

Innovative Concretes:

Course, Exercises and Experimental Applications



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Preface

This course booklet provides a synthesis of the main innovative concretes used in the field of civil engineering. It is intended for first-year Master's students in the specializations *Intelligent Rehabilitation of Buildings* and *Structures*, within the framework of the modules Innovative Materials and Experimental Approaches.

The document addresses the fundamental concepts related to the mix design, properties, and performance of several types of advanced concretes. In particular, it discusses self-compacting concrete (SCC), high-performance concrete (HPC) and very high-performance concrete (VHPC), ultra-high-performance fiber-reinforced concrete (UHPFRC), as well as self-healing concrete.

Each chapter combines theoretical concepts, application exercises, and the presentation of several experimental tests used to characterize these materials. The objective is to provide students with the necessary foundations to understand, design, and evaluate these innovative concretes in modern civil engineering applications.

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Symbol Notation

Abs : Absolute

App : Apparent

B : Binder

C, CEM : Cement

C_{op} : Optimal compactness

D_i : particle size class i

FA : Fly Ash

FACE : French Association of Civil Engineering

G : Gravel

G/S : gravel-to-sand ratio

GGBFS : Ground Granulated Blast Furnace Slag

HPC : High-Performance Concrete

ITZ : interfacial transition zone

k : homothety factor

M_{liq} : liquid mass

M_{sol} : Solid Mass

P : Laitance

P : Paste

S : Sand

SCC : *Self-Compacting Concrete*

SHC : *Self-Healing Concretes*

SP : Superplasticizer

SSD : saturated surface-dry density

UHPFRC : Ultra-High-Performance Fiber-Reinforced Concrete

VGra : the granular skeleton volume

V_{liq} : Liquid volume

VMA : viscosity-modifying agents

VP : cement paste volume

V_{PC} : paste volume filling the voids

V_{PE} : excess paste volume

W : Water

W/B : water-to-binder ratio

W/C : water-to-cement ratio

Introduction

Nowadays, concrete is the main *construction material* used by the majority of construction companies. Its mix design is increasingly tailored to the specific requirements of each structure, whether in terms of flowability for placement, mechanical behavior to withstand various loads, or durability to resist aggressive environments. In addition to these performances, modern construction also demands other requirements such as aesthetics, reduction of nuisances on construction sites, rapid return to service, and sustainable development.

The emergence of innovative concretes has marked a new stage in the history of concrete as a material. These innovative concretes in the fields of civil engineering, building, and public works provide *new* solutions and offer several technical advantages (pumpability, improved ductility, high strength, etc.) as well as socio-economic benefits (resource savings).

Among these innovative concretes, one can notably mention self-compacting concrete (SCC), which is characterized by its high flowability and its ability to place itself without vibration. There are also high-performance concretes (HPC) and very high-performance concretes (VHPC), which exhibit mechanical strengths and durability significantly higher than those of conventional concretes. In addition, ultra-high-performance fiber-reinforced concretes (UHPFRC) combine a very dense matrix with fibers that improve tensile strength and post-cracking behavior. More recently, the development of self-healing concretes has opened new perspectives by enabling the autonomous repair of microcracks and improving the durability of structures.

These innovative concretes now represent a promising approach for designing structures that are more efficient, more durable, and better adapted to the technical and environmental requirements of modern civil engineering.

The present course booklet provides a synthesis of the main innovative concretes taught to **first-year Master's students** in two different specializations : *Intelligent Rehabilitation of Buildings and Structures*. It is part of two teaching modules, namely **Innovative Materials** and **Experimental Approaches**.

This document is structured into four chapters, designed according to a similar organization. Each chapter includes fundamental theoretical concepts, application exercises, and the presentation of several material characterization tests. However, each chapter focuses on a specific type of innovative concrete.

Thus, the first chapter is devoted to self-compacting concrete (SCC), the second chapter deals with high-performance concrete (HPC) and very high-performance concrete (VHPC), the third chapter concerns ultra-high-performance fiber-reinforced concrete (UHPFRC), while the last chapter is dedicated to self-healing concrete.

Chapter 1 : Self-Compacting Concrete

1.1. Definition of Self-Compacting Concrete

Self-compacting concrete (SCC) is a special type of highly flowable concrete that can spread and place under its own weight, without the need for internal or external vibration, even in formworks with a high density of reinforcement.

The distinctive feature of self-compacting concrete mainly lies in its properties in the fresh state. According to EN 206-1, it is defined as follows: “Fresh concrete is referred to as self-compacting when it is able to compact sufficiently under its own weight while remaining homogeneous, without segregation.”

1.2. Properties of Self-Compacting Concrete (SCC)

1.2.1. Workability of Self-Compacting Concrete

The workability properties of SCC can be divided into three measurable criteria: filling ability, resistance to segregation, and passing ability through obstacles.

First, self-compacting concrete must be capable of filling voids and confined spaces under its own weight, without any external compaction energy (vibration), and with sufficient flow rate. Two main aspects are highlighted:

- Filling ability (deformation capacity), expressed by the percentage of space filled or the distance reached within a given area.
- Filling rate, expressed by the flow velocity of the concrete.

Optimizing the coarse aggregate-to-sand ratio (G/S) is essential for SCC, which requires high fluidity and good passing ability. The optimal value of this ratio generally lies between 0.8 and 1.2. For G/S ratios lower than this range, the slump flow typically decreases due to the higher sand content, which reduces the amount of free water responsible for mixture fluidity. This is because sand absorbs more water than coarse aggregates, mainly due to its higher fines content.

On the other hand, when the G/S ratio exceeds 1.2, contacts between sand particles become less influential than those between coarse aggregates. Blocking becomes more governed by aggregate size, which may lead to granular congestion. It is therefore clear that a G/S value close to unity is generally adopted in most SCC mix designs.

The European Guidelines for Self-Compacting Concrete indicate that slump flow depends not only on the proportions of aggregates but also on the paste volume, which typically ranges between 330 and 400 l/m³ of concrete.

Passing ability through obstacles is another key parameter for SCC. A difference may arise between the velocity of aggregates and that of the paste, the latter being higher. This may cause paste washout through the aggregate skeleton at reinforcement openings. The aggregates tend to come into contact upstream of the opening between reinforcing bars, leading to arch formation and flow blockage due to clogging (Figure 1.1).

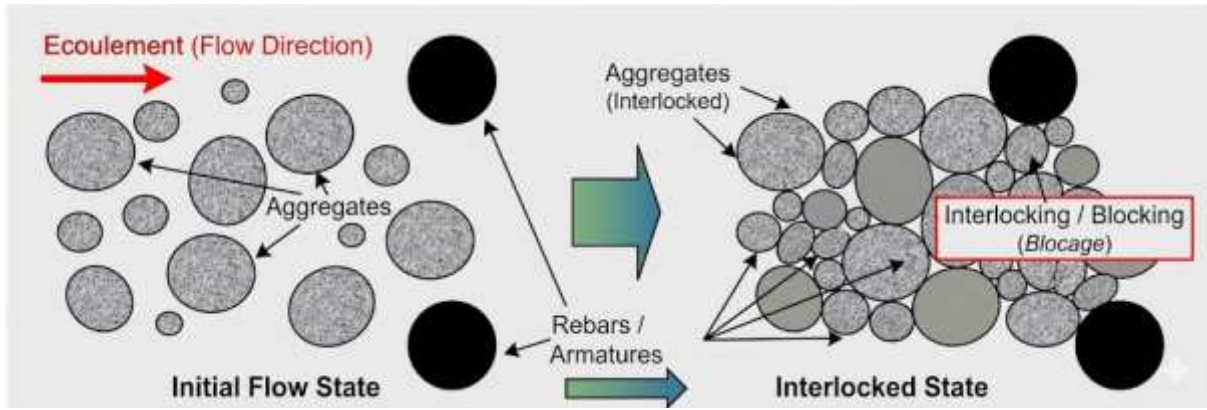


Figure 1.1: Representation of aggregate blocking through two reinforcing bars

Passing ability is therefore mainly affected by the paste volume and the characteristics of the aggregates. Reducing the maximum size of the coarse aggregates, as well as improving the particle size distribution, can be beneficial for enhancing passing ability. It is also necessary to reduce the aggregate content in the concrete and increase the paste volume in order to minimize friction and interparticle contact between aggregates.

The new classification of self-compacting concrete (SCC), presented in Table 1.1, distinguishes three categories of SCC according to their field of application.

Table 1.1 : SCC Classification

		Horizontal Application				Vertical Application	
		Thickness ≤ 300 mm		Thickness > 300 mm			
Maximum Path length (m)		Less than 5 m	Between 5 m and 10 m	Less than 5m	Between 5m and 10 m	Less than 5 m	Between 5 m and 10 m
Flow Interval (mm)	Categorie 1 : $I \geq 100$ mm	1		2(a)	2(b)	2(a)	2(b)
	Categorie 2 : $80 \leq I < 100$ mm	2(a)	2(b)	2(a)	2(b)	2(a)	2(b)
	Categorie 3 : $I < 80$ mm	3(a)	3(b)	3(a)	3(b)	3(a)	3(b)

The subclasses a and b depend on the maximum horizontal flow distance of SCC in the formwork (5 m for 2(a) and 3(a), and 10 m for 2(b) and 3(b)).

The flow interval I is the dimension (in mm) of the smallest space through which the concrete must pass in order to properly fill the structural element.

1.2.2. Segregation Resistance

In SCC, the mortar must have a consistency that allows it to keep the coarse aggregates suspended. Similarly, in mortar, the cement paste must have a consistency that enables it to keep the sand particles in suspension, and furthermore, the cement grains must form a stable suspension in water. When one or all of these three conditions are not fulfilled, bleeding and/or segregation may occur. Segregation in SCC therefore corresponds to the separation of the solid and liquid phases, or to the separation of solid particles according to their size, which may lead to flow blockage in confined areas.

Segregation in self-compacting concrete (SCC) results from an imbalance between gravitational forces and the mixture's ability to remain homogeneous. It generally occurs when the paste volume is insufficient to properly coat the aggregates, or when the paste viscosity is too low, promoting the settling of heavier particles. Excess water, improper superplasticizer dosage, or poorly optimized aggregate grading (lack of fines or excess coarse aggregates) can further exacerbate this phenomenon. In addition, poor mixture cohesion or an inadequate paste-to-aggregate ratio reduces the stability of SCC. Therefore, controlling segregation relies on achieving an appropriate balance between fluidity and viscosity, often ensured by a sufficient paste volume and the use of fine additions or viscosity-modifying agents.

To prevent segregation problems, it is necessary not only to reduce the amount of free water in the concrete by lowering the water-to-cement ratio (W/C), but also to optimize the dosage of admixtures and to increase the viscosity of the water in suspension by using viscosity-modifying agents.

1.3. Constituents of Self-Compacting Concrete

Self-compacting concrete is formulated using several constituents, namely: cement, aggregates of different size classes, water, chemical admixtures, viscosity-modifying agents, and mineral additions.

1.3.1. Cement Paste

Cement paste consists of cement, mineral additions, effective water, air, and admixtures.

a. Cement

Portland cement is a fundamental component in concrete design, as its hydration products provide cohesion to the granular skeleton, thereby ensuring the mechanical strength of both the material and the concrete structure.

In principle, all cements complying with EN 197-1 (NA 442) are suitable for the production of self-compacting concrete.

In the presence of a superplasticizer, increasing the cement content thickens the lubricating layer around the aggregates, thereby improving the fluidity of SCC.

b. Mineral Additions

The incorporation of various mineral additions into concrete as partial replacements for Portland cement not only improves certain properties and reduces cost, but also helps protect the environment by lowering carbon dioxide emissions associated with cement production.

The main mineral additions, identified from 1352 mixtures reported in 250 studies, used in SCC formulations are summarized in Table 1.2.

Table 1.2 : Main types of mineral additions used in SCC (1352 mixtures)

Type of addition	% of studies	Type of addition	% of studies
Limestone fillers	40.7%	Natural pozzolan	0.2%
Fly ash	35.1%	Quartz powder	1.8%
Granite powder	0.3%	Metakaolin	0.7%
Kiln dust	0.1%	Ground granulated blast furnace slag	9.0%
Basalt powder	0.2%	Silica fume	9.2%

- Limestone Fillers

Limestone fillers are among the most commonly used mineral additions in SCC in our country. They are finely ground dry products derived from limestone quarries. As such, they tend to fill the voids between particles in the mortar, thereby increasing the compactness of the mixture and improving particle packing within the matrix.

Although generally inert, limestone fillers can, in some cases, participate in hydration reactions associated with the aluminate phase by forming monocarboaluminate, and they may also react with C_3S and C_2S to form calcium carbo-silicate hydrates. In the long term, however, the effects of limestone fillers are less significant due to the absence of pozzolanic reactions.

Partial replacement of cement with limestone fillers, up to 20%, is generally recommended for SCC.

- Natural Pozzolan

Natural pozzolan is another widely used addition in cementitious materials in Algeria, especially considering the significant reserves of this material in the western region (Oran area). Natural pozzolan originates from volcanic or sedimentary rocks with suitable chemical composition.

Natural pozzolan does not have intrinsic hydraulic properties; however, in the presence of lime released by clinker during hydration, it forms stable hydrates similar to those produced by clinker hydration.

Replacing cement with natural pozzolan has little positive effect on flow parameters, as pozzolan either increases water demand or requires a higher dosage of superplasticizer due to its alumina content (Al_2O_3). In general, the workability of SCC can be improved by replacing cement with natural pozzolan up to a substitution level of 20%.

1.3.2. Water

The water used must comply with EN 1008. For concrete production, water should not contain compounds that could chemically attack the cement, additions, aggregates, or reinforcement, nor suspended particles in quantities that could alter its original quality or affect mix uniformity. For this reason, potable water is often used as a reference in concrete formulation due to its availability.

It should be noted that a portion of the water added to concrete is absorbed or adsorbed by aggregates, another portion is consumed by hydration of the binder, and the remaining free water in the matrix

is responsible for concrete fluidity, influencing the solid concentration in the suspension between aggregates. Therefore, water plays a key role in concrete workability. Excess water can lead to reduced mechanical strength and the appearance of bleeding and segregation phenomena.

1.3.3. Admixtures

Several types of admixtures exist, but those that can modify the flow of SCC and are part of the basic formulation include superplasticizers and viscosity-modifying agents (VMA).

a. Superplasticizers

For a fixed water-to-binder ratio, superplasticizers make the concrete more fluid and workable, facilitating placement. For a targeted consistency, this type of admixture allows reducing the water-to-binder ratio to increase both short- and long-term mechanical strength and to reduce shrinkage.

The effects of superplasticizers on concrete include:

- Maintaining workability in the fresh state,
- Improving compactness,
- Enhancing the concrete-to-steel bond,
- Reducing capillary porosity of the cement paste,
- Decreasing the permeability coefficient,
- Improving pumpability.

It is preferable to introduce superplasticizers in liquid form to quickly achieve their benefits. If in powder form, some time is needed for dissolution before they become effective.

SCC is generally produced using third-generation superplasticizers based on polycarboxylate ethers (PCE). Second-generation superplasticizers based on sulfonates (polynaphthalene sulfonates (PNS), lignosulfonates, polymelamine sulfonates (PMS)) can also be used, though at higher dosages.

However, excessive dosage may cause segregation and bleeding issues.

• Mechanism of Action of Superplasticizers

The fluidization of fresh concrete by superplasticizers can be explained by the dispersion of cement and addition particles. Superplasticizers are currently considered powerful dispersing agents, as they prevent the agglomeration of cement particles and release the water trapped within these agglomerates.

The deflocculation and dispersion of cement particles are directly related to the adsorption of superplasticizers on the particle surfaces. When a superplasticizer adsorbs onto a cement particle, its dissociated acidic functional groups modify the particle's surface charges, imparting a negative charge (Figure 1.2). As a result, interactions between neighboring particles are minimized through electrostatic repulsion, leading to the deflocculation and uniform dispersion of solids in the suspension.

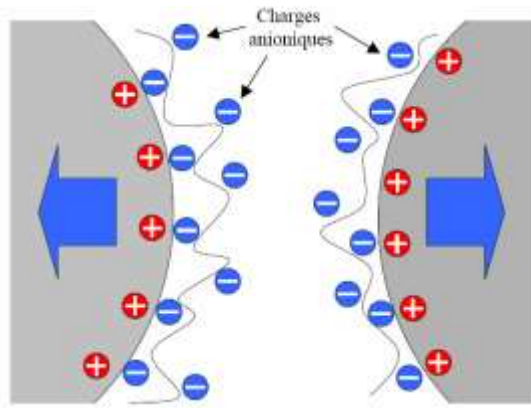


Figure 1.2 : *Electrostatic repulsion between two cement and/or supplementary material particles*
(El Barrak, 2005)

Additionally, a repulsion due to the steric effect, also called the crowding effect (Figure 1.3), is induced by the presence of macromolecules that make up the superplasticizer coating the particle surfaces. Steric hindrance is therefore a purely repulsive force that prevents Van der Waals interactions from generating an attractive force between the particles. This effect is particularly noticeable when the distance between polymers decreases, or for superplasticizers with very long molecular chains, such as polycarboxylates.

