

Chapter 1: Formulation and mechanical properties of reinforced concrete

1.1 Definition of concrete

Concrete is a composite building material obtained by mixing several elements (Figure 1.1) :

- **Binder** (cement, often Portland type),
- **Aggregates** (sand, gravel , pebbles),
- **Water** (to activate the chemical reaction of the binder),
- Sometimes **adjuvants** (additives to modify its properties) or **fibers** (for reinforcement).

During mixing, cement and water form a paste that hardens through **hydration** , coating the aggregates to create a solid, strong, and durable material. Concrete is widely used for structures (buildings, bridges, roads, dams) due to its moldability, compressive strength, and longevity. Its formulation can be adjusted according to specific needs (strength, fluidity, setting time, etc.).

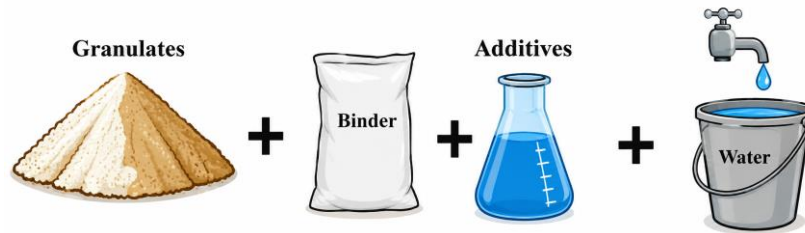
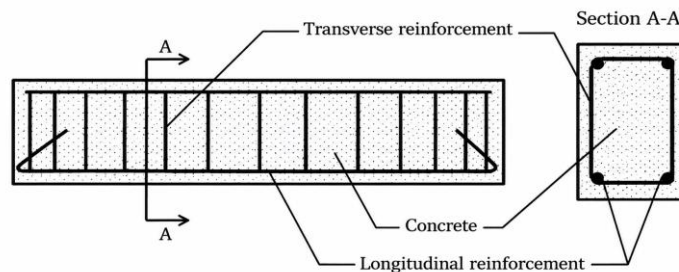


Figure 1.1. Concrete compositions

1.2. Definition of reinforced concrete

Reinforced concrete is a composite material combining concrete and steel reinforcement . This reinforcement, generally in the form of bars (rebar) or mesh (Figure 1.2), is integrated into the concrete before it sets to compensate for the low resistance of concrete to tensile and bending stresses.



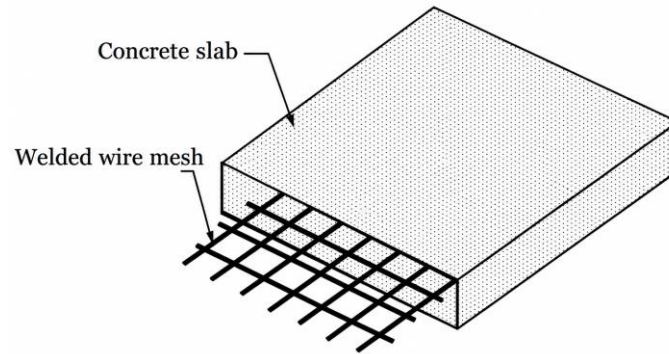


Figure 1.2. Reinforced concrete structural elements.

Concrete is characterized by good compressive strength; however, its tensile strength represents only about 1/10th of its compressive strength. Steel, on the other hand, offers excellent tensile and compressive strength, while also exhibiting ductile behavior (significant deformation before failure).

Figure 1.3 shows a simply supported beam subjected to a bending moment due primarily to its own weight and an external load (F). The bending of the beam results in compressive deformations in the upper part of the beam and tensile deformations in the lower part (cracks due to tensile stresses). Since concrete has poor tensile strength, the placement of steel reinforcement (main longitudinal reinforcement) is necessary to prevent, reduce, or limit crack propagation and beam failure. The reinforcement is sometimes placed in the compression zones if the concrete's strength is insufficient to balance the compressive stresses.

