

Chapter 2: Materials used in prestressed concrete

2.1. Introduction:

The behavior of a prestressed concrete member throughout its entire loading range depends on the mechanical properties and performance of its constituent materials. To ensure adequate structural strength, the ultimate strengths of both concrete and prestressing steel must be accurately determined. In addition, the factors influencing material strength and the nonlinear behavior of each material under overload conditions must be taken into account.

To verify serviceability requirements, it is also necessary to consider the instantaneous and time-dependent properties of concrete and prestressing steel under normal service stress levels.

The objective of this chapter is to provide a general overview of the behavior of the constituent materials of prestressed concrete and to present the essential mechanical properties required for the analysis and design of prestressed concrete structures.

2.2. Concrete:

The concrete used in prestressed concrete members and structures is similar to that used in reinforced concrete. However, because prestressed concrete is subjected to higher stress levels, the concrete must possess superior mechanical and durability properties.

In general, the concrete used for prestressed members has a higher compressive strength than that used for conventional reinforced concrete. Its modulus of elasticity, deformation capacity, and strength characteristics must be carefully considered during design. In addition, the time-dependent properties of concrete, such as creep and shrinkage, are of particular importance because they directly influence prestress losses and the long-term performance of prestressed concrete structures.

- **High mechanical strength**

They determine the magnitude of the prestressing force and the behavior of the concrete under the action of static and dynamic loads.

- **High modulus of elasticity**

The transfer of stress from the tension reinforcement to the concrete causes elastic deformation and, implicitly, a reduction in prestressing force due to the shortening of the reinforcement. To minimize this loss of tension in the reinforcement, the concrete must exhibit very small deformations.

- **Deformation due to shrinkage and creep kept to a minimum**

The prestressing force is reduced over time thanks to the concrete. A good mix design is essential, especially the *water-cement ratio*.

- **Compact concrete free of aggressive materials**

Concrete, especially for the elements mentioned, constitutes the main material for protecting tension reinforcement against corrosion.

- **Good Workability**

The concrete should possess adequate workability to ensure proper placement and complete filling of the formwork, particularly in regions with congested reinforcement, without causing segregation or excessive bleeding.

2.2.1. Main characteristics of concrete

a. Characteristic compressive strength

Concrete is defined by its compressive strength at 28 days. This value, denoted f_{c28} , is determined from standardized tests on 16x32 cm cylinders.

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

$$\text{Concretes of standard strength: } f_{cj} = \frac{j}{4.76 + 0.83j} f_{c28} \text{ for } f_{c28} \leq 40 \text{ MPa} \quad (\text{Eq.2.1})$$

$$\text{High-strength concretes: } f_{cj} = \frac{j}{1.4 + 0.95j} f_{c28} \text{ for } f_{c28} > 40 \text{ MPa} \quad (\text{Eq.2.2})$$

$$\text{For } j \geq 28 \rightarrow f_{cj} = 1.1 f_{c28} \quad (\text{Eq.2.3})$$

b. Characteristic tensile strengths:

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

$$f_{tj} = 0.6 + 0.06 f_{cj} \quad (\text{Eq.2.4})$$

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

c. Instantaneous deformation

- **Longitudinal deformation**

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

$$E_{ij} = 11000 f_{cj}^{\frac{1}{3}} (\text{MPa}) \quad (\text{Eq.2.5})$$

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

$$E_{ij} = 3700 f_{cj}^{\frac{1}{3}} (\text{MPa}) \quad (\text{Eq.2.6})$$

- **Transverse deformation**

$\mu = 0.2$ in uncracked zones

$\mu = 0$ in cracked zones

- **Stress-strain diagram**

In Ultimate Limit State (ULS) calculations, when a precise evaluation of deformations is not required, the parabola-rectangle diagram (Fig. 2.1) can be adopted.