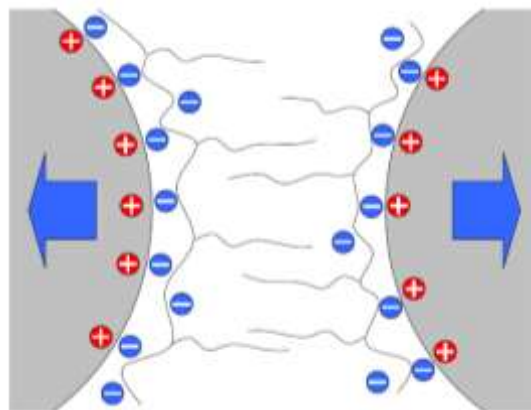


Figure 1.3 : *Cement and/or supplementary material particles coated with polymers exhibiting high steric hindrance* (El Barrak, 2005)

The dosage of the superplasticizer must be sufficient to ensure that a portion remains available in the interstitial solution, which will firstly contribute to greater workability over a longer period and secondly replace the superplasticizer molecules consumed during hydration. Moreover, a cement/superplasticizer combination is considered incompatible when a superplasticized concrete rapidly loses its initial slump. The issue arising between cement and superplasticizers manifests as early stiffening, where fluidization was expected.

b. Viscosity Agents

These are generally cellulose derivatives, polysaccharides, colloidal suspensions, or suspensions of siliceous particles. Their role is to ensure good resistance to segregation in concrete without adversely affecting the workability provided by superplasticizers. Viscosity agents consist of long-chain polymer molecules that stabilize the interstitial water, making it more viscous and adhesive, thereby preventing the separation of coarse particles.

There appears to be a threshold dosage of viscosity agents, beyond which segregation is effectively controlled. Their use is particularly justified in concrete with a high water-to-binder (W/B) ratio, as the fine particles alone may not be sufficient to retain the water within the mix. Conversely, their use is not warranted for SCC (Self-Compacting Concrete) with a low W/B ratio ($W/B < 0.3$).

Viscosity agents increase the robustness of concrete, making it more stable by preventing bleeding, reducing sensitivity to W/B variations, and minimizing shrinkage by thickening the paste and maintaining a homogeneous distribution of the constituents. However, they may lead to excessive air entrainment and a reduction in flowability.

Typically, viscosity agents are supplied as powders and are mixed either with the dry materials or with a portion of the mixing water. In effect, their action is somewhat opposite to that of superplasticizers. Nevertheless, it is essential to always control the compatibility between cement, viscosity agents, and superplasticizers.

Regarding the order of addition, some authors report that the viscosity agent is generally added first to the mixture, while the superplasticizer is introduced only during the final stage of mixing.

1.3.4. Granular Phase

This phase consists of sand and gravel, which form the skeleton of the concrete. The mechanical strength of the concrete strongly depends on their properties. Aggregates must be chemically inert with respect to cement, water, and air. Accordingly, they must comply with EN 12620.

To prevent blocking of SCC during placement in formwork around reinforcement, the maximum aggregate size is generally limited to 20 mm. Choosing a larger maximum size is possible but only justified when confinement is low.

Aggregate shape also affects workability. For self-compacting concrete, both rounded and crushed aggregates can generally be used. Rounded aggregates, due to their shape, provide a smaller intergranular void volume, requiring less cement paste to fill and generally reducing water demand. They also have good intrinsic strength but form a weaker bond with the cement paste. Conversely, crushed aggregates, with their larger specific surface area, offer better dispersion within the paste but require more water due to their density and absorption. Additionally, these aggregates exhibit excellent adhesion to the cement matrix because of their chemical composition, porosity, angularity, and rough texture.

Recommendations from the FACE (2000) suggest adopting a gravel-to-sand ratio of approximately 1 for SCC.

1.4. Formulation of SCC

The composition of self-compacting concrete is chosen to satisfy both fresh and hardened state requirements. Accordingly, several formulation methods have been developed.

1.4.1. Experience-Based Methods

a. Empirical Formulation

This method is based on an empirical approach. The first step involves synthesizing formulation principles from published research and adapting them to the materials used. The second step is verification and validation through trial tests, which is essential to ensure reliability of the designed mix.

This method relies on criteria proposed in the specialized literature, namely:

- A gravel-to-sand ratio close to 1,
- A water-to-binder ratio close to 0.5,
- Paste volume between 33–40% of the concrete volume, i.e., 330–400 L/m³,
- Cement content between 350–450 kg/m³,
- Supplementary material-to-cement ratio close to 0.20,
- Superplasticizer dosage near its saturation point,
- Gravel volume between 30–34% of the concrete volume,
- Sand mass between 48–55% of the aggregate mass.

A trial batch should be prepared to validate the formulation or make necessary adjustments.

1.4.2. Japanese Method

The Japanese approach to SCC formulation was developed at Kochi University, Japan. This method prioritizes paste volume over aggregates. The procedure first sets the gravel dosage in the concrete and the sand dosage in the mortar, then optimizes the cement paste to achieve the best overall performance in the resulting concrete.

Concrete produced with this approach is under-aggregated and therefore less economical.

a. Gravel Dosage :

Japanese researchers showed that the risk of blocking is minimized when the gravel volume for 1 m³ of concrete is limited to half of its packing density. Consequently, the gravel volume is set at 50% of the total solid volume in the concrete. However, the researchers do not specify how the packing density is measured. Nevertheless, it can be calculated by dividing the bulk density by the absolute density.

$$Compacity = \frac{Solid\ Volume}{Total\ Volume} = \frac{Bulk\ density}{Absolute\ density}$$

b. Sand dosage:

To ensure good workability, the sand volume is set at 40% of the total mortar volume. In this approach, it should be noted that sand particles below a certain size are considered as powder. The authors of the method recommend a threshold of 90 µm, while others suggest a threshold of 125 µm.

c. Binder dosage:

The paste is optimized using two mortar tests, as shown in Figure 1.4. The volumetric water-to-binder ratio (W/B) is generally set between 0.9 and 1.0 depending on the powder properties. The superplasticizer dosage and the final W/B ratio are then adjusted until an SCC is obtained that meets the desired performance requirements.

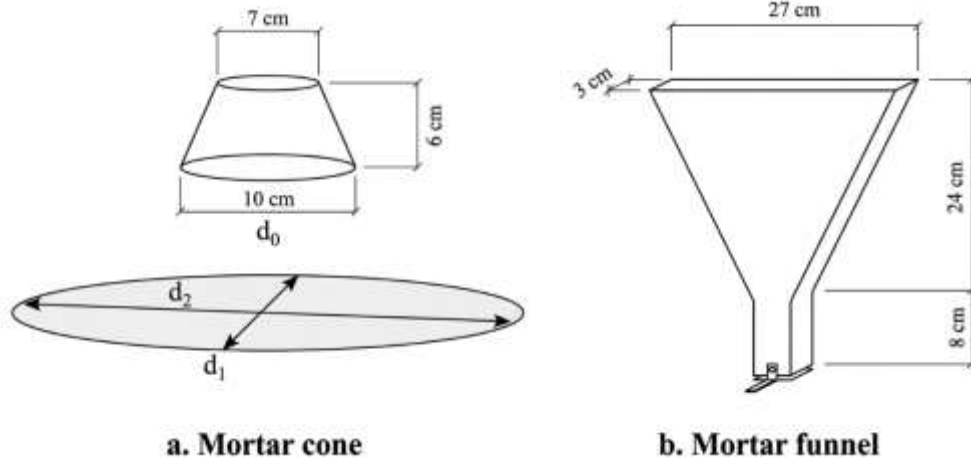


Figure 1.4 : *Dimensions of the cone and mortar funnel (EFNARC, 2002)*

The measured parameters are the spread diameter of the mortar pat and the flow time through the funnel. These parameters are :

The relative spread, which represents fluidity :

$$\Gamma_m = \frac{(d_1 \cdot d_2 - d_0^2)}{d_0^2} \quad (1)$$

here:

- d_1 and d_2 : spread diameters measured in two perpendicular directions,
- d_0 : bottom diameter of the cone (10 cm).

The relative flow velocity, which represents viscosity :

$$R_m = \frac{10}{t} \quad [s^{-1}] \quad (2)$$

Where:

- t : flow time through the funnel, in seconds.

The method does not specify how to proportion the binder. However, the cement content may be fixed in accordance with the relevant standard or selected based on strength requirements. The authors, nevertheless, optimize the superplasticizer dosage and the water-to-binder ratio (W/B) in order to simultaneously achieve the desired relative spread $\Gamma_m = 5$ and relative flow velocity $R_m = 1 \pm 0,1 \text{ [s}^{-1}\text{]}$.

1.4.3. Excess Paste Method

The excess paste theory considers that, in order to obtain concrete with good workability, it is necessary to have sufficient paste to coat the surface of the aggregates so as to minimize friction at their contact points, as well as an additional amount of paste to further improve workability (Figure 1.5).

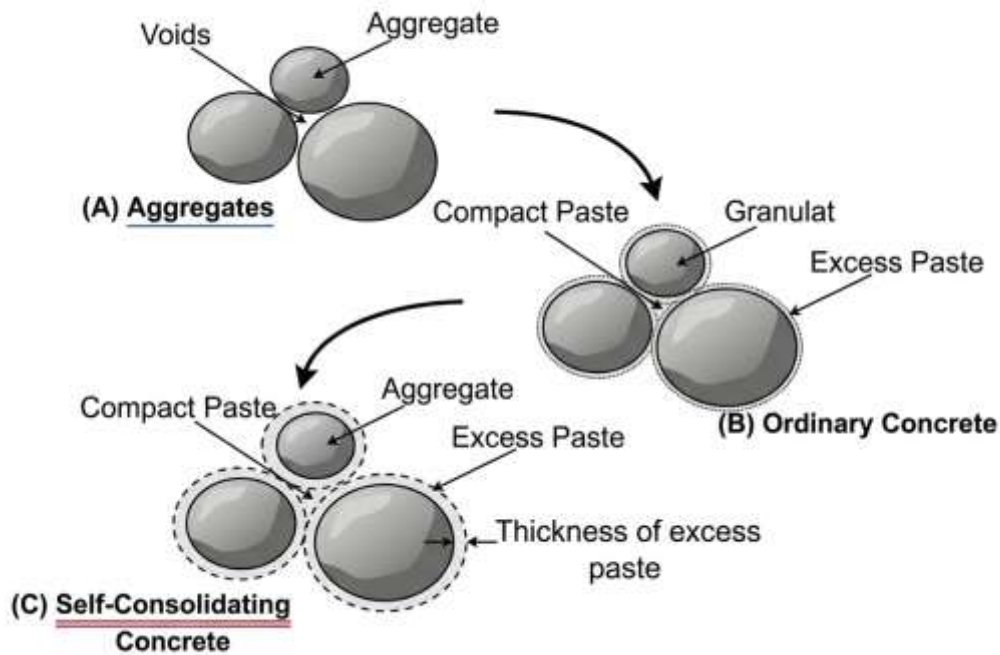


Figure 1.5 : *Excess Paste Theory (Shi et al., 2005)*

By combining cement paste with compacted aggregates, the latter become dispersed and separated by a layer of cement paste. The greater the thickness of this layer, the lower the friction between particles and, consequently, the better the workability of the mixture.

The excess paste theory assumes that the aggregates in concrete are spherical and that the particle size distribution in the concrete is uniform and continuous.

Figure 1.6(a) shows the composition of concrete, where the aggregates are well spaced by the cement paste. If we imagine that the aggregates in the sample are compacted to their maximum density, two paste volumes are considered:

- one volume (V_{PC}) used to fill the voids within the granular skeleton, and
- another volume (V_{PE}) intended to coat the aggregates (Figures 1.6(b) and 1.6(c)).

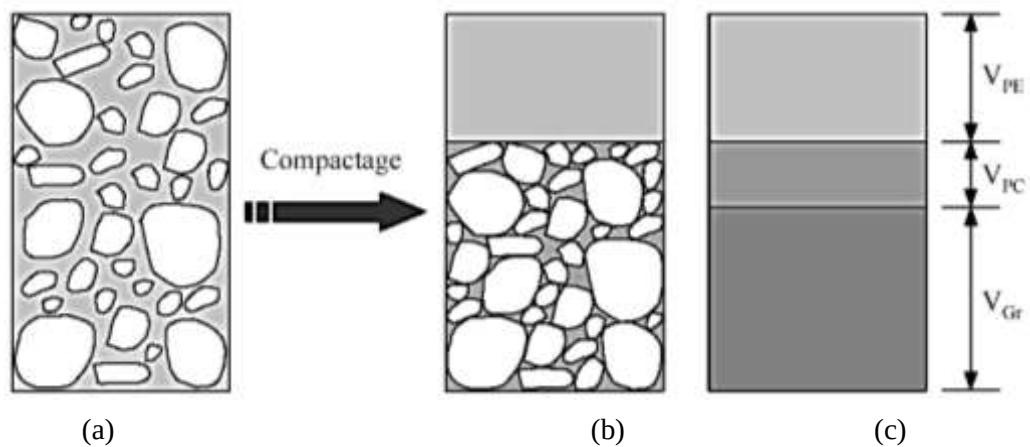


Figure 1.6 : *Excess Paste Theory – Concrete Composition (El Barrak, 2005)*

Concrete therefore consists of two main volumes: the volume of aggregates (VGra) and the volume of paste, which is divided into two components: the excess paste volume (VPE) and the paste volume filling the voids (VPC).

The excess paste method is based on the assumption that the thickness of the excess paste layer surrounding an aggregate particle is proportional to its size (or diameter), due to a mass effect.

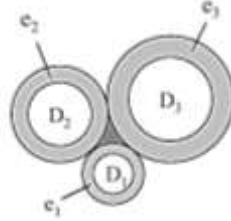


Figure 1.7 : Homothety Principle (El Barrak, 2005)

$$\frac{D_1 + 2.e_1}{D_1} = \frac{D_2 + 2.e_2}{D_2} = \frac{D_3 + 2.e_3}{D_3} = k \quad (3)$$

Therefore, for an aggregate class i with particle size D_i , the thickness of the excess paste layer is denoted as e_i :

$$\frac{D_i + 2.e_i}{D_i} = k \quad (4)$$

Consequently, the parameter k (homothety factor), which relates the thickness of the excess paste layer to the aggregate diameter, is the same for all aggregate classes (n).

The total excess paste volume (VPE) can therefore be expressed, for n classes, as follows:

$$V_{PE} = \sum_{i=1}^n \left(\frac{\pi \cdot (D_i + 2 \cdot e_i)^3}{6} - \frac{\pi \cdot D_i^3}{6} \right) \cdot N_i \quad (5)$$

Where

N_i is the number of aggregates of size D_i belonging to class i .

The homothety factor k can be determined as a function of the excess paste volume as follows:

$$k = \sqrt[3]{1 + \frac{6 \cdot V_{PE}}{\pi \cdot \sum_{i=1}^n N_i \cdot D_i^3}} = \sqrt[3]{1 + \frac{V_{PE}}{V_G}} \quad (6)$$

The value of k ranges between 1.121 and 1.139 for concrete made with rounded aggregates, and between 1.135 and 1.154 for concrete made with crushed aggregates:

- For crushed aggregates:

$$k = -0.026 (G/S) + 1.176 \quad (7)$$

- For rounded aggregates:

$$k = -0.025 (G/S) + 1.159 \quad (8)$$

From the obtained value of k , it is possible to determine, for each aggregate of size D_i , the corresponding excess paste thickness e_i :

$$e_i = \frac{(k-1)}{2} \cdot D_i \quad (9)$$

The paste volume within one unit volume of concrete can then be deduced, as well as the total volume of the granular skeleton and the water retained by this skeleton.

The sum of the cement paste volume (V_p), the granular skeleton volume (V_{Gra}), and the water retained (V_{ER}) by this skeleton constitutes one unit volume of self-compacting concrete:

$$V_p + V_{Gra} + V_{ER} + V_v = 1 \quad (10)$$

The void volume (V_v) is generally estimated at 2.5%.

1.5. Characterization of Self-Compacting Concrete (SCC)

To characterize self-compacting concrete in the fresh state, EN 206-9 specifies that three main properties must be considered:

- Flowability in unconfined conditions,
- Passing ability in confined conditions,
- Stability, i.e., resistance to segregation and bleeding.

1.5.1. Filling and Passing Ability

a. Slump Flow Test (Abrams Cone) (EN 12350-8)

This is the most commonly used test to assess the fluidity of concrete. It is easy to transport, perform on site, and clean. In addition, it provides information on the concrete's fluidity, viscosity, and risk of segregation (Figure 1.8).

The test requires an Abrams cone and a flat metallic plate measuring 90 cm on each side, marked with a 50 cm diameter circle.

The cone may be positioned with the smaller opening either at the bottom or at the top; however, it is essential to always follow the same procedure. It should be noted that when the smaller opening is placed at the bottom, filling the cone with SCC is facilitated, and lifting of the cone during filling is prevented.

