ABDELHAFID BOUSSOUF UNIVERSITY - MILA
INSTITUTE OF SCIENCE AND TECHNOLOGY
∞∞∞∞∞∞
Department of Civil and Hydraulic Engineering

Course
Construction materials

Prepared by: Dr TIOUA Tahar

For student’s 2nd year license degree in Civil Engineering

Academic year:2023/2024

BEFORE - ABOUT

This educational handout, above all, aims to present in a concise manner the essential information relating to the raw materials used in the field of civil engineering in general and construction materials in particular.

This document includes four chapters. In the first part, the essential properties of construction materials and characterization methodologies are presented.

The second part is devoted to aggregates used as construction materials or as raw materials used for the manufacture of concrete, for their applications in the field of civil engineering.

The third chapter deals with the manufacturing and properties and standardized classifications of mineral binders, limes, plasters and cements.

The last part constitutes an introduction to cementitious matrix materials. Concepts on mortars, their constituents, their compositions, their properties, their characterizations and their uses are recalled in a synthetic manner.

This document is made available to Civil Engineering License students and constitutes a memory aid from which students can deepen and update their knowledge.

CHAPTER I

GENERAL INFORMATION ON CONSTRUCTION MATERIALS

CHAPTER I - GENERAL INFORMATION ON CONSTRUCTION MATERIALS

1. INTRODUCTION

Construction materials are materials used in the construction sectors: buildings and public works (BTP). They cover a wide range of materials which mainly includes wood , glass , steel , aluminum , textiles , plastics (in particular insulation) and materials resulting from the transformation of quarry products, which can be more or less elaborate (including concrete and various clay derivatives such as bricks, tiles and various sanitary elements).

2. CLASSIFICATION OF CONSTRUCTION MATERIALS

In construction, it has become common to distinguish materials:

a) Depending on use:

- Mechanical resistance materials: intended to build the supporting structures of Constructions (stone, wood, steel, concrete, etc.).
- Comfort materials: materials which do not have significant effects on mechanical resistance but are necessary for the operation of constructions (glass, plaster, coatings, hollow bricks, etc.).
- Protective materials: materials allowing the maintenance of constructions (paint, bitumen, sealants, etc.).

b) Basic materials and composite products:

- Basic materials: cement, aggregates, clay, bitumen, steel, etc.
- Composite products: Hydraulic concrete (aggregates + cement + water), Bituminous concrete (aggregates + bitumen) etc.

3. PROPERTIES OF CONSTRUCTION MATERIALS

Before using a material for construction, it is important to know these properties in order to prevent its behavior. These properties are of four types:

- **Physical properties:** density, porosity, permeability to liquids and gases, etc.
- **Mechanical properties:** tensile strength, compressive strength, impact strength, wear resistance, resistance to the cyclical freezing – unfreeze effect, etc.
- **Chemical properties:** alkalinity, acidity, stabilities in the presence of certain chemical products and materials, etc.
- **Thermal properties:** specific heat, thermal conductivity, expansion, fire resistance, etc.

3.1. physical properties

3.1.1. Apparent density

It is the mass of a body per unit of apparent volume in its natural state, including voids and pores, after drying in oven at 105°C ± 5°C. The apparent density is expressed in (gr/cm^3; kg/m^3; Ton/m^3).

$$\rho_{app} = \frac{m_S}{V_{app}} \text{ [g/cm}^3\text{, kg / m}^3\text{, T / m}^3\text{]}$$

ρ_{app} – apparent density
m_S – mass of the sample in the dry state in g, kg or Ton
V_{app} – Apparent volume of the sample in cm^3 or m^3.

3.1.2. Absolute density

It is the mass of a body per unit of absolute volume of solid matter (volume of matter alone, without pores and voids), after drying in oven at 105 °C ± 5 °C. The absolute density can be expressed in (g/cm^3, kg/m^3 or Ton/m^3) or without unit

$$\rho_{abs} = \frac{m_S}{V_{abs}} \text{ [g /cm}^3\text{, or without unit]}$$

ρ_{abs} – absolute density
m_S – mass of the sample in the dry state in g, kg or Ton
V_{app} – Absolute volume of the sample in cm^3 or m^3.

3.1.3. Bulk density

Bulk density is the apparent density of powder (powder) and granular (grain) materials, which expresses the mass per unit of apparent volume (including intergranular voids).

$$\rho_{app} = \frac{m_S}{V_{app}} \text{ [g/cm}^3\text{, kg/m}^3\text{, T/ m}^3\text{]}$$

Table 1.I – Apparent, absolute and bulk densities of some materials

Materials	Absolute density g/cm²	Apparent density g/cm²	Bulk density g/cm²
Steel	7.8 – 7.9	7.8 – 7.9	-
Basalt	2.9 – 3.2	2.8 – 3.0	1.5 – 1.8
Granite	2.6 – 3.0	2.6 – 2.8	1.4 – 1.75
Marble	2.5 – 2.9	2.5 – 2.8	1.35 – 1.75
Limestone	2.4 – 2.7	2.1 – 2.7	1.1 – 1.7
Plaster	2.3 – 2.7	-	1.1 – 1.2
Lime	2.2 – 2.3	-	0.5 – 0.75
Sand	2.6 – 2.7	-	1.45 – 1.7
Normal concrete	1.8 – 2.5	-	-

Heavyweight concrete	2.5 – 4.0	0.4 – 2.6	-
Lightweight concrete	0.8 – 1.8		-
Ceramic shard	2.5 – 2.8	1.6 – 2.4	-
Glass	2.5 – 2.9	0.1 – 2.4	-
Plastic materials	0.9 – 2.2	0.01 – 2.2	-
Drink	1.5 – 1.6	0.1 – 1.3	0.2 – 0.3
Expanded clay	2.5 – 2.8	0.8 – 1.2	0.4 – 1.2
cement	2.9 – 3.2	-	1.2 – 2.1

3.1.4. Porosity

Porosity is the volume of voids per unit of total or apparent volume. It influences

$$P = \frac{\text{Volume of voids}}{\text{Total volume}} . 100\ \%$$

3.1.4.1. Pore structure

Pores are small spaces of the order of microns, contained in the bodies of materials generally filled with air or water. The structure of the pores differs from one material to another, we distinguish:

- **Closed pores**

Closed pores (figure 1.I) do not communicate with each other, whose absorbency is very low.

- **Open pores**

The open pores (figure 2.I) communicating with each other through capillaries allowing the penetration of water into the body of the material

Porosity influences:

- Mechanical resistance,
- Water absorption capacity,
- Thermal conductivity,
- freezing resistance
- Durability

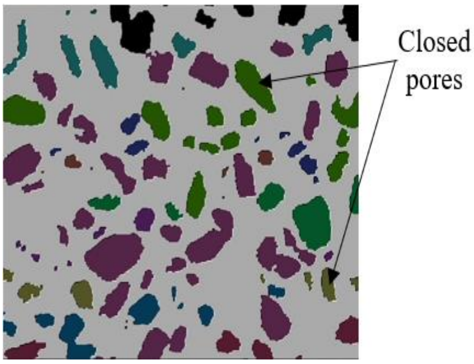


Figure 1.I – Interconnected pore network

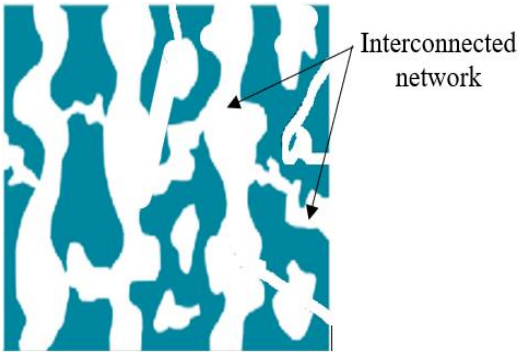


Figure 2.I – Discontinuous pore network

3.1.5. Compactness

Compactness is the ratio of the volume of the full to the total volume.

$$\boldsymbol{C} = \frac{\textbf{Volume of matter}}{\textbf{Total volume}}\ 100\ \%, [\%]$$

Porosity and compactness are related by relationship: $\mathrm{P} + \mathrm{C} = 100\ \%, \mathrm{P} + \mathrm{C} = 1$

Porosity and compactness are often expressed in (%). The sum of the two is then equal to 100%. Indeed :

$$\boldsymbol{P} + \boldsymbol{C} = \frac{\textbf{Volume of matter}}{\textbf{Total volume}} + \frac{\textbf{Volume of Voids}}{\textbf{Total volume}} = \frac{\textbf{Total volumel}}{\textbf{Total volume}} = \mathbf{1}$$

If we know the apparent density ρ_{app} and the absolute density ρ_{abs} of a material, it is easy to calculate its compactness and porosity.

$$C = \frac{\text{Volume of matter}}{\text{Total volume (Apparent)}}\ 100\ \% = \frac{V_{\text{abs}}}{V_{\text{app}}}\ 100\%, [\%]$$

$$C = \frac{V_{\text{abs}}}{V_{\text{app}}}\frac{m_S}{m_S}\ 100\ \%$$

$$\frac{m_S}{V_{\text{app}}} = \rho_{\text{app}} \quad \text{et} \quad \frac{V_{\text{abs}}}{m_S} = \frac{1}{\rho_{\text{abs}}}$$

$$C = \rho_{\text{app}}\ \frac{1}{\rho_{\text{abs}}}\ 100\%$$

$$\boldsymbol{C} = \frac{\boldsymbol{\rho_{app}}}{\boldsymbol{\rho_{abs}}}\ \boldsymbol{100\%}, [\%]$$

$$P = \frac{\text{Volume of voids}}{\text{Volume total (apparent)}}\ 100\ \%, [\%]$$

$$V_{\text{Voids}} = \left[V_{\text{app}} - V_{\text{abs}}\right]\ 100.\%$$

$$P = \left(\frac{V_{\text{app}} - V_{\text{abs}}}{V_{\text{app}}}\right)\ 100\% = \left(1 - \frac{V_{\text{abs}}}{V_{\text{app}}}\right)\ 100\ \%,$$

$$P = \left(1 - \frac{V_{\text{abs}}}{V_{\text{app}}}\ \frac{m_s}{m_s}\right)\ 100\% = \left(1 - \frac{m_s}{V_{\text{app}}} . \frac{V_{\text{abs}}}{m_s}\right)\ 100\%$$

$$\frac{m_S}{V_{\text{app}}} = \rho_{\text{app}} \quad \text{et} \quad \frac{V_{\text{abs}}}{m_S} = \frac{1}{\rho_{\text{abs}}}$$

$$\mathrm{P}\ = \left(1 - \rho_{\text{app}}\ \frac{1}{\rho_{\text{abs}}}\right)\ 100\%,$$

$$\boldsymbol{P = \left(1 - \frac{\rho_{app}}{\rho_{abs}}\right) 100\%}, [\%]$$

3.1.6. State of water in a material

There are three main categories of water:

- Absorbed water: found in pores and voids between particles of solid matter;
- Adsorbed water: which is found on the surface of solid particles;
- Chemically bound water: which is part of solid particles.

3.1.6.1. Humidity, Hygroscopicity (Hygroscopic power)

Humidity has a great influence on the properties of constructions, it is the main cause of disorders and damage to constructions. High humidity can lead to serious consequences:

- crumbling and crumbling leading to detachment of coatings
- Cracking and bursting of materials
- Swelling and warping of wood.

Humidity is one of the important properties of construction materials. It is an index to determine the actual water content of the materials at the time of the experiment. In general, humidity is denoted H and is expressed as a percentage (%). The humidity of a material can be determined using the following formula:

$$H = \frac{m_w - m_d}{m_d} 100\ \%, [\%]$$

m_d – is the dry mass of sample (after oven drying at t = 105 to 110) °C

m_w – is the wet mass of the sample.

The degree of humidity of the materials depends on many factors, especially the atmosphere where they are stored, the wind, the temperature and the porosity of the material.

3.1.6.2. Water absorption

Water absorption of material is the ability of material to absorb and retain water when immersed in water at normal temperature (20 ± 2°C) and atmospheric pressure. Under this condition, water can penetrate most of the interstitial voids of the material. If the porosity of the material is large and open, the absorption of water is greater, but the absorption is still less than the porosity of the material, because some pores are closed and are inaccessible to water. The degree of absorption can be determined in two ways:

- **Absorption mass noted A_m (%)**

$$A_m = \frac{m_w - m_d}{m_d} 100\%$$

m_w – is the mass of the material after water absorption (wet mass)

m_d – is the dry mass of sample (after oven drying at t = 105 to 110) °C

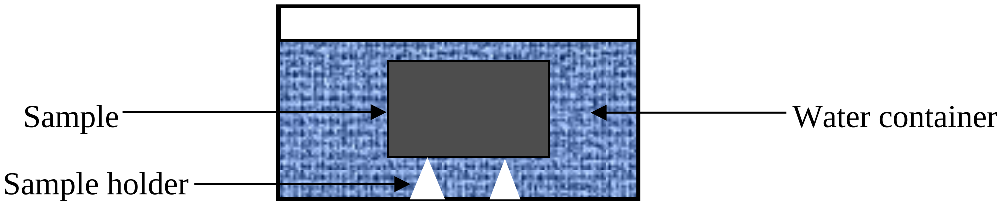


Figure 3.I – Measurement of water absorption capacity

- **Absorption Volume noted A_v (%)**

$$A_v = \frac{m_w - m_d}{V_{app}}\ [gr/cm^3]$$

m_w – is the mass of the material after water absorption ((wet mass)

m_d – is the dry mass of sample (after oven drying at t = 105 to 110) °C

V_{app} – Apparent volume

The mass and volume water absorptions can be linked by the following relationship:

$$\frac{A_V}{A_m} = \frac{\frac{m_w \cdot m_d}{V_{\text{app}}} 100\%}{\frac{m_w \cdot m_d}{m_d} 100\%} = \frac{m_w \cdot m_d}{m_w \cdot m_d} \times \frac{m_d}{V_{\text{app}}} = \frac{m_d}{V_{\text{app}}} = \rho_{\text{app}}$$

$$A_v = A_m \times \rho_{app}, \left[\frac{gr}{cm^3}\right]$$

- **Capillary absorption**

It is the power of a material to absorb, retain and conduct the water absorbed in the part submerged under water towards the emerged part. The flow of water takes place through capillaries (capillaries are very fine channels with a diameter of the order of microns and variable lengths.

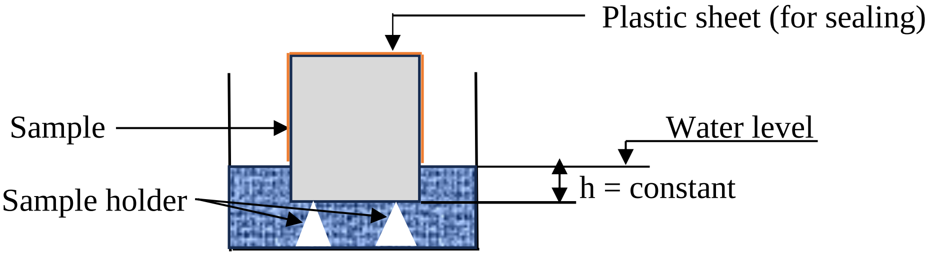


Figure 4.I – Capillary absorption test

The test proceeds as follows:

- Dry the sample to constant mass
- Immerse a height (h) of the sample under water for 24 hours
- Weigh the sample in the wet state

Capillary absorption is expressed by:

$$CA = \frac{m_w - m_d}{s \times t} \; [\text{gr}/m^2\text{h}]$$

AC – Capillary absorption, [g/m² h].
m_W – wet mass, [g].
md – dry mass, [g].
s – surface in contact with water, [m²].
t – duration of immersion, [hour].

3.1.6.3. Concept of degree of water saturation

When all the voids in body are filled with water, it is said to be saturated. The degree of saturation is the ratio of the volume of voids filled with water to the total volume of voids. The degree of saturation is the maximum absorption of materials under pressure and temperature conditions. There are two ways to achieve saturation in material samples: sample immersion

- in boiling water
- in air pressure: To determine the degree of saturation in air pressure, we follow the following procedure:
- Immerse the samples in water.
- Give the baseline pressure of 20 mm Hg until all air bubbles can be eliminated.
- Then we lower the base pressure by 20 mm Hg to atmospheric pressure. At this point, almost the entire void is filled with water and in this case, we say that the samples are saturated. The degree of saturation can be expressed in relation to mass or volume:

- **Degree of volume saturation**

$$\boldsymbol{D}_{\mathrm{S}} = \frac{\boldsymbol{m_{sat} - m_d}}{\boldsymbol{V_{app}}} \ [\mathrm{gr}/\boldsymbol{cm^3}]$$

D_S – is the degree of saturation (%)
m_{sat} – is the sample mass at the time of saturation.
m_d – is the dry mass of sample.
V_{app} – is the apparent volume of the material.

- **Degree of mass saturation**

$$\boldsymbol{D_S = \frac{m_{Sat} - m_S}{m_s} 100}, [\%]$$

In practice, it is not possible to completely fill the voids of the sample with water, because some pores and micropores are inaccessible to water, which is why it would be more accurate to present this value in another form "coefficient of saturation", denoted K_S. This coefficient can be calculated with the following formula:

- **Saturation coefficient K_S**

$$\boldsymbol{K_S = \frac{D_S}{P} 100}, [\%]$$

P - total porosity.
D_S – is the degree of saturation.

Water has a considerable influence on the properties of materials when they are wet or saturated, we can note:

- an increase in apparent density
- an increase in thermal conductivity
- swelling
- a reduction in the mechanical resistance of certain materials

This is why it is useful to check the mechanical resistance of materials in the dry state and in the wet or saturated state.

3.1.6.4. Softening coefficient

To evaluate the reduction in the mechanical resistance of materials in the presence of water, we use the softening coefficient which is expressed by the following relationship:

$$\boldsymbol{K_r = \frac{\sigma_{\mathrm{Sat}}}{\sigma_{\mathrm{dry}}}, \%}$$

K_r – Softening coefficient or soft index
σ_{sat} – Sample resistance in the water-saturated state
σ_{dry} – Sample resistance in the dry state.

3.1.6.5. Water and air permeability

Is the property of a material to allow water or air to pass through its thickness, it is characterized by the quantity of water or air which flows through the material during a time t at constant pressure. Control of permeability is important for concrete intended for use in a confined environment in contact with water such as dams, bridge piers, water towers, reservoirs, basins, etc. …or in contact with gas, nuclear power plant reactors, chemical or radioactive waste storage tanks.

Permeability is an indicator of durability. Construction materials are porous and like any porous medium, present a solid phase and a void space filled with water and air, in proportion varying with the degree of saturation.

Theoretically, the intrinsic permeability coefficient of a given material should be the same regardless of whether a gas or liquid is used for testing. However, gases give a higher value of this coefficient due to a sliding phenomenon, because at the limit of the flow the speed of the gas is not zero. The difference between gas and water permeability is greater as the intrinsic permeability coefficient is lower.

The air permeability of material is strongly influenced by its degree of humidity: it has been observed that, when going from a practically saturated state to a dry state (oven drying), the gas permeability coefficient k increases by almost two orders of magnitude.

Gas permeability of a material can be determined by the so-called CEMBUREAU method.

- **Principle of the method**

This method is applicable to molded or cored test bodies within the limits of the dimensions (table 2.I) imposed by the device, it makes it possible to measure permeabilities between 10^{-15} and 10^{-19} m²

Table 2.I - Dimensions of test pieces

Φ of the sample in cm	15 ± 1	12 ± 1	11 ± 1
H of sample in cm	5 ± 1		

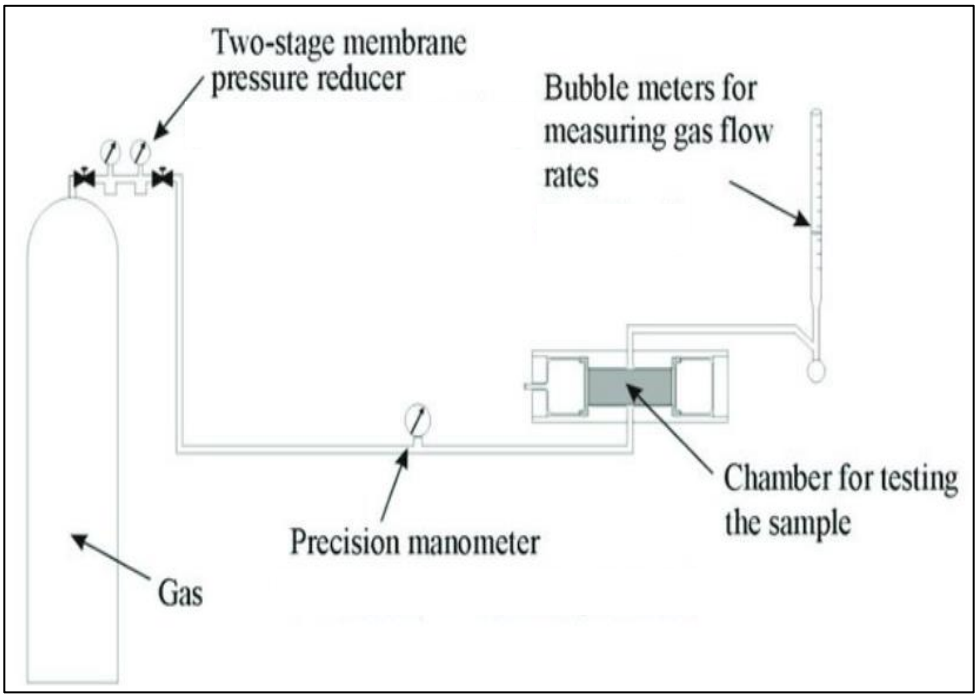


Figure 5.I – Schematic presentation of the apparatus used in the Cembureau method

The test consists of subjecting a cylindrical test body to a constant pressure gradient and measuring the flow time of the gas in steady state through the thickness of the sample.

The following formula gives the permeability coefficient of each test body:

$$\boldsymbol{k = \frac{2.P_{a}.Q.L.\mu}{A.(\,P_{0}^{2}\,.-\,.P_{a}^{2}\,)}}$$, k is here expressed in m^2

A: section of the test body (m^2)
L: thickness of the test body (m)
D: diameter of the test body (m)
k: permeability (m^2)
P_0: absolute pressure at the inlet (Pa)
P_a: atmospheric pressure (Pa)
Q: volume flow ($m^3 s^{-1}$)
μ: dynamic viscosity of oxygen ($2.02.10^{-5}$ Pa.s at 20 °C ± 2 °C)
With: $Q = \frac{V}{\mathrm{t_{avg}}}$

V: volume portion between two marks of the bubble flow meter (m^3)
t: time taken by the bubble to travel through the volume portion V (s)
t_{avg}: average travel time (s)

Simplified calculation of k: $\boldsymbol{k = \frac{404 \times L}{A} \times \frac{Q}{\Delta P} \cdot 10^{-16}\, m^2}$, with: $\Delta P = P_0^2 - P_a^2$ in Pa^2

3.2. Mechanical properties

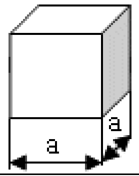
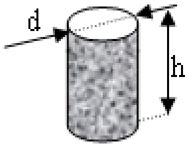
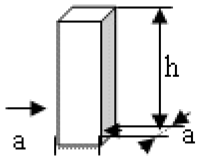
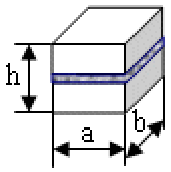
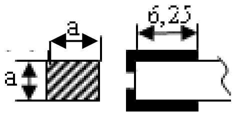
Construction materials must adapt and respond perfectly to the demands to which they are subjected. A structure can be subjected to different stresses which generate different types of constraints. The mechanical behavior of construction materials depends on the loading duration. The structures are in practice subjected to long-term stresses, while the mechanical tests are carried out on reduced models (test specimens) whose loading duration is very short. The strength of a material is determined by the maximum load leading to failure in relation to the loading time.

3.2.1. Compressive strength

Compressive strength is obtained by applying a compressive load to the cylindrical or cubic specimen using a hydraulic press. Table (3.I)

presents the materials to be tested and the shape and dimensions of the corresponding specimens.