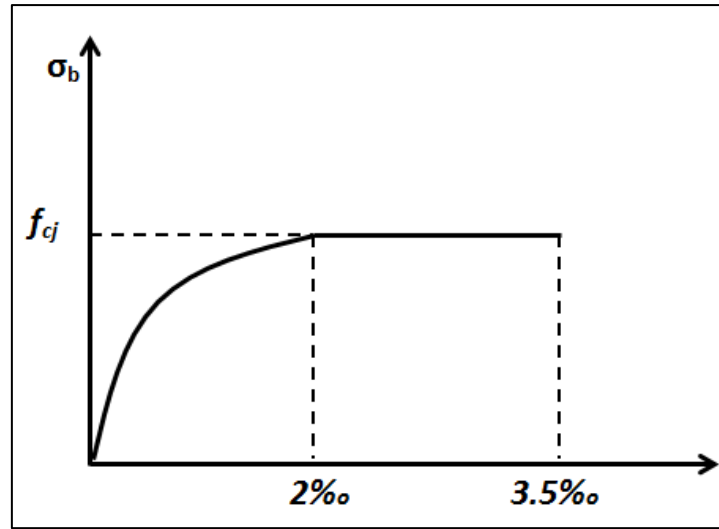


Figure 2.1. Characteristic stress-strain diagram of concrete.

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

$$f_{bc} = 0.85 \cdot \frac{f_{cj}}{\theta \cdot \gamma_b} \quad (\text{Eq.2.7})$$

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.

d. Time-Dependent Deformations (shrinkage, creep)

- **The shrinkage:**

Shrinkage is the time-dependent shortening of concrete, primarily caused by the loss of free water from the cement paste. The ultimate shrinkage strain depends on several factors, including:

- the concrete composition, particularly the water-to-cement ratio (W/C), with shrinkage generally increasing as the W/C ratio increases;
- the relative humidity of the surrounding environment;
- the cross-sectional dimensions of the structural member.

Under the climatic conditions of Algeria, the following simplified values of the shrinkage strain $\varepsilon_{sh}(t)$: (Climatic zoning map of Algeria, CBA 93)

- 2×10^{-4} in humid climate (Zone A)
- 3×10^{-4} in a dry temperate climate (Zone B)
- 4×10^{-4} in hot and dry climates (Zones B, C and D1)

- 5×10^{-4} in very dry or desert climates (Zones D2 and D3)

The value of the Shrinkage as a function of time can be expressed in the following form:

$$\varepsilon_{sh}(t) = \varepsilon_{sh} \cdot r(t) \quad (\text{Eq.2.8})$$

Or ε_{sh} and the final removal of the concrete

And $r(t)$ is a function of time varying from 0 to 1 when time t varies from 0 to infinity from the date of concreting.

$$r(t) = \frac{t}{t + 9r_m} \quad (\text{Eq.2.9})$$

t : the age of concrete, in days

r_m : the average radius of the part (cm) (Figure 2.2)

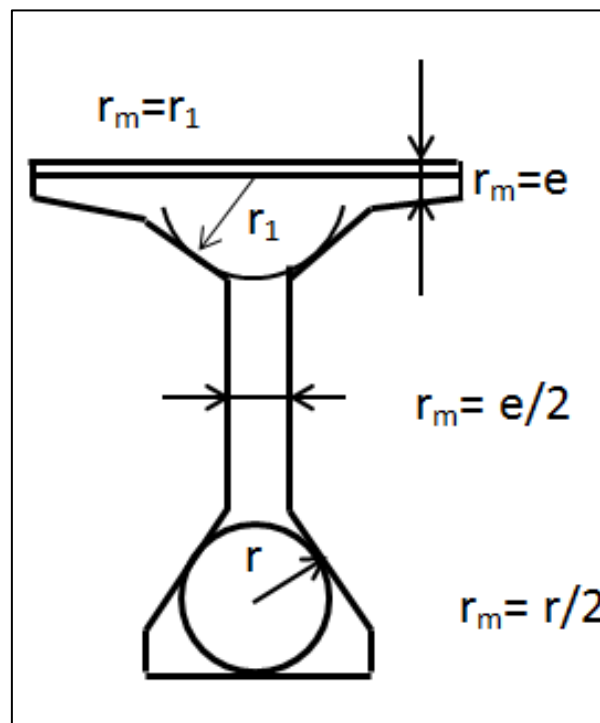


Figure 2.2. Part for shrinkage measurement

- **Creep**

Concrete creep is a long-term deformation under constant stress or load. The rate of increase in deformation is rapid at first, but decreases over time until a constant value is asymptotically approached.