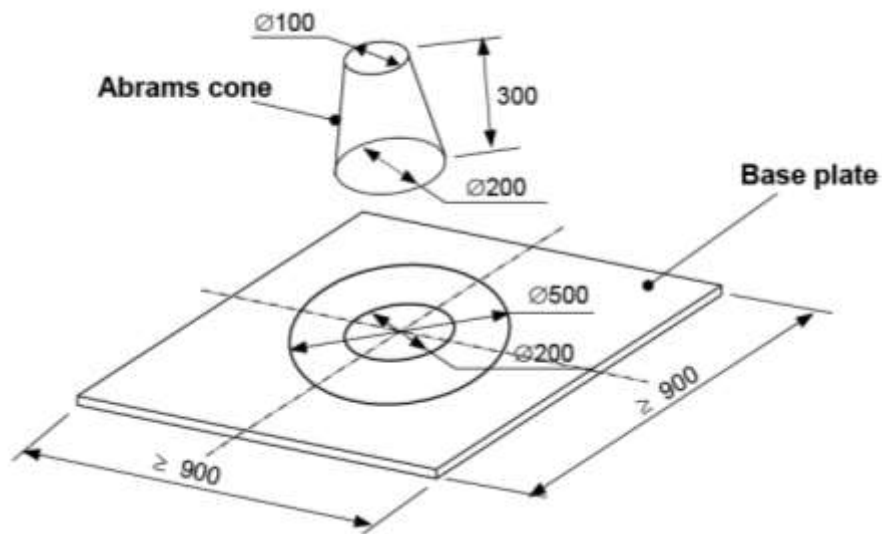
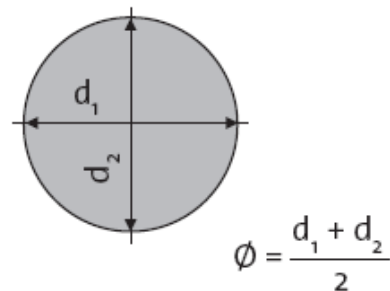


Figure 1.8 : Slump Flow Test Using the Abrams Cone (EFNARC, 2005)

The slump flow test using the Abrams cone provides information on two aspects: fluidity and deformation rate.

Indeed, the final diameter reached by the concrete pat corresponds to its deformation capacity (i.e., fluidity). According to Association Française de Génie Civil (AFGC), the slump flow value corresponds to the average diameter of the concrete spread obtained and should range between 550 mm < Φ < 850 mm, depending on the intended application of the concrete.

Furthermore, if the difference between the two perpendicular diameters $|d_1 - d_2|$ exceeds 50 mm, the test must be considered invalid and repeated.



NF EN 206-9 (2010) distinguishes three slump flow classes. These classes are defined based on the measured slump flow diameter (Φ) obtained from the Abrams cone test:

- SF1: 550 to 650 mm
- SF2: 660 to 750 mm
- SF3: 760 to 850 mm

These classes correspond to different levels of flowability, depending on the application and structural.

b. Deformation Rate – T500

The deformation rate of concrete corresponds to the T_{500} time, i.e., the time required for the concrete to reach a diameter of 500 mm during the slump flow test. This value is very difficult to measure, especially for highly flowable concretes.

According to NF EN 206-9 (2010), two viscosity classes can be distinguished (Table 1.3):

Table 1.3. : Flow class according to the T_{500} time according to the standard NF EN 206.

	Flow Class	
	V_{S1}	V_{S2}
T_{500} (s)	≤ 2	> 2

The slump flow test also allows visual detection of the first signs of segregation, which appear as a ring of laitance at the perimeter of the concrete spread and an accumulation of coarse aggregates at the center of the mortar pat (Figure 1.9). It is therefore advisable to illustrate the test results with photographs.



Figure 1.9 : *SCC segregation*

b. Japanese Ring Test (J-Ring)

The J-Ring test (Figure 1.10) is used to evaluate the difference between the behavior of concrete with and without obstacles. It consists of a ring on which different reinforcing bars can be installed. This device is used in conjunction with the slump flow test using the Abrams cone.

The ring and the Abrams cone are centered on the base plate before lifting the cone and observing the flow of concrete through the reinforcing bars.

According to the referenced standards, the reinforcing bar diameters and the spacing between bars may vary within the ranges of 10–18 mm and 34–48 mm, respectively, while the ring diameter varies between 23.5 and 30 cm.



Figure 1.10 : (a) *Japanese Ring (J-Ring) and Abrams Cone*, (b) *J-Ring (Holcim, 2004)*

The slump flow test using the Abrams cone must be carried out twice: the first time without the J-Ring and the second time with the Japanese ring installed.

The difference between the average diameters obtained from the two tests highlights the loss of filling ability due to the presence of reinforcement. This difference must not exceed 50 mm.

It is also possible to measure the difference between the concrete heights inside and outside the Japanese ring. A recommended self-compacting concrete (SCC) should exhibit a difference of approximately 10–15 mm. However, this measurement remains delicate and difficult to perform accurately (Figure 1.11).

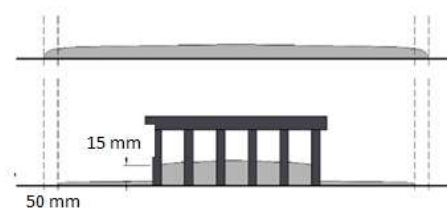


Figure 1.11 : *Values recommended for self-compacting concrete*

c. L-Box Flow Test (EN 12350-10)

This test setup makes it possible to evaluate concrete flow in confined conditions (passing ability) and to verify that placement will not be hindered by blocking phenomena (dynamic segregation). It also allows measurement of the filling ratio and the concrete flow time.

The test apparatus consists of an L-shaped box with a total height of 60 cm, a length of 70 cm, and a width of 20 cm (Figure 1.12).

The vertical section is separated from the horizontal section by a gate. Reinforcing bars may be installed in front of the gate.

For SCC intended for heavily reinforced structures, it is recommended to use:

- Three Ø14 mm bars spaced 39 mm apart, or
- Three Ø12 mm bars spaced 41 mm apart.

For normally reinforced concrete (NRC) or SCC intended for structures with lower reinforcement density, two Ø12 mm bars spaced 59 mm apart may be used.

Test Procedure

- The vertical section is filled with concrete (approximately 13 liters required).
- After leveling, the concrete is left at rest for 1 minute (to check homogeneity).
- The gate is then lifted to allow the concrete to flow through the reinforcement.
- At the end of the test, the concrete heights in the vertical section and at the end of the horizontal section are measured (denoted H1 and H2, respectively).

The ratio: H_2/H_1 characterizes the blocking behavior and must be greater than 0.8.

Poor flow through the reinforcement and accumulation of coarse aggregates at the grid indicate blocking or segregation problems.

Although the acceptable H_2/H_1 ratio is 0.8, the number and arrangement of reinforcing bars acting as obstacles are not identical for all SCC applications. Therefore, NF EN 206-9 (2010) distinguishes between two passing ability classes depending on the type of application (Table 1.4).

Table 1.4: *Passing Ability Classes in the L-Box Test*

	Passing Class	
	PL ₁	PL ₂
Minimum requirement (L-Box)	$H_2/H_1 \geq 0,8$ with 2 reinforcing bars	$H_2/H_1 \geq 0,8$ with 3 reinforcing bars

Table 1.5 : *Arrangement of Reinforcing Bars in the L-Box According to SCC Classes*

Subclasses	Subclasses 1	Subclasses 2 (a) & 2 (b)	subclasses 3 (a) & 3 (b)
Minimum requirement	No specific requirement	0,80 with 2 bars Ø 12 mm	0,80 with 3 bars Ø 14 mm

For the subclasses, reference should be made to Table 1.1.

The flow velocity may be evaluated by measuring the concrete passing times T20 and T40, corresponding respectively to the 20 cm and 40 cm marks (Figure 5.8).

Some authors recommend values of :

- $T_{20} < 1.5$ s,
- $T_{40} < 3.5$ s,

in order to remain within the self-compacting domain.

According to Swiss recommendations (2004), the total flow time should range between 3 and 7 seconds.

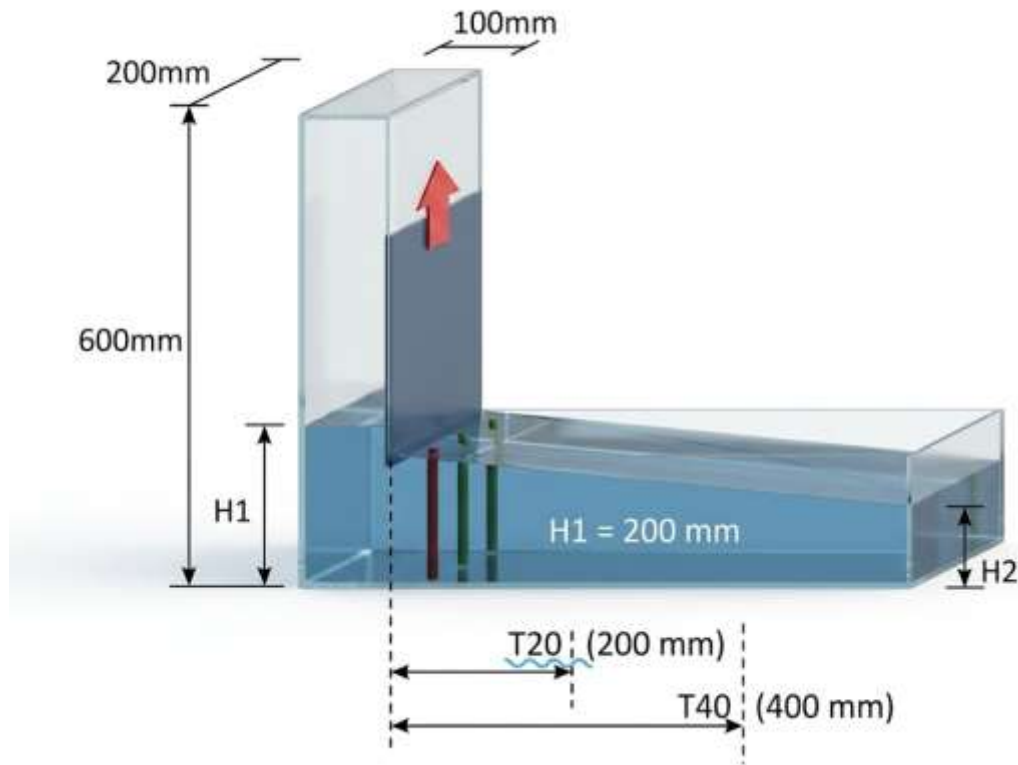


Figure 1.12: Positions of T20, T40, and T60

d. V-Funnel Flow Test (EN 12350-9)

This test consists of observing the flow of 12 liters of concrete through a V-shaped funnel and measuring the flow time from the moment the gate is opened until light becomes visible through the outlet.

The test is repeated after 5 minutes to obtain a better assessment of segregation resistance.

A rectangular section was selected in order to impose a flow condition similar to that occurring between two parallel reinforcing bars. The lower part of the funnel, rectangular in shape with dimensions 7.5 cm × 6.5 cm, is closed by a gate (Figure 1.13).

Self-compacting concrete (SCC) should flow at a constant rate. Any noticeable change in flow velocity is a sign of blocking and therefore segregation. An excessively long flow time and discontinuous flow during the V-Funnel test may indicate separation of aggregates from the mortar matrix and the formation of arching that obstructs flow.

This test also makes it possible to evaluate the **viscosity** of the concrete during flow.

Some recommendations suggest a V-Funnel flow time between 5 and 12 seconds to obtain concrete with sufficient viscosity, while other authors recommend a range between 8 and 14 seconds.

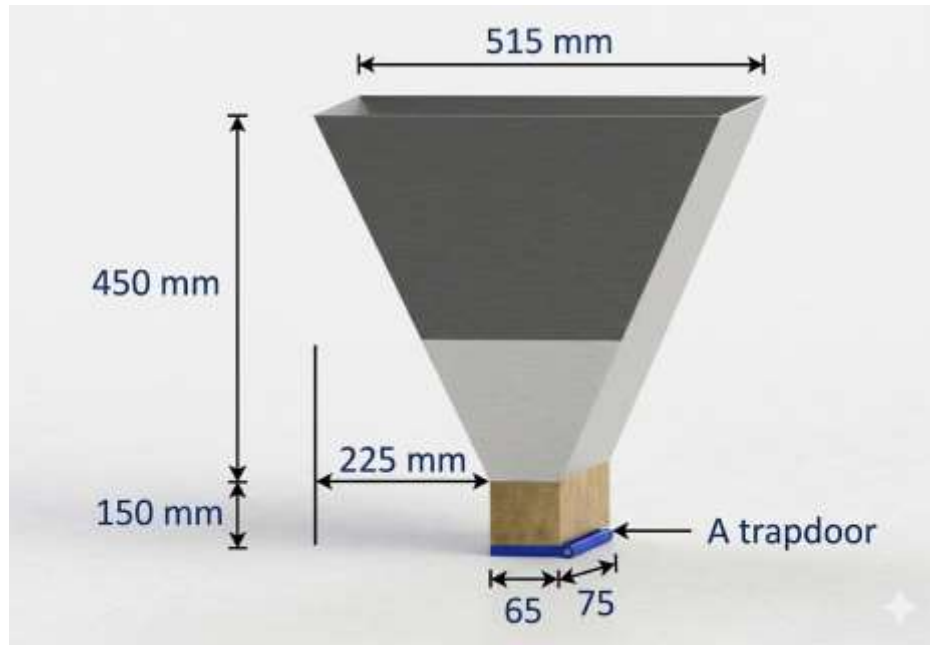


Figure 1.13: V-Funnel

V-Funnel flow times depend on the type of application; however, they are grouped into only two classes (Table 1.6), according to NF EN 206-9.

Table 1.6 : V-Funnel Flow Classes

Class	V-Funnel (s)
VF ₁	≤ 8
VF ₂	9 à 25

1.5.2. Sieve Stability Test (EN 12350-11)

Resistance to static segregation of self-compacting concrete (SCC) must be characterized due to the previously mentioned concerns.

In this context, the company GTM Construction developed this test to evaluate the percentage by mass of laitance (mortar fraction) in a concrete sample, thereby assessing the SCC with respect to segregation risk.

Apparatus Required:

- A 10-liter bucket with a lid,
- A 5 mm mesh sieve (300–350 mm in diameter and 40–75 mm in height),
- A bottom pan.

Test Procedure :

1. Fill the 10-liter bucket with concrete.
2. Cover and leave the concrete at rest for 15 minutes.
3. Take a sample of 4.8 ± 0.2 kg from the concrete.
4. Pour the sample through the 5 mm sieve placed over the bottom pan.
5. Leave for 2 minutes, then weigh the mass of laitance passing through the sieve (Figure 1.14).

This test makes it possible to quantify the segregation potential of SCC by determining the proportion of fine mortar separating from the coarse aggregate skeleton.

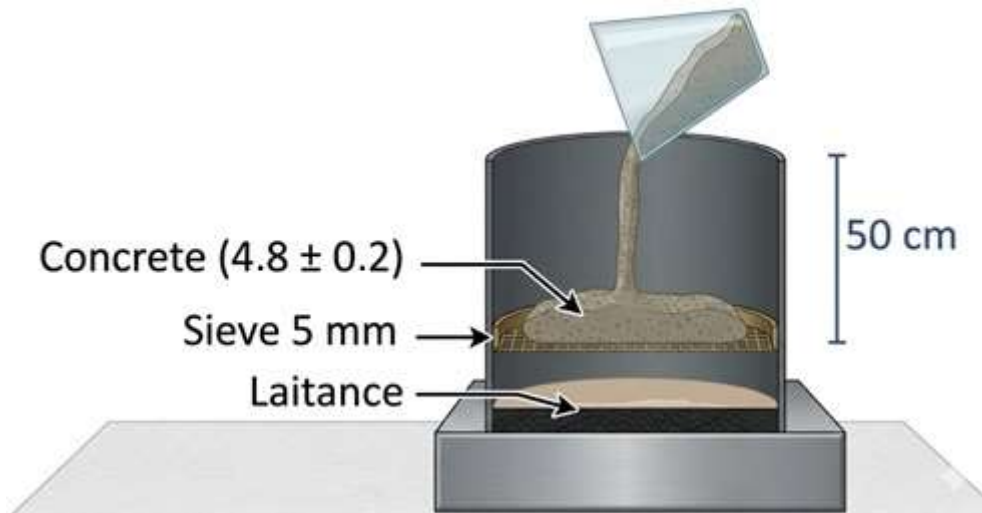


Figure 1.14 : Schematic Diagram of the Sieve Stability Test

The percentage P of laitance passing through the sieve relative to the total mass of the sample is calculated using the following equation:

$$P = \frac{\text{Mass of laitance passing through sieve}}{\text{Mass of sample}} \cdot 100$$

The acceptability criteria for a self-compacting concrete (SCC) formulation are divided into three classes, as summarized in Table 1.7:

Table 1.7: Stability Criteria (GTM)

Condition	Stability	Remarks
$0 \leq P \leq 15 \%$	Satisfactory	Homogeneous and stable concrete
$15 \leq P \leq 30 \%$	Critical	Check other workability criteria
$P \geq 30 \%$	Very poor	Systematic segregation ; concrete is unusable

Table 1.8 : Maximum Laitance Percentage Through the Sieve According to SCC Subclass

Subclass	Subclass 1	Subclass 2(a)	Subclass 2(b)	Subclass 3(a)	Subclass 3(b)
$P_{\max} (\%)$		20		15	10

1.6. Conclusion

Self-compacting concrete (SCC) represents a significant advancement in the field of cementitious materials due to its ability to flow and consolidate under its own weight without the need for vibration. This property improves the quality of concrete placement, reduces compaction defects, and results in more homogeneous structures.

The mix design of SCC is based on a precise balance between its constituents, particularly the amount of fines, the water content, and the use of superplasticizers and viscosity-modifying agents. Proper control of these parameters ensures both good flowability, mixture stability, and satisfactory mechanical strength.

Thus, self-compacting concrete provides an effective solution for facilitating concrete placement, improving the quality of structures, and meeting the increasing requirements for durability and performance in the field of civil engineering.