Table 3.I – Compression tests

Materials	shape	Schema	Formula	Size (cm)
Concrete Mortar Rock	Cube		$\sigma_c = \frac{F}{a^2}$	a 10x10x10 15x15x15 20x20x20
Concrete Mortar Rock	Cylinder		$\sigma_C = \frac{F}{\frac{\pi d^2}{4}}$	d = 11, h = 22 d = 15, h = 30 d = 16, h = 32
Wood	Prism		$\sigma_C = \frac{F}{a^2}$	a = 2 h = 3
Brick	Samples assembled		$\sigma_C = \frac{F}{ab}$	a =12; b =12, h =14
Cement	Half sample of Mortier		$\sigma_C = \frac{F}{S}$	a = 4 S = 25 cm^2 S = 16 cm^2

The compressive strength is equal to the ratio of the maximum load F leading to rupture of the specimen at the surface S

Table 4.I – Compressive strength of some materials

Materials	σ_c (MPa)
Aerated concrete	3 – 5
Lightweight concrete	2 – 45
Normal concrete	5 – 60
Clay brick	10 – 25
Granite	160 – 200
Steel bar	400 – 850
Steel cables	1000 - 2000

- **Influence of the shape of the specimen on the compressive strength**

Depending on the shape of the test specimen, different results are obtained for the same quality of concrete:

- Prisms and cylinders compressive strength less well than cubes of the same cross section

- Low prisms whose height is less than the side compressive strength better than cubes of the same cross section.

- **Influence of the size of the specimen on the compressive strength**

The standardized specimen for the compression test on concrete is today a cylinder whose diameter of 32 cm is twice the height of 16 cm and section of 200 cm². We can adopt the coefficients given in the table for the results found for the same concrete on test pieces of different dimensions. The 16/32 cylinder with a section of 200 cm² being taken as a basis.

$$\sigma_{\text{Cylindre}} = \varphi_{\text{Cylindre}} \frac{F}{S}$$

Table 5.I – Influence of size on compressive strength

Cylinder $\frac{h}{d}$, cm	$\frac{11}{22}$	$\frac{16}{32}$	$\frac{20}{40}$	$\frac{25}{40}$	$\frac{30}{60}$	$\frac{40}{80}$
Coefficient φ	1.02	1.00	0.97	0.95	0.91	0.85

For cubes an analogous relationship is proposed, the cube of 14 cm side and 200 cm²

$$\sigma_{\text{Cube}} = \varphi_{\text{Cube}} \frac{F}{S}$$

Table 6.I – Influence of size on compressive strength

cube, cm	**10**	**14**	**20**	**25**	**30**
Coefficient φ	1.10	1.00	0.95	0.92	0.90

The relationship between cubic specimens and cylindrical specimens is:

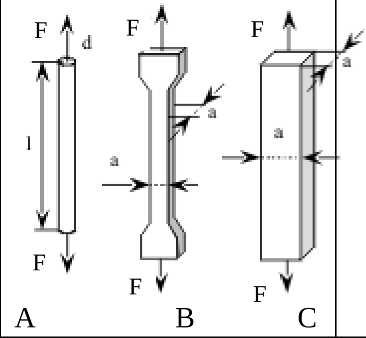
$$\sigma_{Ccylindre} = \frac{\sigma_{Cube}}{K}$$

K = 1.25 for σ_{Cubic} > 25 MPa
K = 1.20 for σ_{Cubic} < 25 MPa

3.2.2. Tensile strength

Tensile strength can be determined either by direct or indirect tests. Direct tests are carried out mainly for homogeneous materials whose tensile strength is approximately equal to that in compression (metals and some plastics). Indirect tests are generally carried out for fragile materials (concretes and mortars). For these materials, direct traction tests can be carried out exceptionally because of the difficult and costly preparation of the specimens.

Table 7.I – Direct traction strength tests

Samples		Formula	Materials	Size (cm)
Cylindrical Prismatic		$\sigma_t = \frac{P}{a^2}$ $\sigma_t = \frac{P}{a^2}$ $\sigma_t = \frac{P}{\frac{\pi d^2}{4}}$	Steel wood Concrete	A. $d_0 = 1$; $l_0 = 5$; ≥ 10 B. 5x5x50 C. 10x10x80

3.2.3. Tensile test on a mild steel specimen.

Consider a mild steel bar of initial length L_0 and whose initial section S_0 is constant over the length L_0 .

Let us subject this bar to a tensile stress by applying a force F at each end:

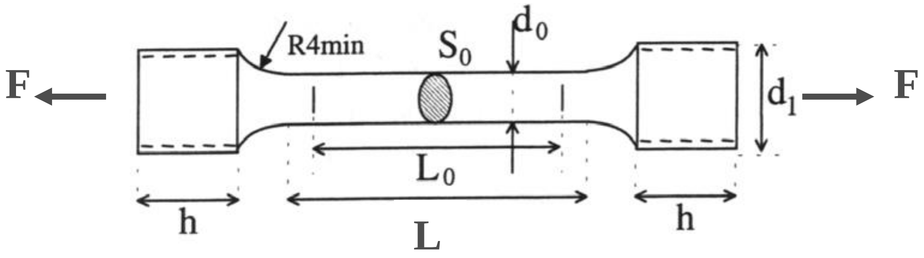


Figure 6.I - Mild steel specimen for direct tensile test

Using comparators, the elongation ΔL of the test piece can be recorded as a function of the intensity of the force F.

ΔL is called the elongation ($\Delta L = L - L_0$)

To be able to compare the mechanical characteristics of the materials, they must be established independently of the sections S_0 and lengths L_0 of the specimens.

Thus, we report on a graph:

- on the abscissa: the relative elongation, $\varepsilon = \frac{\Delta L}{L_0}$, ε is unitless since it is the ratio of two lengths

- on the ordinate: the stress $\sigma = \frac{F}{S_0}$, σ is the force per unit of surface in N/mm², or MPa.

We then obtain the “stress – strain curve” of the test material which has the following appearance:

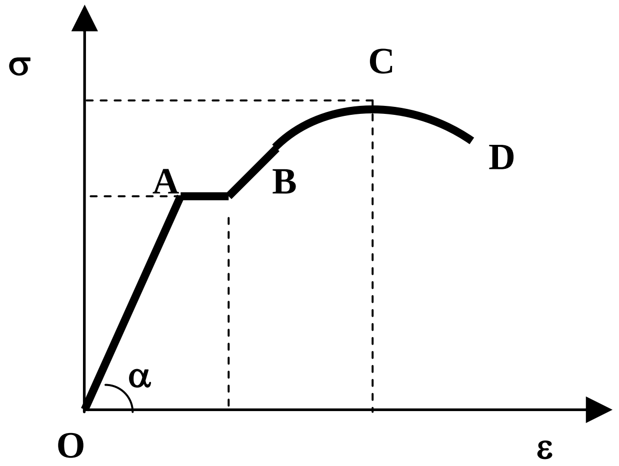


Figure 7.I – Courbe contrainte – déformation de l'acier doux

- **Analysis of the stress - strain curve - Hooke's law, Young's modulus**

- Part OA: the curve is substantially rectilinear, which means that the deformation is proportional to the force exerted (or that the relative elongation is proportional to the stress). (OA = straight line with slope E),

In this zone, if we unload the test piece, it returns to its initial length, like a spring. The material is said to have, in this phase, linear elastic behavior.

This translates into Hooke's law: $\frac{F}{S_0} = E\,\frac{\Delta L}{L_0}$, $\boldsymbol{\sigma = \varepsilon\ E}$

E is the Young's modulus, or longitudinal modulus of elasticity (E), of the material and characterizes the stiffness of the material. E is expressed in MPa

Point A marks the end of the elastic zone of the curve. The corresponding stress is called the yield strength.

- Part AD: beyond point A, we enter the domain of large deformations, the **plastic domain**, where the elongations are no longer proportional to the forces. At this stage, if we unload the test piece, it does not regain its initial length, we see a **residual elongation**, that is to say a permanent deformation.

- Between A and B: the specimen lengthens while the intensity of the load practically does not vary, this part of the curve is called **"plastic bearing"**.

- Beyond B: a significant elongation is observed for a small increase in stress. The curve rises to a maximum C which corresponds to the **rupture limit** σ_r. At this stage, we observe a reduction in the section of the bar in the zone where the rupture will occur, this is the **phenomenon of necking**. Then the break occurs (point D).

- **Contraction or lateral expansion - Poisson's ratio** ν.

During a tension or compression test on a beam, it undergoes a longitudinal deformation ε, x, respectively an elongation or a shortening, but also a lateral (transverse) deformation perpendicular to the direction of the force, respectively a contraction or expansion.

- **Case of traction:** Longitudinal deformation: $\Delta L > 0$ and Lateral contraction: $\Delta d < 0$
- **Compression Case:** Longitudinal elongation, $\Delta L < 0$ and lateral contraction; $\Delta d > 0$

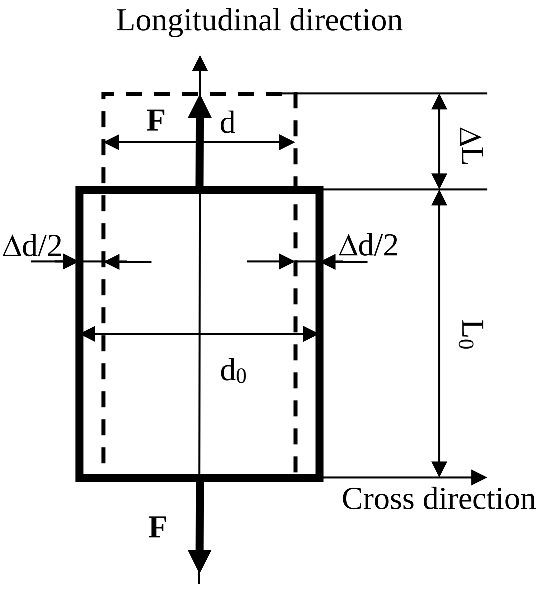


Figure 8.I – Traction case

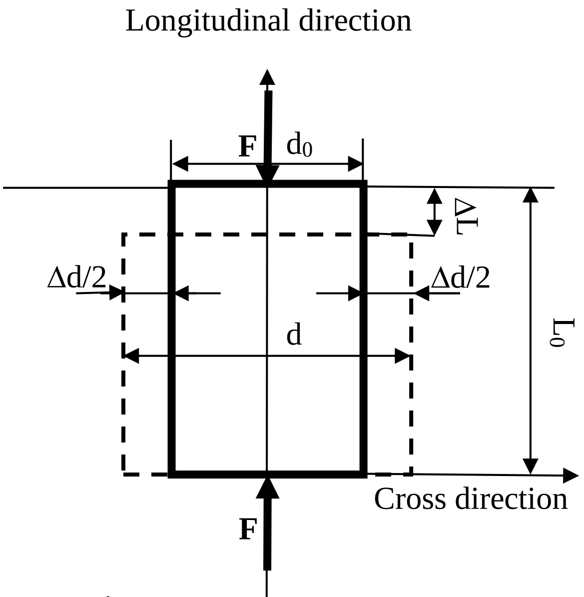


Figure 9.I – Compression case

- **Longitudinal deformation:** $\varepsilon_L = \dfrac{\Delta L}{L_0}$ and **Transverse deformation:** $\varepsilon_T = \dfrac{\Delta d}{d_0}$

- **Poissson's ratio** ν : is the ratio of transverse and longitudinal deformations: $\nu = -\dfrac{\varepsilon_T}{\varepsilon_L}$

ν is between 0.1 and 0.5 (0.3 for metals and 0.15 for concrete).

- **Conclusion:**

To define the mechanical characteristics of the materials, tests are carried out on test specimens:

- direct traction on metals,
- traction by flexion, by splitting or direct for mortars and concretes,
- -compressions on concrete,
- traction, compression, flexion on the wood.

These tests make it possible to determine the following characteristics:

- elastic limit: σ_e,
- breaking stress: σ_r,
- Young's modulus: E,

Table 8.I – traction by flexion tests

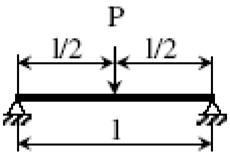
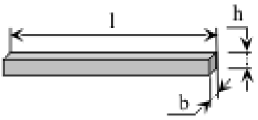
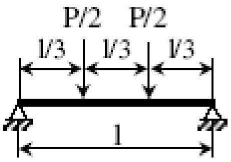
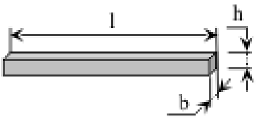
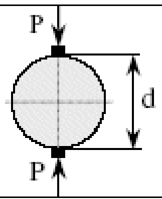
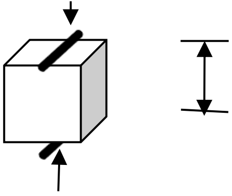
Samples		Formula	Materials	Size (cm)
Prismatic		$\sigma_f = \frac{3}{2}\frac{Pl}{bh^2}$	Cement Brick	 4x4x16 15x15x15
		$\sigma_f = \frac{Pl}{bh^2}$	Concrete wood	 15x15x60 2x2x30

Table 9.I – Splitting tensile tests

Samples		Formula	Materials	Size (cm)
Cylindrical		$\sigma_f = \frac{2P}{\pi d l}$	Concrete	d = 11, h = 22 d = 15, h =30 d = 16, h = 32
Cubic	P has P 	$\sigma_f = \frac{2P}{\pi a^2}$	Concrete	a = 10 cm a = 15 cm a = 20 cm

3.2.4. Resistance measurement by non-destructive methods

The method of non-destruction of samples is one of the methods, which allows the rapid obtaining of the strength of the materials of the structures (concrete of a structure), without taking samples of hardened concrete by coring. Generally, there are a few common ways:

- We use a device called “sclerometer”. In fact, it involves testing the surface hardness of hardened (structural) concrete. This hardness increases as the concrete is more resistant, which allows us to have an order of magnitude of the resistance reached by a concrete at a given age.

- The use of sonic auscultation: The principle of the test consists of measuring the speed of sound inside the concrete. This speed is higher as the concrete is more resistant; this allows us to have an order of magnitude of the resistance reached by a concrete at a given age.

3.3. Chemical properties

3.3.1. Introduction

In the current context of sustainable development, chemical properties represent the chemical resistance of materials to certain aggressive environments such as sea water, selenite waters, carbon dioxide, etc…

Durability or chemical resistance is the quality of a material to maintain the stability of its initial properties over a calculated or estimated duration. Building materials have, without exception, a limited lifespan. Over time, any work undergoes alterations more or less quickly.

Durability directly linked to the immediate or future environment of structures and parts of structures is today the important parameter to consider to optimize the resistance of concrete to external influences: bad weather, aggressiveness of soils, chemically aggressive atmospheres. With this in mind, we examine the recognition and classification of the main environments and their main effects on construction materials in general and cementitious matrix materials in particular, because these are the most used materials and which present a strong interaction with the surrounding environment.

3.3.2. Classification of aggressive environments

Solids: mainly soil and waste of various origins. Four classes of aggression are defined:

Table 10.I – Definition of aggressiveness classes

Environment	**Symbol**	**Protection level**
Low aggressive	A_1	1
Moderately aggressive	A_2	2
Highly aggressive	A_3	3
Very strongly aggressive	A_4	4

Aggressive environments are varied, they can be classified into three categories:

- Gases: of natural origin or resulting from atmospheric pollution and fermentation, the most frequently encountered of which are carbon, sulfur and nitrogen dioxides, hydrogen sulphide, chlorinated, brominated and iodized vapors, ammonia, etc…
- Inorganic or organic liquids, which independently of their possible purely physical effects act mainly through their acidic or basic character and through the aggressive ions they may contain.

- weakly aggressive, moderately aggressive, highly aggressive and very highly aggressive environment. They are grouped together in table 10.I which also gives their symbols and the corresponding levels of protection.

3.3.3. Modes of action of aggressive agents on concrete

- **Mode of action of gases:** The transfer of gases in concrete generally occurs by diffusion and depends very strongly on the relative humidity of the material. Transfers by diffusion can occur in two forms: in the liquid phase and in the gas phase.

- **Mode of action of liquids:** Liquid transfer occurs either by movement of the liquid under hydraulic pressure gradient or by capillarity on the one hand, or by diffusion on the other hand. Liquid flow or movement occurs when concrete is subjected to a hydraulic pressure gradient (damming). The flow in the liquid phase is generated by capillary tensions or, when the concrete is dry, it undergoes a capillary rise of water of external origin.

- **Mode of action of solids:** The harmfulness of solid substances is directly linked to their capacity for extraction and passage into solution in the waters with which they come into contact. Their actions are then reduced to phenomena similar to those observed in the case of attacks by liquids.

3.3.4. Normative aspects

The French standard NF P 18 – 011 defines the most common aggressive environments: Three categories can be distinguished: Table (11.I) gives the degree of aggressiveness of the most common solutions and floors

Table 11.I – Aggressiveness of solutions and soils

a) aggressiveness of solutions depending on their concentration of agents and their pH: stagnant or slow-moving water, temperate climate, normal pressure				
Degree of aggressiveness	A_1	A_2	A_3	A_4
Aggressive agents	**Concentration in mg/l**			
CO_2 *	15 to 30	30 to 60	60 to 100	> 100
SO^{--}_4	250 to 600	600 to 1500	1500 to 6000	> 6000
Mg^{++}	100 to 300	300 to 1500	1500 to 3000	> 3000
NH^{++}_4	15 to 30	30 to 60	60 to 100	> 100
pH	**6.5 to 5.5**	**5.5 to 4.5**	**4.5 to 4**	**<4**
The limit is set at 3000 mg/l for sea water				

b) Case of fresh water				
TAC **	< 1 meq / l	-	-	-

c) Aggressiveness of soils depending on SO content $^{--}{}_{4}$				
% NA $^{--}{}_{4}$ in dry soil ***	0.24 – 0.6	0.8 – 1.2	1.2 – 1.4	> 2.4
Mg/SO $^{--}{}_{4}$ extracted from the ground ****	1200 to 2300	2300 to 3700	3700 to 6700	> 6700
Protection level	1	2	2	3

* Aggressive CO_2 = excess dissolved CO_2 compared to the CO_2 necessary to maintain Ca and Mg hydrocarbonates in solution
** TAC full alcalimetric title (NF T 90 – 036 standard)
The complete alkaline titer (TAC) indicates the content of free hydroxyls (OH^-), carbonates ($CO^{2-}{}_3$) and bicarbonates ($HCO^-{}_3$) and is expressed in hydrotimetric degree.
1 hydrotimetric degree = 10 mg /l of $CaCO_3$
The milliequivalent is the mass of a millimole divided by the valence
1 me = 5 French degrees = 2.8 German degrees
*** Hot HCl extraction
**** Extraction by water (water / solution ratio = 2/1)

3.3.5. Climatic and environmental factors and their effects on concrete

- **Cold climate:**
  - Internal cracking due to freeze-thaw
  - Flaking due to melting salts
  - Corrosion of reinforcements

- **Hot and humid climate**
  - Attack by aggressive waters
  - Alkali – aggregate reactions
- **Semi-humid climate**
  - Carbonation
- **Marine environment**
  - Attack by sea water
  - Corrosion of reinforcing steels
  - Abrasion

3.4. Thermal properties

3.4.1. Thermal conductivity

Thermal conductivity is the ability of material to transmit through its thickness thermal flow resulting from temperature difference between its two faces. The thermal conductivity of materials is expressed by the thermal conductivity coefficient λ .

Consider flat and homogeneous wall, of thickness e (cm), of surface F (cm^2) of flat and parallel faces, if the temperatures t_1 and t_2 on the two faces are different such that ($t_1 > t_2$), the wall is crossed by a thermal flux Φ which is equal to the quantity of heat expended per unit of time

$$\boldsymbol{\Phi = \frac{Q}{t},} \left[\frac{\text{Kcal}}{\text{heure}}, \text{Watt}\right]$$

Q – Quantity of heat spent in Kcal,
t – time in hours

The quantity of heat passing through the material is directly proportional to the temperature difference (t_1 - t_2), to the surface of the wall and to the time T and inversely proportional to the thickness of the wall if we set: $\Delta t = (t_1 - t_2) = 1°C$, e = 1 m, F = 1 m^2, T = 1 hour, the thermal conductivity coefficient λwill take the numerical value of the quantity of heat Q.

$$\boldsymbol{Q = \lambda \frac{F \ \Delta t \ T}{e}} \quad [\text{Kcal}]$$

$$\boldsymbol{\lambda = \frac{Qe}{F \ \Delta t \ T}} \left[\frac{\text{Watt}}{\text{m °C}}\right]$$

Heat transfer increases with increasing thermal conductivity coefficient, the influencing factors are:

- Porosity: Heat is better conducted by the material than still air which has a very low coefficient of thermal conductivity $\lambda_{\text{still air}} = 0.024$ [Watt/m°C], which explains that the conduction of materials with closed pores is lower than that of materials with open and communicating pores which promote air movement leading to heat. Heat transfer is proportional to bulk density.
- Humidity and temperature of material: Thermal conductivity increases with increasing temperature and vice versa. The thermal conductivity coefficient $\lambda_{\text{water}} = 0.597$ [Watt/m°C] is approximately 25 times greater than that of air. If the humidity of a material increases and water replaces the air in the pores, the thermal conductivity of the material increases significantly. If

water crystallizes (turns into ice under the effect of low temperatures), the thermal conductivity increases significantly because the thermal conductivity coefficient of ice is high ($\lambda_{ice} = 2.25$ [Watt/m°C].

The values indicated in table (12.I) take into account an average humidity level.

Table 12.I – Thermal conductivity coefficient of construction materials

MATERIALS	$\lambda.\left[\frac{\text{Watt}}{\text{m.°C}}\right]$	**MATERIALS**	$\lambda.\left[\frac{\text{Watt}}{\text{m.°C}}\right]$
Copper	390	Glass wool	0.04
Aluminum	125 – 230	Terra cotta	0.3 – 0.96
Steel	37 – 60	Brick	0.7
Natural rocks	0.5 – 5	wood	0.1 – 0.25
Marble	3	Oak	0.23
Granite	2.5	Fir tree	0.12
Concrete	1.5 – 2	wood fibers	0.04
Lightweight concrete	0.3 – 1.2	Cork	0.04 – 0.05
Aerated weight concrete	0.1 – 0.4	Plastics	0.1 – 0.5
Window glass	0.8 – 1.15	Foamed plastics	0.025 – 0.5
Foamed glass	0.05 - 0.07	still dry air	0.024

- Materials in construction always contain certain quantity of water due to the phenomenon of hygroscopicity, which varies depending on the humidity of the air, which also leads to variation in their conductivity.

3.4.2. Thermal resistance

Thermal resistance is the power of a material to oppose the passage of heat through its thickness, it is proportional to this and inversely proportional to the coefficient λ of the material:

- For a single layer wall

$$R_{th} = \frac{e}{\lambda}, \left[\frac{\text{m}^2\text{°C}}{\text{Watt}}\right]$$

- For a multi-layer wall

$$R_{th} = \frac{e_1}{\lambda_1} + \frac{e_2}{\lambda_2} + \frac{e_3}{\lambda_3} + \dots \frac{e_i}{\lambda_i} \left[\frac{\text{m}^2\text{°C}}{\text{Watt}}\right]$$

R_{th} - Thermal resistance
e - wall thickness in m
λ - thermal conductivity coefficient in [Watt/m °C]

3.4.3. Specific heat

Specific heat is the power of material to absorb certain quantity of heat to heat up; it is characterized by the specific heat coefficient C.

To heat body of mass m (kg) from the initial temperature t_1 to the final temperature t_2, it is necessary to expend an amount of heat Q (kcal) which is directly proportional to the mass of the body and the difference in temperatures.

$$\boldsymbol{Q = C\,G\,(t_1 - t_2)}\ \text{[kcal]}$$

C the specific heat coefficient

$$\boldsymbol{C = \frac{Q}{G\,(t_1 - t_2)}}\ \left[\frac{\text{kcal}}{\text{kg.°C}}\right]$$

If we set: $\Delta t = (t_1 - t_2) = 1°C$, and m = 1 kg, the specific heat coefficient C will take the numerical value of the quantity of heat Q. In other words, the specific heat is the quantity of heat in kcal, necessary to raise the temperature of a body of 1 kg mass by 1 °C. The specific heat coefficients (C, Kcal / Kg °C) for certain materials are:

- Masonry: 0.18 to 0.22
- Steel: 0.11
- Water: 0.1
- Various wood: 0.57 – 0.65

3.4.4. Fire resistance

Fire resistance is the power of material to resist the action of high temperatures without a significant reduction in mechanical strength and without significant deformation. Fire resistance refers to the fire behavior of material in the sense of the length of time during which the material maintains its functional properties.