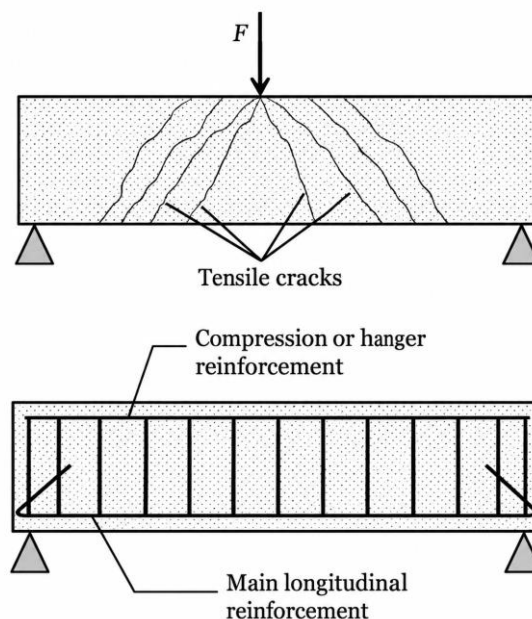


Figure 1.3. Cracking zones and reinforcement in a beam

1.3. History:

Before **the emergence** of modern concrete, Louis Vicat , a young engineer from the École nationale des ponts et chaussées, made a major breakthrough in 1818: he produced artificial hydraulic limes for the first time by controlling their components and proportions.

In 1848 , Joseph-Louis Lambot He innovated by combining concrete and metal reinforcement to build a boat, which was presented at **the** Universal Exhibition in Paris in 1855. Shortly after, Joseph Monier , a gardener at Versailles, used a similar method to make flower boxes, earning him recognition as the inventor of reinforced concrete . His process was commercialized in Germany by the company *Monier Béton Brau* , which filed a patent in 1868 .

The following years marked key milestones:

- 1891 : François Coignet uses prefabricated reinforced concrete beams for a building.
- 1886 : Mathias Koenen publishes the first theoretical treatise on the dimensioning of reinforced concrete structures.
- 1897 : Charles Rabut integrated reinforced concrete into the teaching of the École des ponts et chaussées, creating the first academic course on the subject.
- Late 19th century : François Hennebique established the calculation bases for a rational use of the material.

Technical advances led, as early as 1910 , to the creation of dedicated institutions (*German Reinforced Concrete Committee* , *American Concrete Institute* , etc.). In the 20th century , reinforced concrete became widespread in buildings , civil engineering structures , reservoirs , and other infrastructure.

A revolution occurred with Eugène Freyssinet , who invented prestressed concrete : in 1928 , he patented a process in which tensioned steel cables compress the concrete, allowing it to withstand future tensile stresses. Named "prestressing" in 1933 , this system enabled structures with bold shapes, such as the Luzancy Bridge (1940) , a symbol of long and slender spans.

1.4. Evolution of calculation rules

In France

- **1906** : *Circular from the Ministry of Public Works* – First official regulation on reinforced concrete.
- **1934** : *Ministerial Circular* (30 pages) – Expands the technical requirements.
- **BA 45 Rules** (90 pages) – Standardization of design methods.
- **BA 60 Rules** – Introduction of new sustainability requirements.
- **1964** : *Ministerial Circular* – Update of safety criteria.
- **CC BA 68 rules** – Incorporates advances on limit states.
- **BAEL 80** (modified in 1983): *"Technical rules for the design and calculation of reinforced concrete structures according to the limit state method"* – Major reference until Eurocode .
- **Eurocode 2** (applicable from the 2000s): *"Common unified rules for concrete structures"* – European harmonization of standards.

In Algeria

- **CBA 93** : *Regulatory Technical Document DTRBC 2.41* – *"Design and calculation rules for reinforced concrete structures"* , approved by the Ministry of Housing in

1993. This text is based on French standards while adapting to local specificities (climate, materials, practices).

1.5. Composition of reinforced concrete

Concrete is a composite material that combines a concrete matrix (*aggregates* bound by hydraulic cement) and integrated steel reinforcements , ensuring resistance to tensile forces.

1.5.1. Concrete Matrix

Concrete is a composite material made up of aggregates (gravel, crushed stone, sand) bound together by hydraulic cement.

1.5.1.1. Cement :

Cement is produced by heating a finely ground mixture of limestone, clay, and sand to 1450°C in a rotary kiln. This process generates *clinker* , an intermediate product.