1.7. Exercises

Exercise 1:

To formulate a self-compacting concrete (SCC) using limestone fillers, the following criteria were considered:

- $G/S = 1$
- $W/B = 0.45$ with a binder dosage of 500 kg/m^3
- $F/B = 25\%$
- Entrapped air volume (A) $\approx 3\%$
- Superplasticizer dosage at saturation = 1.5% of binder mass
- Solid content of the admixture (E_s) = 48%

	Cement	Limestone	Admixture	Gravel	Sand
Absolute density (T/m^3)	3,1	2,7	1,2	2,5	2,6

1. Determine the Mass-Based Formulation of SCC

Step 1: Calculate Binder, Limestone fillers, and Water Volumes

- $W/B = 0.45 \Rightarrow W = 0.45 \times B = 0.45 \times 500 = 225 \text{ kg/m}^3 = 225 \text{ l/m}^3$
 - $F/B = 25\% \Rightarrow F = 25\% \times B = 25\% \times 500 = 100 \text{ kg/m}^3$
- $\Rightarrow M_C = 500 - F = 400 \text{ kg/m}^3$.

$$M_C = 400 \text{ Kg/m}^3 \Rightarrow \text{Cement volume : } V_C = \frac{400}{3.1} = 129 \text{ l/m}^3.$$

$$F = 100 \text{ Kg/m}^3 \Rightarrow \text{Limestone fillers volume : } V_F = \frac{100}{2.7} = 37 \text{ l/m}^3.$$

$$\text{Superplasticizer} = 1.5\% \times (500) = 7.5 \text{ kg}$$

The solid content of the admixture is $E_s (\%) = 48$, which means that 52% of the admixture is additional water.

Therefore, for a total admixture mass of 7.5 kg , the admixture volume is calculated as:

$$V_{Sp} = \frac{7.5}{1.2} = 6.25 \text{ l/m}^3.$$

Solid content and water adjustment from the admixture:

- Solid content (E_s):
$$E_s = \frac{6.25 \times 48}{100} = 3 \text{ l/m}^3.$$
- Water provided by the admixture:
$$V_{\text{water from admixture}} = 6.25 - 3 = 3.25 \text{ L for } 1 \text{ m}^3$$

Step 2: Adjust Water Volume

$$V_W = 225 - 3.25 = 221.75 \text{ l/m}^3$$

Step 3: Air Volume

$$V_{\text{air}} = 3\% \times 1000 = 30 \text{ l/m}^3$$

We have :

$$V_G + V_S + V_{Cim} + V_{Fil} + V_A + V_{Sp} + V_W = 1000 \text{ litres } (1\text{m}^3)$$

$$V_G + V_S = 1000 - V_C + V_F + V_A + V_{Adj} + V_W$$

$$V_G + V_S = 1000 - 129 - 37 - 30 - 6,25 - 221,75 = 576 \text{ l/m}^3$$

$G/S = 1 \Rightarrow \text{Mass of Gravel (G)} = \text{Mass of sand (S)}$

$$\Rightarrow \begin{cases} M_G = M_S \\ V_G + V_S = 576 \text{ l/m}^3 \end{cases}$$

$$\Rightarrow \begin{cases} M_G = M_S \\ \frac{G}{\rho_G} + \frac{S}{\rho_S} = 576 \text{ l/m}^3 \end{cases}$$

ρ_G and ρ_S are respectively absolute densities of gravel and sand.

$M_G = 734 \text{ kg for } 1 \text{ m}^3$

$M_S = 734 \text{ kg for } 1 \text{ m}^3$

The formulation of 1 m^3 of SCC BAP is :

Cement	:	$M_{\text{Cem}} = 400 \text{ kg}$
Limestone fillers	:	$M_{\text{Limestone}} = 100 \text{ kg}$
Water	:	$W = 221.75 \text{ liters}$
Admixture	:	$M_{\text{Sp}} = 7,5 \text{ kg (6.25 liters)}$
Gravel	:	$M_G = 734 \text{ kg}$
Sand	:	$M_S = 734 \text{ kg}$

2. Solutions for Instability in the Mixture

To address instability problems observed during trial formulations, the following adjustments can be made:

- Reduce the superplasticizer dosage
- Reduce the G/S ratio
- Reduce the water content
- Add a viscosity-modifying agent (VMA)

These measures improve cohesion, reduce segregation, and enhance the stability of SCC.

Exercise 2 :

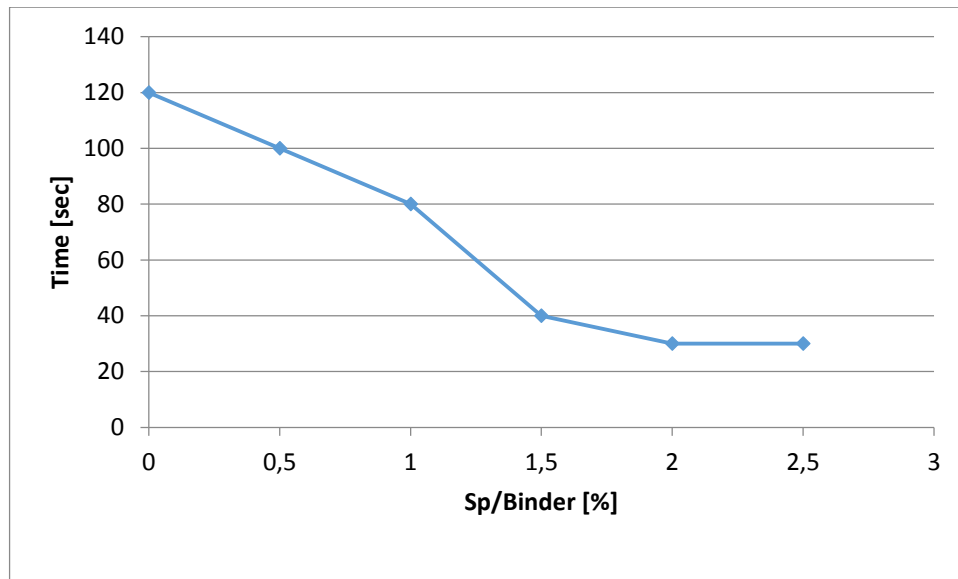
We propose to formulate a self-compacting concrete (SCC) using the Japanese method. This SCC is composed of the following constituents:

- A CEM II/A 42.5 type cement
- Limestone fillers
- Aggregates (sand and gravel)
- A superplasticizer with 50% solid content by volume

The characteristics of the constituents are summarized in the following table:

	Cement	Limestone	Gravel	Sand	Admixture
Absolute density (T/m^3)	3.1	2.7	2.5	2.6	1.2
Bulk density (T/m^3)	1	1.3	1.4	1.5	-

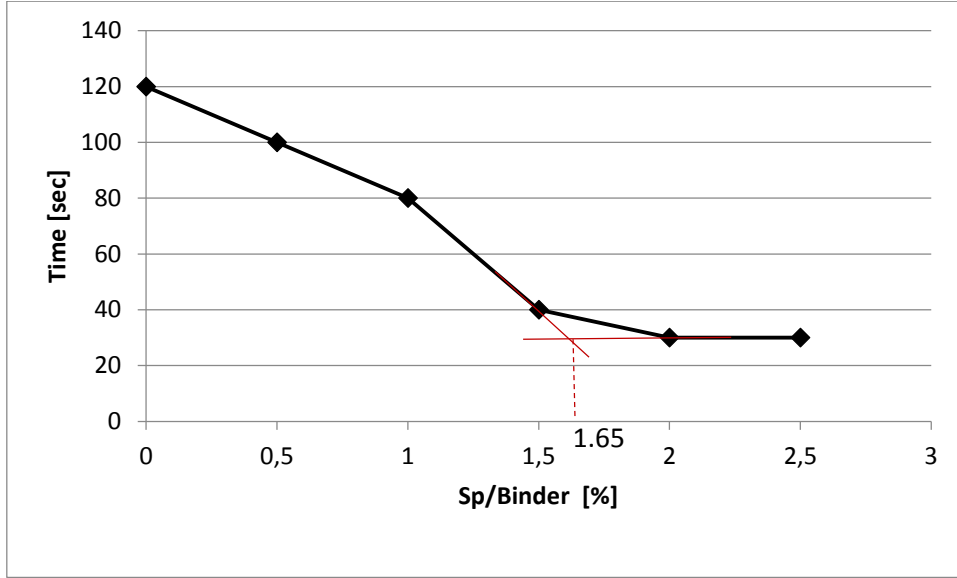
We consider a mass ratio of Filler/Binder equal to 0.25 and a Water/Binder ratio of 0.4. The air void volume is 2%. The saturation dosage of the admixture has been determined in the laboratory for the recommended W/B ratio (see figure).



- By which test was the saturation dosage determined? What is the saturation dosage of the superplasticizer? What is the dosage close to saturation?
- Express the relation of the filler volume as a function of the cement volume.
- Express the relation of the superplasticizer volume as a function of the cement volume.
- Express the relation of the water volume as a function of the cement volume.
- Calculate the compacity of the gravel.
- Determine the mass of the gravel.
- Calculate the mass of the sand.
- Calculate the volume of cement.
- Deduce the volumes of fillers, superplasticizer (considering the saturation dosage), and water.
- Determine the mass-based formulation of this concrete.
- When testing the previous mix, we noticed that the relative spread had a value of 3 and the relative flow rate was 0.5. What modifications should be applied?

Solution :

1/ Since a flow time was measured, the test used is the Marsh cone test. The saturation dosage is 2%.
The dosage close to saturation: The dosage close to saturation is 1.65%.



2/ The relationship of the volume of fillers as a function of the cement volume :

$$\frac{M_F}{M_B} = 0.25 \Rightarrow \frac{V_F \cdot \rho_F}{V_F \cdot \rho_F + V_{Cem} \cdot \rho_{Cem}} = 0.25 \Rightarrow V_F = \frac{V_{Cem} \cdot \rho_{Cem}}{3 \cdot \rho_F} \quad (1)$$

In general , if : $\frac{M_F}{M_B} = a$, we have $V_F = \frac{\rho_{Cem}}{\rho_F} \cdot \frac{a}{(1-a)} \cdot V_{Cem}$

3/ The relationship of the superplasticizer volume as a function of the cement volume:

$$\frac{M_{Sp}}{M_{Cem} + M_F} = 2\% \Rightarrow \frac{V_{Sp} \cdot \rho_{Sp}}{V_F \cdot \rho_F + V_{Cem} \cdot \rho_{Cem}} = 0,02 \Rightarrow V_{Adj} = \frac{0,02 \cdot (\rho_{Cem} \cdot V_{Cem} + \rho_F \cdot V_F)}{\rho_{Sp}}$$

Avec $V_F = \frac{V_{Cem} \cdot \rho_{Cem}}{3 \cdot \rho_F}$

We have:

$$V_{Adj} = \frac{0,08 \cdot (\rho_{Cem} \cdot V_{Cem})}{3 \cdot \rho_{Sp}}$$

In general, if : $\frac{M_{Sp}}{M_B} = b$ et $\frac{M_F}{M_B} = a$, We have : $V_{Adj} = \frac{\rho_{Cem}}{\rho_{Sp}} \cdot b \cdot V_{Cem} \cdot \left(1 + \frac{a}{(1-a)}\right)$

4/ The relationship of the water volume as a function of the cement volume:

$$\frac{W}{B} = 0.40 \Rightarrow \frac{V_W \cdot \rho_W}{V_F \cdot \rho_F + V_{Cem} \cdot \rho_{Cem}} = 0.40$$

Note: To account for the amount of water contributed by the superplasticizer, the volume V_E should be the sum of the mixing water and the water contained in the superplasticizer.

$$V_W = V_{W \text{ mixing}} + V_{W(Sp)}$$

In general, if the admixture consists of a percentage (α) of dry extract and a percentage ($\beta = 1 - \alpha$) of water, we have :

$$V_W = V_{W \text{ mixing}} + \beta V_{Sp}$$

Using the formula determined in question (3) (taking, in general $\frac{M_{Sp}}{M_B} = b$)

We have : $V_{Sp} = \frac{\rho_{Cem}}{\rho_{Sp}} \cdot b \cdot V_{Cem} \cdot \left(1 + \frac{a}{(1-a)}\right)$

If : $\frac{W}{M_L} = d$, we have $\frac{V_W \cdot W}{V_{Cem} \cdot \rho_{Cem} + V_F \cdot \rho_F} = d \Rightarrow V_W \cdot \rho_W = d \cdot (V_{Cem} \cdot \rho_{Cem} + V_F \cdot \rho_F)$

Moreover $V_W = V_{W \text{ mixing}} + V_{W(Sp)} \Rightarrow V_{W \text{ mixing}} = V_W - \beta \cdot V_{Sp}$
 $\Rightarrow V_{W \text{ mixing}} = V_W - \beta \cdot \frac{\rho_{Cem}}{\rho_{Sp}} \cdot b \cdot V_{Cem} \cdot \left(1 + \frac{a}{(1-a)}\right)$
 $\Rightarrow V_{W \text{ mixing}} = d \cdot (V_{Cem} \cdot \rho_{Cem} + V_F \cdot \rho_F) - \beta \cdot \frac{\rho_{Cem}}{\rho_{Sp}} \cdot b \cdot V_{Cem} \cdot \left(1 + \frac{a}{(1-a)}\right)$

Knowing that : $\frac{M_F}{M_B} = a$, We have $V_F = \frac{\rho_{Cem}}{\rho_F} \cdot \frac{a}{(1-a)} \cdot V_{Cem}$

Therefore :

$$V_{W \text{ mixing}} = d \cdot (V_{Cem} \cdot \rho_{Cem} + \frac{\rho_{Cem}}{\rho_F} \cdot \frac{a}{(1-a)} \cdot V_{Cem} \cdot \rho_F) - \beta \cdot \frac{\rho_{Cem}}{\rho_{Sp}} \cdot b \cdot V_{Cem} \cdot \left(1 + \frac{a}{(1-a)}\right)$$

We obtain : $V_{W \text{ mixing}} = \left(d \cdot \rho_{Cem} - \beta \cdot b \cdot \frac{\rho_{Cem}}{\rho_{Sp}}\right) \cdot \left(1 + \frac{a}{(1-a)}\right) \cdot V_{Cem}$

In our application :

$$a = 0.25 ; \quad b = 2 \% ; \quad d = 0.4 ; \quad \beta = 0.5$$

we obtain $V_{W \text{ mixing}} = \frac{4}{3} \cdot \left(0.4 \cdot \rho_{Cem} - 0.01 \cdot \frac{\rho_{Cem}}{\rho_{Sp}}\right) \cdot V_{Cem}$

5/ The compactness (C) of the coarse aggregates :

$$C = \frac{\rho_{app}}{\rho_{abs}} = \frac{1400}{2500} = 0.56.$$

6/ Determination of the mass of coarse aggregates:

The volumetric dosage of coarse aggregates will therefore be 50% of the compactness, giving:

$$0.56 \times 50\% = 0.280 \text{ m}^3.$$

The corresponding mass dosage is: $G = 0.280 \times 2500 = 700 \text{ kg}$.

7/ Determination of the sand dosage:

The volumetric dosage of sand is 40% of the total mortar volume and is calculated as follows:

$$V_G + V_S + V_{Cim} + V_F + V_{Sp} + V_{W \text{ gâchage}} + V_A = 1000 \text{ liters}$$

$V_G, V_S, V_{Cim}, V_F, V_{Sp}, V_{W \text{ gâchage}}, V_A$: are respectively volumes of gravel, sand, cement, limestone, admixture (Sp), water and air.

$$\text{Volume of mortar mortier} = 1000 - V_G$$

$$\text{Volume of mortar} = 1000 - 280 = 720 \text{ liters}$$

$$V_S = 40\% (\text{volume of mortar}) = 40\% (720) = 288 \text{ liters } (0.288 \text{ m}^3)$$

$$\text{Mass of sand} : 288 \times 2.6 = 748.8 \text{ kg}.$$

8/ Volume of cement :

$$V_G + V_S + V_{Cim} + V_F + V_{Sp} + V_{E \text{ gâchage}} + V_A = 1000 \text{ liters}$$

$$\Rightarrow V_{Cem} = 1000 - (V_G + V_S + V_F + V_{Sp} + V_{W \text{ mixing}} + V_A)$$

$$V_{Cem} = 1000 - \left(V_G + V_S + V_A + \frac{V_{Cem} \cdot \rho_{Cem}}{3 \cdot \rho_F} + \frac{4}{3} \cdot \left(0.4 \cdot \rho_{Cem} - 0.01 \cdot \frac{\rho_{Cem}}{\rho_{Sp}} \right) \cdot V_C + \frac{0.08 \cdot (\rho_{Cem} \cdot V_{Cem})}{3 \cdot \rho_{Sp}} \right)$$

$$V_{Cem} = 134.2 \text{ liters}$$

9/ Volume of limestone :

$$V_F = \frac{V_{Cem} \cdot \rho_{Cem}}{3 \cdot \rho_F} = 51.36 \text{ liters}$$

$$V_E = \frac{1.6 \cdot V_{Cem} \cdot \rho_{Cem}}{3} = 221.87 \text{ liters} \approx 222 \text{ liters}$$

$$V_{Sp} = \frac{0.08 \cdot (\rho_{Cem} \cdot V_{Cem})}{3 \cdot \rho_{Adj}} = 9.24 \text{ liters}$$

10/ The mass-based mix design of this concrete for 1 m³

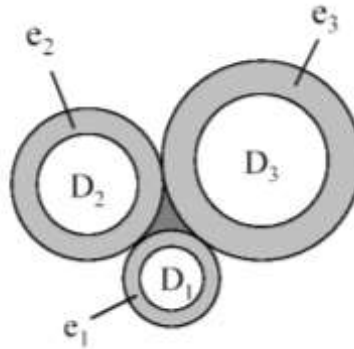
Constituents	Volume (liters)	ρ_{abs} (kg/l)	Mass (kg)
Cement	134.2	3.1	416
Limestone	51.36	2.7	138.6
Admixture	9.24	1.2	11.1
Water	222	1	222
Sand	288	2.6	750
Gravel	280	2.5	700

11/ The relative spread = 3 and the relative flow rate = 0.5, therefore it is necessary to increase workability by:

- Increasing the paste volume.
- Increasing the water-to-binder ratio (W/B).
- Using a continuous fine particle grading (if possible).