The combustion of material takes place in the presence and under the effect of:

- an ignition source to heat the material to the combustion temperature,
- oxygen,

- combustible material.
- the burning rate of material depends on:
- the chemical nature of the material
- the shape and dimensions of the material
- the surface / volume ratio of the material
- the volume of available oxygen.

3.4.4.1. Non-combustible materials

Under the action of high temperatures or fire, combustible materials will not burn (incinerate). Such behavior is encountered in certain natural and artificial materials and metals. Some of these materials, such as clay bricks, resist fire without cracking or warping. Other materials such as concrete, although not containing combustible elements, are characterized by limited fire resistance for the following reasons:

- The dehydration of calcium hydroxides begins from 300 °C and particularly that of calcium hydroxide [$Ca(OH)_2$]
- The quartz aggregates are subjected to significant expansion which generates significant stresses which leads to microcracking and the destruction of the concrete. Likewise at temperature of 500°C, reinforced concrete constructions can be destroyed, the thermal conductivities of steel and concrete are very different, that of steel is approximately 30 times greater than that of concrete, for example Consequently, the adhesion between the two materials is reduced and the concrete coating is often destroyed.

3.4.4.2. Low combustible materials

Subjected to the action of fire or high temperatures, they carbonize, consume or ignite with difficulty, they continue to burn or consume in the presence of a flame only like wood impregnated with fire-retardant additions.

3.4.4.3. Combustible materials

Under the action of fire or high temperatures, they burn, consume and continue to burn even after the fire has been suppressed, such as wood, all organic materials, macromolecular materials, bitumen, tar, etc.…

3.4.4.4. Refractory materials

- **Definition:** Refractory material is any material that resists the action of high temperatures without deforming.

A material is refractory when, under the action of heat within the limits of determined temperatures, it does not undergo any physical modification likely to reduce its mechanical resistance.

Refractory materials are divided into three categories:

- Refractory materials: thermal resistance > 1580°C
- Low fuse materials: Thermal resistance between 1350 and 1580 °C
- Fusible materials: thermal resistance < 1350 °C

CHAPTER II

THE AGGREGATES

CHAPTER II – AGGREGATES

1. INTRODUCTION

- **Definition:** Aggregates are granular substances formed from a set of solid elements with dimensions generally between 0 and 80 mm; these elements obtained: by exploiting deposits of sand and gravel of alluvial, terrestrial or marine origin; by crushing massive rocks ; or by recycling products such as demolition concrete.

These are inert materials which can be used alone or combined with a binder to produce concrete (with cement) or coatings. Used alone, aggregates were, for example, used in large quantities during the construction of railways: they form the ballast, which supports the sleepers and ensures pressure distribution.

2. DIFFERENT TYPES OF AGGREGATES

An aggregate, depending on its nature and origin, may be:

2.1. Natural aggregate: of mineral origin, from loose rocks (fluvial or marine alluvium) or massive rocks (eruptive, limestone, metamorphic rocks, etc.).

Natural aggregates are classified into two categories:

2.1.1. Alluvial aggregates: called rolled aggregates, whose shape was acquired by erosion. These aggregates are washed to eliminate clay particles, which are harmful to the strength of the concrete, and screened to obtain different size classes. Although we can find different rocks depending on the region of origin, the aggregates used for concrete are most often siliceous, limestone or silico-limestone.

Photo 1.II - Alluvial aggregates

2.1.2. Quarry aggregates: are obtained by felling and crushing, which gives them angular shapes. A pre-screening phase is essential to obtain clean aggregates. Different crushing phases result in obtaining the desired granular classes. Crushed aggregates have characteristics which depend on a large number of parameters: origin of the rock, regularity of the bench, degree of crushing, etc. The selection of this type of aggregate must therefore be made carefully and after agreement on sample.

Photo 2.II - Quarry aggregates

2.2. Artificial aggregate: of mineral origin resulting from an industrial process including, for example, thermal transformations: industrial by-products, refractory aggregates. There are several types of artificial aggregates which can be used for specific uses:

2.2.1. Industrial by-products: The most commonly used are crushed crystallized slag and granulated blast furnace slag obtained by water cooling. These aggregates are used in particular in road concrete. The different characteristics of slag aggregates and their specifications are the subject of standards NF P 18-302 and 18-306.

Photo 3.II - granulated blast furnace slag

2.2.2. Industrially developed aggregates with high characteristics: These are aggregates specially developed to meet certain uses, in particular very hard aggregates to reinforce the wear resistance of industrial paving (ferrous aggregates, carborundum, etc.) or refractory aggregates.

2.2.3. Lightweight aggregates: The most common are expanded clay or shale (NF P 18-309 standard) and expanded slag (NF P 18-307). With a variable density between 300 and 1000 kg/m^3 depending on the type and granularity, they make it possible to produce both structural concrete and concrete with good thermal insulation.

We also use lightweight components which are of plant and organic as well as mineral origin (wood, expanded polystyrene, cork, vermiculite)). They are particularly suitable for insulating concrete, but also for the production of lightweight elements: formwork blocks, filling blocks, slabs, or resurfacing on weak floors.

Photo 4.II - Lightweight aggregates

2.2.4. Heavyweight aggregates*:* These aggregates are characterized by their high density (barite, magnetite, ferrous waste, etc.). Heavyweight aggregates are mainly used for the manufacture of heavyweight concrete.

2.3. Recycled aggregate: obtained by processing an inorganic material previously used in construction, such as concrete from the demolition of buildings or road structures.

Photo 5.II - recycled aggregates

3. GRANULAR CLASSES

Aggregates are classified according to their granularity (dimensional distribution of grains) determined by particle size analysis using sieves.

An aggregate is designated by its granular class expressed by the couple d/D with:

d: lower grain size

D: upper grain size.

There are five main granular classes characterized by the extreme dimensions d and D of the aggregates encountered (Standard NFP18-101) :

- Fine 0/D with D ≤ 0.08 mm,
- 0/D sands with D ≤ 6.3 mm,
- Gravel d/D with d ≥ 2 mm and D ≤ 31.5 mm,
- Coarse gravel d/D with d ≥ 6.3 mm and D ≤ 80 mm,
- Pebbles d/D with d ≥ 20 mm and D ≤ 80 mm.

3.1 Particle size analysis by sieving of aggregates:

We consider a sample of weight P of aggregate. The sample is placed in the upper sieve of a series of sieves classified in descending order according to mesh size (from the largest at the top to the smallest at the bottom).

The series of sieves used in the standardized particle size test in (mm): (**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**; **6.3**; **16;**

The choice of sieves to use depends on the dimensions of the aggregate to be tested. For sand for example, we can take the series of sieves noted in bold.

After vibration of the series of sieves, the grains of the sample are separated according to their dimensions and each sieve retains a part called **partial retained of the sieve. The cumulative weight retained** of sieve is the sum of all the partial retainers of the sieves above.

The proportion (in %) of the cumulative retained of sieve in relation to the total weight retained is expressed:

$$\% \boldsymbol{Retain} = \frac{\boldsymbol{Cumulative\ weight\ retained}}{\boldsymbol{Total\ weight\ retained}} \times \mathbf{100}\%$$

The proportion (in %) of the cumulative **passing** of sieve is expressed:

$$\% \boldsymbol{Passing} = \mathbf{100}\% - \% \mathbf{Retain}$$

The particle size curve is the graphic representation of %Passing depending on the size of the sieve mesh. In order to take into account, the large variation in grain sizes in aggregate, the size of the sieve mesh is represented on a logarithmic scale.

Thus the **particle size curve** is: **%Passing = *f* (log(*d*)),** with ***d*** : size of the sieve mesh.

Table 1.II: Example of particle size analysis of sand sample

Sieve size (mm)	**weight retained (g)**	**cumulative weight retained (g)**	**Retain (%)**	**Passing (%)**
6,3	43	43	2,19	97,81
4	15	58	2,96	97,04
3,15	48	106	5,41	94,59
2,5	96	202	10,32	89,68
2	110	312	15,95	84,05
1,6	175	487	24,89	75,11
1	290	777	39,72	60,28
0,5	600	1377	70,39	29,61
0,4	95	1472	75,25	24,75
0,315	310	1782	91,10	8,90
0,25	40	1822	93,14	6,86
0,2	55	1877	95,96	4,04
0,16	15	1892	96,72	3,28
0,1	56	1947	99,53	0,47
0,08	6	1953	99,84	0,16
Pan	3	1956	100	0

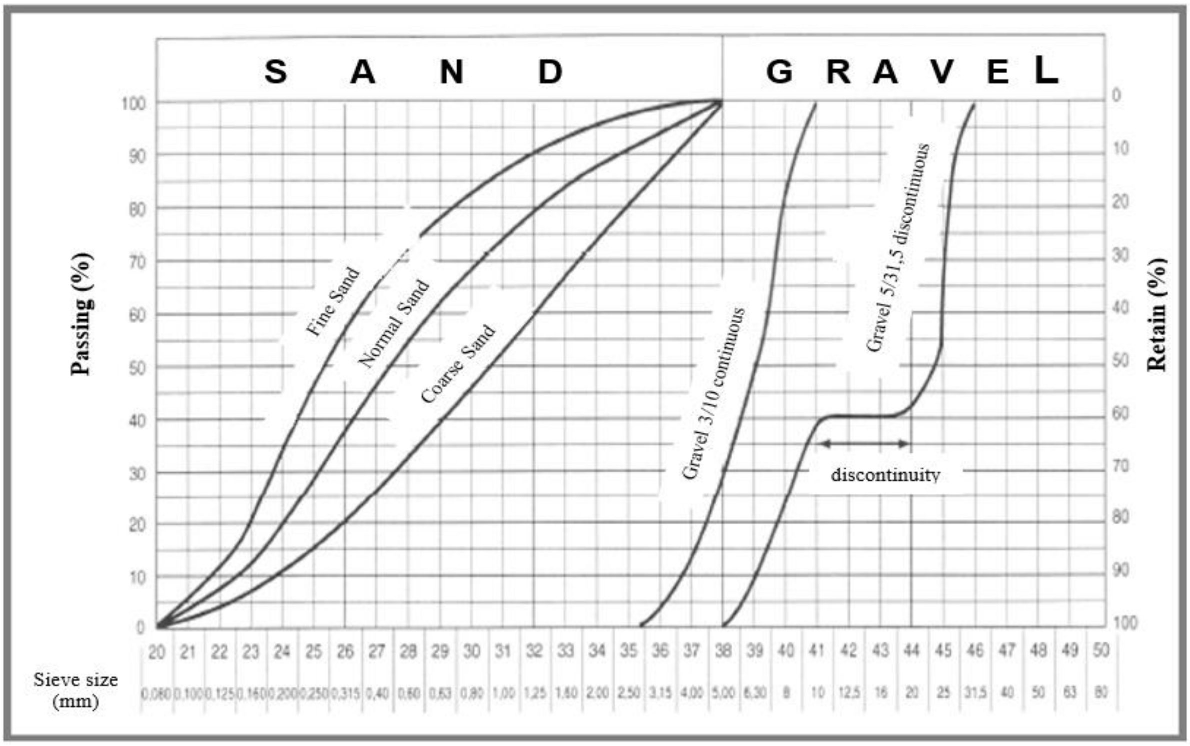


Figure 1.II – Example of particle size curves for some aggregates

4. CHARACTERISTICS OF AGGREGATES

The aggregates must meet quality and regularity requirements and criteria which depend, on the one hand, on the nature of the rock (resistance to shocks and wear, physicochemical characteristics, etc...) and, on the other hand, physical characteristics linked to the process of producing the aggregates (dimensions, shapes, cleanliness, etc...).

4.1 Physical characteristics

- **Apparent density**

  The apparent density depends on the packing of the grains. It is measured according to a precise operating procedure using a 1 dm^3 container by slowly pouring the sand into the funnel 10 cm above the container which is leveled with a ruler. The contents are weighed. It is between 1400 kg/m^3 and 1600 kg/m^3 for common aggregates.

- **Absolute density**

The absolute density of the aggregate, that is to say volume of voids excluded, is significantly higher: from 2500 to 2600 kg/m^3 for common aggregates.

- **Water absorption:**

In general, the natural aggregates used to make concrete are not very porous and absorb practically no water when mixed with cement and water. On the other hand, artificial aggregates, such as lightweight expanded clay aggregates, are porous. It is then necessary to take into account the absorption of water by the aggregates when determining the quantity of water required to make the concrete.

4.2 Cleanliness of aggregates

Fines and dust in asphalt and concrete aggregates have always been a problem. Whether naturally occurring or resulting from degradation during handling and transport, undesirable or unknown amounts of fines can impact the performance and cost of composite materials.

Although controlled amounts of fines and dust can improve some characteristics of asphalt or concrete mixes, too much negatively affects the behaviors of the materials. Excessive fines increase the total surface area of solids in concrete and reduce workability while increasing water demand. In asphalt, high fines contribute to a loss of adhesion between asphalt binder and aggregate, and more binder is required.

In 1953, the sand equivalent test was presented in the Highway Research Board Proceedings, by Francis N. Hveem a materials and research engineer with the California

Division of Highways. The test measures the proportions of clay-like fines in granular soils and aggregates and can be run in as little as 40 minutes. The procedure can be performed in a fully-equipped laboratory or at a remote field outpost for on-the-spot quality control checks.

The Sand Equivalent Test Method described in ASTM D2419, the procedure of which is recalled below.

- A prepared sample of fine aggregate passing the (4.75 mm) sieve is added to a working solution of calcium chloride and glycerin in a unique graduated cylinder.
- The cylinder is agitated in a prescribed manner, either manually or by a mechanical shaking device (photo 6.II).

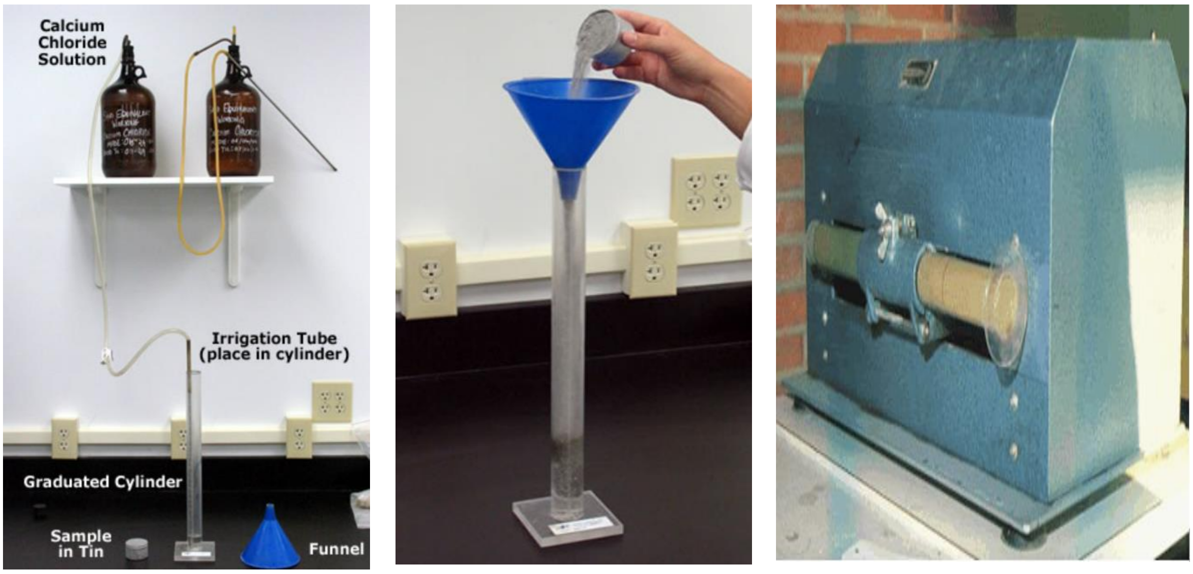


Photo 6.II - First steps of sand equivalent test

- After agitation, a metal irrigation tube is manually worked into the sample with a stabbing action, introducing more solution and flushing the finer particles into suspension.
- The fines then settle to the top of the column of solids.
- After a sedimentation period, the level of the top of the clay suspension is observed and recorded as the clay reading.
- A weighted-foot assembly is carefully lowered into the cylinder to rest on the sample to determine the sand reading (photo 7.II).

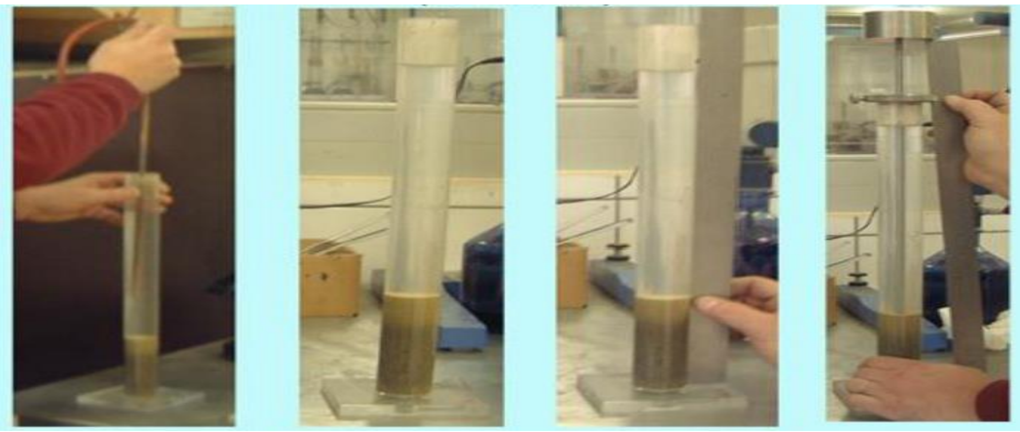


Photo 7.II - Second steps of sand equivalent test

Calculate the sand equivalent (SE) using the following equation:

$$(S \div C) \times 100 = \text{Sand Equivalent Value}$$

S = Sand Reading
C = Clay Reading

4.3 Aggregates shape

The production of cement concrete, as well as the production of road bodies and wearing courses, requires the use of only aggregates having a fairly compact shape, excluding flat and elongated aggregates. In fact, these do not make it possible to produce very compact concrete, and, moreover, in road engineering, they cannot be used because they lead to wearing courses that are too slippery.

The shape of an aggregate is defined by:

- The length L, minimum distance of two parallel planes tangent to the ends of the aggregate,
- The thickness E, minimum distance of two parallel planes tangent to the aggregate,
- Size G, dimension of the minimum square mesh of the sieve which allows the aggregate to pass.

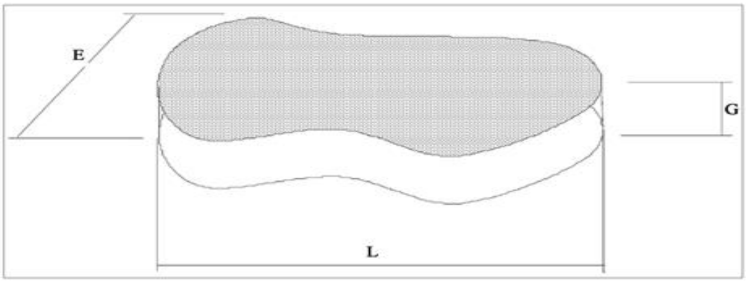


Figure 2.II – Geometrical characteristics of an aggregate.

Determining the **flattening coefficient** is one of the tests making it possible to characterize the more or less massive shape of the aggregates.

The flattening coefficient "A" is determined by a double sieving, first through the series of square mesh sieves used for the study of the particle size, then by a second sieving of the rejects retained on the different sieves on a series of grids with parallel slots, The coefficient A is the weight percentage of the elements which verify the relationship G/E > 1.58.

4.4 Mechanical characteristics

The mechanical characteristics of the aggregates are determined by tests attempting to reproduce certain stresses specific to specific uses of the aggregates, for example the degree of wear for aggregates used for road concrete.

- **Shock resistance**

Resistance to impact fragmentation is determined using the Los Angeles test. The test consists of measuring the mass (m) of elements less than 1.6 mm, produced by the fragmentation of the material tested (diameters between 4 and 50 mm) and which are subjected to the impacts of standardized balls, in the cylinder of the Los Angeles machine in 500 rotations (photo 8.II).

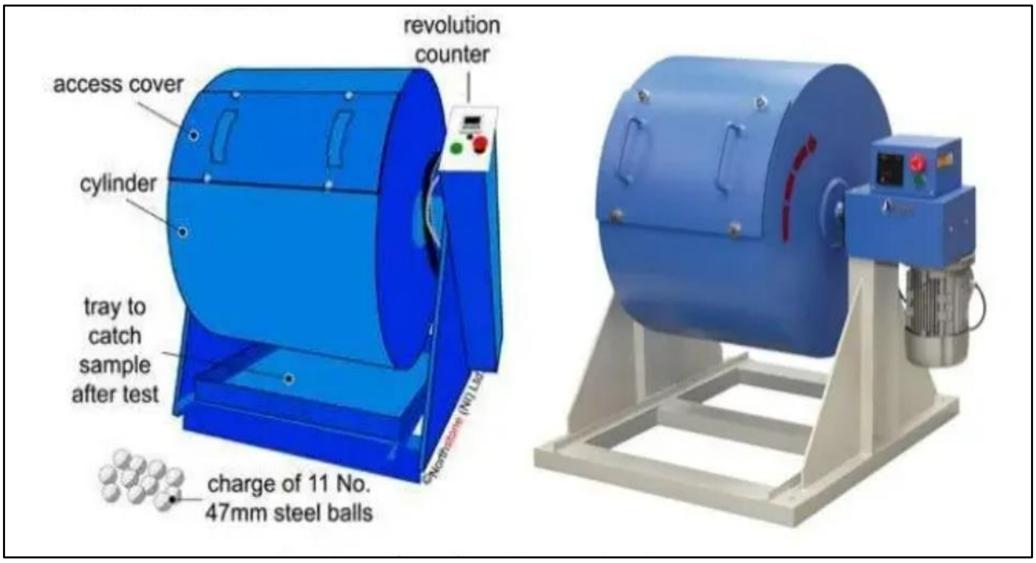


Photo 8.II - Los Angeles machine

- **Wear resistance**

Resistance to frictional wear is determined using the Micro Deval test (photo 9.II). The test consists of measuring the mass (m) of elements less than 1.6 mm, produced by reciprocal friction of the material tested and which are subjected to the friction of 2 to 5 kg of steel balls of 10 mm in diameter in a cylindrical jar filled with water, turn for 2 hours 30 minutes.

Photo 9.II - Micro-Deval apparatus with two drums

4.5 Chemical characteristics

- **Chloride ion content**

Chlorides modify the hydration kinetics of cement and cause corrosion of reinforcements. The chloride content of all the constituents of concrete is therefore limited.

- **Reactivity to alkalis**

In unfavorable conditions (aggregates containing a significant fraction of soluble silica reactive in an environment rich in alkali) and in the presence of humidity, alkali reaction phenomena can cause swelling of the concrete. Aggregates are designated as non-reactive, potentially reactive.

- **Sulphate content**

Aggregates may contain small quantities of sulphates (SO_3) must be less than 0.2%. The sulphates present in the aggregates can generating swelling phenomena in the concrete. It is therefore necessary to limit the sulphates content to protect against this phenomenon. Sulphates can disrupt the setting and action of the admixtures, hence the need to limit their content in the concrete.

CHAPTER 3

MINERAL BINDERS

CHAPTER III - MINERAL BINDERS

1. INTRODUCTION

During prehistory and early antiquity, clay was used as a binder to mason stones. When building the pyramids, the Egyptians used plaster obtained by baking gypsum. Later, the Greeks, then the Romans, used lime produced by cooking limestone in their constructions. They subsequently improved the binder by adding volcanic ash (very fine particles of natural origin) from the Pozzuoli region (pozzolans). They thus obtained Roman cement. This binder was used without major modifications until 1756, when the Englishman SMEATON, during the construction of the Eddy stone lighthouse, mixed hydraulic lime and pozzolans. He thus obtained the first artificial binder, with which he prepared a mortar as hard as Portland stone.

In 1817, the French engineer Louis Vicat, followed in early 1824 by the Ecossais ASPDIN, gave the name Portland to the cement he manufactured and which equaled the stone of this region. The first cement factory with a vertical kiln was created by DUPONT and DEMARQUE in 1846. Development was only possible thanks to the appearance of rotary kilns around 1880 and are still used. Cement manufacturing processes were constantly improved. The production of ton of clinker, the basic constituent of cement, required 40 hours in 1870; it currently takes around 3 minutes.

