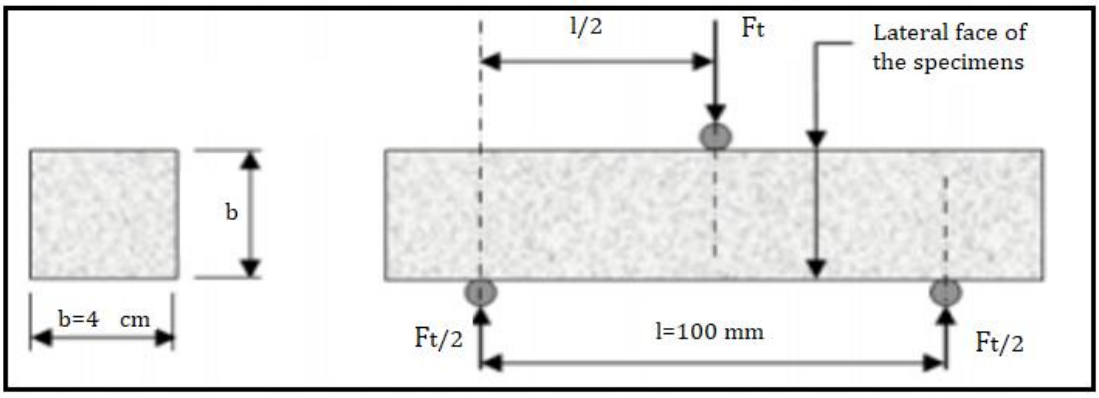


Figure IV.13: Flexural strength test apparatus.

b- Compressive Strength:

The compressive strength (Figure IV.14) is evaluated using the following formula:

$$\sigma_c = \frac{F_c}{b \times b} \qquad \text{(IV.3)}$$

where:

- σc: compressive strength [N/mm^2]
- Fc: maximum load at failure [N]
- b: side of the square cross-section of the prism [mm]

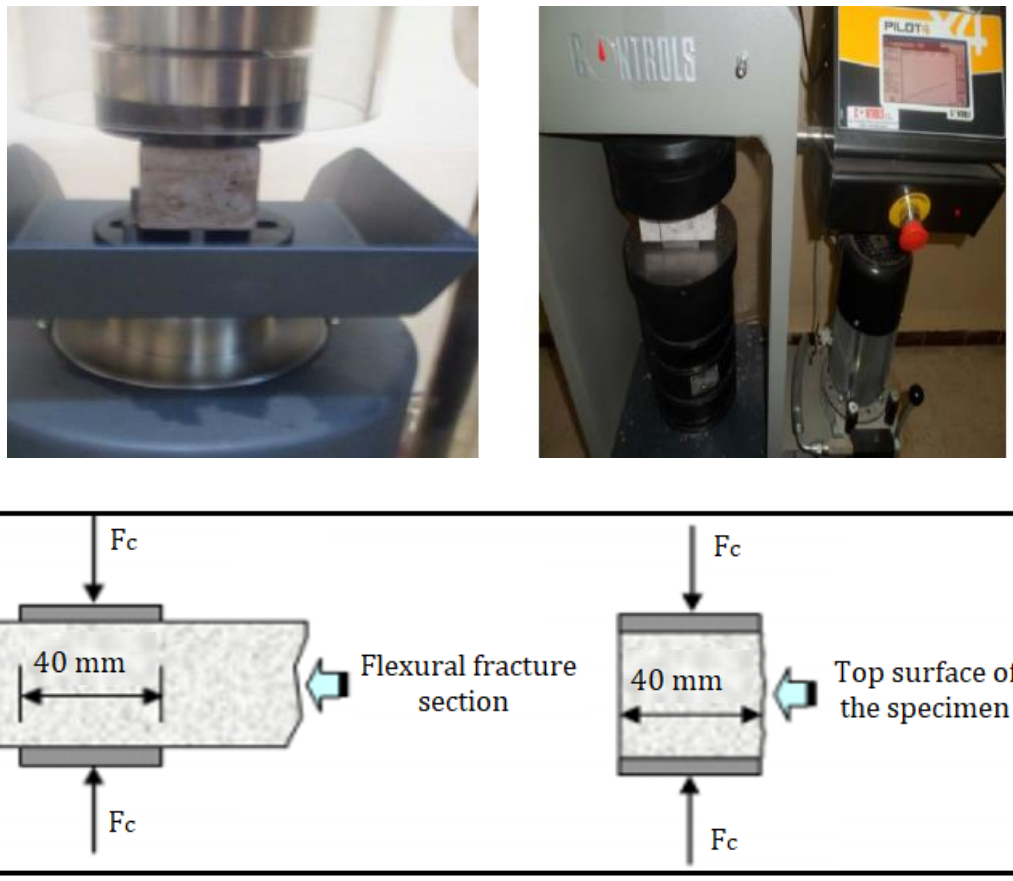


Figure IV.14: Compression testing apparatus.