Exercise 3:

We propose to work using the excess paste method. Let k be the scaling parameter.



$$\frac{D_1 + 2 \cdot e_1}{D_1} = \frac{D_2 + 2 \cdot e_2}{D_2} = \frac{D_3 + 2 \cdot e_3}{D_3} = k$$

1/ Show that k (the scaling factor) can be expressed as a function of V_{Gra} (the volume of aggregates) and V_{PE} (the volume of excess paste) as follows :

$$k = \sqrt[3]{1 + \frac{V_{PE}}{V_{Gra}}}$$

Hints: Express V_{Gra} and V_{PE} using the particle size distribution, considering that the aggregate mixture consists of n particle size classes D_i , each containing N_i elements.

2/ Considering a unit volume of concrete, write the relationship between V_{PE} , V_{PC} , V_{GRA} , and V_A (air volume).

3/ Give the expression of V_{PC} as a function of V_g and the compactness granular skeleton density, denoted C .

4/ Deduce the expressions of V_g and V_P as functions of V_a , k , and C .

Solution :

$$\frac{D_1 + 2.e_1}{D_1} = \frac{D_2 + 2.e_2}{D_2} = \frac{D_3 + 2.e_3}{D_3} = k$$

Thus, for a particle size class i with aggregates of size D_i , the thickness of the excess paste is e_i :

$$\frac{D_i + 2.e_i}{D_i} = k \Rightarrow D_i + 2.e_i = k \cdot D_i$$

$$V_{Gra} = \frac{\pi}{6} \cdot D_i^3 \Rightarrow V_{Gra} = \sum_{i=1}^n N_i \cdot \frac{\pi}{6} \cdot D_i^3$$

$$V_{PE} = \frac{\pi}{6} \cdot [(D_i + 2.e_i)^3 - D_i^3] \Rightarrow V_{PE} = \sum_{i=1}^n N_i \cdot \frac{\pi}{6} \cdot [(D_i + 2.e_i)^3 - D_i^3]$$

Where N_i : is the number of aggregates of size D_i in class i .

Consequently, the scaling factor k is the same for all particle size classes (n). The total volume of excess paste V_{PE} , can then be written for n classes as:

$$V_{PE} = \sum_{i=1}^n \left(\frac{\pi \cdot (D_i + 2 \cdot e_i)^3}{6} - \frac{\pi \cdot D_i^3}{6} \right) \cdot N_i$$

$$V_{PE} = \sum_{i=1}^n N_i \cdot \frac{\pi}{6} \cdot [(D_i + 2.e_i)^3 - D_i^3]$$

By substituting $D_i + 2 \cdot e_i$ with $k \cdot D_i$, we will have:

$$V_{PE} = \sum_{i=1}^n N_i \cdot \frac{\pi}{6} \cdot D_i^3 \cdot (k^3 - 1)$$

Hence

$$V_{Gra} = \sum_{i=1}^n N_i \cdot \frac{\pi}{6} \cdot D_i^3$$

Thus :

$$V_{PE} = V_{Gra} \cdot (k^3 - 1)$$

The scaling factor k as a function of the excess paste volume can be written as follows:

$$k = \sqrt[3]{1 + \frac{V_{PE}}{V_{Gra}}}$$

2/ $1 = V_{Gra} + V_P + V_A$

With

$$V_P = V_{PE} + V_{PC} \Rightarrow 1 = V_{Gra} + V_{PE} + V_{PC} + V_a$$

$$1 - V_{PE} - V_a = V_g + V_{PC}$$

3/ Compactness :

$$C = \frac{V_{\text{solide}}}{V_{\text{total}}} = \frac{V_{\text{Gra}}}{V_{\text{Tg}}} = \frac{V_{\text{Gra}}}{1 - V_{\text{PE}} - V_{\text{a}}}$$

V_{Tg} : Total volume of aggregates (apparent volume).

From question (2), we have:

$$V_{\text{Tg}} = V_{\text{Gra}} + V_{\text{PC}} = 1 - V_{\text{PE}} - V_{\text{a}} \quad (\text{apparent volume})$$

$$4/ (1) \Rightarrow V_{\text{Gra}} = C \cdot (1 - V_{\text{PE}} - V_{\text{a}})$$

$$\text{Or } V_{\text{PE}} = V_{\text{Gra}} \cdot (k^3 - 1)$$

$$V_{\text{Gra}} = C - C \cdot V_{\text{Gra}} \cdot (k^3 - 1) - C \cdot V_{\text{a}}$$

$$V_{\text{Gra}} + C \cdot V_{\text{Gra}} \cdot (k^3 - 1) = C - C \cdot V_{\text{a}}$$

$$V_{\text{Gra}} (1 + C \cdot (k^3 - 1)) = C \cdot (1 - V_{\text{a}})$$

$$V_{\text{Gra}} = (1 - V_{\text{a}}) \cdot \frac{C}{1 + C \cdot (k^3 - 1)}$$

With : V_{g} : Volume of aggregate (Sand + Gravel)

$$V_{\text{p}} = V_{\text{PE}} + V_{\text{PC}} = (1 - V_{\text{a}}) - V_{\text{Gra}}$$

Exercise 4 :

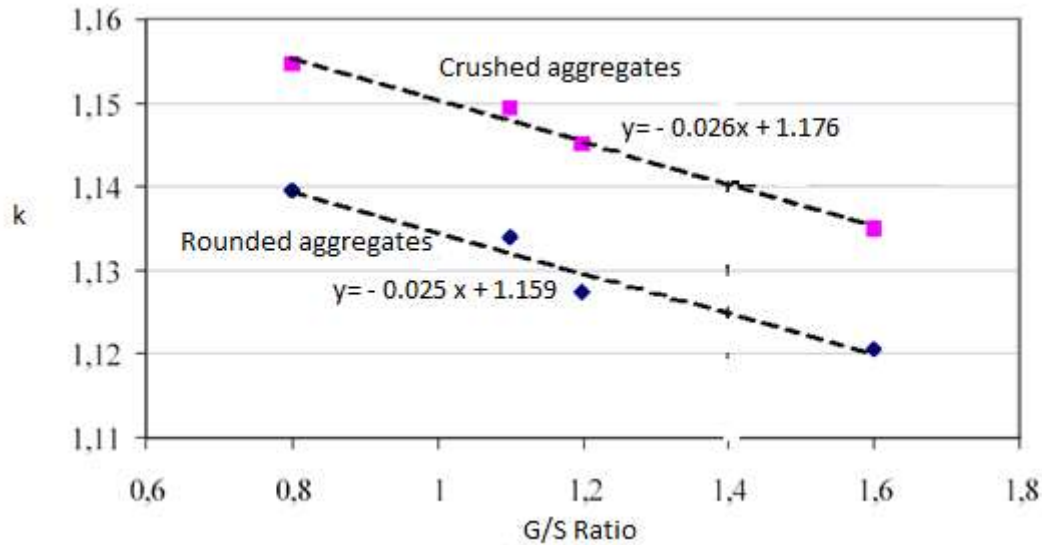
We aim to design a self-compacting micro-concrete using the excess paste method, targeting a compressive strength of 30 MPa at 28 days, with crushed gravel 4/8 mm and sand 0/4 mm of density 2.65. The cement used is a CEM II 42.5 with a true strength class of 55 MPa and a density of 3.15, along with a limestone filler of density 2.7. The cement mass is set at 350 kg/m³, and the entrained air volume is estimated at 25 l/m³.

1/ Determine the mass of water required to achieve the target strength using Bolomey's formula (granular coefficient G=0.5).

Compacity measurements were carried out on gravel/sand mixtures with different proportions. The results are summarized in the following table.

Mass of gravel (%)	40	45	50	55	60	65	70
Compacité	0.76	0.78	0.80	0.80	0.79	0.77	0.76

2/ Determine the mixture that provides the highest compactness, and deduce the mass ratio G/S and the volume ratio $V_{\text{G}}/V_{\text{S}}$.



Parameter k as a function of the G/S ratio

- 3/ Evaluate the scaling parameter k.
- 4/ Calculate the aggregate volumes and deduce the masses of coarse aggregates (G) and sand (S) as well as the paste volume.
- 5/ Calculate the mass of filler.
- 6/ Propose an experimental method to determine the superplasticizer dosage.
- 7/ Provide the final mix design formula in kg/m³.
- 8/ Upon testing the previous formula, we observed that the spread is less than 60 cm. Specify the modifications to be made.

Solution :

$$1/ R_c = G \cdot F_{CE} \cdot \left(\frac{B_{eq}}{E+V_a} - 0.5 \right)$$

B_{eq} : The mass-based dosage of the equivalent binder.

R_c : Target average compressive strength at 28 days, in MPa.

G : Granular coefficient (depending on the size and quality of aggregates).

V_a : The mass of water corresponding to the filling of the entrained air volume

$R_c = 30 \text{ MPa}$; $G = 0.5$; $F_{CE} = 55 \text{ MPa}$

Since a CEM II 42.5 is used, the mass of the equivalent binder would correspond to the mass of the cement ($k = 0$).

$$R_c = G \cdot F_{CE} \cdot \left(\frac{B_{eq}}{E+V_a} - 0.5 \right) \Rightarrow \frac{B_{eq}}{E+V_a} = \frac{Cem}{E+V_a} = 1.59$$

$$\Rightarrow E = 195.5 \text{ l/m}^3$$

$$Cem = 350 \text{ kg/m}^3 \Rightarrow V_{Cem} = \frac{350}{3.15} \approx 111 \text{ l/m}^3.$$

2/ The maximum compactness occurs when the ratio $\frac{G}{G+S}$ (%) varies within the range [50 – 55] %.

We will take the average, i.e., $\frac{G}{G+S} = 52.5\% \Rightarrow \frac{G}{S} = 1.1$ (mass ratio)

3/ The value of the scaling parameter « k » = 1.147 obtained from the graph.

$$4/ \quad V_{Gra} = (1 - V_a) \cdot \left(\frac{C_{op}}{1 - C_{op} \cdot (k^3 - 1)} \right) \quad [\text{m}^3/\text{m}^3]$$

$$\text{Ou} \quad V_{Gra} = (1000 - V_a) \cdot \left(\frac{C_{op}}{1 - C_{op} \cdot (k^3 - 1)} \right) \quad [\text{l}/\text{m}^3]$$

C_{op} : Optimal compactness = 0.8 (for $G/S = 1.1$).

V_a : entrained air volume = 25 l/m³.

V_{Gra} aggregate volume

$k = 1.147$

$$V_{Gra} = (1000 - 25) \cdot \left(\frac{0.8}{1 - 0.8 \cdot ((1.147)^3 - 1)} \right) = 553.8 \text{ l/m}^3 = 0.5538 \text{ m}^3/\text{m}^3.$$

$$\approx 554 \text{ l/m}^3.$$

$$V_p = 1 - V_{Gra} - V_a = 1 - 0.554 - 0.025 = 0.421 \text{ m}^3/\text{m}^3.$$

$$\frac{M_G}{M_S} = \frac{V_G}{V_S} = 1.1 \quad \text{car} \quad \rho_G = \rho_S.$$

We have :

$$\begin{cases} \frac{V_G}{V_S} = 1.1 \\ V_G + V_S = V_{Gra} \end{cases} \Rightarrow V_S \approx 0.264 \text{ m}^3/\text{m}^3 \quad \text{et} \quad V_G \approx 0.290 \text{ m}^3/\text{m}^3.$$

$$\Rightarrow M_S \approx 700 \text{ Kg/m}^3 \quad \text{et} \quad M_G \approx 770 \text{ Kg/m}^3.$$

5/ Mass of fillers (limestone “F”) :

$$V_p = V_W + V_{Cem} + V_F \Rightarrow V_F = V_p - V_W + V_{Cem} = 421 - 195.5 - 111 = 114.5 \text{ l/m}^3$$

$$F = 114.5 \times 2.7 = 309.15 \text{ Kg/m}^3.$$

6/ The superplasticizer dosage can be determined using the following tests:

- Marsh cone test
- Mini-cone test
- Rheology tests (Rheometer)

7/ Therefore, the mix design for 1 m³ of self-compacting concrete (SCC) will be:

Cement	:	$M_{Cim} = 350 \text{ Kg}$
Limestone fillers	:	$M_F = 309.15 \text{ Kg}$
Water	:	$W = 195 \text{ litres}$ – the water contributed by the superplasticizer
Admixture	:	close to the saturation dosage
Coarse aggregate	:	$M_G = 770 \text{ Kg}$
Sand	:	$M_S = 700 \text{ Kg}$

8/ Adjustment of the mix to achieve a spread > 600 mm :

- Increase the paste volume
- Increase the superplasticizer dosage
- Increase the G/S ratio

Chapter 2 : High-Performance Concrete (HPC)

2.1. Definition of High-Performance Concrete

High-performance concrete (HPC) and ultra-high-performance concrete (UHPC) are specially formulated concretes designed to exhibit high mechanical properties and significantly improved durability compared to ordinary concrete.

For both HPC and UHPC, compressive strength is the primary criterion. HPC typically exhibits compressive strengths above 50 MPa, whereas UHPC exceeds 125 MPa.

In another classification, HPC is divided into Classes I to V according to mechanical strength:

- Class I HPC: compressive strength between 50 and 75 MPa
- Class II HPC : compressive strength between 75 and 100 MPa
- Class III HPC : compressive strength between 100 and 125 MPa
- Class IV HPC : compressive strength between 125 and 150 MPa
- Class V HPC : compressive strength above 150 MPa

However, the compressive strength of HPC and UHPC is strongly linked to the details of the concrete microstructure, which also governs other properties such as elastic behavior and permeability.

2.2. Properties of High-Performance Concrete (HPC)

2.2.1. Workability

Despite the relatively low water contents compared to conventional concrete, HPC generally achieves a slump of around 20 cm due to the use of superplasticizers. Nevertheless, the consistency of HPC, though fluid, is often viscous. The concrete places well but still requires vibration comparable to that of conventional “plastic” consistency concretes.

High-performance concrete (HPC) can exhibit a wide range of workability, varying from relatively stiff mixes to highly fluid mixtures comparable to Self-Compacting Concrete, depending on the mix design and the dosage of admixtures (Figure 2.1).



Figure 2.1 : Workability of High-Performance Concrete (HPC)

2.2.2. Microstructure

The microstructure of HPC is very dense and largely amorphous. It contains an unusually high volume of anhydrous grains—unhydrated cement remnants due to limited water availability.

Furthermore, the paste–aggregate interfaces, commonly referred to as transition zones, exhibit particularly low porosity and do not show the typical accumulation of portlandite crystals (Figure 2.2). This phenomenon is explained by the high pozzolanic activity of the silica fume used in HPC, which reacts with the lime released during cement hydration, thereby densifying the microstructure.

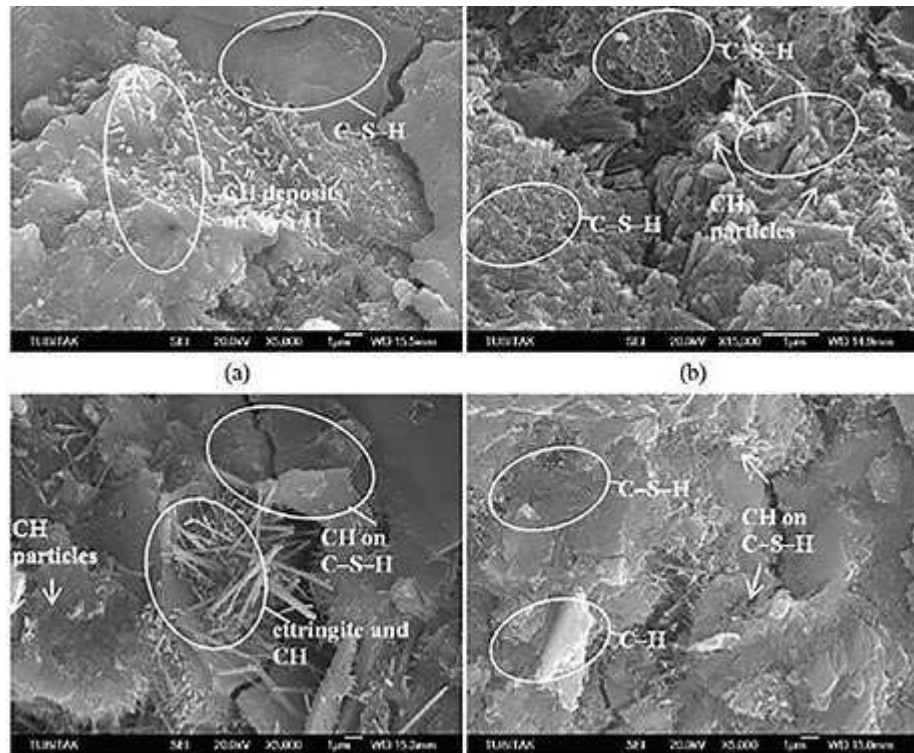


Figure 2.2 : SEM observations reveal a dense microstructure of high-performance concrete (Biricik, 2014)

a. Compressive Strength

Mechanical strength is the most critical service property of this material. HPC is characterized by particularly high compressive strengths. Its strength development kinetics are significantly faster than those of ordinary concrete. This performance results from the closer initial proximity of cement grains in fresh concrete and the accelerating effect of silica fume on hydration reactions.