2. CLASSIFICATION OF BINDERS

There are two types of mineral binders:

- Air binders
- Hydraulic binders

Aerial binders are materials which, mixed with water, form a plastic paste that can only harden and be stored in the open air. Air binders are water soluble.

Hydraulic binders are materials that can harden and be preserved both in the open air and in water. Their durability depends on the chemical nature of the environment.

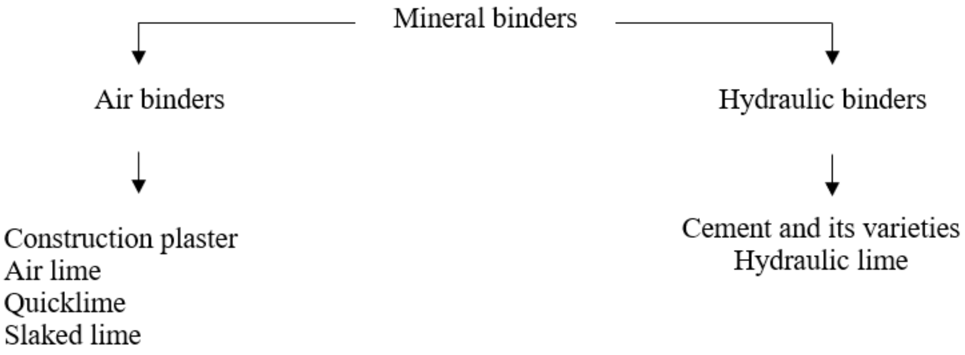


Figure 1.III – Classification of binders

3. PLASTER AND ITS PRODUCTS

- **Definition**

Plaster, white powder that is mixed with water (mixing) to obtain paste which hardens as it dries. The plaster is composed of weakly hydrated calcium sulfate ($CaSO_4.\frac{1}{2}H_2O$) obtained by calcination of gypsum ($CaSO_4.2.H_2O$) in an oven at a temperature of around 160 °C

$$(CaSO_4.2.H_2O \rightarrow CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O)\text{, gypsum.}$$

3.1. Construction plaster

3.1.1. Manufacturing process

- **Raw materials**

Gypsum is natural rock, mineral of sedimentary origin, widespread on the earth's crust. We can (rarely) encounter the rock in the form of natural anhydrite ($CaSO_4$). Gypsum is white in color if it is pure like alabaster, but often colored by impurities, such as sand, clay, limestone, bituminous materials, its color then changes from yellow to pink, density 2.3 hardness 2. Gypsum is soluble in pure water:

In deposits, depending on the conditions, gypsum crystallizes in different ways, in particular forming larger or smaller crystals.

- Raw formula $CaSO_4 \cdot 2H_2O$
- Color white to gray, sometimes pink
- Perfect cleavage
- Hardness on the Mohs scale 1.5-2
- Density 2.31 - 2.33
- Solubility
  - 2 g/l in water at 20°C
  - 2.30 g/l at t = 12°C
  - 2.54 g/l at t = 35 °C
  - 2.17 g/l at t = 100 °C

- **Extraction**

Gypsum is extracted in underground or open-air quarries. The gypsum is crushed and transported to the plant by large capacity trucks or conveyor belt. Gypsum is crushed and dried simultaneously in a grinder dryer and fired in a vertical (vanishing) or horizontal (rotating) kiln. It should be noted that modern installations allow the grinding, drying and cooking of gypsum simultaneously in the grinder-cooker, in this case the preparation of the overcooking is carried out separately in overcooking tube.

Gypsum dehydrates under the effect of heat; more than 70% of the water contained in gypsum is only weakly bound. The products obtained when heating gypsum depend on three factors:

- Heating temperature
- Heating time
- The humidity level of the oven

Photo 1.III – Open pit gypsum mining

- **Cooking**

Ordinary (commercial) plaster is obtained at the temperature:

- **t = 110 – 160 °C:** the lime sulfate loses the weakly bound water, by absorbing a certain quantity of heat, we obtain ordinary plaster ($CaSO_4 . \frac{1}{2} H_2O$). It is also called low temperature plaster. At higher temperatures other types of plaster are obtained which can be found in ordinary plaster in small proportions.

- **t = 180 – 250 °C:** the hemihydrate still contains 6% of constitutional water, we obtain the anhydrite ($CaSO_4$) which is soluble and sets quickly because it is hungry for water. Soluble anhydrite activates the setting of the plaster.
- **t = 250 – 600 °C:** at this temperature range, we obtain the unusable anhydrite ($CaSO_4$), only the overcooked is reactive, slow setting, this is hydraulic plaster or high temperature plaster, which can be prepare specially in overcooked ovens at a temperature of 500°C.
- **t = 600 to 800 °C:** we obtain the plaster cooked to death, incapable of setting.
- **t = 1100 °C:** the product obtained regains its ability to set, it is soluble anhydrite with very slow setting.
- **t = 1350 °C:** the anhydrite melts and dissociates.

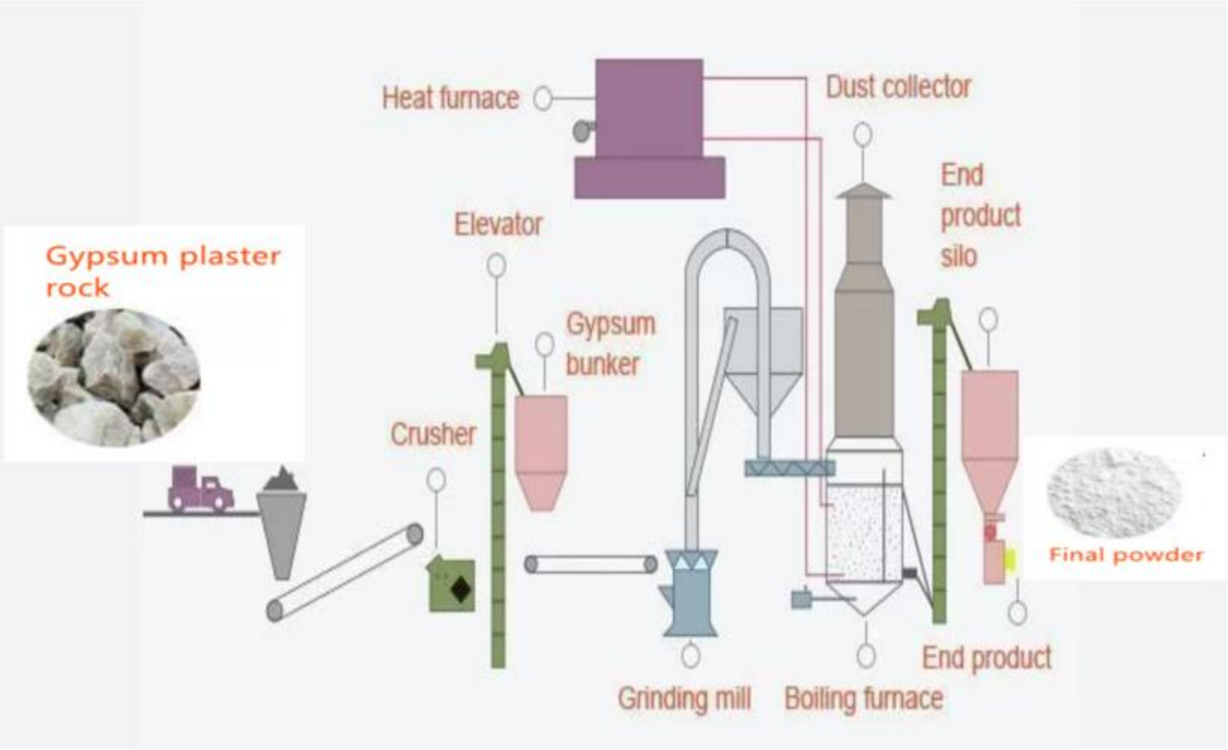


Figure 2.III – Ordinary plaster manufacturing process

The manufactured products are stored in silos. The products are then dosed in proportions defined by the type of plaster that we wish to produce. and sent to the crusher to achieve the desired fineness and homogenize the mixtures.

The finished product is stored in silos before being bagged in 40 kg bags to be shipped and marketed.

Photo 2.III – plaster rotary kiln

3.1.2. The development of finished products

At the exit from the oven, the various products obtained during cooking (hemi-hydrate and overcooked) are crushed and measured to produce different types of plaster,

The production of finished products consists of two essential operations:

- Grinding and sieving
- Dosage of plaster constituents

The aim of these operations is to obtain varied plaster products that comply with standards.

- **Dosing of plaster products**

Plasters are, most often, mixtures of semi-hydrates and overfires which are prepared separately in overfired kilns, in varying proportions and granularity depending on the qualities required.

The quality of the plasters will be further improved by the addition of different products (synthetic resin, setting modifier and adjuvants) in order to obtain a varied range of products for each particular use.

The homogeneity of the mixtures is ensured by mechanical or air mixing.

- **The composition of plasters**

- **Ordinary plaster:** Ordinary plaster is white to yellow in color, with an apparent density that varies depending on the size of the grains (650 to 1650) kg/m^3, and density of 2.7. Plaster is five times more soluble than gypsum, unalterable and unattackable by fungi and insects. Ordinary plaster consists of:

    - semi hydrate (low temperature plaster) major component
    - hydraulic plaster (high temperature plaster)
    - heavily overfired plaster
    - finely ground unfired gypsum

- **Molding plaster:** Is obtained from pure raw materials, cooked at temperature of 300°C in a rotary kiln or autoclave in order to easily maintain the constant temperature during cooking

- **Plasters for coatings:** Are made from crushed anhydrite or very pure gypsum possibly mixed with mineral salts. Cooking takes place at very high temperature.

- **Storage and packaging of plaster in the factory**

The plaster is stored in fluidized bed silos. The plaster is packaged in paper bags with standardized weights of 40 and 25 kg, the bagging of which is carried out automatically by mechanical processes (slides, roller conveyors, belt conveyors, generally terminated by a telescopic conveyor for direct loading on flatbed trucks.

Distribution is also carried out in bulk by containers and by trucks, wagons or pumped air handling tanks.

The terms of packaging, delivery and receipt are set by standards, which specify, in particular, the mandatory standardized marking conditions.

3.1.3. Hydration of the plaster

The gypsum is regenerated by hydration, according to CHATELIER the phenomenon takes place as follows:

- the plaster dissolves until a saturated solution is formed
- the plaster hydrates within a supersaturated solution causing the precipitation of assembled micro-crystals:

$$CaSO_4.\frac{1}{2}H_2O + \frac{3}{2}H_2O \longrightarrow CaSO_4.2.H_2O.$$

The hydration reaction is rapid and occurs with a rise in temperature of 20 to 25°C and an expansion of 0.5% after one hour and 1.2% after 24 hours.

The delayed crystallization of the slow-setting anhydrite contained in ordinary plaster increases cohesion and opposes the shrinkage likely to accompany drying.

3.1.4. Tests on plaster

- **Chemical tests**
  - degree of purity, $CaSO_4$ content
  - the content of impurities (free water, sand, clay and carbonates)
  - quantity of water combined with anhydrite ($CaSO_4$)
  - rate of hydration, by measuring the quantity of water fixed by the plaster over time (T min ≥ 2 hours)

- **Physic-mechanical test**

- **Fineness of grinding by sieving:** The test consists of sieving a sample of plaster of mass m_e through a 0.4 mm sieve and expressing the quantity of the passer m_p in % by the following formula:

$$P = \frac{m_t}{m_e} .100, [\%]$$

- **Normal consistency of plaster:** The test consists of determining a water/plaster ratio = (0.5 to 0.7) by measuring the spreading diameter of cast of plaster which must be equal to 12 cm.

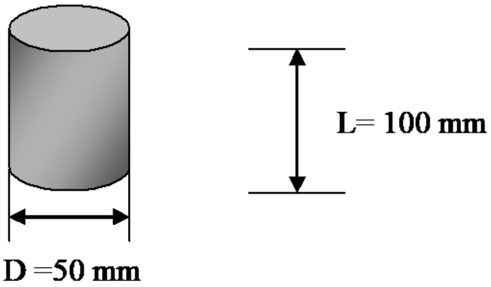


Figure 3.III – Souttard mold for consistency testing on plaster

- **Setting times (Vicat apparatus):** The test consists of determining the times during which the material begins to lose its plasticity (start of setting) corresponding to the instant t_1 or the needle no longer penetrates to the bottom of the mold and when the material completely loses its plasticity (end of setting) corresponding to time t_2 when the needle no longer penetrates the material. The start and end of takes can be calculated as follows:

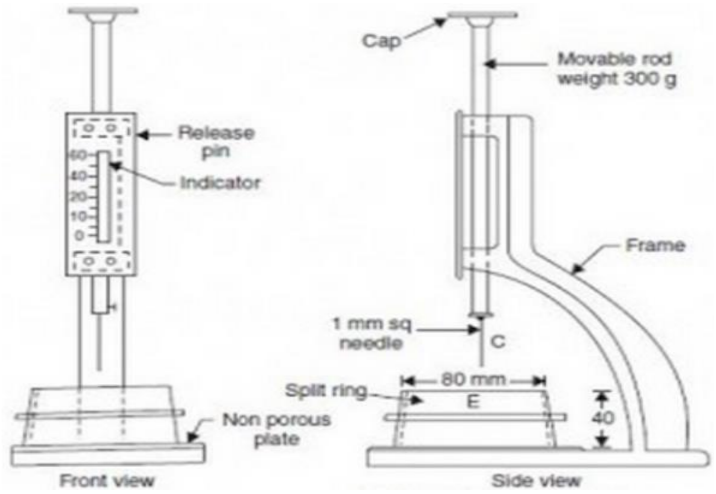


Figure 4.III – Vicat apparatus

$$\mathbf{SS = t_1 - t_0}\ [\text{Minutes}]$$

$$\mathbf{ES = t_2 - t_0}\ [\text{Minutes}]$$

$\mathbf{t_0}$ – mixing time

- **Mechanical resistance**

In compression and tension by bending on a test piece (4.4.16) cm with a ratio (plaster / water) of 1 to 1.4, corresponding to the normal consistency of plaster.

3.1.5. Varieties of plasters

The marketed products depend on certain properties which are given in table 1.III:

- their finesse: big 'B' and Fine 'F'
- working time: 1 Fast, 2 Slow
- quantity of mixing water
- mechanical resistance

Table 1.III – Physical characteristics of plasters

Category	**Moving on to 0.4 mm, %**	**density, g/l**	**Mixing water, %**	**Delivery times**		**σ'_{28}, MPa**	
				Beginning	**END**	**com**	**flex**
BCP 1	65 – 80	1000	60	6 – 15	15 – 45	5.5	1.2
BCP 2	60	950	75			6.0	1.6
FCP 1	80 - 85	850	75	3 - 8	10 - 20	4.5	1.5
FCP 2							

3.1.6. Uses

There are several qualities and several types of plaster; we are interested in common plasters for frequent use in civil engineering:

- Big construction plasters (1): It serves as a binder (plaster mortar) for the construction of partitions, smoke ducts, for sealing floors, roughing up coatings, as a form for curved formwork, plaster concrete without sand and cellular plaster.

- Big construction plaster (2): PGC2 is used for the manufacture of plaster tiles, for the installation of cut stones and marble. It is also used for the prefabrication of plaster elements (solid, perforated sheets and panels) for partitions, ceilings, etc.…

- fine construction plaster (1 and 2): PFC 1 and 2 are used for final coatings, sealings and moldings.

- molding plaster: It is used for multiple uses, moldings, staff (fibrous mixture of plaster suitable for modeling used in interior decoration and in industry), grouting (filling of gaps in the surface of a masonry work), veneer (embellishment), final moldings, certain paint fillings. It makes molds for porcelain, earthenware, mechanical tiles and cast iron.

3.1.7. Qualities of plaster:

- **Plaster is protection against fire**

It is fireproof, because the hardened plaster contains 20% water, dehydration requires a lot of heat:

- 10 mm of plaster coating guaranteed 30 minutes of protection at 800°C
- 30 mm of plaster coating guarantees protection for 40 minutes at 1100°C

- **Plaster is hygrometric regulator:**

Plaster is a porous material; it absorbs and releases water vapors; provided you do not cover it with waterproof paint

- **Plaster is a thermal insulator:**

Simply compare the thermal conductivity coefficients of the materials given in Table 2.III

Table 2.III – Thermal conductivity coefficients

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

- **Acceptable acoustic insulation:**

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

Plaster remains necessary material because of the solutions it provides to the problems of comfort, safety, aesthetics and economy.

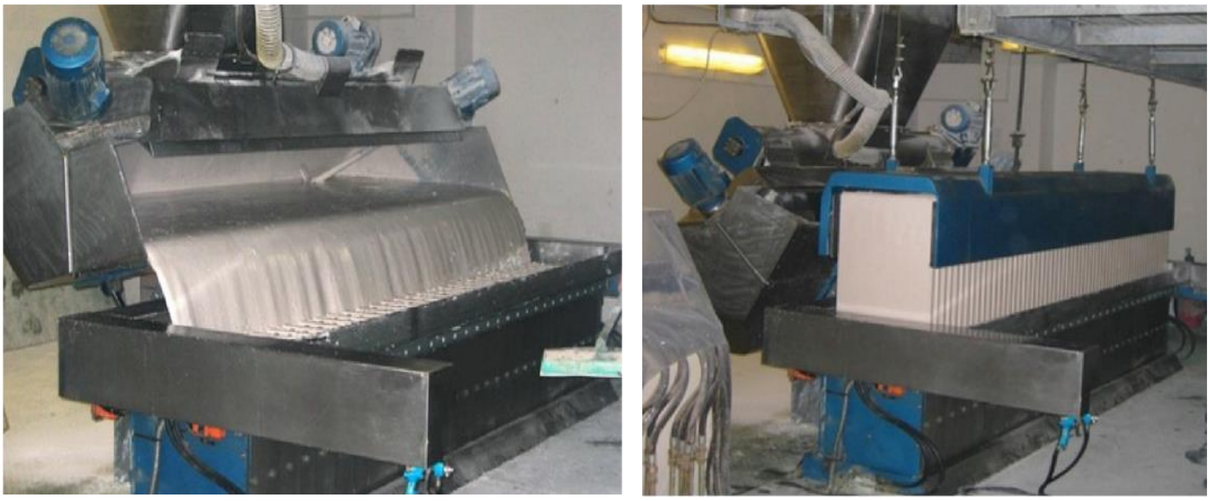
3.2. Plaster tiles

3.2.1. Manufacturing process

- Preparation of the mixture: The mixture of water plaster and possibly adjuvant is made in mixer at temperature of around 70°C.

- Molding: The molding of the tiles is carried out using a roller which fills battery of molds

- Drying: After pouring and finishing, the batteries are stored until they set before undergoing natural or artificial drying to evaporate excess water



Molding **Demolding**

Photo 3.III – Plaster tiles manufacturing process

3.2.2. Tile nomenclature

Plaster tiles are elements, solid or honeycomb, of dimensions (50 × 60), (40 × 60) and (35 × 65), the most common thicknesses are 6 and 7 cm, but we also find some of different thicknesses ranging from 5 (and even 4 in lining) up to 15 cm.

These elements can be sawn, cut, sliced with shears, milled, stamped, etc. Their assembly is carried out by interlocking with solid or serrated tenons and mortises, single or double depending on the thickness. They are linked by gluing with a special plaster-based glue which gives invisible joints that can be easily sanded.

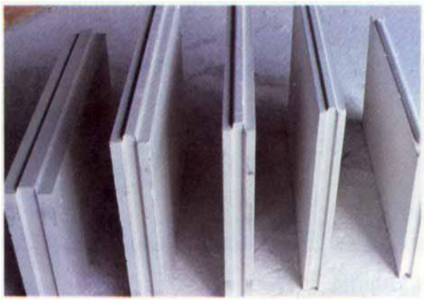


Photo 4.III – Plaster tiles

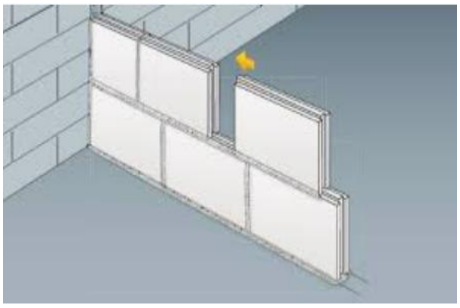


Figure 5.III – Plaster tile partition

3.3. Manufacturing gypsum board

3.3.1. Manufacturing process

In the factory, the plaster is mixed in mixer (its temperature is maintained at 70°C) with various additions (setting retarders and fluidizers), enclosed in sheets of cardboard, thus composing thin elements, which nevertheless retain interesting mechanical properties .

The plaster board manufacturing line extends over 450 m.

Plaster board is made from two sheets of cardboard that sandwich plaster. The first cardboard serves as a support for pouring the plaster, the second cardboard is then placed as a cover, and the plate is left to dry. Finally, after cooling, the plates are cut to the desired dimensions, then they are stored in the form of pallets before delivery.

They are installed by screwing onto specific wooden or metal uprights, or by direct gluing onto masonry supports using an adhesive mortar.

Photo 5.III – Unrolling the cardboard roll

Photo 6.III – Pouring the plaster

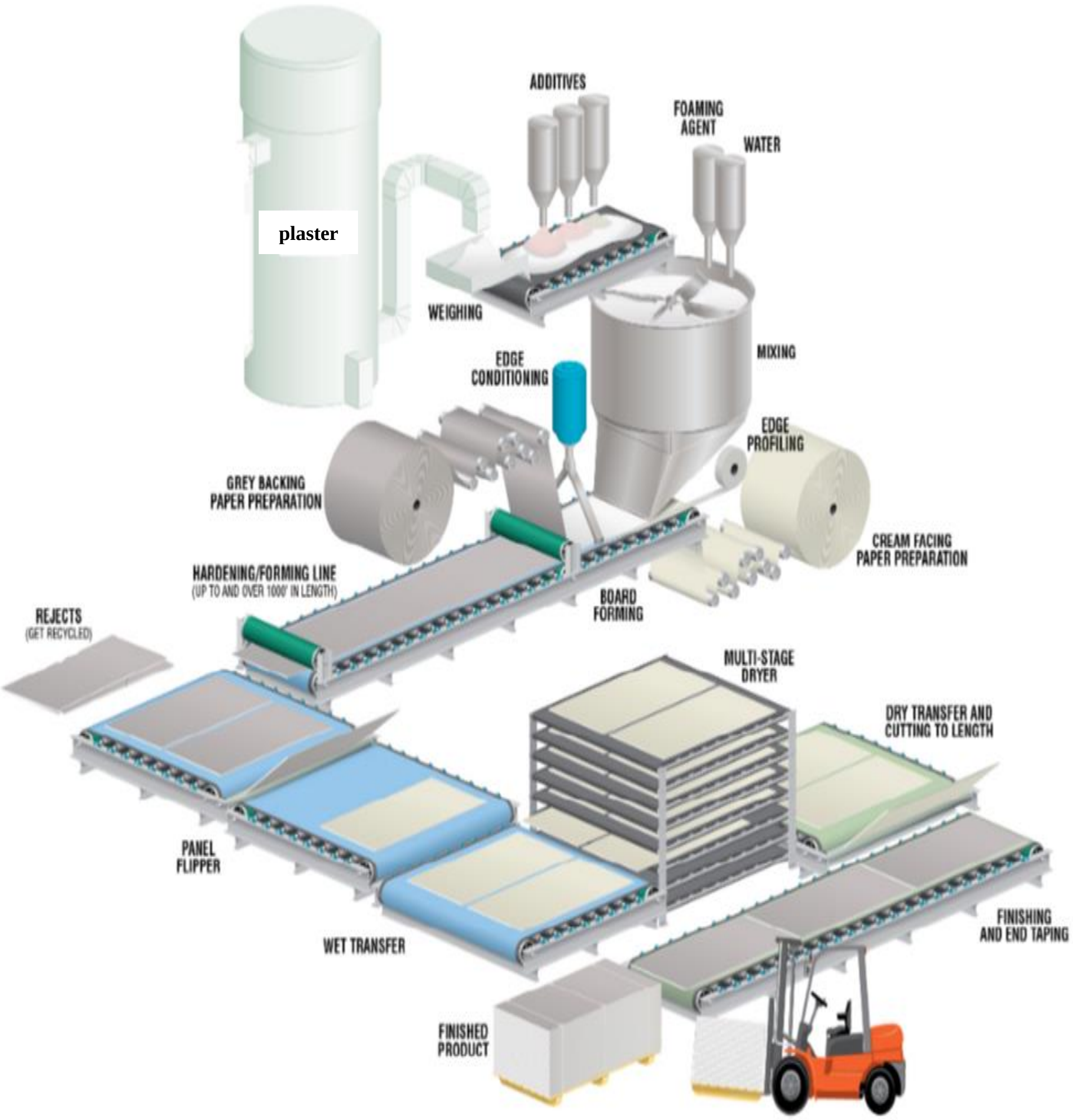


Figure 6.III – Plaster board manufacturing process

4. LIME

4.1. Introduction

Limes have been used for millennia. The Chinese and Egyptians built durable buildings with lime-based mortars of a hydraulic nature, obtained by cooking local limestone. Closer to us, the Romans and then our ancestors used the same processes to construct works and buildings which are part of our heritage.