7.4- Shrinkage and Swelling:

Shrinkage is measured on 4 × 4 × 16 cm mortar prisms with a composition conforming to standard mortar, fitted with studs at their ends and, after demolding, stored in a chamber at 20 °C and 50% relative humidity. Shrinkage must be less than 800 µm/m at 28 days (standard reference value for normal mortar).

Swelling of mortars (which occurs when they are stored in water) is measured on the same 4 × 4 × 16 cm prismatic specimens kept in water at 20 °C. It is generally quite low.



Figure IV.15: Measuring shrinkage of mortar.

8. Exercise:

Exercise 01:

A mortar specimen with a square cross-section of 40 × 40 mm is subjected to a failure load of 64 kN.

- Calculate the compressive strength.

Solution:

Cross-sectional area:

$A = 40 \times 40 = 1600\ mm^2$

Applied load:

$F = 64\ kN = 64000\ N$

Compressive strength:

$\sigma_c = \frac{F}{A} = \frac{64000}{1600}$

$\sigma_c = 40\ MPa$

Therefore, the compressive strength of the mortar is 40 MPa.

Exercise 02:

We want to prepare 3 m^3 of mortar with:

- 400 kg of cement/m^3
- W/C = 0.55
- 1500 kg of dry sand/m^3

The available sand has a moisture content of 4%.

Calculate:

1- The total mass of cement.
2- The total mass of dry sand.
3- The total amount of water required.
4- The amount of water supplied by the sand.
5- The amount of water to be added.

Solution:

1. Cement:

$m_c = 400 \times 3 = 1200kg$

2. Dry sand:

$m_s = 1500 \times 3 = 4500$ kg

3. Total water required:

$M_W = 0.55 \times 1200 = 660$ L

4. Water contained in the sand:

$M_{w\ (sand)} = 4500 \times \frac{4}{100} = 180$ L

5. Water to be added:

$m_{\ w\ (added)} = 660 - 180 = 480$ L

References

[Dreux 2002]Dreux G., Festa J., «Nouveau guide du béton et ses constituants», Edition Eyrolles, France, 409p.

[Nonat 2004] Nonat A « The structure and stoichiometry of C-S-H » Cement and Concrete Research, vol.34, pp. 1521-1528.

[Pliskin 1995] Pliskin L « La fabrication du ciment » Editions Eyrolles.

[Lea's 2004] Lea's, «Chemistry of Cement and concrete».

[Dupain 2004]Dupain R, Lanchon R, Saint J, Arroman « Granulats, Sols, Ciments et Bétons ».

[Shan 2008] Shan Somayaji, «Civil Engineering Materials, » 2nd Edition, Prentice Hall, New Jersey.

[Varghese 2008] Varghese. P.C, «Building Materials, »Prentice-Hall of India, New Delhi.

[Marius 1961] Marius Duriez, Jean Arrambide «Nouveau traité de matériaux de construction»

[NF P 18-554] Norme NF P 18-554 « Granulats - Mesures des masses volumiques, de la porosité, du coefficient d'absorption et de la teneur en eau des gravillons et cailloux » Décembre (1990).

[NF P 18-560] Norme NF P 18-560 « Granulats - Analyse granulométrique par tamisage » Septembre (1990).

[NF P 18-561] Norme NF P 18-561 « Granulats - Mesure du coefficient d'aplatissement » Septembre (1990).

[NF P 18-572] Norme NF P 18-572 « Granulats - Essai d'usure micro-deval » Décembre (1990).

[NF P 18-573] Norme NF P 18-573 « Granulats - Essai Los Angeles» Décembre (1990).

[NF P 18-598] Norme NF P 18-598 « Granulats - Équivalent de sable » Octobre (1991).