The clinker is cooled, then ground into a fine powder. Upon contact with water, it hydrates to form a hardening paste , essential for solidifying concrete.

Common types of cement (Table 1.1):

- **Portland Cement (CP)** : Standard.
- **CPHR** (High Resistance): used in prefabrication.
- **CPHS** (Sulfate Resistance): For foundations exposed to sulfate-rich water.

Table 1.1 lists the types of cement with their strength classes

Types of cement	Designation
Portland cement	CPA-CEM I
Portland cement compound	CPJ-CEM II/A; CPJ-CEM II/B
Blast furnace cement	CHF-CEM III/A; CHF-CEM III/B; CHF-CEM III/C
Pozzolanic cement	CPZ-CEM IV/A; CPZ-CEM V/B
Slag and ash cement	CLC-CEM V/A; CLC-CEM V/B

1.5.1.2. Aggregates :

They form the skeleton of concrete. Depending on their origin, we distinguish between rounded aggregates, extracted from rocks quarried or dredged from rivers or the sea, then crushed. Sand fills the gaps between the larger aggregates. The aggregates that give concrete its strength must be frost-resistant and free of clay or organic impurities. The maximum grain diameter is chosen based on the structural element, its minimum dimensions, and the smallest spacing of its reinforcing bars. Generally, the maximum aggregate diameter is 32 mm.

1. 5.1.3. Mixing water :

Must be potable, without salt (excluding seawater).

1.5.1.4. Admixtures ($\leq 0.4\%$ of the weight of concrete):

- **Plasticizers** : Improve handling and reduce the amount of water needed, increasing strength.
- **Retarders** : Extend the working time of fresh concrete (long distance transport, pumping).
- **Air entrainers** : Improve freeze-thaw resistance.

1.5.1.5. Mineral additions ($\approx 10\%$ of the cement weight):

Fly ash, slag, fillers: Enhance durability and performance through their physico-chemical properties.

Concrete composition : Defined by the cement content ($\geq 300 \text{ kg/m}^3$ recommended to protect the reinforcement). Water/cement ratio (W/C) : Between 0.4 and 0.6. A reduction in the W/C increases strength. These parameters directly influence mechanical strength and durability (see Table 1.2 for typical proportions). Table 1.1 provides an overview of the approximate proportions of each concrete component.

Table 1.2. Order of magnitude of the proportions of solids and air by mass and volume

Material	Cement	Granule	Water	Air
Volume	7% - 14%	60% - 78%	14% - 22%	1% - 6%
Weight	9% - 18%	63% - 85%	5% - 9%	

1.5.2. Steel reinforcement

Steel is an alloy of iron and carbon (in small proportions). In reinforced concrete, mild , medium-hard **and** hard steels are mainly used .

For reinforced concrete, smooth round bars (symbol ϕ or RL), high adhesion reinforcement (symbol HA) and welded wire mesh (symbol TS) are used (Figure 1.4) .



(a) Smooth round steel (b) High-adhesion steel (c) Welded wire mesh

Figure 1.4: Steel reinforcement used in reinforced concrete:

The available bar shapes are : straight bars of standard lengths of 12 m , wires : used for prefabricated elements, welded wire mesh (TS) which are assembled by welded crossed wires ready for use (Figure 1.5).



(a) Bars (b) Wire in coils (c) Welded mesh

Fig. 1.5. Available steel shapes for reinforced concrete

Standardized bar diameters :

6, 8, 10, 12, 14, 16, 20, 25, 32 and 40 mm.

For each nominal diameter, the following are defined:

- **Nominal section** : Equivalent to that of a smooth round of the same diameter.

- **Nominal perimeter** : Corresponding to the theoretical perimeter of the smooth circle.
 - **Linear mass** : Given as a function of diameter (see technical references).
- Table 1.3 gives the nominal cross-section and linear mass corresponding to the different nominal diameters.

Table 1.3: Table of steel sections.