- **Definition**

Lime is a solid substance, white when pure. It is obtained by calcination of soft natural limestone and chalk, with reduction to powder by slaking followed or not by grinding. There are basically two categories of lime: aerial fat lime and hydraulic lime. Limes are generally classified according to the proportion of clay impurities they contain. The ratio i represents the hydraulicity index (table 3.III)

$$i = \frac{SiO_2 + Al_2O_3 + Fe_2O_3}{CaO + MgO}$$

Table 3.III – Classification of lime according to the hydraulicity index i

Type of lime	% clay	Value of i
Fat lime	0	0 – 0.1
Low hydraulic lime	5 - 8	0.1 – 1.16
Medium hydraulic lime	8 - 14	0.16 – 0.3
Highly hydraulic lime	14 - 19	0.3 – 0.4
	19 - 22	0.4 – 0.5

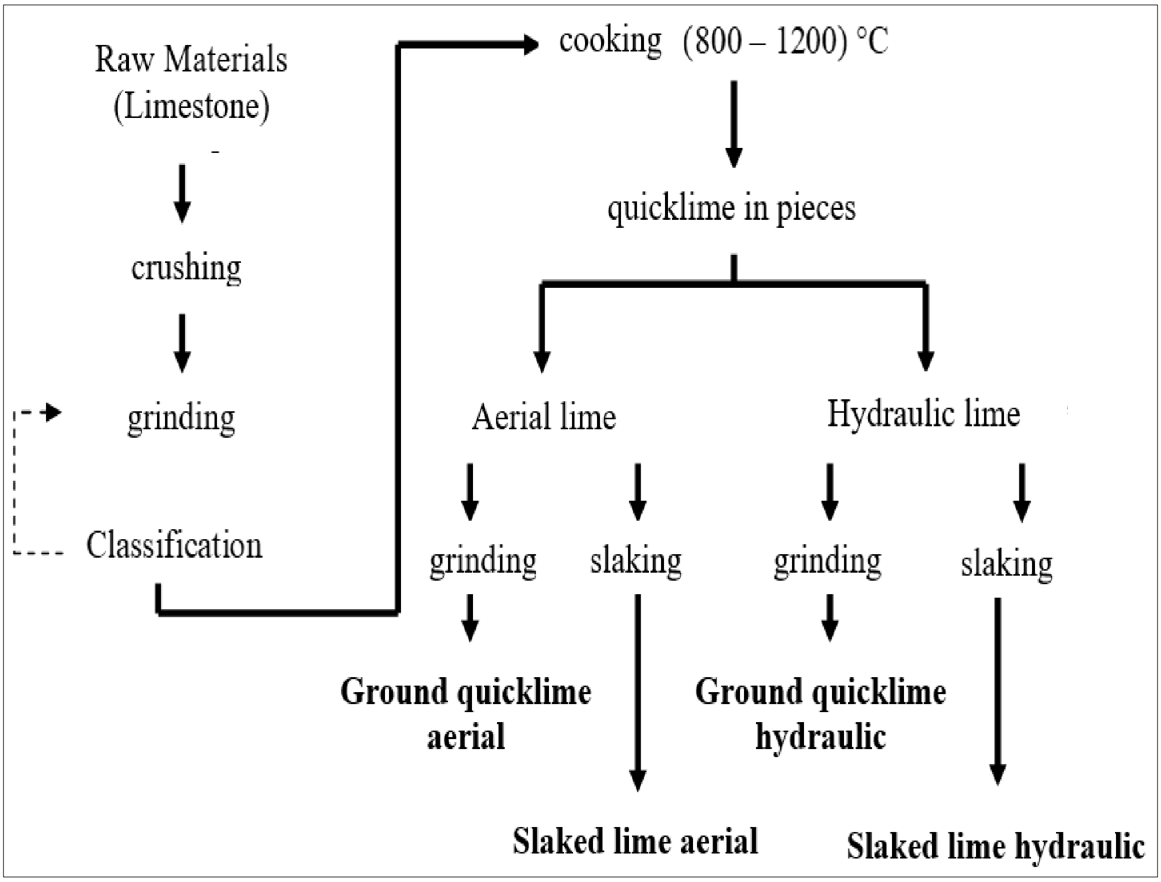


Figure 7.III – Schematic diagrams for manufacturing different types of lime

4.2. Aerial lime:

4.2.1. Raw materials

The raw materials used for the manufacture of aerial lime consist of more or less pure soft limestone rock or chalk. The raw material is extracted from open-air or underground quarries. After slaughter, it is crushed and screened.

4.2.2. The cooking

Cooking is generally carried out in continuous-running vertical ovens, into which the limestone and fuel are introduced into the upper part, in successive layers. The material descends slowly, first passing through a preheating zone, causing evaporation of free water and dehydration (around 200 °C). It then passes through a calcination zone where it is decarbonated at a temperature of 900°C. Quicklime is then obtained in pieces. During cooking, the calcium ($CaCO_3$) and possibly magnesium ($MgCO_3$) carbonates are decomposed into calcium and magnesium oxide with the release of carbon dioxide (1.1)

$$CaCO_3 \xrightarrow{1000\ °C} CaO + CO_2 \quad \text{et} \quad MgCO_3 \xrightarrow{1000\ °C} MgO + CO_2 \qquad (1.1)$$

Quicklime in pieces is a semi-product; after fine grinding we obtain **Ground quicklime** or **caustic lime** and after slaking we obtain **slaked lime**.

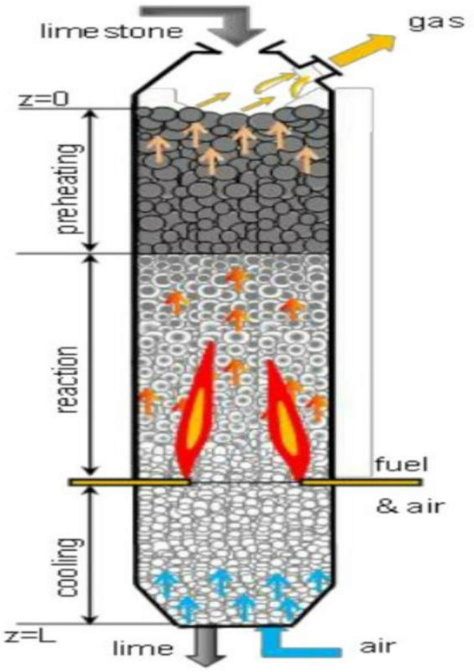


Figure 8.III – Schematic of a normal shaft kiln for limestone calcination

4.2.3. Ground quicklime:

Is a white powder of great finesse, it has the ability to set and harden quickly. The mixing of quicklime-based mortars is accompanied by a large release of heat. The reaction can be violent if the ratio (water/lime) is low. A ratio (water / lime) between 1 and 1.5 is sufficient to guarantee a quenching reaction of the quicklime under conditions favorable to the hardening of the mortar. The quantity of heat released serves to evaporate excess water in the mortar and accelerates its maturation, particularly in freezing weather.

4.2.4. Slaked lime:

Lime treated with water releases a large amount of heat and turns into powder, sold commercially in the form of white powder and under the name slaked lime or hydrated lime.

$$CaO + H_2O \longrightarrow Ca(OH)_2 + Q(1.2)$$

4.3. Hydraulic limes

4.3.1. Manufacturing process

The manufacturing process of hydraulic lime is the same as that of aerial lime. The difference lies in the quality of the raw materials and the cooking temperature.

Hydraulic lime is obtained by calcination, at a temperature above 1000°C, of limestone rocks which contain siliceous and aluminous elements. During calcination, it is formed simultaneously:

- calcium oxide (quicklime) coming from the decomposition of calcium carbonate, the main constituent of limestone;

$$CaCO_3 \rightarrow CaO + CO_2$$

Calcium carbonate → calcium oxide + carbon dioxide

- calcium silicates and aluminates coming from the combination of part of the quicklime with siliceous and aluminous elements at a temperature of approximately 1000 °C to 1200 °C.

At the end of the calcination, the lime is hydrated, to extinguish the uncombined quicklime. Calcium silicates and aluminates give hydraulic lime the property of setting and even hardening under water. It is to this property that it owes its designation “hydraulic lime”. Like aerial lime (calcic or dolomitic), hydraulic lime also hardens in air by slow carbonation.

Table 4.III – Types of lime

Materials	**Calcination (900)°C**	**Slaking by hydration**	**After grinding and sieving, products marketed**
Siliceous and aluminous limestone	**QUICKLIME** + silicates and aluminates	**SLAKED LIME** + silicates and aluminates	**NATURAL HYDRAULIC LIME** (NHL)*
Low silica and alumina limestone	**QUICKLIME**	**SLAKED LIME**	**CALCIUM LIME** (CL)*
Low silica and alumina dolomite limestone			**DOLOMITIC LIME** (DL)*

* Designations from European standardization (ENV 459-1)

- NHL: Natural hydraulic lime
- CL: Calcium lime
- DL: Dolomitic lime

4.3.2. characteristics of hydraulic lime

- **Designation**

The designation includes the letters NHL followed by the resistance class (example: NHL 3.5). When an addition of pozzolanic or hydraulic materials is made within the limit of 20% as authorized by the standard, natural hydraulic lime is designated NHL-Z.

- **Resistance classes**

Natural hydraulic limes (NHL) are classified according to their resistance at 28 days expressed in N/mm^2 or MPa ($1\ N/mm^2 = 1$ MPa). There are 3 resistance classes designated by the minimum value: 2; 3.5 and 5. Each class corresponds to a range of variation between this minimum value and a maximum value, as indicated in table 5.III.

Table 5.III – Lime resistance classes

Classes	Compressive strengths, in MPa	
	7 days	28 days
2	**-**	**2 to 5**
3.5	**≥ 1.5**	**3.5 - 10**
5	**> 2**	**5 - 15**

If NHL5 has a bulk density less than 0.90 kg/dm^3, it is allowed to have a strength of up to 20 MPa.

the fineness of grinding: refusal to sieves: As an indication, these values correspond to a Blaine specific surface area of 8,000 cm^2/g to 10,000 cm^2/g.

- 90 µm (0.09 mm) < 7%
- of 200 µm (0.2 mm) < 2%

- **stability:** expansion must be less than or equal to 2 mm.
- **free water ≤ 2%** (NHL 2 and 3.5) and ≤ 1% (NHL 5).
- **CO$_2$ ≤ 20%** (NHL 2); ≤ 18% (NHL 3.5); ≤ 16% (NHL 5).
- **free lime** <15%.

In addition, the standard provides indicative ranges for apparent density in kg/l

- NHL 2: 0.4 to 0.8,
- NHL 3.5: 0.5 to 0.9
- NHL 5: 0.6 to 1.0.

4.3.3. Uses

Lime is used mainly as building materials in the preparation of mixed mortars, diluted in water, lime is used for the preparation of whitewash (milk of lime). It is used to neutralize acidic soils in agriculture. It is also used in the manufacture of paper (lime paste), glass, in leather tanning, sugar refining and as a softening agent in water. Lime water, an alkaline solution of slaked lime in water, is mainly used in medicine as an antacid to neutralize poisoning and in the treatment of burns.

Natural hydraulic lime mortars find their applications mainly in construction, where their qualities are appreciated for coatings, small masonry works, laying old tiles, pointing and consolidating walls, whitewashing and in a way general, for restoration work.

- **Coatings:** Natural hydraulic lime is a clear binder which, mixed with local sand, ensures perfect restitution of old coatings. Added with pigments, it also makes it possible to manufacture mortars with a wide range of vibrant colors. The many qualities of natural hydraulic lime, notably plasticity and adhesion, make its use very interesting and very effective in the manufacture of interior and exterior coatings where the resistance of the coating must be adapted to that of the soft supports.
- **Coatings for new buildings:** Recommendations for the composition of mortars based on natural hydraulic lime are detailed in standard P 15-201 “DTU 26.1. Building works. Coated with cement mortars, The use of natural hydraulic lime on old masonry helps limit the risks of cracking and various disorders. However, it is essential to carry out preliminary studies when considering the use of hydraulic lime mortars on plaster-based supports outdoors.

- **Coatings on old masonry:** Natural hydraulic lime is particularly suitable for the restoration of old buildings and historic monuments (churches, towers, castles). These structures were often built using natural hydraulic lime. The use of natural hydraulic lime on old masonry helps limit the risk of cracking and various disorders. However, it is essential to carry out preliminary studies when considering the use of hydraulic lime mortars on plaster-based supports outdoors.
- **Whitewashes:** Natural hydraulic lime are well suited for making whitewashes, which can be colored throughout. These limes are fine enough and rich in calcium hydroxide to remain in aqueous suspension and give a milk of lime that can be used with a brush or sprayer.
- **Laying and pointing mortars:** Thanks to its qualities of plasticity and adhesion to supports, natural hydraulic lime is well suited to the filling and pointing of blocks, bricks and stones. It can be used pure or mixed depending on the desired hardening speed.
- **Consolidation grout:** Some old masonry was mortared into the earth. Over the years it has disintegrated, settled or leaked through the damaged joints of the facing. They are consolidated by blindly injecting a grout of natural hydraulic lime in successive courses as the repointing of the facing progresses.

4.3.4. Other possible uses outside buildings

- **Soil stabilization:** Fine clay, loamy and sandy soils can be mixed with natural hydraulic lime (3 to 5% by weight). This aims to lower their water content, facilitate their compaction and greatly improve their mechanical resistance properties.
- **Treatment of urban waste sludge:** The addition of natural hydraulic lime allows not only sanitization, but also hardening of the treated material, promoting its shoveling.
- **Neutralization of acidic waters:** Natural hydraulic limes can be used as a pH-correcting agent for liquid effluents.

Photo 9.III – Use of lime in soil

5. CEMENT

5.1. Introduction

- **Definition:** Cement is a hydraulic binder, that is to say, which when mixed with water forms a paste which sets and hardens as a result of reactions and hydration processes, and which when hardened, retains its strength and its stability even underwater.

There are 4 methods of manufacturing cement which essentially depend on the material (hardness and humidity): Clinker manufacturing processes can be classified into four techniques

- The wet process: Very little used worldwide, even in Algeria, because it requires a lot of energy and water, and which consists of the preparation of a slip in large basins called diluters. This route is necessary when the raw materials extracted have a high humidity level.

- The semi-wet process: It consists of filtering the paste made in a similar way to the wet process, and preparing granules in the granulator which are then cooked on a grill.

- The semi-dry method: It consists of moistening the powder obtained after grinding and simultaneous drying to agglomerate it in the form of granules which are then cooked on a grill.

- The dry process: Today the most used process is the dry process, because it has several advantages compared to the wet process, notably saving energy and water. We can summarize the technological operations of clinker manufacturing:

5.2. Dry manufacturing process

- **Raw materials:**

- Limestone: natural rock of sedimentary origin composed essentially of calcium carbonate ($CaCO_3$) and impurities such as sand and clay. Pure limestones contain at least 95% calcite.
- Chalk: natural rock of sedimentary origin composed almost entirely of soft calcium (98%).
- Marl: natural rock of sedimentary origin composed of a mixture of limestone and clay. The limestone content in the marl is very variable, it varies on average between 30 and 70 (%).
- Clay: natural rock of sedimentary origin, hydrated alumina silicates, composed essentially of silica, alumina and water. Clay may contain impurities such as magnesia (MgO),

sulfur (S), soda (NaOH), potash (K_2O) in small quantities. We know three main families of clay that are most widespread on the earth's crust:

- Kaolin: $Al_2O_3 2SiO_2 2H_2O$
- Montmorillonite: $Al_2O_3 2SiO_2 2H_2O + n.H_2O$
- Illite: $Al_2O_3 2.SiO_2 4H_2O$

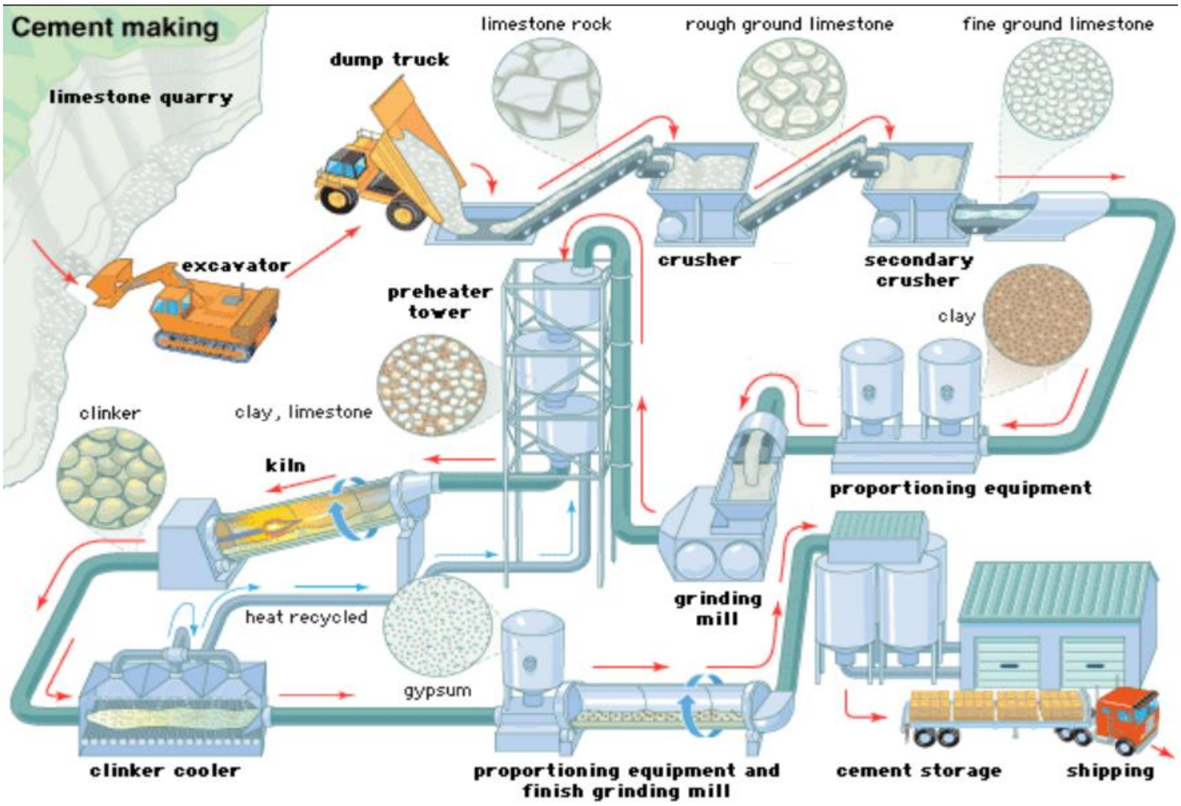


Figure 10.III – Cement manufacturing process

• Extraction and crushing

The extraction of raw materials takes place in open-air quarries. The quarries are located close to the factory in order to facilitate the transport of raw materials and reduce operating costs. Limestone is extracted by blasting using explosives. Stone blocks measuring 1 m maximum are crushed (primary and secondary crushing) at the quarry to reduce their dimensions to 50 or 100 mm and facilitate their transport to the factory. The extraction of clay is done by direct felling using a mechanical shovel or bucket excavator, because clay is a soft and friable rock and therefore easy to extract, unlike limestone which is harder.

The transport of raw materials is done by conveyor belt, by trucks or by wagons depending on the distance which separates the quarries from the factory.

- **Pre-homogenization of the raw mixture**

The raw materials are pre-dosed in defined proportions according to their chemical compositions in a ratio close to 80% limestone and 20% clay. The mixture is stored in a shed in long longitudinal cords.

This creates a pile of a few hundred tons. The raw material is analyzed at a regular frequency using samplers which take and send the material to be analyzed to the laboratory automatically, which allows the dosage to be corrected upstream of the shed. In practice, the storage and pre-homogenization shed for the raw mixture has two piles: the first is in operation and the second is in training.

Photo 11.III – Pre-homogenization of the raw mixture

- **Drying, grinding and storing the raw mixture**

The stored mixture is taken up using a shovel wheel perpendicular to the axis of formation of the pile, so as to vertically mix the various cords. This results in improvement in homogeneity. The raw material is dried and crushed simultaneously in a crusher – dryer. The flour has a fineness of around 100 to 200 µm, it is stored in two silos depending on the lime content or the strength of the mixture: the first silos is called “low-title” silos and the second is called “high title”. The raw material is taken to feed the oven from two silos, which allows the composition of the mixture to be corrected with great precision.

Raw flour is stored in homogenizing silos. The powder is homogenized by injecting compressed air from the porous silos. The mixing of the powder is continuous, we say that the powder is fluidized.

- **Cooking process**

The kiln consists of two parts: a fixed vertical kiln, preheater (heat exchanger cyclones) and a rotary kiln.

The cooking of the raw begins with its preheating in the heat exchanger comprising four to five cyclones in which the powder poured into the upper part progresses to the entrance to the kiln. The flour heats up on contact with countercurrent gases and is partially decarbonized. More complete decarbonation can be achieved by adding a precalciner located in the lower cyclone. The material enters upstream of the rotary kiln and progresses to the clinker formation zone at a temperature of around 1450 °C. The kiln is a cylinder made of sheet steel with an interior refractory lining, 60 to 90 m, diameter of 4 to 6 m, slightly inclined.

Under the effect of heat at a temperature ranging from 500°C to 800°C, clay decomposes into simple oxides (SiO_2 and Al_2O_3) and limestone decarbonates to form lime (CaO). At higher temperatures of 900 to 1450 °C the oxides of the clay combine with the lime to form the four main minerals of the clinker according to the following simplified diagram:

- **Departure of water from the clay**

$Al_2O_3\,2.SiO_2\,2.H_2O \xrightarrow{500°C} Al_2O_3\,2.SiO_2 + 2.H_2O$

- **Decomposition of clay into simple oxides**

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

- **Decarbonation of limestone**

$MgCO_3 \xrightarrow{700\ °C} MgO + CO_2$ $CaCO_3 \xrightarrow{900\ °C} CaO + CO_2$

- **Combination of simple oxides**

$CaO + Fe_2O_3 \xrightarrow{800\ °C} CaO.Fe_2O_3$ $CaO + Al_2O_3 \xrightarrow{800\ °C} CaO.Al_2O_3$

- **formation of aluminates and Ferro – calcium aluminates:** There are at least five calcium aluminates anhydrous [$CaO.6Al_2O_3$ **(CA_6)**] **,** [$3CaO.5Al_2O_3$ **(C_3A_5)**], [$CaO.Al_2O_3$ **(CA)**]**,** [$5CaO.3Al_2O_3$ **(C_5A_3)**], [$3CaO.5Al_2O_3$ **(C_3A_5)**], [$3CaO.Al_2O_3$ **(C_3A)**]. Monocalcium aluminate CA is easily obtained by direct combination, or by calcining a mixture of alumina and carbonate of lime; the reaction is already very sensitive at 950 °C although the aluminate only melts at 1600 °C. It is the main constituent of aluminous cements.

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

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

$2.CaO + CaO.Fe_2O_3 + CaO.Al_2O_3 \xrightarrow{1000\ °C}$ **$4.CaO.Al_2O_3Fe_2O_3$ [C_4AF]**

- **Formation of calcium silicates**

tricalcium silicate C_3S is obtained directly by prolonged and repeated heating of the constituents around 1450 °C. The dicalcium silicate is first formed which gradually fixes the third molecule of lime.