The creep deformation of concrete has been found experimentally to depend not only on temperature, but also on the proportions of the mix, humidity, curing conditions and the age of the concrete when it is first loaded.

The delayed deformation is approximately 2 times the instantaneous deformation (Figure 2.3).

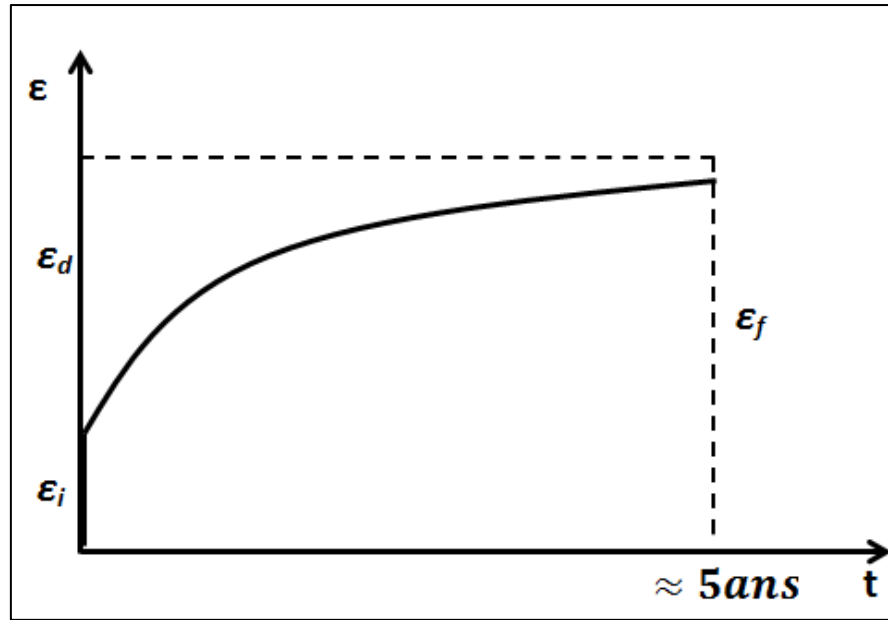


Figure 2.3. Creep deformation curve as a function of time

It is important to note that creep deformations increase proportionally to stresses if these do not exceed the elastic range, a range in which creep deformations are considered linear. After the appearance of microcracks and entry into the plastic range, creep increases more intensely than in the elastic range; it becomes non-linear.

The creep deformation at time t of concrete subjected to age $j = t_1 - t_0$ at a constant stress σ_1 is expressed by the formula :

$$\varepsilon_{cr} = \varepsilon_{ic} k_f (t_1 - t_0) f(t - t_1) \quad (\text{Eq. 2.10})$$

With: t_0 : date of concreting, t_1 : date of loading.

$\varepsilon_{ic} = \frac{\sigma_1}{E_{t28}}$ is the conventional instantaneous deformation under the effect of the stress σ_1 .

K_{cr} : Is the creep coefficient, which depends in particular on the age ($t_1 - t_0$) of the concrete at the time where it undergoes the stress σ_1 , and $f(t - t_1)$ a function of the duration of the loading ($t - t_1$), expressed in days, which varies from 0 to 1 when this duration varies from 0 to infinity.

It can also be written ε_f in the form:

$$\varepsilon_{cr} = \varepsilon_i \Phi (t_1 - t_0) f(t - t_1) \quad (\text{E. 2.11})$$

Where ε_i : Is the actual instantaneous deformation: $\varepsilon_i = \frac{\sigma_1}{E_{t28}}$

$\Phi = k_{cr} E_{ij} / E_{t28}$: is the ratio between the final creep deformation and the actual instantaneous deformation. In common cases, we can take:

$$\varepsilon_{cr} = \frac{\sigma_1}{E_{t28}} \Phi f(t - t_1) \quad (\text{Eq. 2.12})$$

The creep evolution law $f(t - t_1)$ is given by the formula:

$$f(t - t_1) = \frac{\sqrt{(t-t_1)}}{\sqrt{(t-t_1)+5\sqrt{r_{mf}}}} \quad (\text{Eq. 2.13})$$

Where: t (j) is the age of the concrete, t_1 (j): date of loading. r_m (cm): mean radius.