Diameter of bar D (mm)	Mass kg/m	Total steel cross-section in $\text{cm}^2 = n \cdot \frac{\pi D^2}{4}$									
		Number of bars (n)									
		1	2	3	4	5	6	7	8	9	10
6	0.222	0.28	0.57	0.85	1.13	1.41	1.7	1.98	2.26	2.54	2.83
8	0.395	0.50	1.01	1.51	2.01	2.51	3.02	3.52	4.02	4.52	5.03
10	0.617	0.79	1.57	2.36	3.14	3.93	4.71	5.50	6.28	7.07	7.85
12	0.888	1.13	2.26	3.39	4.52	5.56	6.79	7.92	9.05	10.18	11.31
14	1.210	1.54	3.08	4.62	6.16	7.70	9.24	10.78	12.31	13.85	15.39
16	1.580	2.01	4.02	6.03	8.04	10.05	12.06	14.07	16.08	18.10	20.11
20	2.466	3.14	6.28	9.42	12.57	15.71	18.85	21.99	25.13	28.27	31.42
25	3.850	4.91	9.82	14.73	19.63	24.54	29.45	34.36	39.27	44.18	49.09
32	6.313	8.04	16.08	24.13	32.17	40.21	48.25	56.30	64.34	72.38	80.42
40	9.864	12.57	25.13	37.70	50.26	62.83	75.40	87.96	100.53	113.09	125.66

1.6 Mechanical characteristics of reinforced concrete constituents

1.6.1. Concrete

1.6.1.1 Characteristic resistances

a. Characteristic compressive strength (f_{cj})

The characteristic compressive strength of concrete, denoted f_{cj} , corresponds to its capacity to withstand a compressive load after "j" days of hardening. The reference strength is taken at 28 days, referred to as the required (or specified) characteristic value. This strength depends on the concrete production conditions, the class of cement used, and the cement dosage. cement per m^3 .

The characteristic compressive strength is obtained experimentally by applying the direct compression test (Figure 1.6) to a standard cylinder ($\varnothing 16 \text{ cm} \times 32 \text{ cm}$). The compression test is performed using a compression testing machine that measures the compressive force, the rate of deformation, and the breaking stress (Figure 1.6).



Figure 1.6. Compression test on a cylindrical specimen

The compressive stress is given by the following relationship:

$$f_{cj} = \frac{F_r}{S} \text{ (en MPa)} \quad (\text{Eq.1.1})$$

Or F_r = breaking load (in kN), and the surface area of the cylinder is given by:

$$S = \frac{\pi \cdot \phi^2}{4} = \frac{3.14 \cdot 16^2}{4} = 200 \text{ cm}^2 \quad (\text{Eq.1.2})$$

For $F_r=500 \text{ kN}$, $f_{cj} = 25 \text{ MPa}$

The simple compression test on a 16x32 specimen causes deformations (See Figure 1.7):

- Relative longitudinal deformation (Equation Eq.1.3):

$$\varepsilon = \frac{\Delta l}{l} = \frac{l' - l}{l} \quad (\text{Eq.1.3})$$

ε' relative transverse deformation (Equation Eq.1.4):

$$\varepsilon' = \frac{\Delta d}{d} = \frac{d' - d}{d} \quad (\text{Eq.1.4})$$

ν : Poisson's ratio (Equation Eq.1.5):

$$\nu = \frac{\text{déformation relative transversale}}{\text{déformation relative tlongitudinale}} = \frac{\varepsilon'}{\varepsilon} \quad (\text{Eq.1.5})$$

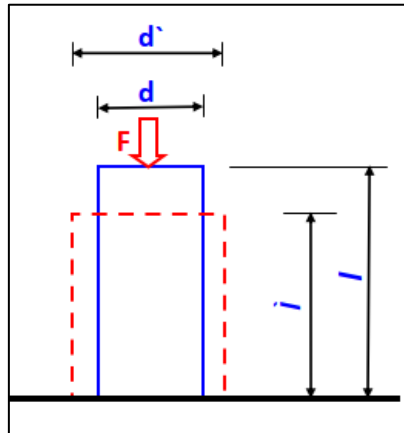


Fig. 1.7: Determination of relative longitudinal and transverse deformations
The concrete compression test allows us to obtain the experimental "stress-strain" diagram of the concrete below (see Fig. 1.7).

- **Stress-strain diagram**

In ULS calculations, when a precise evaluation of deformations is not required, the parabola-rectangle diagram (Fig. 1.8) can be adopted.