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

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

- **Cooling**

At the end of cooking, the material undergoes sudden cooling to prevent the transformation of $C_2S\beta$ into $C_2S\gamma$. The clinker is reduced using a hammer crusher and is in the form of granules with a diameter of 0 to 40 mm.

- **Cement grinding**

The different components are extracted from their storage location, to be measured and ground to a Blaine fineness of around 3000 to 3500 cm²/g.

The grinding operation may appear to be secondary, but is in fact very important because it will give the cement a characteristic as essential as its composition, namely its fineness. However, we know that fineness plays an important role through the influence it exerts on the main physical, chemical and mechanical properties:

- Classically, the finer the grains, the greater their hydraulic activity.
- When the grains are finer, their hydration rate is greater, which explains the fact that cements of higher strength classes are ground more finely.

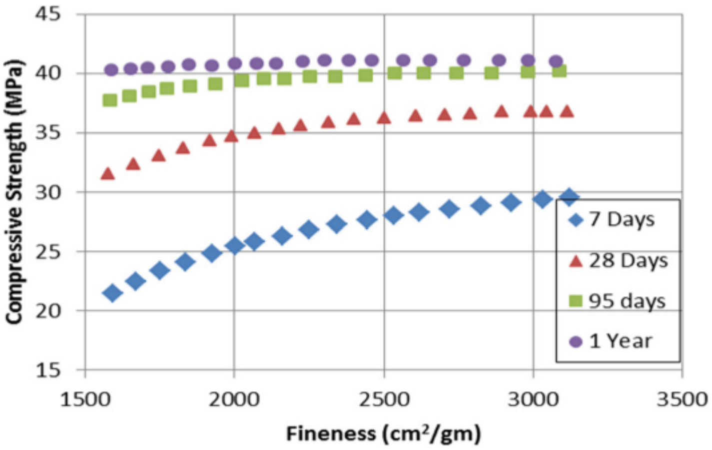


Figure 12.III – Influence of grinding fineness on cement strength

- **Storage and shipping cement**

The cement obtained is stored in silos and put in 50 kg bags or shipped in bulk in tanks on wagons or trucks.

5.3. Main, secondary constituents and additions of cement

Portland cement is composed of ground clinker to which a quantity of gypsum is added, intended to regulate the setting. To modify the properties of the cement, other constituents associated with the clinker are added thanks to their chemical or physical characteristics.

5.3.1. The main constituents

- **Clinker (K):**

Portland clinker is a hydraulic material which must consist of at least 2/3 by mass of calcium silicates ($3CaO.SiO_2$) and ($2CaO.SiO_2$), the remaining part containing aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3) and other oxides. The ratio (CaO/SiO_2) must not be less than 2.0. The magnesium oxide content must not exceed 5.0 % by mass.

The clinker is essentially composed of calcium oxide, predominant, silica, alumina, and iron oxide, with accessory elements magnesia, alkalis, etc., and impurities of the raw materials in trace form. The chemical and mineralogical compositions of cement are given in tables 4.III and 5.III

Table 4.III – Chemical composition of clinker

Oxide	**Lime**	**Silica**	**Alumina**	**Iron**	**Magnesia**	**Potash**	**Soda**	**Oxide sulfur**
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	0.0 – 2.0		≤ 3.50

Table 5.III – Mineralogical composition of clinker

Minerals	Chemical formula	Simplified designation	Content in %
Tricalcium silicate	$3CaO.SiO_2$	(C_3S)	50-70
Dicalcium silicate	$2CaO.SiO_2$	(C_2S)	10-30
Tricalcium aluminate	$3CaO.AlO_3$	(C_3A)	2-15
Tetracalcium aluminoferrite	$4CaOAl_2O_3.Fe_2O_3$	(C_4AF)	5-15

- **Granulated blast furnace slag (S)**

Granulated blast furnace slag is obtained by rapid cooling of molten slag of suitable composition from the smelting of iron ore in a blast furnace.

Granulated blast furnace slag is a latent hydraulic material, that is to say which has hydraulic properties when it has undergone suitable activation.

If the proportion of granulated blast furnace slag in the cement exceeds 5.0% by mass (main constituents), only slags meeting the following specifications must be used. Granulated blast furnace slag must contain at least 2/3 by mass of vitreous slag. Granulated blast furnace slag must consist of at least 2/3 by mass of the sum of CaO, MgO and SiO_2. The remainder contains Al_2O_3 with additionally small quantities of other oxides. The mass ratio (CaO + MgO) / (SiO_2) must be greater than 1.0

- **Natural pozzolans (Z)**

Natural pozzolans are:

- substances of volcanic origin or sedimentary rocks having an appropriate chemical and mineralogical composition;
- thermally activated clays and shales

Natural pozzolans do not harden by themselves when mixed with water, but - they react at usual room temperature, in the presence of water, with dissolved calcium hydroxide [$Ca(OH)_2$] to form calcium silicate and calcium aluminate compounds developing mechanical strength. These compounds are similar to those formed during the hardening of hydraulic materials.

If the proportion of natural pozzolans in the cement exceeds 5% by mass (main constituent), only pozzolans meeting the following specifications must be used: The pozzolans must be composed essentially of SiO_2 reactive and Al_2O_3. The remaining part contains iron oxide (Fe_2O_3) and other oxides. The proportion of reactive CaO is negligible. The content of SiO_2 reagent must be at least 25% by mass.

- **Fly ash (V and W)**

If the proportion of fly ash in the cement exceeds 5% by mass (main constituent), only fly ash meeting the following specifications must be used: Fly ash may be silico-aluminous or silico-limestone in nature. The first have pozzolanic properties; the latter can also have hydraulic properties. The loss on ignition of dry ashes must, in all cases, be less than or equal to 7% by mass. In addition, within this limit, for a given factory, a delivery of ash must not present a loss on ignition deviating from more than 2% in absolute terms of the average fire loss calculated over all annual deliveries.

Fly ash is obtained by electrostatic or mechanical dusting of powdery particles coming from the boiler gas stream, fueled with pulverized coal. Ashes obtained by other methods should not be used in cements conforming to the new standard.

- **Siliceous fly ash (V)**

Siliceous fly ash is a fine powder consisting mainly of vitrified spherical particles with pozzolanic properties. It must contain essentially reactive silica (SiO_2) and alumina ($Al_2O_{3.}$). The remaining part contains iron oxide (Fe_2O_3) and other oxides. The proportion of reactive CaO lime must be less than 5% by mass. The content of SiO_2 reagent must be at least 25% by mass.

- **Calcium fly ash (W)**

Calcium fly ash is a fine powder with hydraulic and/or pozzolanic properties. It must essentially contain reactive lime (CaO), reactive silica (SiO_2) and alumina (Al_2O_3). The remaining part contains iron oxide (Fe_2O_3) and other oxides. The proportion of reactive CaO lime must be less than 5% by mass. Fly ash containing between 5 and 15% must contain more than 25% by mass of reactive silica SiO_2.

- **Calcined shales (T)**

The calcined shales are produced in a special furnace at a temperature of around 800°C. Finely ground, they exhibit strong hydraulic properties like portland cement and also pozzolanic. Due to the composition of the natural material, as well as the manufacturing process, calcined shales contain clinker phases, mainly dicalcium silicate and monocalcium aluminate, and small quantities of free lime CaO and calcium sulfate $CaSO_4$, as well as larger quantities of oxides reacting pozzolanically, particularly SiO_2.

- **Limestone (L)**

These are products obtained by fine grinding of natural limestone rocks. When used in a proportion exceeding 5% by mass (main constituent), limestone must meet the following specifications:

- limestone content [calcium carbonate ($CaCO_3$) ≥ 75% by mass
- clay content ≤ 1.20% by mass
- Organic matter content ≤ 0.50%

- **Silica fume (D)**

Silica fumes are made up of very fine spherical particles (around 1 µm) with a very high content of amorphous silica (SiO_2). They come from the reduction of high purity quartz with coal in electric arc furnaces used for the production of silicon and ferrosilicon alloys. Silica fumes have pozzolanic properties.

Only silica fumes meeting the following specifications must be used:

- amorphous silica content ≥85%
- losses on fire ≤ 4% by mass
- fineness 15 m 2 /g

5.3.2. Secondary constituents

Secondary constituents are natural mineral materials or mineral materials derived from the clinker manufacturing process or constituents described in the paragraphs above or fillers (F), unless they are already included as primary constituents of cement. They cannot exceed 5% by mass. The “secondary constituents” act through their particle size on the physical properties of the binders (handleability, water retention power).

- **Fillers (F)**

Are natural or artificial mineral materials, which, after appropriate preparation depending on their particle size, improve the physical properties (workability and water retention power). They can be inert or have weakly hydraulic, latent hydraulic or pozzolanic properties.

- **Calcium sulfate**

Calcium sulfate acts doubly on the cement, on the one hand it slows down the hydration of the tricalcium aluminate and accelerates that of the tricalcium silicate.

Calcium sulfate in the form of gypsum or natural anhydrite ($CaSO_4\ 2H_2O$, $CaSO_4$) must be added in small quantities to the other constituents of cement during its manufacture, in order to regulate the setting of the cement (the SO_3 content ≤ 3.5%).

5.3.3. Additives

Additives are constituents not listed above that are added to improve the manufacturing or properties of cement. The total quantity of additives must not exceed 0.5% by mass, in all cements, with the exception of CEM III /C in which chlorinated salts may be added up to 1% by mass of cement. These additives have no significant harmful effect on cements and concrete reinforcements.

5.4. Different types of cements

Common compliant cements are subdivided into five main types: The composition of the common cements mentioned must comply with Table 6.III

Table 6.III – Main types of cement

Types of cements	**Designation**	**Clinker (%)**	**One of the following constituents (slag, pozzolans, ashes, limestone, shale, silica fume,**	**secondary constituents (%)**
Portland cement	CEM I	95 - 100		0 to 5
Compound portland cement	CEM II-A	80 – 94	• 6 – 20 of one of the constituents, except silica fumes whose content is limited to 10% and fillers to 5%.	
	CEM II-B	65 – 79	• 21 to 35, with the same limits as above	
Blast Furnace Cement	CEM III A	35 – 64	• 36 – 65% slag	
	CEM III B	20 – 34	• 66 – 80% slag	
	CEM III-C	5 – 19	• 81 – 95% slag	
Pozzolanic cement	CEM IV-A	65 – 90	• 10 – 35% pozzolans, siliceous ashes, silica fumes are limited to 10%	
	CEM IV-B	45 – 64	• 36 – 55% pozzolans, siliceous ashes, silica fumes are limited to 10%	
Slag and ash cement	CEM V-A	40 – 64	• 18 – 30% slag and 18 – 30% siliceous ash or pozzolans	
	CEM V-B	20 - 39	• 31 - 50 of slag and siliceous ash or pozzolans	

5.5. Other types of cement

- **Lime slag cement NF P 15-306**

This cement is the mixture of two constituents (100 – N) of hydraulic lime and N parts of granulated blast furnace slag. N being 70 (possibly with fillers or fly ash within the % limit).

- **Masonry cement NF P 15-307**

This cement contains in lower proportions the same active elements as portland cement. Hydraulic binder manufactured in a factory and whose development of resistance is essentially due to the presence of Portland clinker. There are three resistance classes (5, 12.5 and 2.5) depending on the minimum resistance at 28 days. The start time of setting must not be less than 60 min. The SO_3 content is limited to 3.5% for classes 12.5 and 22.5 and to 2.0% for class 5.

- **Natural cement NF P 15 – 308**

This cement results from the grinding of clinkerized rocks, obtained by cooking marly limestone of very regular composition and close to that of a mixture of clay and limestone used in the manufacture of portland cement.

- **Prompt cement NF P 15-314**

Natural prompt cement with rapid setting and hardening results from the cooking at moderate temperature of a clayey limestone of regular composition, extracted from homogeneous benches, followed by very fine grinding.

- **Fused aluminous cement NF P 15-315**

Molten aluminous cement is a hydraulic binder which results from the grinding to a fineness comparable to that of portland cements, after cooking until fusion, of a mixture composed mainly of limestone and bauxite, in proportions such that the cement obtained contains at least 30% of its mass of alumina.

It is a slow-setting and fast-hardening cement which allows high strengths to be obtained at a young age. Its hydration reaction is strongly exothermic.

Aluminous cement has the particularity of being able to be mixed with clinker-based cements, but in this case, setting takes place much more quickly; the final resistance will be all the lower the more the setting has been accelerated.

- **Cements for work at sea NF P 15 - 317**

These cements, also called “sea setting” cements, have limited contents of tricalcium aluminate (C_3A) which allow them to give the concrete increased resistance to attack by sulfate ions in the presence of chloride ions, during and after setting.

These cements are:

- CEM I, CEM II, CEM III and CEM V, defined in Table 6 which have complementary physical and chemical characteristics.
- Natural prompt cements and fused aluminous cements having presented good behavior in the environment considered.

- **White cements**

The white color is obtained using very pure raw materials (limestone and kaolin) free of all traces of iron oxide. The characteristics are similar to those of gray Portland cements. There are two resistance classes of white cements CEM I white 42.5 and 52.5.

5.6. The characteristics of portland cement

5.6.1. Apparent and absolute density

- **Apparent volumetric mass**

The apparent density of cement is the ratio between its mass and its apparent volume. For a given cement, this ratio is a constant which is specific to the physical characteristics of the cement, of the order of 900 to 1000 kg/m^3).

$$\rho_{app} = \frac{m}{V} \qquad \left[\frac{gr}{cm^3}, \frac{kg}{m^3}, \frac{T}{m^3}\right]$$

Determining the apparent density of a cement therefore requires weighing the mass of a sample filling (using a funnel) a known apparent volume of 1 liter.

Photo 12.III – Le Chatelier hydrometer

- **Absolute density**

The absolute density of cement is the ratio between its mass and its absolute volume. For a given cement, this ratio is a constant which is specific to the physical characteristics of the cement which is of the order of 2900 to 3100 kg/m^3).

$$\rho_{abs} = \frac{m}{V} \qquad \left[\frac{gr}{cm^3}, \quad sans\ unité \right]$$

Photo 13.III – Determination of the apparent density of cement

The absolute density of cement can be determined using a densimeter: the test consists of determining the volume V of a mass m of cement powder by introducing it into a densimeter filled with a volume V_1 of liquid non-reactive with cement. The difference of the volumes V_2 (total volume after introduction of the sample) and V_1 (volume before introduction of the sample) gives us the volume of the cement sample and it becomes easy to calculate the absolute density of the cement.

5.6.2. Normal consistency

The Consistency of the cement characterizes the quantity of water necessary to mix with the powder to obtain a plastic paste of so-called normal consistency. To assess this fluidity, we use the Vicat device and probe. The distance (d) characterizes the suitability of the consistency of the dough studied.

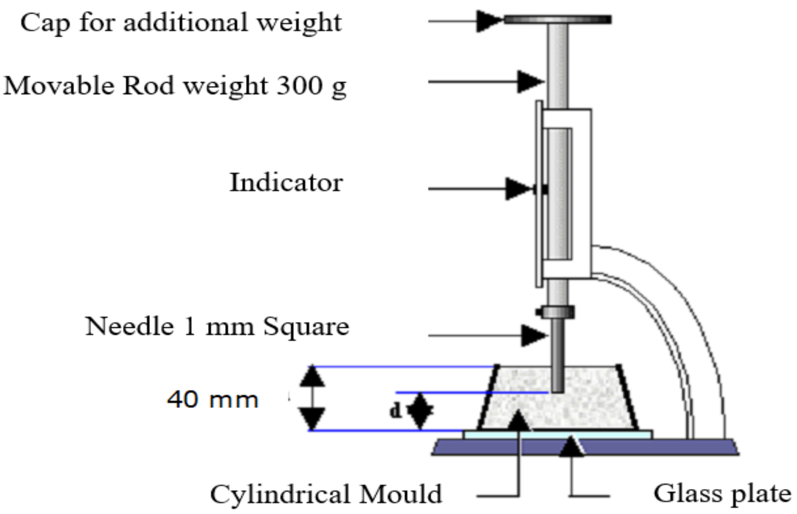


Figure 13.III – Vicat apparatus

- If d = 6mm ± 1mm, we say that the dough is of normal consistency.

- If d does not reach this value (d > 7 mm or d < 5mm), the test should be repeated with a different value of the W/C ratio until the desired consistency value is reached.

The quantity of water required to obtain a paste of normal consistency for all types of cement varies from 24 to 30% relative to the mass of the cement

5.6.3. Setting Time

Setting time is usually measured on a pure cement paste of normal consistency (24 to 30% water) using the Vicat apparatus. It is possible to obtain (non-standard) the setting time of a mortar with the same equipment but by placing an excess of 700 grams on the upper plate. The weight of the needle penetrating the mortar is 1000 grams.

- The start of setting is the moment when the needle stops at a distance d = 4 ± 1 mm from the bottom

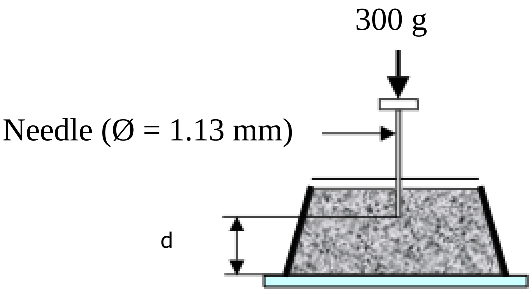


Figure 14.III – measurement of the depth of insertion of the needle (start of setting)

- the end of setting is the instant when the needle stops at a distance d = 39.5 mm.

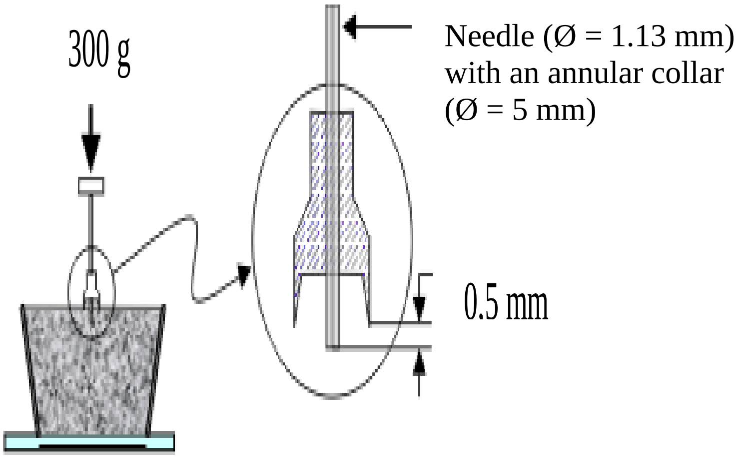


Figure 15.III – measurement of the depth of insertion of the needle (end of setting)

Depending on their resistance class, the standards specify a minimum setting time which is, at a temperature of 20ºC, of:

- 1 hour 30 minutes for class 35 and 45 cements.
- 1 hour for class 55 cement.

It should be noted that practically all cements have setting times well beyond these minimum values, the order of magnitude being 2.5 to 3 hours for the majority of cements.

Setting phenomenon is linked to numerous parameters such as:

- the nature of the cement,
- the fineness of the cement grind; the finer the cement, the faster the setting,
- temperature; while at zero degrees the setting is stopped, the higher the ambient temperature the faster the setting, for a given cement the start of setting will be 18 hours at 3ºC, 4 hours at 10ºC, 2h30 min at 20 ºC and 30 min at 35 ºC (figure 3.15),
- excess mixing water which has, among other disadvantages, a retarding action on setting (Figure 3.16)

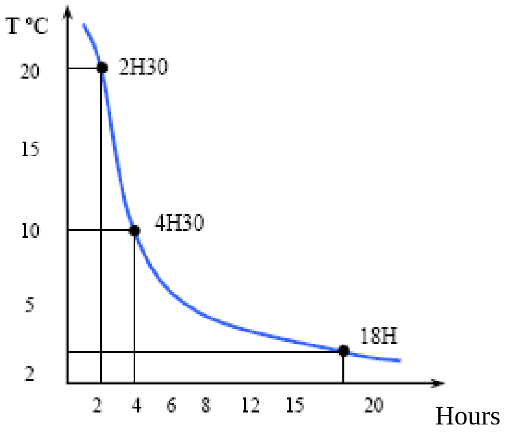


Figure 16.III – Evolution of setting time depending on temperature

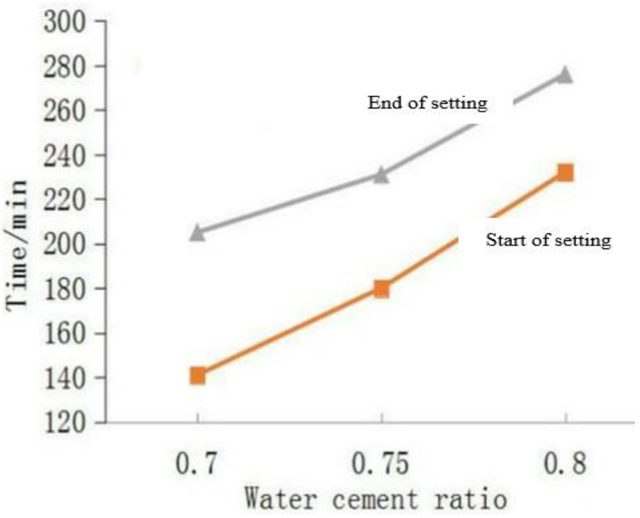


Figure 17.III – Influence of the W/C ratio on the setting time

5.6.4. Grinding fineness (Blaine fineness)

It is characterized by the specific surface area of the cement grains, expressed in (cm^2/g). In common cases, it is of the order of 3000 to 3500 cm^2/g.

The greater the grinding fineness, the higher the speed of hydration reactions and the greater these mechanical resistances at a young age.

The mass surface area of cement is not measured directly, it involves passing a known volume of air through cement powder. All things being equal, the greater the specific surface area of this powder, the longer the time t it takes for the air to pass through the powder. Under the standard conditions described, the device used to determine the fineness of cement grinding is called a "blaine air permeability". This device is schematically shown in Figure 3.17. It essentially consists of a cell in which the cement to be tested is placed and a pressure gauge made up of a U-shaped glass tube filled, up to its lower mark (N°4) with a light oil. The cell is equipped with a grid in its lower part. A piston is used to compact the cement in the cell under a defined volume V.

$$S = K \,.\sqrt{t}\,.\,\frac{1}{\rho}\,.\,\frac{\sqrt{P^3}}{1-P}\,.\,\frac{1}{\sqrt{0{,}1\eta}}$$

K- device constant
P- porosity of the cement layer (taken equal to 0.5)
t- air flow time between two marks (2 – 3)
ρ- absolute density of cement (g/cm^3)
η- air viscosity at the test temperature

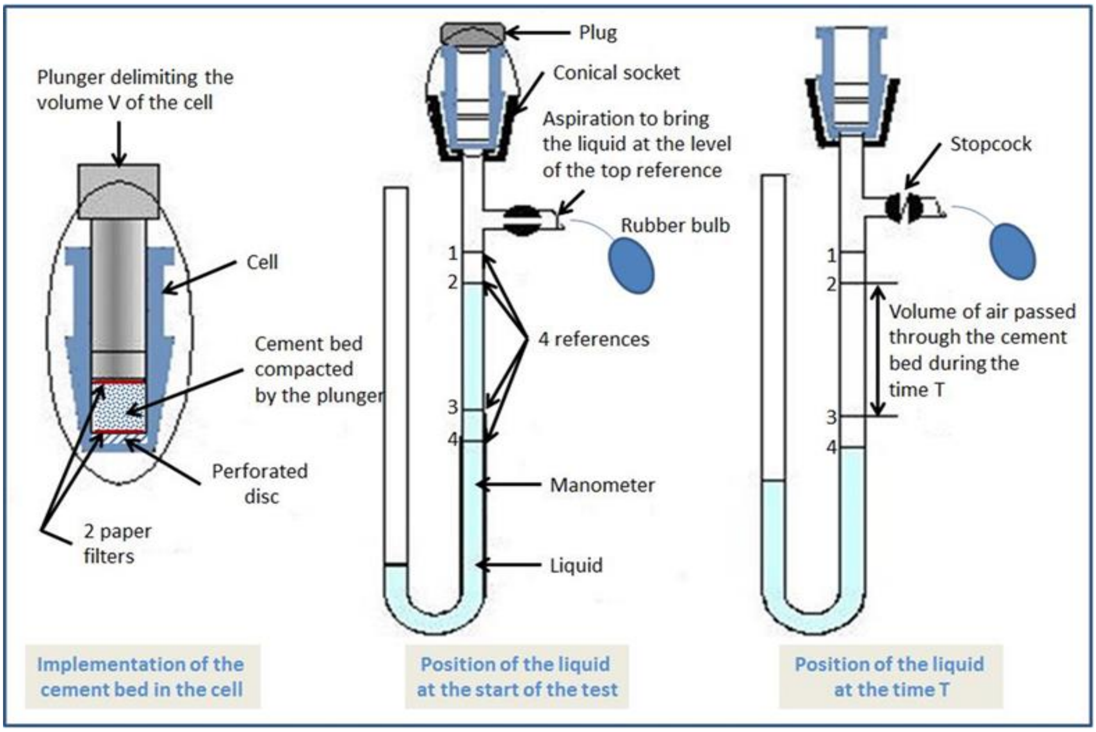


Figure 18.III – fineness test of cement by blaine's air permeability method.