2.3. Prestressing Steel

In prestressed concrete members, the high-strength steel used for prestressing is available in the form of wires, bars, or strands. Its high tensile strength is primarily achieved by using steel with a slightly higher carbon content than that of mild steel. The typical chemical composition of prestressing steel is as follows:

- 0.60–0.85% carbon, to increase hardness and tensile strength;
- 0.70–1.00% manganese, to improve hardenability;
- a maximum of 0.05% sulfur and phosphorus, to limit impurities;
- small amounts of silicon, to enhance strength.

The manufacturing process begins with the hot rolling of high-carbon steel billets into bars. These bars are then cold-drawn through a series of dies, a process that progressively reduces their diameter while significantly increasing their tensile strength through strain hardening.

2.3.1. Stress - strain diagram :

The BPEL code recommends the stress-strain relationship shown in Figure 2.4 for cold-drawn wires and prestressing strands. Since these high-strength prestressing steels do not exhibit a well-defined yield plateau, it is difficult to identify a true yield strength. Therefore, the conventional yield strength is defined as the intersection of the stress-strain curve with a line parallel to the initial elastic portion of the curve and offset by 1‰ (0.1%) strain.

Based on this stress-strain relationship, the following expressions are adopted:

$$\text{For } \sigma_p > 0.9f_{peg}: \varepsilon_p = \frac{\sigma_p}{E_p} + 100 \left(\frac{\sigma_p \gamma_p}{f_{peg}} - 0.9 \right)^5 \quad (\text{Eq. 2.14})$$

$$\text{For } 0 < \sigma_p < 0.9f_{peg}: \varepsilon_p = \frac{\sigma_p}{E_p} \quad (\text{Eq. 2.15})$$

The term f_{peg} refers to the guaranteed yield strength (or guaranteed 0.1% proof stress) of prestressing steel.

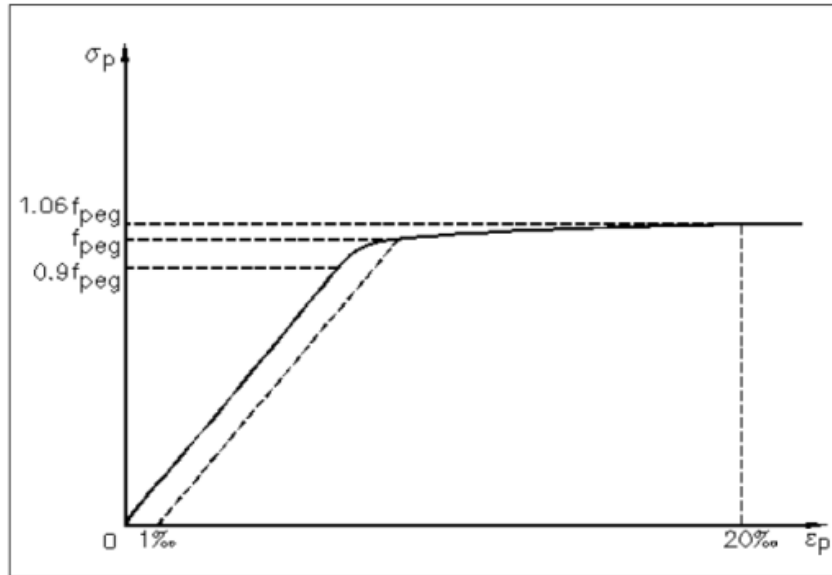


Figure 2.4: Stress–strain diagram for quenched wires and prestressing bars.