Early strength development depends on several parameters, including the type and dosage of cement (grind fineness, aluminate content), the proportion of incorporated silica fume, and the quality of the aggregates used.

Tensile strength also increases significantly, although to a lesser extent than compressive strength, and its development is generally even faster. This improvement is mainly attributed to the densification of the cement matrix and the paste–aggregate transition zone, which enhance the internal cohesion of the material.

2.3. Constituents of High-Performance Concrete (HPC)

HPC can be manufactured using only the conventional constituents of ordinary concrete. However, the integration of certain supplementary materials can offer advantages not only mechanically but also rheologically and economically.

2.3.1. Cement Paste

a. Cement

The choice of cement in HPC is strategic. It must ensure high strength and compatibility with superplasticizers and other supplementary materials, while also promoting a dense microstructure. Portland cement CEM I is most commonly used, particularly CEM I 52.5 R and CEM I 42.5 R, which are preferred for their high reactivity due to elevated clinker content and C_3S richness favoring rapid strength development.

CEM II and CEM III cements can also be used in HPC, especially for structures exposed to aggressive environments, such as chloride- or sulfate-rich conditions, or marine environments. CEM III cements are also suitable for massive structures requiring low heat of hydration, provided prolonged curing periods are possible, or when high medium- to long-term strength is desired. HPC formulated with CEM II generally exhibits better pumpability.

When aiming to better control HPC rheology, it is preferable to use cement with as low a C_3A content as possible.

- **Essential Cement Criteria for HPC**

Regardless of the cement type, it should have:

- High fineness (large specific surface area)
- Stable chemical composition
- Good compatibility with superplasticizers
- Low alkali content, to minimize durability risks

b. Cementitious Additions

Most supplementary cementitious materials (SCMs) contain reactive amorphous silica that, in the presence of moisture, reacts with the lime released during hydration of silicate phases of cement (C_2S and C_3S) to form calcium silicate hydrates (C-S-H) similar to those from Portland cement hydration. Excess free lime in the cement paste contributes little to mechanical strength and may even cause durability problems, as it is easily leachable in the presence of water, increasing paste porosity. Its main beneficial effect is maintaining a high pH, ensuring the stability of the passive oxide layer on reinforcement and protecting against corrosion.

Incorporating 20–30% pozzolanic material promotes near-complete consumption of the free lime, transforming it into C-S-H. Commonly used pozzolans include silica fume and fly ash.

- **Silica Fume**

Silica fume is a byproduct of silicon and ferrosilicon alloy production, consisting of ~90% SiO_2 , mostly in amorphous form. Morphologically, particles are spherical, with diameters between 0.1 μm and 2 μm —about 100 times smaller than ordinary cement particles.

Silica fume has a density around 2.2 and a very high specific surface area (15,000–25,000 m²/kg), giving it strong pozzolanic reactivity and a pronounced filler effect. Typical HPC dosages range from 3 to 10%.

- Fly Ash (FA)

Fly ash particles, collected from power plant filtration systems, are primarily composed of SiO₂, Al₂O₃, Fe₂O₃, and CaO. Morphologies vary (spherical, hollow spheres, angular particles). Effective pozzolanic activity requires a significant proportion of glassy phases. Typical HPC dosages average around 15%, though 5–30% may be used.

- Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is a byproduct of iron production in blast furnaces. After grinding, it has a density of ~2.8 and is used in HPC to achieve dense microstructures, controlled heat of hydration, and high long-term performance. Typical dosages are 15–30%.

2.3.2. Admixture

The choice of superplasticizer is critical in HPC formulation, especially given the very low water-to-cement (W/C) or water-to-binder (W/B) ratios. Not all superplasticizers have the same dispersing efficiency, and cement–superplasticizer compatibility must be verified.

a. Determination of Superplasticizer Dosage

The dosage providing good workability should be close to or equal to the saturation dosage. Above this point, paste fluidity does not improve, and risks of segregation and delayed setting increase. Two common tests verify compatibility and determine the saturation dosage: the mini-cone test and the Marsh cone flow test. These assess the evolution of paste fluidity over up to 1.5 hours, corresponding roughly to typical concrete delivery times.

- Marsh Cone Method

The Marsh cone is a test for evaluating the workability of cement pastes and slurries. It involves preparing a specific volume of slurry and measuring its flow time (Figure 2.3).

The test requires approximately 1.8 kg of cement. It is performed using a water-to-binder ratio similar to that of the concrete being produced. The sample preparation includes the following steps:

- Weigh the water and superplasticizer in the mixing container.
- Start the mixing system and gradually introduce the cement within 150 seconds.
- Stop mixing for 15 seconds to scrape off any cement adhering to the container walls with a spatula.
- Resume mixing for 60 seconds.
- Measure the temperature of the paste.
- Measure the time required to fill a 1-liter graduated cylinder with the paste.
- Measure the flow time at different intervals up to 60 or 90 minutes, recording the paste temperature each time.

Flow time is measured for different superplasticizer dosages (expressed as a percentage of solids relative to the cement mass). This produces a curve composed of two linear segments with different slopes. The intersection of these two linear parts is called the “saturation point”, i.e., the point beyond

which any further increase in superplasticizer dosage has no significant effect on the paste rheology. The superplasticizer dosage corresponding to this point is referred to as the **saturation dosage**.

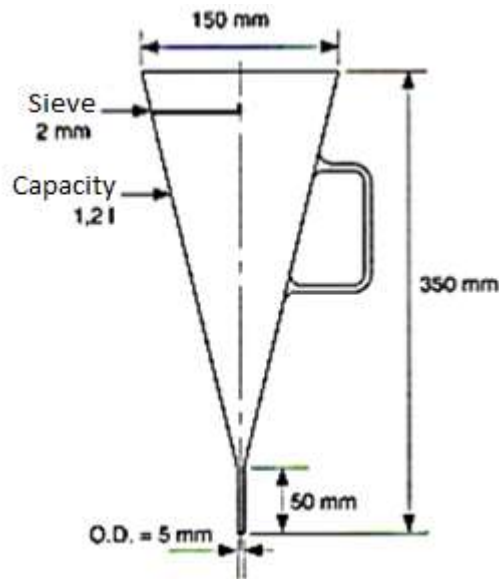


Figure 2.3 : Marsh cone

• **Mini-Cone Method:**

The mini-cone test also allows evaluation of cement–superplasticizer compatibility and determination of the saturation dosage. The advantage of this method is that it evaluates the superplasticizer saturation dosage using a small amount of cement paste in a mini-cone (Figure 2.4). The amount of cement required is 200 g, approximately ten times less than that needed for the Marsh cone test.

The test consists of determining the spread as a function of superplasticizer dosage over increasing time intervals. The procedure is as follows:

- Weigh 200 g of cement or binder.
- Weigh the appropriate amount of water in a 250 ml beaker.
- Weigh the required amount of superplasticizer and add it to the water.
- Mix the cement and water with a spatula for approximately one minute, starting the timer simultaneously.
- Adjust the paste temperature to room temperature using a thermostatic bath.
- Place a Plexiglas plate, on which the test will be performed, on a perfectly flat surface.
- Place the mini-cone at the center of the plate and, after 15 seconds of manual mixing to homogenize the paste, fill the mini-cone with the paste.
- Tap the top of the mini-cone ten times before quickly lifting it, allowing the paste to spread on the Plexiglas plate.
- Measure two perpendicular diameters of the spread disc and calculate the average.
- Clean the Plexiglas plate and mini-cone with water and dry them before the next test.
- Measure the spread at different time intervals up to 120 minutes to monitor the paste's loss of workability over time.

The curves obtained show an inflection point at a specific superplasticizer dosage, called the saturation point. Beyond this point, adding more superplasticizer does not improve paste fluidity. Excessive dosage may unduly delay concrete setting, cause segregation, or lead to bleeding issues.

For dosages below the saturation point, fluidity decreases proportionally to the actual dosage relative to the saturation dosage.

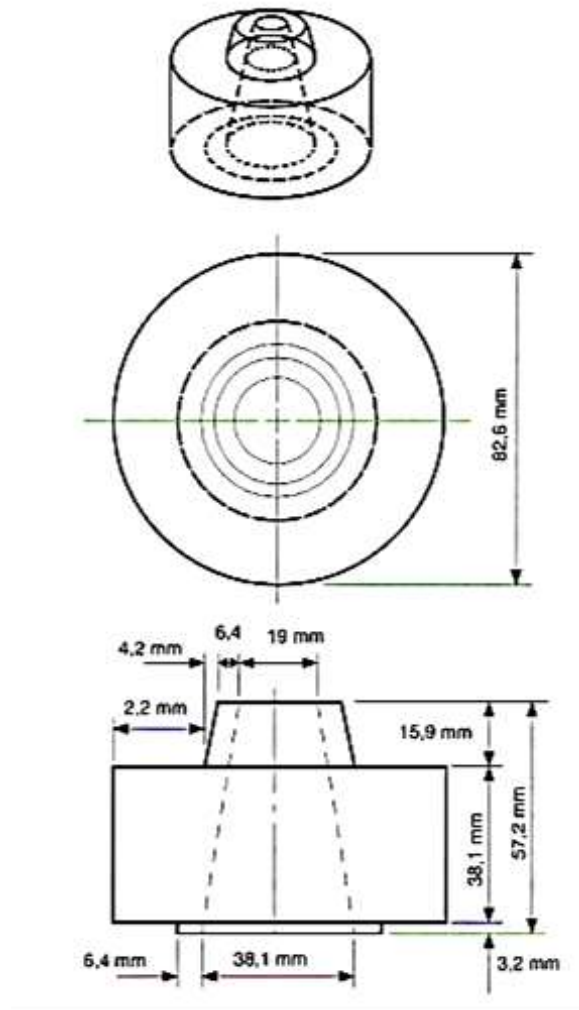


Figure 2.4 : Mini-Cone

b. Superplasticizer Content

It is always preferable to express superplasticizer content as a percentage of solids relative to the cement mass, since different superplasticizers vary in solids content and density.

• Density of a Superplasticizer

The density of a superplasticizer is calculated as:

$$d_{sup} = \frac{M_{liq}}{V_{liq}}$$

Where M_{liq} in [g] and V_{liq} in [cm^3]

• Solids content

$$s = \frac{M_{sol}}{M_{liq}} \times 100$$

Therefore

$$M_{sol} = \frac{s \times M_{liq}}{100} = \frac{s \times d_{sup} \times V_{liq}}{100}$$

Since $M_{liq} = M_W + M_{Sol}$

Therefore

$$M_{liq} = \frac{100 \times M_{sol}}{s}$$

Therefore

$$M_W = M_{sol} \left(\frac{100}{s} - 1 \right) = M_{sol} \left(\frac{100 - s}{s} \right)$$

$$M_W = M_{sol} \left(\frac{100 - s}{s} \right) \left(\frac{s \times d_{sup} \times V_{liq}}{100} \right) = d_{sup} \times V_{liq} \times \left(\frac{100 - s}{100} \right)$$

• Useful Relations:

Let:

- d : dosage of superplasticizer solids
- d_{sup} : density of the superplasticizer
- s : solids content of the superplasticizer
- L : mass of the binder

$$M_{Sol} = L \times \frac{d}{100}$$

And since $M_{Sol} = \frac{s \times M_{liq}}{100}$

Therefore $L \times \frac{d}{100} = \frac{s \times M_{liq}}{100}$

Therefore $L \times \frac{d}{100} = \frac{s \times d_{sup} \times V_{liq}}{100}$

From which $V_{liq} = \frac{L \times d}{s \times d_{sup}}$

Mass of solid particles and volume of the superplasticizer

$$M_{Sol} = L \times \frac{d}{100}$$

The volume of liquid superplasticizer containing M_{Sol} can be calculated as follows:

$$V_{liq} = \frac{M_{liq}}{d_{sup}}$$

And

$$M_{liq} = \frac{M_{sol} \times 100}{s}$$

Therefore

$$V_{liq} = \frac{M_{sol} \times 100}{s \times d_{sup}}$$

Volume of solids contained in V_{liq}

$$V_{Sol} = V_{liq} - V_E$$

Therefore:

$$V_{Sol} = V_{liq} - d_{sup} \times V_{liq} \times \left(\frac{100 - s}{100} \right)$$

2.3.3. Aggregates

The choice of aggregates is very important in the formulation of high-performance concrete (HPC), because as the target strength increases, the aggregates can become the weakest link where concrete failure may initiate under high stresses.

For HPC, it is recommended to use a slightly coarse sand with a fineness modulus between 2.7 and 3.0. This can reduce the amount of mixing water required to achieve a given workability and also improves the shear of the cement paste during mixing.

For coarse aggregates, it is preferable to use aggregates from hard, dense, cubical rocks rather than flat or elongated particles. A maximum size of 10–12 mm is generally considered optimal for HPC production, although the use of 20 mm or 25 mm aggregates is not excluded.

2.4. Optimization of Compactness in HPC

In high-performance concrete, optimizing compactness is a fundamental parameter for achieving the desired high levels of mechanical strength and durability. Increased compactness reduces the volume of capillary voids, improves the cohesion of the cement matrix, and limits material permeability.

This densification is generally achieved through:

- Optimizing granulometry (continuous particle size distribution)
- Incorporating fine mineral additions (silica fume, limestone fillers, slag, etc.)
- Carefully adjusting the water-to-binder ratio

A compact mix promotes better paste–aggregate interaction, reduces internal defects, and simultaneously improves mechanical performance, durability, and volumetric stability of HPC.

2.4.1. Measuring the compactness of cementitious materials

Different methods for measuring the compactness of cementitious materials are presented in the following section.

The cement compactness can then be determined using Equation:

$$C_{cem} = \frac{1}{1 + d_c \frac{M_w}{M_p}}$$

Where: $M_w = M_{w6}$ represents the total added water mass,

d_c is the true density of the cement,

and M_p is the cement mass (500 g).

Cement compactness can also be measured in the presence of a superplasticizer. In this case, the presence of the admixture leads to a different behavior, resulting in a paste that is too fluid before the end of mixing (the needle sinks directly to the bottom of the mold). Here, the mixing cycle still follows the EN 196-3 standard; however, a second mixing cycle identical to the first must be applied to the material that appears dry.

Nevertheless, the total added water mass (M_w) used in Equation includes both the added water and the water contained in the admixture (Figure 2.5).

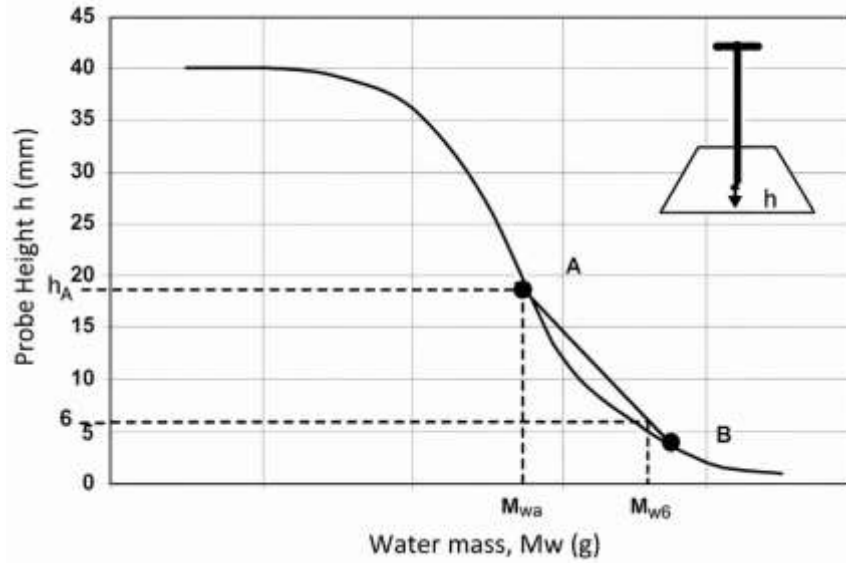


Figure 2.5 : Evolution of needle penetration as a function of water dosage

$h_A \leq 30$ mm

$h_B \geq 2$ mm

$M_{wB} - M_{wA} \leq 5$ g

2.4.2. Determination of Mineral Additions Compactness

For mineral additions, the method consists of identifying the water-to-binder ratio $W/(C+A)$ that yields normal consistency, first using a mixture of 10% cement and 90% addition, then with 20% cement and 80% addition. The corresponding compactness is then extrapolated to determine the compactness of the addition alone (Figure 2.6).