5.6.5. Shrinkage

The cement paste shrinks in dry air, while on the contrary it swells in water, this phenomenon continuing over time and for periods that are all the longer as the pieces are massive. Shrinkage is one of the main causes of cracks observed in concrete parts.

The shrinkage test is carried out on prismatic test pieces (4x4x16) fitted with gauge studs, made from normal mortar and stored under normal conditions (t = 20°C ± 2°C and RH = 50% ± 5%). Shrinkage is measured using length comparator apparatus given in Photo 3.9.

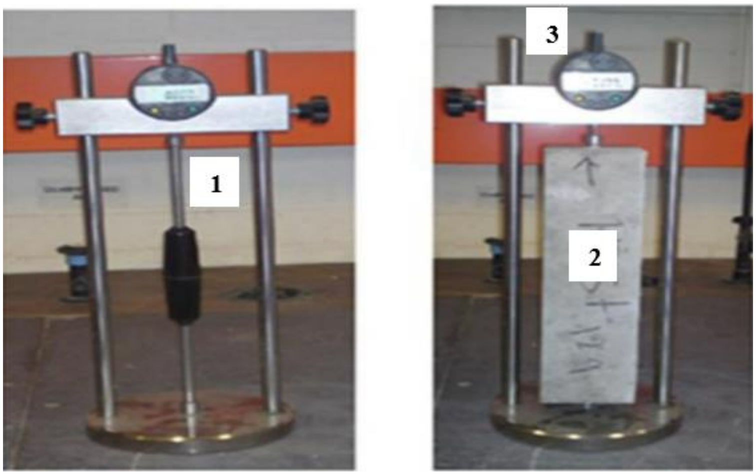


Photo 14.III – Measuring shrinkage with length comparator apparatus

- The importance of hydraulic shrinkage, apart from the time factor, depends on numerous parameters including:
- the water/cement ratio (W/C) (figure 3.18)

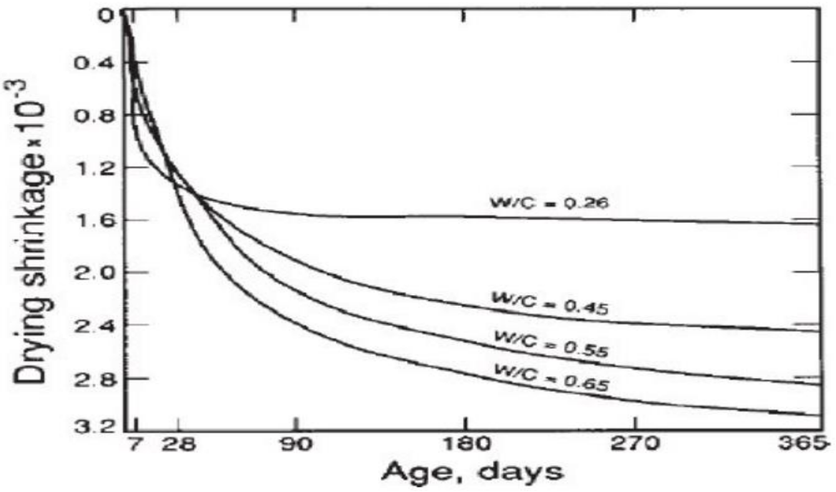


Figure 19.III – Influence of W/C on mortar shrinkage.

- the nature of the cement
- the cleanliness of the sand
- the shape and size of the aggregates

5.6.6. Volume stability

For all types of cement and all strength classes, expansion is expressed by Soundness test. The test is carried out on pure dough using the Le Chatelier apparatus given photo 3.10 and figure 3.19.

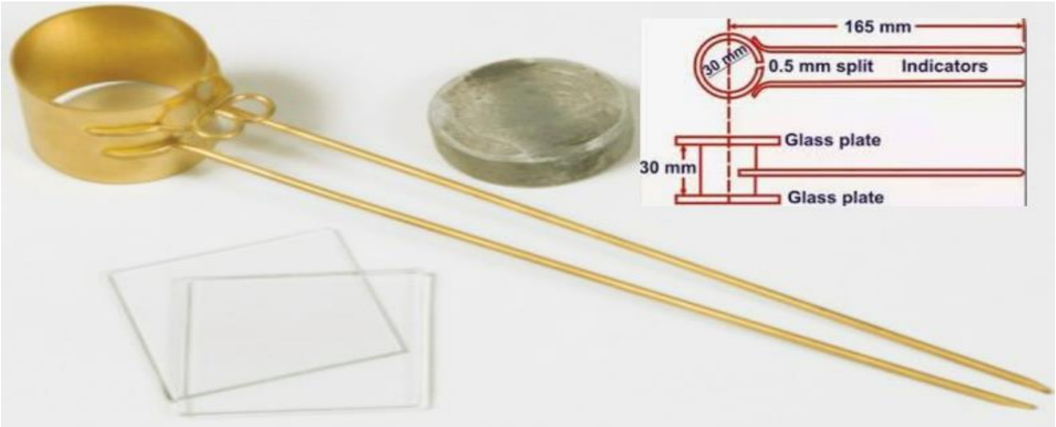


Photo 15.III – Le Chatelier apparatus

This involves checking the increase in cement volume that could cause expansive oxides such as calcium and magnesium oxide.

The hydration reaction is accelerated by heat treatment of the paste, so that any expansion of the cement can be observed in a very short time.

The test includes the following steps:

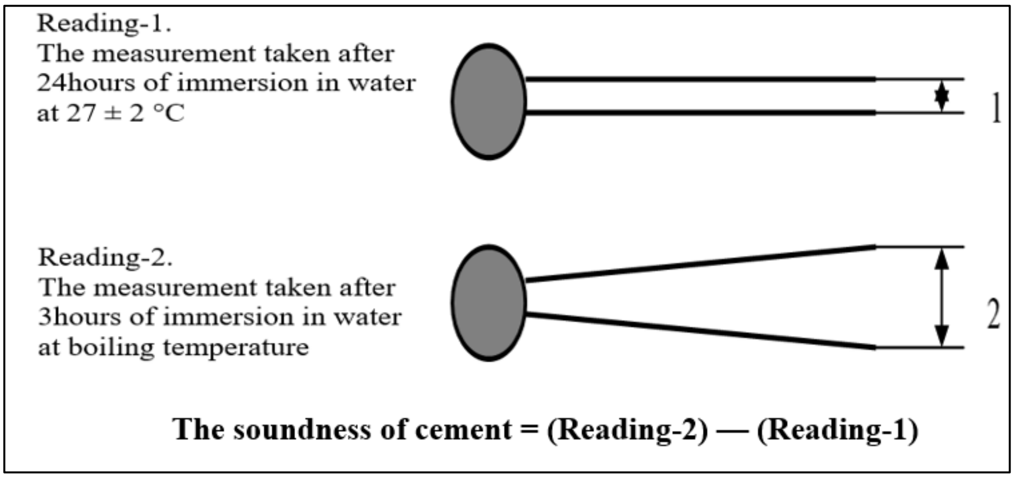
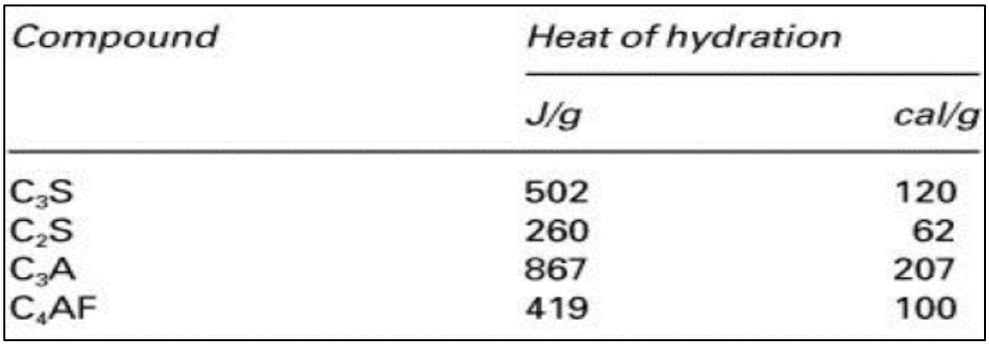


Figure 20.III – Procedure for soundness test of cement

5.6.7. Hydration heat

The phenomenon of cement setting is accompanied by an exothermic reaction whose importance depends on different parameters, in particular:

Table 7.III – Thermal characteristics of clinker minerals



Compound	*Heat of hydration*	
	J/g	*cal/g*
C_3S	502	120
C_2S	260	62
C_3A	867	207
C_4AF	419	100

- the fineness of grinding: the finer the cement is ground, the higher the heat of hydration
- the nature of the constituents: CEM I cement comprising almost exclusively clinker release more heat than cements with secondary constituents

- the mineralogical nature of the clinker: the higher the contents of tricalcium aluminate (C_3A) and tricalcium silicate (C_3S), the greater the heat of hydration
- the outside temperature.

5.7. Mechanical characteristics

The mechanical resistance of the cements is determined by tests on so-called "normal" mortar, at 28 days of age in traction and compression on (4 x 4 x 16) cm^3 test pieces. The strength of the mortar is then considered to be significant of the strength of the cement. It depends on the class of cement and is expressed in MPa.

The mortar used is made in accordance with standard EN 196-1. The sand used is a sand called “normal sand EN 196-1”.

For each type of cement, there are actually several resistance classes for which manufacturers guarantee minimum and maximum values.

The graphs below (figures 3.20 and 3.21) show the development of resistance over time for cements and their pure constituents.

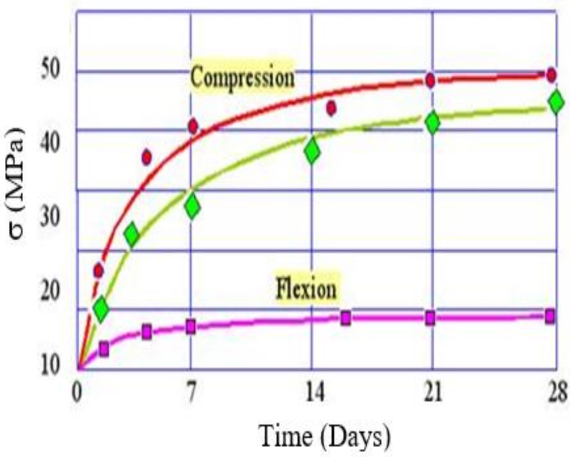


Figure 21.III – Strength of normal mortar

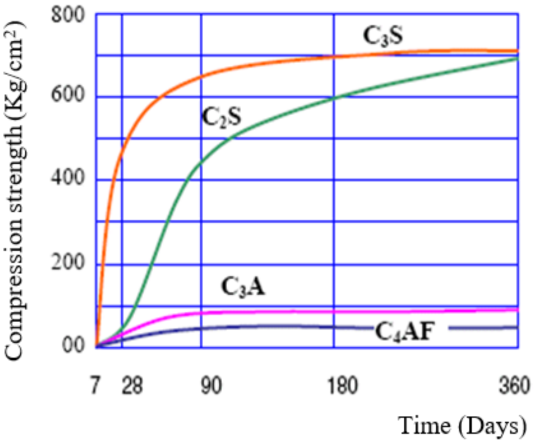


Figure 22.III – Mechanical resistance of clinker constituents

• Normal resistance

It defines the strength class and true strength of a cement. Normal resistance is the mechanical resistance to compression determined on normal mortar after 28 days of storage of the specimens under normal conditions.

- Normal mortar: is a mortar composed of cement, normal sand and water in the following proportions:

- Cement: one part by weight
- Sand: three parts by weight
- Water: half part by weight

Normal sand is sand of medium size which is characterized by a grain size curve which must be located within a spindle.

The molds allowing the production of three prismatic test pieces, with a square section of 4x4 (cm²) and length 16 (cm). These test pieces are called “4x4x16 test pieces”.

Normal storage conditions are characterized by a temperature of 20 ± 1 °C and a relative humidity greater than 90%.

Table 8.III – Classification of cements according to their normal strength

Class	**Compressive strength in MPa**				**shrinkage in 28 days (µm/m)**	**Start setting time (min)**	**Sound ness (mm)**
	2 days	**7 days**	**28 days**				
			mini	**max**			
32.5N		≥16 **14**	≥32.5 **30**	≤52.5	≤ 800	≥75 (90) 60 (90)	≤ 10
32.5R	≥ 10 (13.5) **8** (12)		≥32.5 30	≤52.5	≤ 1000	≥75 (90) 60 (90)	≤ 10
42.5N	≥ 10 (12.5) **10**		≥42.5 **40**	≤52.5	≤ 1000	≥60 50 (60)	≤ 10
42.5R	≥20 **18**		≥42.5 **40**	≤52.5	≤ 1000	≥60 50 (60)	≤ 10
52.5N	≥20 **18**		≥52.5 **50**	≤52.5		≥45 (60) 40 (60)	≤ 10
52.5R	≥30 **28**		≥52.5 **50**	≤62.5		≥45 (60) 40 (60)	≤ 10

*Values in bold are guaranteed values when less than specified values
* Values in parentheses are those indicated

- **Resistance class**

Three classes are defined according to normal resistance at 28 days. They are called “class 32.5”, “class 42.5” and “class 52.5”. Each of them is divided into two subclasses “N” and “R”. The “R” subclass designates cements with high early strengths. They must comply with the specifications and guaranteed values in table 8.III

- **Resistance at young age**

The early age strength of a cement is the mechanical resistance to compression at 2 or 7 days. For each normal strength class, two strength classes are defined, a regular early age strength class and a high early age strength class, indicated by the letter “R” in table 8.III

5.8. Chemical specifications

Chemical specifications are summarized and presented in table 9.III

Table 9.III – Chemical specifications of cements

Properties	Type of cement	Resistance class	Requirement
Fire loss	CEM I CEM III CEM III	All classes	≤ 5%
MgO	CEM I		
Insoluble residue	CEM I CEM III CEM III		
Sulfates (SO_3) Upper limit	CEM I CEM III CEM III CEM V	32.5 - 32.5 R - 42.5	≤ 3.5%
		42.5 R - 52.5 - 52.5	≤ 4%
	CEM III	All classes	
Chlorides	All types	All classes except 32.5	≤ 0.10%
		52.5R	≤ 0.05%
Pozzolanicity	CEM IV	All classes	Satisfied with the test

5.9. Uses of cements

- **Portland cements [CEM I]**

Ordinary CEM I are suitable for work of all kinds, in reinforced concrete or prestressed concrete. On the other hand, their characteristics do not generally justify their use for routine masonry work and large mass or weakly reinforced concrete which does not require great strength. CEM I (R) are suitable for the same work, but allow rapid stripping, which is particularly useful in prefabrication. CEM I 52.5 or 52.5 R are suitable for reinforced or prestressed concrete work where exceptional strength is required.

- **Compound Portland cements [CEM II/ A and B]**

These are the most used. The CEM II 32.5 are well suited for masonry work and lightly stressed concrete. The CEM II 32.5 and 42.5 are suitable for all types of work in reinforced concrete or prestressed concrete. Generally speaking, CEM IIs are well suited for massive works requiring a moderate temperature rise, roads and manufactured concrete. Class R will be preferred for work requiring high initial strengths (prefabrication, rapid stripping).

- **Blast furnace cements [CEM III/A, B and C]**

These cements are well suited to hydraulic, underground, foundation and injection works; work in aggressive waters: sea water, selenite water, industrial water, pure water; massive structures: piles of engineering structures, retaining walls, dams.

- **Pozzolan cement – CEM IV A / B**

These cements are intended for use in tropical areas for works that do not require high mechanical strength.

- **Ash slag cement - CEM VA / B**

They can be used in mass concreting work, foundation work, concrete in contact with aggressive environments (pure water, sea water, water with a high sulfate content) and soil injection work.

- **Prompt cement NF P 15-314**

Natural prompt cement is resistant to aggressive waters (selenite waters, pure waters, acidic waters). It is standardized for work at sea.

Natural prompt cement can be used in pure paste form exceptionally for blinding waterways, in emergency cases requiring immediate setting and filling of cracks; mortar more frequently in a cement/sand ratio of 1/1 or 1/2 for making seals, repairing or repairing edges, joining pipes, sealing porous walls (basins, cellars, etc.), filling cracks , installation of thin partitions, facade coatings (mixed with natural lime); or concrete, dry spraying, castings; coverings and coatings resistant to aggressive water and a large number of chemical attacks, in particular lactic acid and excrement (livestock buildings, silos); sealing and work at sea, underground work, filling of cracks and Some precautions should be taken when using natural quick cement: do not re-mix a mortar or smooth a coating so as not to “break” the setting; especially avoid excess water.

- **Fused aluminous cement NF P 15-315**

It is very resistant to aggressive and acidic environments (up to pH of around 4). It is standardized for work at sea and in waters with a high sulfate content. A high heat of hydration, linked to its rapid hardening, allows the molten cement to be used in cold weather (up to –10°C). It is also a refractory cement (good behavior up to 1,300°C). Molten aluminous cement is particularly suitable for the following areas: work requiring high mechanical resistance to be obtained in a very short time (beams and lintels for buildings, industrial floors); floors resistant to shocks, corrosion and heavy traffic; works in agricultural environments, pipes, sanitation; ovens, chimneys (refractory concrete); repair work; sealing (mixed with Portland cement for the preparation of adjustable setting mortars). In very cold weather, the concrete must be protected until the hardening phase begins.

In all cases, the mortar or molten cement concrete must be kept moist (curing product or protection) throughout its hardening period, to prevent it from drying out. The minimum dosage of molten cement is generally 400 kg/m ^{3} of concrete, the water/cement ratio must not exceed 0.4.

- **Lime slag cement NF P 15-306**

CLX is used for small maintenance and repair work in masonry not requiring high compressive strengths (maximum 10 MPa at 28 days)

- **Masonry cement NF P 15-307**

These cements, whose strengths are deliberately limited compared to conventional cements, are well suited for making mortars used in building work (assembly of brick masonry, coatings, rendering, etc.). They can also be used for the manufacture or reconstitution of artificial stones. These cements are not suitable for high stress concretes or reinforced concretes. They should not be used in aggressive environments.

- **CEM I White cement**

Because to its whiteness, white cement allows the colors of the aggregates to be highlighted in exposed concrete. The paste can itself be colored using mineral pigments, which provides concretes with a wide variety of shades. White cements are mainly used for making reinforced or unreinforced architectural concrete, decorative coatings, prefabricated elements, jointing of stones or tiles. The composition of the concrete must be carefully studied depending on the aggregates and the desired effects.

CHAPTER IV

MORTARS

CHAPTER IV - MORTARS

1. INTRODUCTION

- **The mortar**

Is a mixture of binder, sand, water and possibly additions and adjuvants. Multiple mortar compositions can be obtained by adjusting the different parameters: binder (type and dosage), adjuvants and additions, water dosage.

- **Normal mortar**

Is a mixture of hydraulic cement, sand and water in proportions defined by standards. It is used to define the resistance of cements

The sand used is a standardized sand, of average particle size composition and whose grain size curve is located inside the zone indicated in figure.1

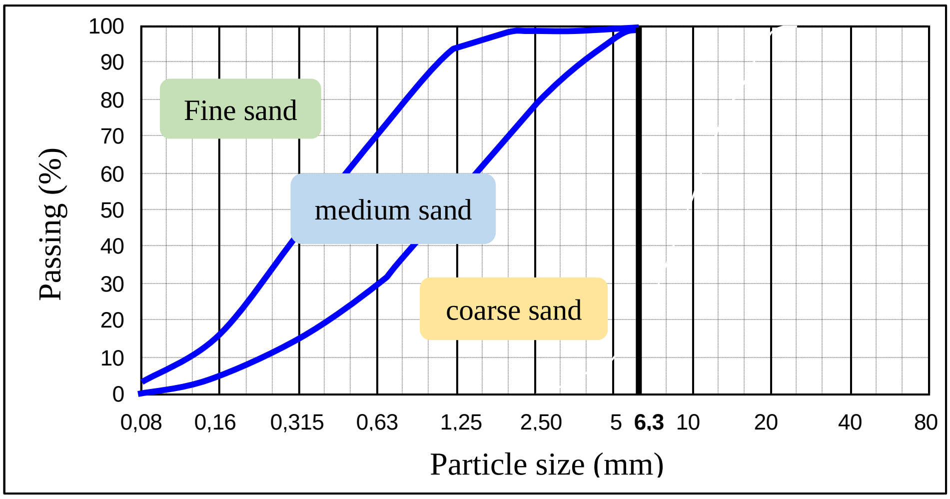


Figure 1.IV – Particle size distribution of sand

2. THE CONSTITUENTS

Mortars are made up of mixtures of binders, sand, water, additives and active or inert mineral additions.

2.2. Binders

Generally, we can use: cements and limes, their choice and dosage depend on the work to be carried out and its environment.

2.3. The sands

- **Rolled sands:** These are rolled sands of siliceous or silico-calcareous nature coming from rivers, dunes and sea
- **Crushed sand**

These are crushed sands made in quarries, such as basalts, porphyries, quartzites. They are angular and hard.

- **Special sands** (heavy, refractory, light)

These are sands resulting from the recycling of certain materials (crushed brick sand), industrial co-products (granulated slag) or manufactured industrially (expanded clay sand, expanded polystyrene sand). Vermiculite and perlite.

- **Vermiculite:**

Is a natural rock, a micaceous mineral consisting of 40% silica linked to oxides of magnesium 24%, iron 7% and hydrated 11% water. It also contains 12% alumina and bases in small proportions of potash soda and 5% lime. Vermiculite comes in the form of grains of 0 to 30 mm, with a density of 500 to 50 Kg/m$^{3.}$ Vermiculite can be transformed into expanded aggregates after heat treatment at 900 °C.

- **Perlite:**

Natural rock of volcanic origin (volcanic glass from lava), light, with a density of 100 to 300 Kg/m^3, with a fine particle size of 0 to 2 mm. Hydrophobic, refractory material but its compressive strength is low (< 1 MPa)

2.3.1. Granulometry

The maximum diameter of sand grains used for mortars is:

- extra-fine: up to 0.8 mm
- fine: up to 1.6 mm
- medium: up to 3.15 mm;
- coarse: up to 5 mm.

2.3. The additives:

Admixtures are chemical products that are used to modify certain properties of concrete and mortars that are added to the mixture in small proportions (around 3% of the weight of cement).

Mortars can contain different types of adjuvants:

- plasticizers (water reducers);

- air trainers;
- setting modifiers (retarders, accelerators);
- water repellents.
- colorings (natural or synthetic);

2.4. Additions:

The additions used in mortars are fine chemically reactive powders:

2.4.1. Fine powders of pozzolanic and/or hydraulic nature:

- **Granulated blast furnace slag** (S)

Granulated blast furnace slag is obtained by rapid cooling of molten slag from the smelting of iron ore in the blast furnace.

- **Natural pozzolans (Z)**

Natural pozzolans are substances of volcanic origin or sedimentary rocks composed essentially of SiO_2 reactive and Al_2O_3. The remaining part contains iron oxide (Fe_2O_3) and other oxides.

- **Fly ash (V and W)**

Fly ash is obtained by electrostatic or mechanical dusting of powdery particles coming from the boiler gas stream, fueled with pulverized coal. Composed essentially of reactive silica (SiO_2) and alumina (Al_2O_3) (siliceous fly ash) and reactive lime (CaO), reactive silica (SiO_2) and alumina (Al_2O_3) (Calcium fly ash), the remaining part contains iron oxide (Fe_2O_3) and other oxides.