For hardened wires and bars (Figure 2.5), it is assumed that:

$$\varepsilon_p < \frac{f_{peg}}{E_p} \text{ SO } \sigma_p = E_p \cdot \varepsilon_p \quad (\text{Eq. 2.15})$$

$$\varepsilon_p \geq \frac{f_{peg}}{E_p} \text{ SO } \sigma_p = f_{peg} \quad (\text{Eq. 2.16})$$

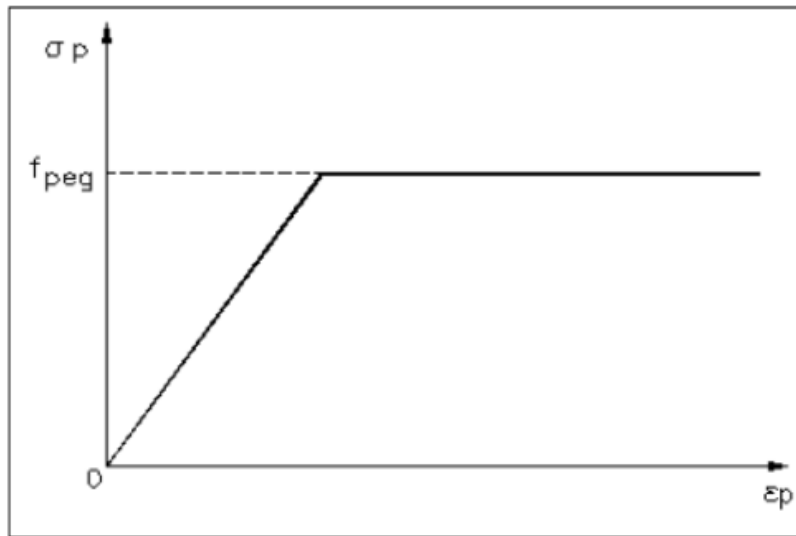


Figure 2.5: Stress-strain diagram for hardened wires and bars.

2.3.2. Types of Prestressing Reinforcement

2.3.2.1. Wires

Cold-drawn prestressing wires undergo a stress-relieving heat treatment (also referred to as stress relieving) at temperatures ranging from 150°C to 420°C to enhance their

mechanical properties. This process significantly increases their tensile strength while reducing residual internal stresses.

Prestressing wires are manufactured in the following standardized nominal diameters:

- 4, 5, 6, 7, 8, 10, and 12.2 mm;
- with an ultimate tensile strength ranging from 1,700 to 1,800 MPa (Figure 2.6).



Figure 2.6. Prestressing wires

2.3.2. 2. Bars:

High-strength steel bars commonly used in prestressed concrete are manufactured in standard nominal diameters of 12.5, 16, 20, 22, 26, 32, and 36 mm, with lengths ranging from 16 to 18 m (Figure 2.7). Their ultimate tensile strength varies depending on the bar diameter.



Figure 2.7. High-strength prestressing bars

2.3.2.3 . Strands:

A prestressing strand consists of several high-strength steel wires helically wound around a central wire or twisted together through an industrial process known as stranding (Figure 2.8). The number of wires forming a strand is given by:

$$N = 1 + 3n(n + 1) \quad (\text{Eq . 2.17})$$

where **(n)** is the number of additional layers of wires surrounding the central core.

Typical strand configurations include:

- **3-wire strand:** one central wire and two outer wires.
- **7-wire strand:** one central wire surrounded by six outer wires.
- **19-wire strand:** one central wire, six intermediate wires, and twelve outer wires.

Prestressing wires and strands are generally assembled to form **prestressing tendons (cables)**.

Requirements for Prestressing Steel

Prestressing steel must possess the following characteristics:

- **High ductility:** The reinforcement should be capable of undergoing strains significantly greater than those experienced by the surrounding concrete (due to shrinkage and creep) in order to maintain the prestressing force over time. Insufficient elongation may result in excessive prestress losses and a reduction in the compressive stresses within the concrete.
- **Adequate surface characteristics (bond):** Good bond between the prestressing steel and concrete is essential to ensure efficient force transfer, particularly in **pretensioned** members.



Figure 2.8. Prestressing strands for prestressed concrete