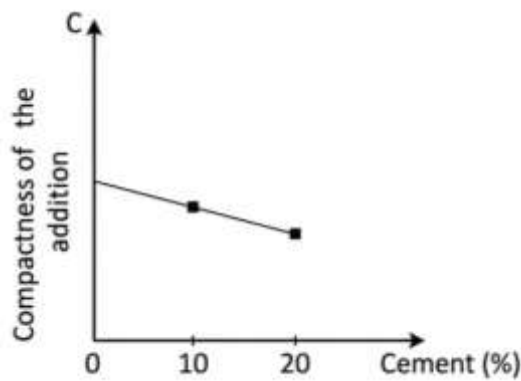


Figure 2.6 : Example of powder compactness determination

The compactness C_{mel} for a binary mixture is calculated using the following relation:

$$C_{mel} = \frac{1}{1 + (y_c d_c + y_{Add} d_{Add}) \cdot \frac{M_w}{M_p}}$$

With : $M_p = M_c + M_{Add}$

(Mass of cement + additions)

$M_w = M_{w6}$

y_c et y_{Add} : represent the volumetric fractions of cement and the mineral addition used ($y_c + y_{Add} = 1$),
 d_c et d_{Add} : are the densities of cement and the mineral addition, respectively.

2.4.3. Measurement of Aggregate Compactness

a. LPC Method No. 61:

The test bench developed at LCPC consists of a cylinder with a diameter of 16 cm and a height of 60 cm (Figure). The cylinder is equipped with an internal piston whose outer diameter equals the internal diameter of the mold minus 1 mm, ensuring free sliding within the mold. Its mass of 20 kg applies a pressure of 10 kPa on the material. The assembly is mounted on a shaking table (without electric power).



Figure 2.7 : Test bench for compactness measurement

The test involves placing a sample of aggregates in the mold under the piston load and applying mechanical vibrations, which rearrange the grains and compact the sample. The measured property is the apparent density of the sample, allowing the calculation of compactness.

- Sample mass for sand compactness measurement : $M = 3 \text{ kg}$
- Sample mass for coarse aggregates : $M = 7.5 \text{ kg}$
- Sample mass for mixed sand + coarse aggregates (after mixing to homogenize): $M=7.5 \text{ kg}$
- Procedure test :
 1. Thoroughly clean the mold with compressed air.
 2. Lower the piston to the bottom of the empty mold, ensuring complete descent.

3. Measure the distance between the top of the piston and the top of the mold at two symmetrical points; note H_{v1} and H_{v2} , then calculate the average H_v (in cm).
4. Pour 1/3 of the sample into the mold and apply 20 vibrations (~2 vibrations per second).
5. Repeat for the second and third thirds of the sample.
6. Lower the piston onto the aggregates and apply 40 additional vibrations.
7. Measure the distance between the top of the piston and the mold at two symmetrical points; note H_{c1} and H_{c2} , then calculate the average H_c (in cm).

- Calculation of the Apparent Volume of the Material

The apparent volume occupied by the material at the end of the test is calculated using the following formula:

$$V = \text{Section. (Hv- Hc)} \quad [\text{cm}^3]$$

$$\text{Section} = \pi \varnothing^2/4$$

- Calculation of Compactness

For each specimen, the compactness is calculated using the formula:

$$\text{Compactness} = \rho_{\text{app}} / \rho_r$$

Where:

- ρ_r : true (real) density of the material
- ρ_{app} : apparent density of the material, calculated using the following expression:
 $\rho_{\text{app}} = M / V$

b. Vibration with Compression Method:

In this method, the sample mass M is the same as that used in the LPC 61 test. The cylinder used has a diameter of 16 cm and a height of 32 cm. The cylinder is equipped with an internal piston whose outer diameter equals the inner diameter of the mold minus 1 mm, ensuring free sliding within the mold. Its mass of 20 kg allows the application of a pressure of 10 kPa on the material. The entire setup is fixed to a vibrating table (Figure 2.8).

The sample must first be dry-mixed to homogenize the material, then poured into the cylinder. This sample is subjected to a vibration of 150 Hz for one minute. The compactness is given by the average of at least two tests according to the following expression:

$$C_{\text{exp}} = \frac{M}{\rho_r \cdot V}$$

With

- ρ_r : real density
- V : final volume of the sample (after vibration)



Figure 2.8 : *Compactness Measurement Device*

2.5. Formulation of High-Performance Concrete (HPC)

2.5.1. Sherbrooke University Method

This method follows the approach of ACI 211-1. It combines empirical results and calculations based on the absolute volume method.

The formulation of high-performance concrete (HPC) is carried out through a progressive and optimized procedure consisting of several interdependent steps.

The first step involves defining the target objectives, particularly in terms of workability, mechanical strength, and durability requirements.

The second step concerns the selection of constituents, including a suitable cement, high-quality aggregates, mineral additions such as silica fume, and superplasticizer admixtures.

The third step consists of optimizing the granular skeleton in order to improve the compactness of the mixture. This phase aims to reduce porosity and minimize intergranular voids, thereby lowering the water-to-binder ratio while maintaining good workability.

The fourth step involves adjusting the water and admixture dosages to achieve the desired workability without compromising mechanical performance.

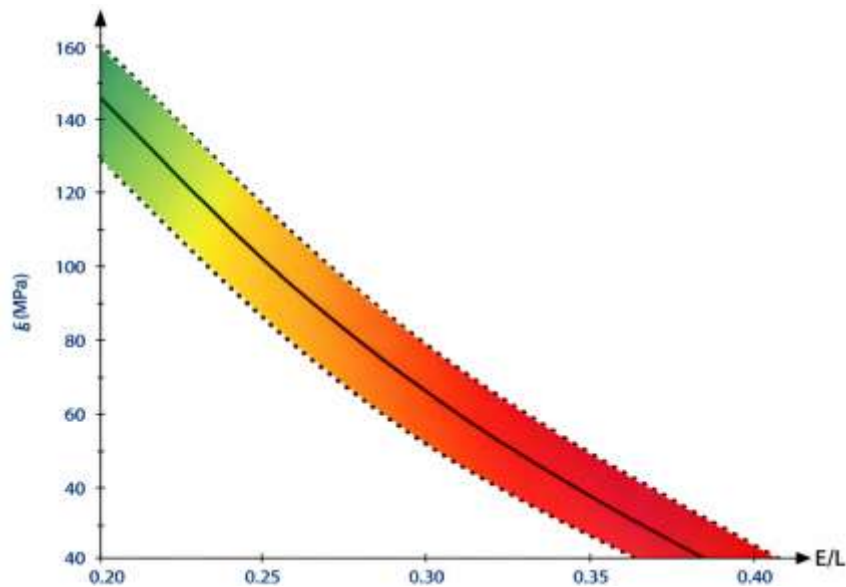
Finally, the fifth step corresponds to the experimental validation of the mix design through tests performed on both fresh and hardened concrete.

All these steps are iterative: the results obtained for workability influence composition adjustments, while mechanical performance and durability guide the final corrections. Thus, HPC mix design is based on an optimized balance between compactness, workability, and strength.

a. Water-to-Binder Ratio

The water-to-binder ratio (W/B) can be determined from Abacus 1 for a concrete with a specified 28-day compressive strength. The range associated with this chart provides a relatively wide interval of water-to-cement ratios corresponding to the same strength. This margin allows adjustment of the selected value according to the actual efficiency of the binders used.

When the efficiency of the binder is not precisely known, it is recommended to initially adopt the average value located at the center of the range and then refine this choice based on experimental results.



Abacus 1: Relationship between W/B Ratio and Compressive Strength (Aïtcin, 2011)

b. Water Dosage

The workability of HPC is controlled by several factors: cement content and reactivity, the amount of superplasticizer and its solid content, the fineness of mineral additions, etc.

An HPC with a slump close to 200 mm can be designed using a low water content combined with a high superplasticizer dosage. In this case, some delay in the setting and hardening of the concrete should be expected.

The authors of this method propose a simplified approach using Abacus 2, based on the concept of the saturation point. To obtain a robust mix design, an additional 5 l/m³ may be added to all the values provided in this Abacus (Aïtcin, 2011).



Abacus 2: Water dosage as a function of the admixture saturation point (Aitcin, 2011)

c. Superplasticizer dosage

The superplasticizer dosage is determined based on the dosage at the saturation point.

d. Coarse aggregate dosage

The coarse aggregate dosage can be determined from Abacus 3 according to the shape of the aggregates. If there is any doubt about the aggregate shape, or if it is unknown, one can always start with a coarse aggregate content of 1000 kg/m³.



Abacus 3 : Coarse aggregate dosage as a function of aggregate shape (Aitcin, 2011).

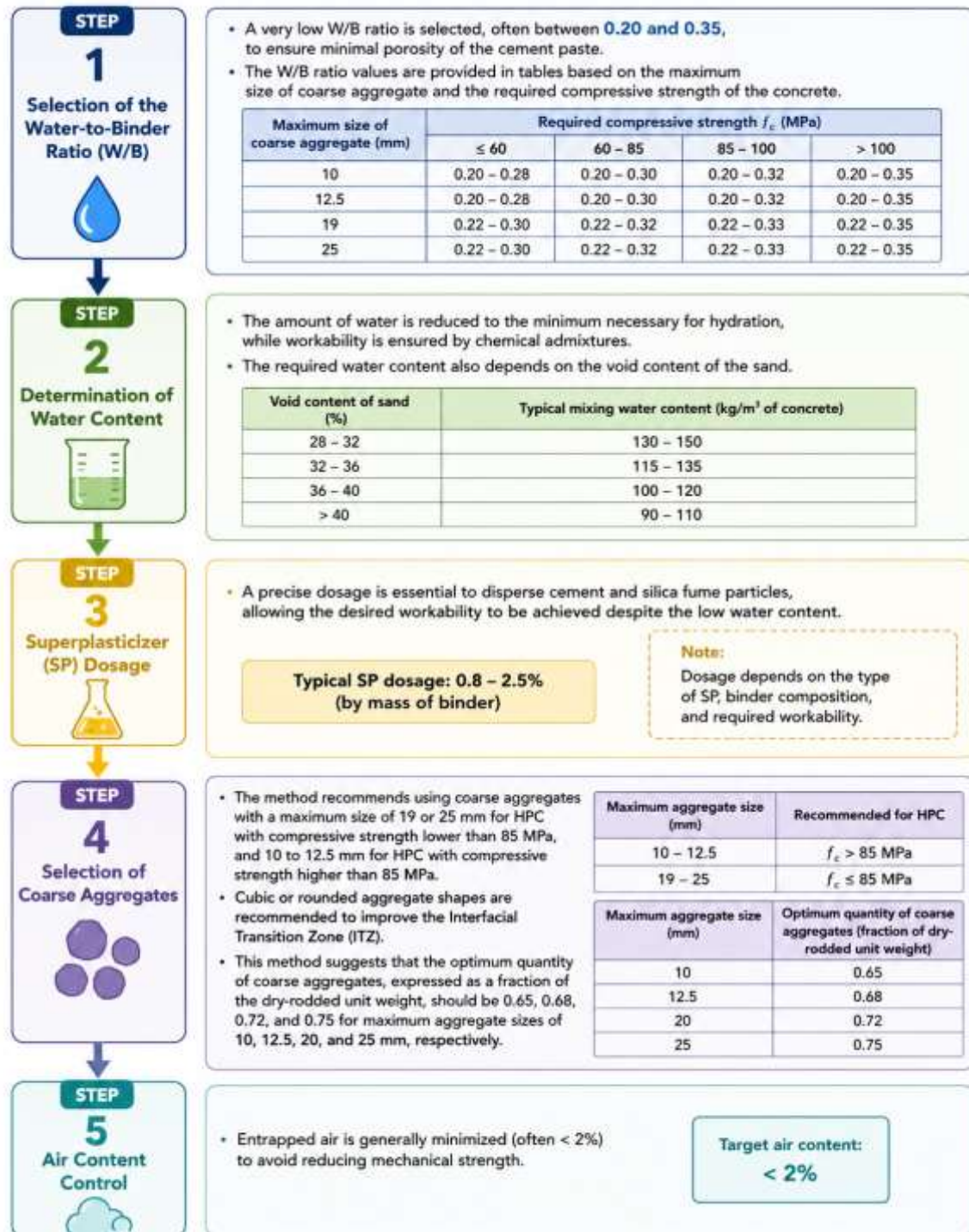
e. Air Content

To facilitate handling and placement of high-performance concrete (HPC), the authors recommend systematically introducing a very small amount of entrained air into the mix. For this purpose, an initial air content of **1.5% entrapped air** is generally recommended. This value constitutes a starting point that may be adjusted later according to the results obtained from trial batches.

f. Sand Content

The sand content is calculated based on the absolute volume method.

2.5.2. ACI 363 Method



2.6. Characterization of High-Performance Concrete (HPC)

The test methods used for conventional concrete characterization are, for the most part, also applicable to high-performance concrete (HPC). However, due to its enhanced mechanical performance and durability, certain tests become particularly important or are supplemented with more advanced investigations.

2.6.1. Fresh State

In the fresh state, HPC characterization mainly focuses on workability. This is assessed using the slump test according to EN 12350-2 or the flow table test in accordance with EN 12350-5. The choice of test depends on the desired level of fluidity.

The fresh concrete density is determined according to EN 12350-6, while the air content is measured following EN 12350-7.

In comparison with ordinary concrete, High-Performance Concrete (HPC) generally exhibits a significantly higher level of workability at equivalent or even lower water content, mainly due to the use of high-range water-reducing admixtures. While conventional concretes often show a more limited slump and a faster loss of workability, HPC is designed to maintain a high flowability and better cohesion, which is essential for placing and pumping in heavily reinforced or complex formwork. Moreover, the fresh density of HPC is typically slightly higher than that of ordinary concrete due to its optimized particle packing and reduced entrapped air content. In terms of air content, HPC usually presents lower and more controlled values, which contributes to its improved mechanical performance and durability compared to ordinary concrete, where higher and less controlled air contents can be observed depending on mixing and compaction quality.

2.6.2. Mechanical Characterization

Mechanical characterization is an essential step. Compressive strength is measured in accordance with EN 12390-3.

Tensile strength is generally determined by the splitting tensile test according to EN 12390-6, while the modulus of elasticity is evaluated following EN 12390-13.

Compared to ordinary concretes, high-performance concrete (HPC) generally exhibits significantly higher compressive and tensile strengths, as well as a higher modulus of elasticity due to its denser microstructure and lower porosity. This enhanced performance is mainly attributed to a lower water-to-binder ratio and the use of supplementary cementitious materials, which improve particle packing and hydration products. However, while HPC shows superior mechanical resistance, it may also present a more brittle behavior at failure compared to conventional concretes, which typically display greater strain capacity before cracking.

2.6.3. Durability Assessment

Durability is a major objective in HPC design. Porosity and absorption are studied through water absorption by immersion, water-accessible porosity, and water permeability measured according to EN 12390-8.

Resistance to chloride penetration is evaluated by the Rapid Chloride Penetration Test (RCPT) according to ASTM C1202 or by the chloride migration test according to NT Build 492.

Carbonation resistance is generally analyzed using an accelerated test in a controlled CO₂ chamber, revealed with phenolphthalein.

Time-dependent behavior is studied by free shrinkage testing according to EN 12390-16 and creep testing in accordance with EN 12390-17.

In comparison with ordinary concretes, HPC consistently demonstrates superior durability performance due to its significantly reduced pore connectivity and refined pore structure. This results in lower water absorption, much lower chloride ion diffusion, and a slower carbonation rate, thereby

enhancing resistance to aggressive environments. Ordinary concretes, with higher porosity and more permeable microstructures, are generally more vulnerable to ingress of harmful agents, leading to faster degradation over time. Moreover, HPC typically exhibits reduced permeability and improved resistance to environmental actions, although its lower internal moisture availability may sometimes influence shrinkage and early-age autogenous deformation more strongly than in conventional concretes.

2.6.4. Microstructural Characterization

Microstructural characterization helps explain the macroscopic performance. It includes analysis by Scanning Electron Microscopy (SEM), mineralogical phase identification by X-ray Diffraction (XRD), and thermal analysis by Thermogravimetric Analysis (TGA/DTG).

The pore structure may also be investigated using Mercury Intrusion Porosimetry (MIP).

Compared to ordinary concretes, HPC exhibits a much denser and more refined microstructure, characterized by a lower total porosity and a reduced connectivity of capillary pores. SEM observations typically reveal a more compact cementitious matrix with fewer microcracks and a better interfacial transition zone (ITZ) between aggregates and paste. XRD and TGA/DTG analyses also show differences in hydration products, often indicating a higher degree of hydration and the presence of additional secondary C–S–H phases due to supplementary cementitious materials. As a result, the pore size distribution obtained from MIP is generally shifted toward finer pores in HPC, whereas ordinary concretes present a higher proportion of large capillary pores, which explains their lower durability and mechanical performance.

2.7. Recommendations After Trial Batch

When the obtained mechanical strength does not reach the target value, analyzing the fracture surface of the specimens can provide valuable insights.

If the fracture surface shows a large number of cracks passing through the aggregates, this indicates that the aggregates do not possess sufficient strength. In this case, it is recommended to replace them with mechanically stronger aggregates.

Conversely, if the fracture surface exhibits a significant number of coarse aggregate pull-outs, this generally means that the aggregates are either too smooth or insufficiently clean. Clean aggregates with a rougher surface texture should therefore be used to improve paste–aggregate bond.

When cracking propagates mainly through the cement paste, this reflects weakness in the matrix phase. It is then advisable to reduce the water-to-binder ratio (W/B) in order to increase compactness and matrix strength.

If the compressive strength does not increase despite a reduction in the W/B ratio, this means that the concrete strength is primarily governed by the aggregate properties and the quality of the paste–aggregate interface. In this case, the use of stronger aggregates becomes necessary.