2.4.2. Limestone Fillers (L)

These are products obtained by fine grinding of natural limestone rocks. They are essentially made of limestone ($CaCO_3 \geq 75\%$)

2.4.3. Fibers of different types

The incorporation of metal, glass or polypropylene fibers makes it possible to obtain mortars with greater cohesion and fewer cracks.

3. CLASSIFICATION OF MORTARS

Mortars can be classified according to several criteria:

3.1. Apparent density

- **Ordinary mortars** with a density $\rho_{app} \geq 1500$ Kg /m ^{3} are made with rolled or crushed natural sand,
- **Light mortars** with a density $\rho_{app} \leq 1500$ Kg /m ^{3} are manufactured with light sands

3.2. The nature of the binder

- **Cement mortars**

The binder part consists solely of cement. These mortars are used when high mechanical resistance and good waterproofing are required or for use in a humid environment.

- **Lime mortars**

The binder used is lime. These mortars are very plastic and strongly adherent, have low shrinkage, but harden slowly.

- **Mixed mortars**

As a binder we use a mixture of cement and lime. The cement/lime ratio depends on the dominant parameter sought (plasticity or mechanical resistance). These mortars are characterized by good workability and guaranteed mechanical resistance.

- **Resin mortars**

Are mortars which contain approximately 50% aggregates (sand and fillers) and 10% epoxy, polyurethane or polyester resin. Fillers, adjuvants or fibers may be included in their composition.

3.3. The method of preparation

- **Traditional mortars (prepared on site)**

The constituents are measured, mixed and mixed on site. Mixing is done with a shovel or using a small concrete mixer. These mortars are therefore not very regular and the sands can be different from one delivery to another. The sand is generally dosed by volume, in the latter case, it is very important to take into account the phenomenon of sand abundance.

- **Industrial mortars**

Industrial mortars have developed greatly in recent years; making it possible to avoid the storage and mixing of constituents on construction sites. Industrial mortars can be:

- **Pre-dosed dry mortars:** The constituents are mixed and mixed on site from dry industrial mortars pre-dosed in the factory and delivered in bags.

- **Fresh mortars delayed, stabilized, ready to use**: Prepared in concrete plants, delivered in non-absorbent tanks, with a capacity of 250 to 500 liters . They can be used within up to 36 hours, which allows them to be stored on site in large quantities.

3.3.The destination

- **Masonry joints**

Construction carried out using masonry elements (concrete blocks, natural stone, brick), requires their assembly with a mortar which must have sufficient mechanical characteristics to ensure the transmission of loads and sufficient compactness to be waterproof.

- join the elements together;
- ensure the stability of the structure;
- fill gaps between building blocks.

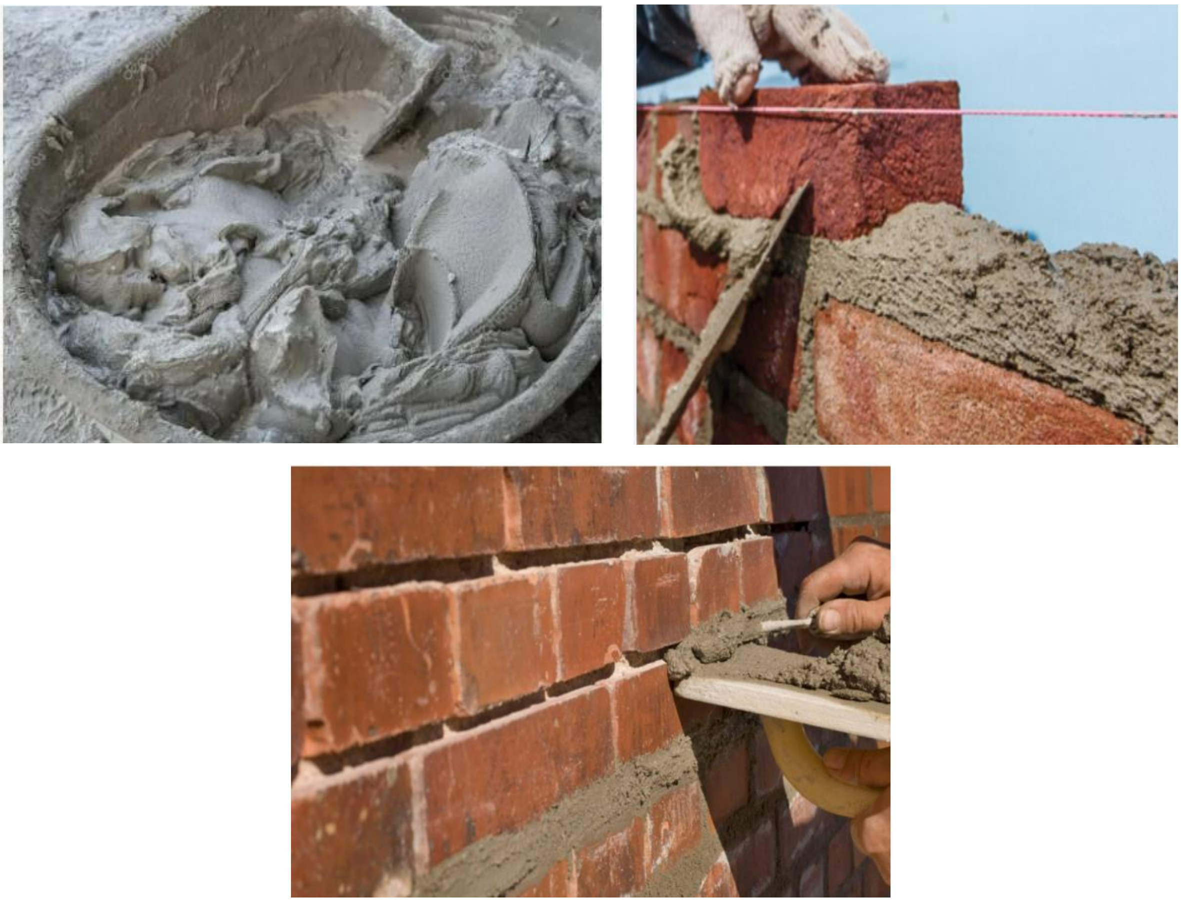


Photo 1.IV – Mortars used in masonry construction

- **Coatings**

Finishing mortars are subdivided into mortars for traditional coating and mortars for decorative coating.

- **Traditional coatings:** Mortars for finishing coatings are used both for new work and for repair work. Are composed of cement, lime or a mixture of cement and lime for exterior work and plaster and air lime for interior work and play a dual role:
  - protection of the structural work (waterproofing, water-repellent)
  - the aesthetics (appearance and color) of the facades

Photo 2.IV – wall coatings with mortar

- **Decorative coatings**

These mortars must have both good workability and guaranteed mechanical resistance. The type of binder used depends on the support on which the mortar will be applied:

- Gray, white or colored cement is used for normal mortar and lightweight mortar.
- Gray, white, colored cement or lime is used for siporex bricks.

To make the finishing layer of a decorative mortar shine, 1% mica or 10% broken glass is introduced into its composition and natural and artificial pigments are added as coloring agents.

- **Sealing and wedging**

These mortars have multiple uses: wedging of industrial equipment, sealing of posts and inspection holes, beams, parapets, doors, windows and finishing elements, street furniture, signaling and sealing work in the marine environment.

The sealing and wedging mortars are composed of higher-class cement (52.5 and 42.5) generally fast hardening (R), prompt cement, aluminous cement, and very clean sand (preferably rolled) a maximum diameter of 2 or 3 mm; various additives and possibly steel or polypropylene fibers.

Binder dosages are generally high (600 to 700 kg for 1 m^3 of sand). The water dosage must be adjusted according to the desired consistency: W/C between 0.40 and 0.50.

Photo 3.IV – Sealing and wedging

- **Zero or compensated shrinkage mortars**

Sealing mortars are special mortars which are characterized by no shrinkage or compensated shrinkage (expansive cement).

The main characteristic of these mortars is that they exhibit little or no shrinkage at all. To achieve this result, a good sealing or wedging mortar must be shrink-free or “with compensated shrinkage”. A conventional mortar can in fact shrink excessively and no longer play its role by separating itself from its surroundings (detachment, appearance of cracks). The usual precautions to avoid shrinkage in a conventional mortar during its hardening of course remain valid.

It is therefore advisable not to exaggerate the mixing water content, and to ensure the protection of the fresh mortar against desiccation (absorption by the support or evaporation).

- **Expansive character of the mortar:**

special sealing and wedging mortars are generally made from expansive materials: metal powders (iron oxides, aluminum), oxidants (expansion after setting due to rust formed).

The removal of a poorly designed mortar results in the separation of the seal from the support. The expansion of the mortar in a seal creates a self-blocking phenomenon. Another commonly used technique involves causing crystal expansion by formation of lime sulfo-aluminate (ettringite). Free expansion can vary from 0.5 to 2% by volume.

- **Resistance at young age**

It is essential to meet the short deadlines imposed by this type of work. It is obtained by an appropriate composition; the binder is generally a class R cement (rapid hardening), or a special fast-hardening cement: prompt cement, aluminous cement.

- **Repair mortars**

Manufactured on site, ready to use or pre-dosed: Mortars must meet various requirements, which vary depending on the nature of the repair and the application or environmental conditions: temperature, deadlines, accessibility. They are either based on hydraulic binders or based on synthetic binders. They must in all cases present characteristics compatible with those of the support, particularly from the point of view of its physico-mechanical (deformability, expansion, resistance) and chemical characteristics. They must also ensure good adhesion to the support and provide effective protection to the reinforcements through their low porosity.

- **Insulating mortars**

These very light mortars, based on expanded polystyrene and cork, have a density 2 to 4 times lower than conventional mortars, which allows them to provide thermal insulation in addition to waterproofing and aesthetic functions. The required thickness will be calculated according to the degree of insulation to be provided to the wall. As an indication, the coefficient (λ) of thermal conductivity can reach, for a wall of 20 cm concrete blocks coated with 7 cm of insulating mortar: 0.8 W/m 2 °C.

- **Grouts**

Grout is a thick paste that is used to fill gaps, voids, or joints. It is mainly a composite material used for grouting, repairing concrete cracks, filling gaps and sealing the joints between tiles, waterproofing, soil stabilization, etc. Differing from mortar, grout has a low viscosity and lack of lime, which makes it thinner and easier to work with.

- Cementitious grouts are the type of traditional grout material used both in residential as well as commercial applications. It is also known as slurry grouting or hydraulic cement grouting. Cementitious grouts are further classified into three types: (Sanded grout; Unsanded / Non-sanded grout; Latex modified grout).

Photo 4.IV – Cementitious grouts

- **The screeds**

The function of the screeds is to ensure the leveling of the paving and the regularity of its surface. The screeds can constitute the finish. They can also constitute the support for a floor covering. The screed can also have a thermal or acoustic function. The mortar used to make the screed includes sand with a particle size not exceeding 0/3 mm, and a dosage of Portland cement with resistance class 32.5 at least equal to that of the support concrete, with a minimum of 350 kg/m^3 of mortar. These screeds are generally made of mortar with a firm consistency, and have an average thickness of 15 to 25 mm.

Photo 5.IV – Waterproofing Screed - Leveling Mortar

4. Main characteristics

The main characteristics of mortars are: workability, setting, mechanical resistance and deformation (shrinkage and swelling).

4.1 Workability

The workability of a mortar is measured using various devices. The most famous are:

- **Flow Table Test**

Carefully wipe the flow table clean and dry, and place the flow mold at the center. Place a layer of mortar about 25 mm in thickness in the mold and tamp 20 times with the tamper. The tamping pressure shall be just sufficient to ensure uniform filling of the mold. Then fill the mold with mortar and tamp as specified for the first layer. Cut off the mortar to a plane surface flush with the top of the mold by drawing the straightedge or the edge of the trowel with a sawing motion across the top of the mold. Wipe the table top clean and dry, being especially careful to remove any water from around the edge of the flow mold. Lift the mold away from the mortar 1 min after completing the mixing operation. Immediately drop the table 25 times in 15 s (figure 4.2).

The flow is the resulting increase in average base diameter of the mortar mass, measured on at least four diameters at approximately equi-spaced intervals expressed as a percentage of the original base diameter

Flow = [(Davg – Do) / Do]*100

Where,

Davg =Average base diameter

Do = Original base diameter.

Photo 6.IV – Mortar flow testing

- **LCPC maniabilimeter test**

The unit consists of a prismatic receiver divided into two unequal volumes by a removable partition, and by an electric vibrator (figure 4.3). The fresh mortar is poured in the large volume place, the separating partition is removed and the vibrator stats automatically. As a result of vibrations, mortar flows from the large volume to the small one, in a time which is a function of the workability of the mortar.

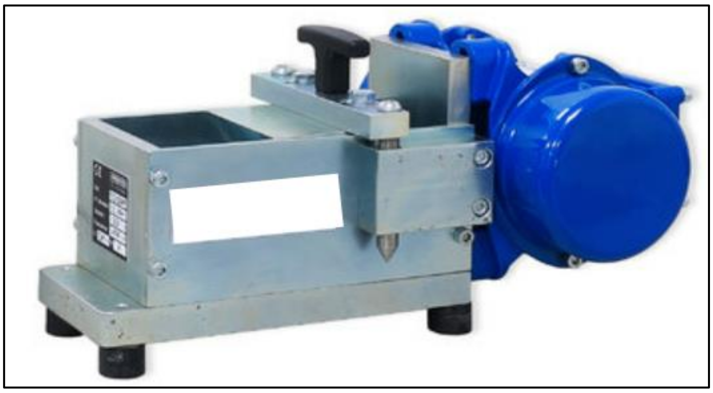


Photo 7.IV – LCPC maniabilimeter apparatus

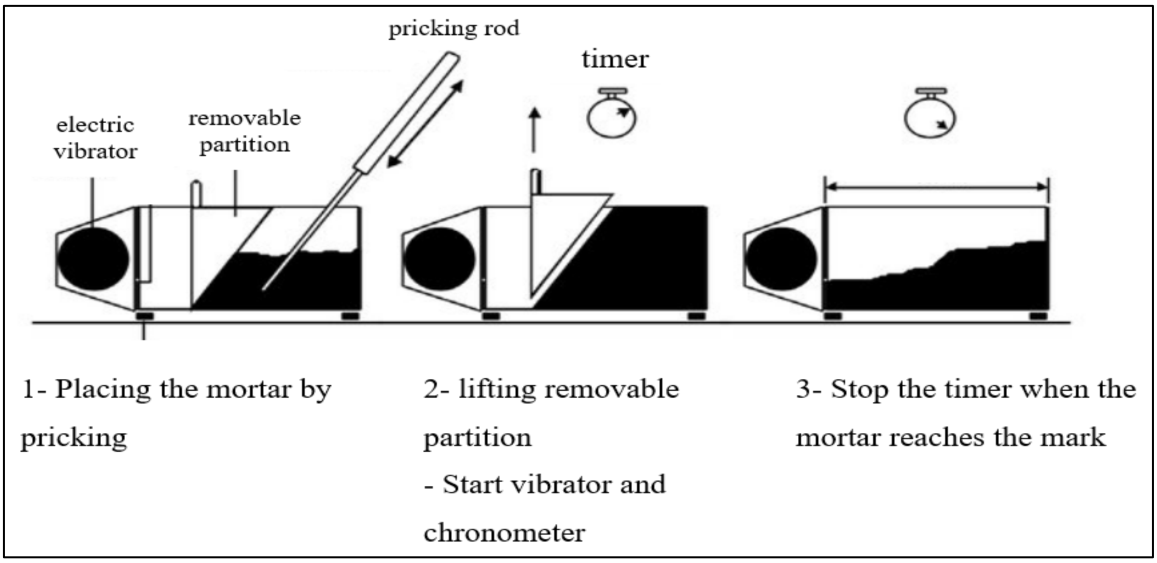


Figure 2.IV – Principle of LCPC maniabilimeter test

4.2. Setting time

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

It is possible to obtain the setting time of a hydraulic cement mortar with the same equipment but by the following modifications: a 2 ± 0.05 mm stainless steel needle shall be substituted for the 1-mm needle. The total mass of the movable rod with the 2-mm needle shall be 300 ± 0.5 g, placing an overload of 700 g on the upper plate. The weight of the needle penetrating the mortar is 1000 g.

Calculate the time of setting to the nearest one minute as follows:

$$\left(\left(\frac{(H-E)}{(C-D)}\right) \times (C-10)\right) + E$$

where:

E = time in minutes of last penetration greater than 10 mm,

H = time in minutes of first penetration less than 10 mm,

C = penetration reading at Time E, and

D = penetration reading at Time H

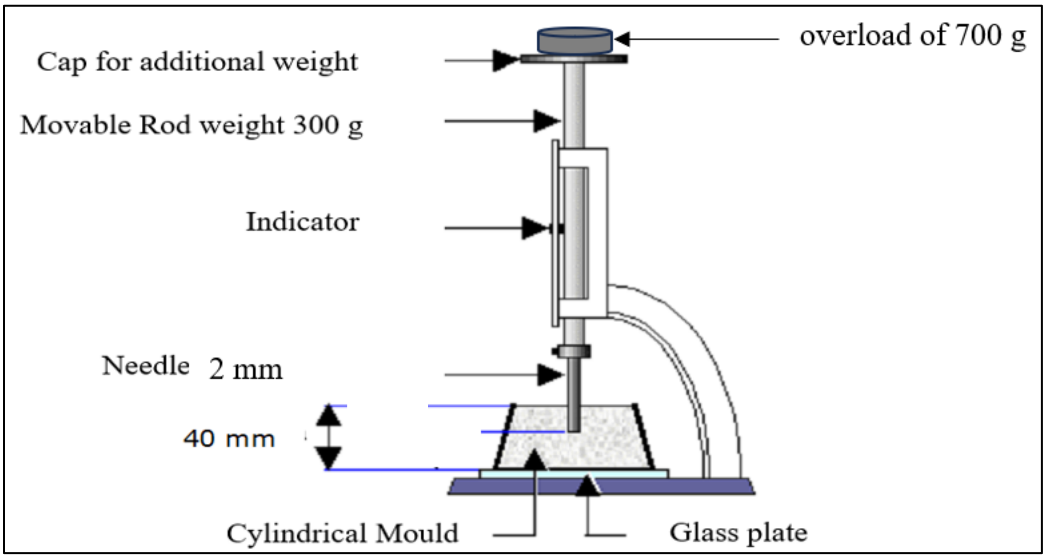


Figure 3.IV – Vicat device with modifications

4.3 Mechanical properties

The tests are carried out on prismatic test pieces (4 x 4 x 16) cm^3 stored in water at 20°C. The flexural strength was measured by three-point bending. After the flexural tests, we used the half-broken samples for the compressive strength tests.The resistance of mortars (as in the case of concrete) depends on many factors:

- nature and dosage of cement;
- P/E ratio;
- grain size and nature of the sand;
- mixing energy and implementation;
- the duration and conditions of treatment

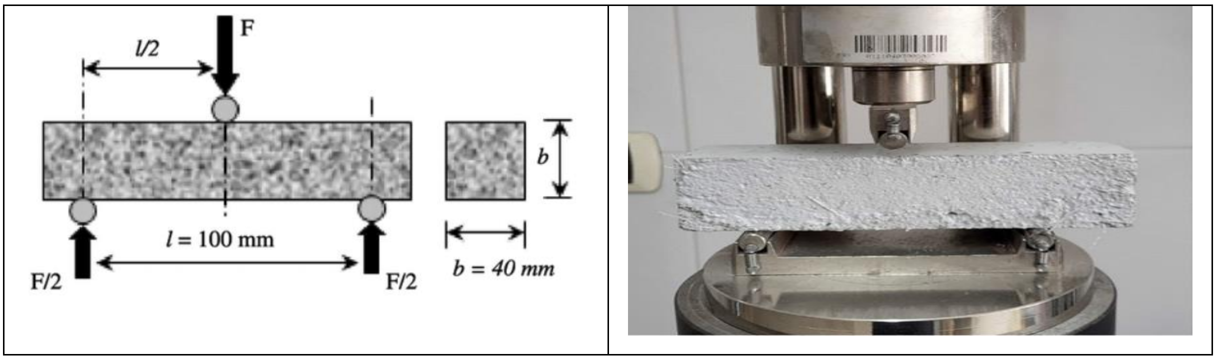


Figure 4.IV – Flexural strength test.

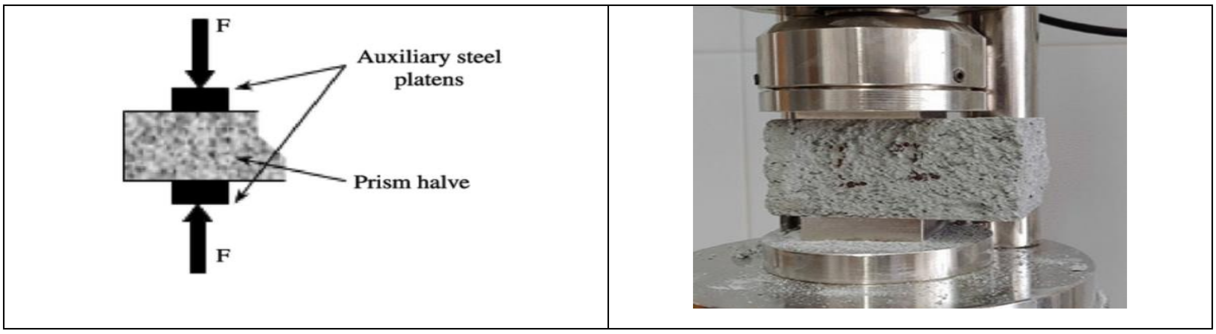


Figure 5.IV – Compression strength test.

4.4 Shrinkages and swellings

Shrinkage is measured on 4 x 4 x 16 cm prisms made of mortar of a composition consistent with normal mortar, provided with studs at their ends and stored, after unmolding, in an enclosure at 20°C and 50% relative humidity. Shrinkage must be less than 800 μm/m at 28 days (standardized value referring to normal mortar)

The swelling of the mortars (which occurs when they are stored in water) is measured on the same 4 x 4 x 16 cm prismatic test tubes stored in water at 20 °C. They are generally quite weak.

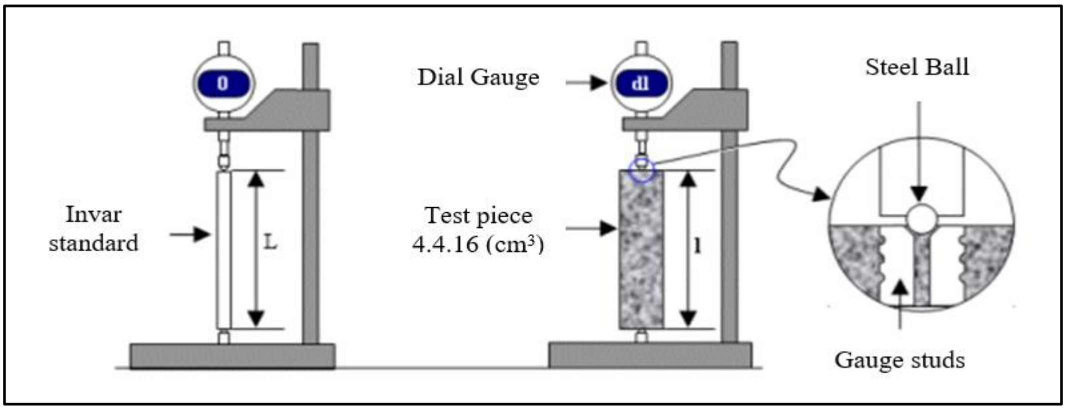


Figure 6.IV – Measuring shrinkage of mortar

Books, websites and references

Shan Somayaji, “Civil Engineering Materials,” 2nd Edition, Prentice Hall, New Jersey, 2008.

P.C. Varghese, “Building Materials,” Prentice-Hall of India, New Delhi, 2008.

G. Dreux, J. Festa, "The new concrete guide". Editions Eyrolles, 1998.

Materials Volume 1, Properties, applications and design: courses and exercises: License 3, master, engineering schools, Edition Dunod, 2013.

The physico-chemical properties of construction materials: matter & materials, rheological & mechanical properties, safety & regulations, thermal, hygroscopic, acoustic and optical behavior, Eyrolles, 2012.

https://theconstructor.org/

https://dailycivil.com/