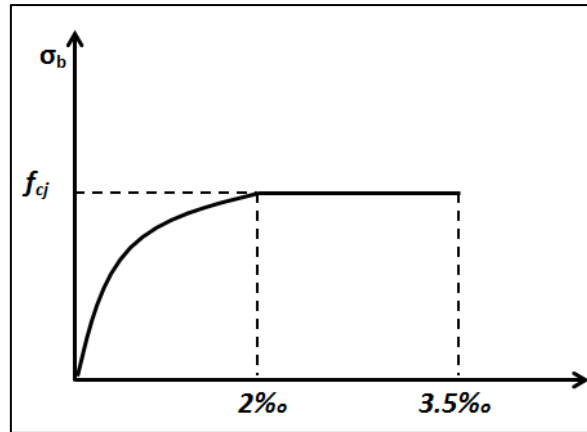


Figure 1.8. Characteristic stress-strain diagram of concrete.

The design strength of concrete is determined by the following relationship:

$$f_{bc} = 0.85 \cdot \frac{f_{cj}}{\theta \cdot \gamma_b} \quad (\text{Eq.1.6})$$

γ_b : the safety factor equal to 1.5 (common case) and 1.15 (accidental case).

θ : Coefficient depending on the duration of load application, where:

$\theta = 1$ if the duration $> 2h$.

$\theta = 0.9$ if: 24 h the duration is 1h.

$\theta = 0.85$ if: the duration is 1 hour.

For a number of days $j < 28$, the resistance f_{cj} of concrete follows the laws given by the BAEL and BPEL rules:

Concretes of standard strength: $f_{cj} = \frac{j}{4.76 + 0.83j} f_{c28}$ for $f_{c28} \leq 40 \text{ MPa}$ (Eq.1.7)

High-strength concretes: $f_{cj} = \frac{j}{1.4 + 0.95j} f_{c28}$ for $f_{c28} > 40 \text{ MPa}$ (Eq.1.8)

For $j \geq 28 \rightarrow f_{cj} = 1.1 f_{c28}$ (Eq.1.9)

b. Characteristic tensile strengths:

The characteristic tensile strength f_{ctj} of concrete at j days is defined by:

$$f_{ctj} = 0.6 + 0.06 f_{cj} \quad (\text{Eq.1.10})$$

With, f_{cj} is the characteristic compressive strength at j days expressed in MPa.

1.6.1.2 Instant deformation

• Longitudinal deformation

In the absence of conclusive experimental results, a conventional value is adopted for the instantaneous longitudinal deformation modulus of concrete E_{ij} , equal to:

$$E_{ij} = 11000 f_{cj}^{\frac{1}{3}} (\text{MPa}) \quad (\text{Eq.1.11})$$

The delayed longitudinal deformation modulus E_{vj} is given by:

$$E_{vj} = 3700 f_{cj}^{\frac{1}{3}} (\text{MPa}) \quad (\text{Eq. 1.12})$$

• Transverse deformation

$\mu = 0.2$ in uncracked zones

$\mu = 0$ in cracked zones

1.6.2. Steel

Steel, an alloy primarily composed of iron and a small proportion of carbon, combines tensile and compressive strength with deformation capacity. Iron provides a solid base

and flexibility, allowing the material to deform without breaking, thus facilitating its shaping. Carbon significantly increases strength but also increases rigidity, reducing flexibility. The composition of steel therefore results from a balance between these two characteristics.

1.6.2.1. Mechanical characteristics:

The mechanical justifications are based primarily on two characteristics:

- The guaranteed yield strength (f_e), specific to each type of steel.
- The longitudinal modulus of elasticity (E_s), practically identical for all steels and taken as equal to 200,000 MPa.

The behavior of steel under stress is represented by its stress-strain diagram in tension σ in Figure 1.9 (the diagram is symmetrical in compression).

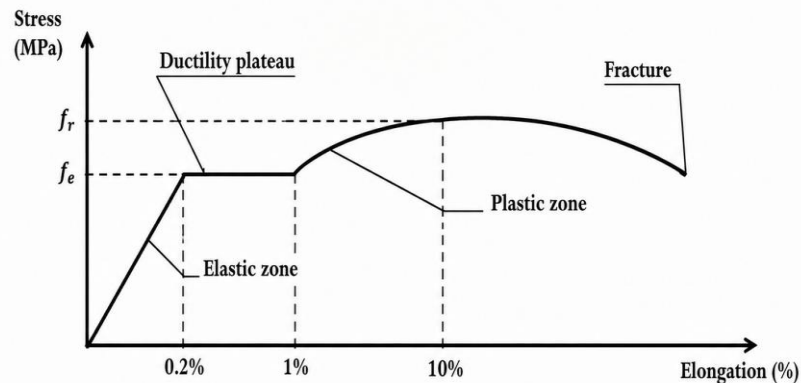


Figure 1.9. Stress-strain diagram of the tensile test on steel.

1.6.2. 1. The conventional stress-strain diagram

The conventional stress-strain diagram for steel, used for structural calculations, is based on the guaranteed yield strength (f_e) and requires verification of the stress corresponding to an elongation of 10‰. This diagram is designed to facilitate calculations, allowing for a practical evaluation of stresses and strains in steel structures, while ensuring consistency with the actual mechanical properties of the material (Figure 1.10). It is broken down into key phases:

- **Linear elastic domain (OA)** : this domain exhibits a proportional relationship between stresses and strains, which correspond according to the following equation:

$$\sigma = E \cdot \varepsilon \quad (\text{Eq.1.13})$$

The elastic limit (f_e) represents the maximum stress before permanent deformations occur.

- **Flow tray (AB)** :

Plastic phase where deformation increases at constant stress (f_e) with irreversible permanent deformations.

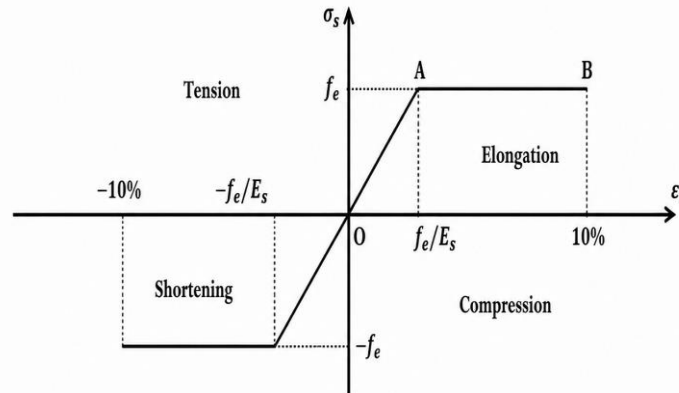


Figure 1.10: Conventional strain-stress diagram of steel

1.6.2. 1. Grade of steel

The following grades of steel are commonly used in construction, characterized by their yield strength and mechanical properties:

- **FeE215**
 - Low-strength mild steel.
 - Guaranteed yield strength: $f_e = 215 \text{ MPa}$.
 - Tensile strength: $\sigma \geq 330 \text{ MPa}$ with elongation of 22 %
 - Used for applications with low stress or requiring easy shaping (e.g., lightweight structures).
- **Fe E 235**
 - Mild steel, ability to deform without breaking, ideal for structures subjected to dynamic loads or shocks.
 - Limit elasticity : $f_e = 235 \text{ MPa}$.
 - Tensile strength: $\sigma \geq 410 \text{ MPa}$ with elongation of 22 %
 - Used for: metal construction (beams, profiles), fasteners (bolts, screws), structures requiring good weldability).
- **Fe E 400**
 - Medium to high strength steel.
 - Limit elasticity : **400 MPa**.
 - Tensile strength: $\sigma \geq 480 \text{ MPa}$ with elongation of 14 %
 - Offers a good compromise between strength and ductility.
 - Used in structures subjected to moderate to high loads.
- **Fe E 500**
 - **High-strength** steel.
 - Limit elasticity : **500 MPa**.
 - Tensile strength: $\sigma \geq 550 \text{ MPa}$ with 12% elongation
 - Ideal for demanding projects (bridges, high-rise buildings) or heavily used areas.
 - Meets modern standards for optimizing steel sections (reducing costs and weight).