Regarding workability, if the obtained slump does not meet the target value, several solutions may be considered: increasing the superplasticizer dosage, slightly adjusting the water and cement contents while maintaining the same W/C ratio, or modifying the nature or grading of the aggregates to improve the compactness of the granular skeleton.

Finally, if the concrete exhibits very rapid slump loss, this may be due to incompatibility between the cement and the superplasticizer. It is then recommended to change either the superplasticizer or

the cement. This situation may also be related to high cement reactivity, in which case a slight increase in water content may help correct the problem.

2.8. Conclusion

High-performance concrete (HPC) represents a major advancement in traditional cementitious materials, meeting increasing demands in terms of mechanical strength, durability, and compactness. Its formulation is based on a rigorous scientific approach that integrates optimization of the granular skeleton, control of the water-to-binder ratio, and the use of high-performance admixtures such as superplasticizers and mineral additions.

The improvement of HPC mechanical properties is closely linked to porosity reduction and microstructure densification, resulting in higher compressive strength and enhanced durability against physico-chemical attacks. However, this high level of performance requires precise control of rheological parameters and particular attention to shrinkage, creep, and cement–admixture compatibility issues.

Thus, HPC design cannot be limited to simply reducing the water-to-binder ratio; it requires a comprehensive approach that considers interactions between constituents, the quality of the paste–aggregate interface, and placement conditions. This chapter has highlighted that the simultaneous optimization of mechanical performance and durability is the central objective of HPC mix design, paving the way for more ambitious structural applications and improved service life of structures.

2.9. Exercises

Exercise 1

Design a very high-performance concrete (VHPC) with a compressive strength of 1200 bars using a CEM I cement with a density of 3.1 g/cm³.

Limestone coarse aggregates with a shape between cubic and rounded, a saturated surface-dry density (SSD) of 2.50, and a water absorption capacity $W_{abs} = 0.8\%$. They are in a completely dry condition.

Limestone sand with an SSD density of 2.60 and a water absorption coefficient of 1.5%. It has a moisture content $w = 2\%$.

Silica fume with a density of 2.2 g/cm³, representing 10% of the binder mass.

To improve the rheological properties, a superplasticizer (SP) with a density of 1.2 g/cm³ was used. It contains 40% solid content.

The results for determining the saturation dosage of the admixture are presented in the following table:

% Sp (E _s)/Ciment	0	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8
Slump (cm)	14	18	19	22	24	24	22	22	16

Questions

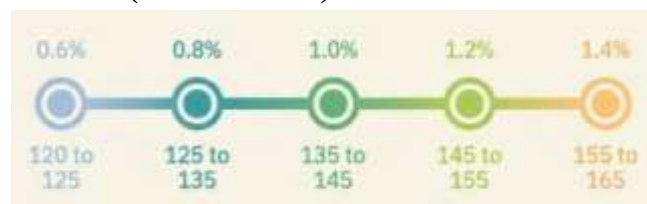
1. Which test is used to determine the superplasticizer (SP) dosage? Estimate the saturation dosage.
2. Provide the mix design of the HPC (with corrections).
3. During the compression test, it was observed that the fracture surface propagated through the cement paste. What solution can be proposed to avoid this phenomenon and improve the quality of the concrete?

Solution

1/ The test used to determine the saturation dosage is the mini-slump cone test (mini-cone test). The saturation dosage is 1%.

2/ $R_c = 120 \text{ MPa} \rightarrow \text{Abacus 1} \rightarrow \frac{W}{B} = 0.235$

▪ Superplasticizer content = 1% (as solid content) $\rightarrow \text{Abacus 2} \rightarrow \text{Water content (W)} = 140 \text{ liters}$.



▪ Binder content : $\frac{W}{B} = 0.235 \Rightarrow B \approx 596 \text{ Kg}$

▪ Silica fume content

$$FS = \frac{596 \times 10}{100} = 59.6 \text{ Kg}$$

- Cement content

$$C = 596 - 59.6 = 536.4 \text{ Kg}$$

- Coarse aggregate with a shape between **cubic and rounded**.



Abacus 3 → Dosage = 1125 kg

- Air content = 1,5% = 15 liters
- Sp content (1%)

$$M_{Sol} = \frac{596 \times 1}{100} = 5.96 \text{ Kg} \approx 6 \text{ Kg}$$

$$V_{liq} = \frac{6}{\left[\left(\frac{40}{100} \times 1,2\right)\right]} = 12.5 \text{ liters}$$

$$V_W = 12.5 \times 1.2 \left(\frac{100 - 40}{100}\right) = 9 \text{ liters}$$

$$V_{Sol} = V_{liq} - V_W = 12.5 - 9 = 3.5 \text{ liters}$$

- Cement volume :

$$V_C = \frac{536.4}{3.1} = 173 \text{ liters}$$

- Silica fume volume :

$$V_{FS} = \frac{59.6}{2.2} = 27.09 \text{ liters}$$

- coarse aggregate volume:

$$V_g = \frac{1125}{2.5} = 450 \text{ liters}$$

- Sand Volume:

$$V_S = 1000 - (140 + 15 + 173 + 27.09 + 450 + 3.5)$$

$$V_S = 191.5 \text{ liters}$$

$$\Rightarrow M_s = 497.9 \text{ Kg}$$

- Correction :

- Coarse Aggregates :

$$M_g = 1125 \cdot \left(1 - \frac{0.8}{100}\right) = 1116 \text{ Kg}$$

Since the coarse aggregates are dry, they will absorb:

$$1125 - 1116 = 9 \text{ liters}$$

- Sand :

$$M_s = 497.9 \cdot \left(1 + \frac{2 - 1.5}{100}\right) = 500.38 \text{ Kg}$$

Therefore, the sand will contribute :

$$500.38 - 497.9 = 2.48 \text{ liters of water}$$

▪ Water Correction :

Water correction = $+9 - 2.48 - 9 = -2.48$ liters

Thus,

$W = 140 - 2.48 = 137.5$ liters

3/ It is therefore recommended to reduce the water-to-binder ratio (W/B) in order to increase the compactness and strength of the cement matrix.

Chapter 3 : Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)

3.1. Definition of UHPFRC

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) is a new generation of concrete characterized by exceptionally high mechanical and durability performance, achieved through a highly optimized mix design and the incorporation of fibers.

UHPFRC is distinguished by an extremely dense matrix without coarse aggregates. The granular packing is finely optimized using several particle size classes, with the largest particles generally not exceeding 4 mm. When metallic fibers are used, they typically have small diameters ranging from 0.1 to 0.3 mm to ensure good bond with the matrix, and lengths generally between 10 and 20 mm. These materials are designed with a very low water-to-binder ratio ($W/B \leq 0.20$), combined with reactive mineral additions (silica fume, fine fillers, etc.) and fibers. This formulation enables the achievement of very high mechanical strength levels while ensuring significant post-cracking ductility.

3.2. Properties of UHPFRC

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) belongs to a family of advanced cementitious materials characterized by mechanical and durability properties far superior to those of conventional concrete and high-performance concrete (HPC). These exceptional properties result from a specific formulation based on an extremely dense matrix, optimized fine particle grading, and the incorporation of fibers that ensure ductile behavior (Figure 3.1).

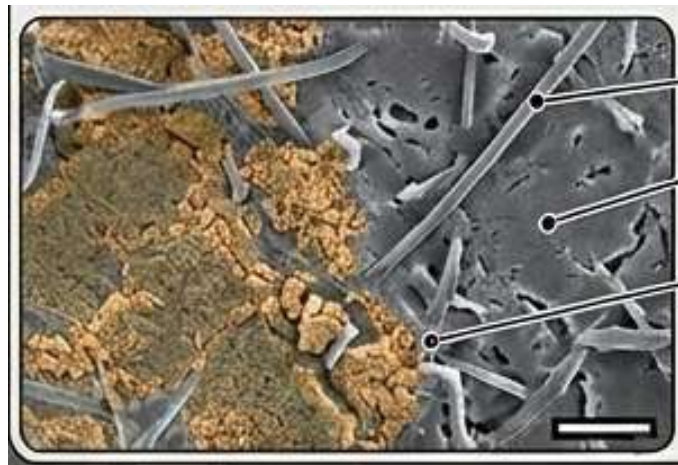


Figure 3.1 : *Microstructure of UHPFRC*

3.2.1. Fresh State Properties

In the fresh state, UHPFRC exhibits very high fluidity, generally achieved without increasing water content, thanks to high-range superplasticizers. This high workability allows self-filling of molds, even for complex geometries or heavily reinforced sections, making vibration unnecessary—and sometimes even inadvisable—to prevent segregation.

This characteristic is particularly advantageous in precasting and in the production of precise architectural elements.

3.2.2. Mechanical Properties

From a mechanical standpoint, UHPFRC develops very high strength at an early age, reaching approximately 60 MPa in compression at 48 hours, which allows rapid demolding and early loading of structures.

At 28 days, compressive strength typically ranges between 130 and 250 MPa. These exceptional values are achieved due to the very low water-to-binder ratio, the use of reactive mineral additions (such as silica fume and ultrafine fillers), and the highly densified microstructure.

This high strength enables significant reduction in structural element cross-sections, leading to slimmer and lighter structures.

Tensile strength, generally between 5 and 12 MPa, is significantly higher than that of ordinary concrete. This improvement is mainly due to the incorporation of fibers—most often steel fibers—which bridge cracks and delay their propagation (Figure 3.2).

Unlike conventional concrete, UHPFRC does not exhibit sudden brittle failure in tension but rather a progressive behavior controlled by fiber–matrix interaction.

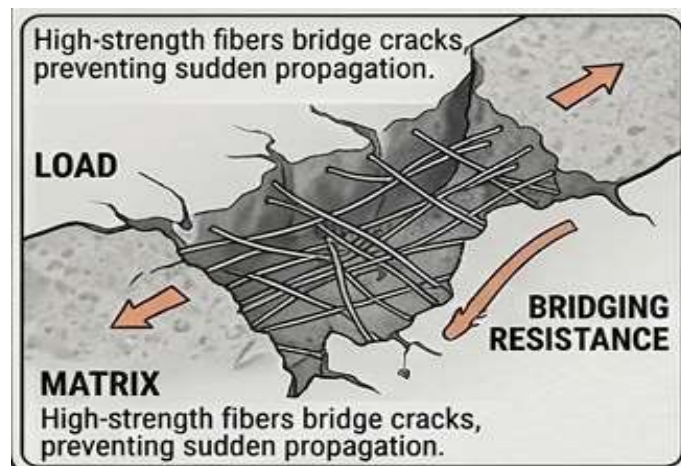


Figure 3.2 : Bridging resistance of UHPFRC

3.2.3. Ductility and Post-Cracking Behavior

The presence of fibers provides remarkable ductility and stable post-cracking behavior, characterized by high energy absorption capacity.

After the appearance of the first cracks, the material maintains significant load-bearing capacity, thereby improving structural safety and resistance to dynamic loads, impacts, and seismic actions.

This ductility is one of the major advantages of UHPFRC compared to conventional concrete (Figure 3.3).

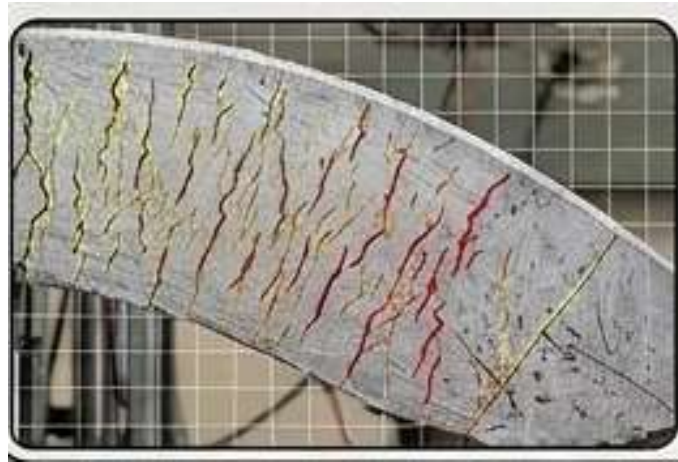


Figure 3.3 : *Ductility and Post-Cracking Behavior of UHPFRC*

3.2.4. Durability

From a durability perspective, the extremely dense matrix of UHPFRC results in very low porosity and reduced permeability.

This microstructure significantly limits the penetration of aggressive agents such as chlorides, carbon dioxide, and sulfates, ensuring excellent durability and extended service life of structures.

As a consequence, reinforcement corrosion, carbonation, and chemical degradation processes are greatly slowed.

3.2.5. Shrinkage and Creep

UHPFRC also exhibits very low shrinkage and creep compared to conventional concrete.

Shrinkage is better controlled due to the dense matrix and the action of fibers, which limit the opening and propagation of microcracks. Reduced creep contributes to improved long-term dimensional stability, particularly beneficial for slender and prestressed structures.

3.2.6. Architectural Quality

The very fine granular structure of UHPFRC allows the production of high-quality surfaces that are smooth, homogeneous, and minimally porous.

This property opens the way for innovative architectural applications combining high mechanical performance and aesthetic requirements, particularly in façades, bridges, and complex precast elements.

3.3. Constituents of UHPFRC

3.3.1. Cement Paste

a. Cement

In UHPFRC, cement plays a central role—not merely through increased dosage, but through its synergy with the other fine constituents of the matrix. UHPFRC typically uses high cement contents ranging from 700 to 1000 kg/m³ to ensure substantial hydration product formation and contribute to microstructure densification.

However, high performance is not based solely on cement quantity, but mainly on optimizing its reactivity and interaction with mineral additions.

The cement used in UHPFRC is most often a high early-strength Portland cement (type CEM I), characterized by high fineness and a high content of reactive phases (particularly C₃S). This fineness promotes rapid hydration and early strength development, allowing high strength levels at young ages.

Cement also ensures effective bonding between solid particles and good adhesion at the fiber–matrix interface.

In UHPFRC, cement is systematically combined with ultrafine mineral additions such as silica fume or limestone fillers, which serve a dual function:

1. They improve particle packing by filling voids between cement grains, increasing compactness and reducing capillary porosity.
2. Reactive additions such as silica fume participate in pozzolanic reactions, consuming portlandite and generating additional C-S-H, thereby strengthening the matrix and enhancing durability.

The extremely low water-to-binder ratio (generally $W/B \leq 0.20$) limits the water available for complete cement hydration. In this context, cement hydrates only partially, but the resulting microstructure remains very dense due to low initial porosity and the action of high-range superplasticizers.

Part of the cement therefore acts as a micro-filler, contributing more to compactness than to hydration itself.

Finally, the use of high cement contents raises environmental concerns related to CO₂ emissions. Consequently, modern UHPFRC formulations tend to optimize or even reduce cement dosage through partial substitution with appropriate mineral additions, without compromising mechanical performance and durability.

This approach reconciles performance requirements, durability, and environmental impact while maintaining the exceptional properties of UHPFRC.

b. Mineral Additions

In addition to the mineral additions mentioned in the formulation of high-performance concrete (HPC) and self-compacting concrete (SCC), other additions can also be used in the formulation of ultra-high-performance fiber-reinforced concrete (UHPFRC).

• Metakaolin

Metakaolin is a highly reactive mineral addition obtained by controlled calcination of kaolin at temperatures between 650 and 800 °C. It exhibits high pozzolanic activity, reacting with portlandite to form additional hydrates, which significantly improves mechanical strength and durability.

In UHPFRC, metakaolin also contributes to reducing porosity and enhancing chemical resistance. The typical content ranges between 5% and 15% of the binder, i.e., approximately 50 to 150 kg/m³. However, its use may increase water demand and require an adjustment of the superplasticizer dosage.

- Glass Powders

Recycled glass powders, obtained by grinding glass waste, represent an alternative mineral addition with high potential in UHPFRC. When sufficiently fine, they exhibit moderate pozzolanic reactivity while improving matrix compactness.

Their use promotes the valorization of industrial waste and reduces the environmental impact of concrete. The content typically studied in UHPFRC ranges between 10% and 25% of the binder. Particular attention must be paid to the fineness of the glass in order to avoid any risk of alkali–silica reaction.

- Ceramic or Crushed Brick Powders

Powders derived from ceramic, tile, or brick waste are obtained by crushing and fine grinding fired clay materials. Their pozzolanic reactivity varies depending on the initial firing temperature and the achieved fineness.

In UHPFRC, these additions mainly improve particle packing and durability, while contributing to a circular economy approach. Incorporation levels generally range between 5% and 20% of the binder, with optimal performance obtained for very fine particles (< 20 μm).

- Finely Ground Chamotte

Chamotte is a refractory material obtained from aluminosilicate clays calcined at high temperature, followed by crushing and sieving.

It is mainly used as an inert or slightly reactive addition in UHPFRC. Thanks to its thermal and chemical stability, it improves high-temperature resistance and dimensional stability. In UHPFRC, chamotte is typically used at relatively low contents, generally between 5% and 15% of the binder, so as not to reduce the initial mechanical strength.

3.3.2. Aggregates

In the formulation of ultra-high-performance fiber-reinforced concrete (UHPFRC), fine sand is the main aggregate. Coarse aggregates are deliberately excluded to ensure a homogeneous and very dense microstructure.

The maximum particle size generally does not exceed 4 mm and most often ranges between 0.1 and 2 mm. This promotes optimal particle packing and limits the formation of discontinuities in the matrix. Rounded or sub-rounded sands are preferred because they improve workability, facilitate placement, and reduce water and admixture demand.

From a mineralogical standpoint, sands used in UHPFRC are characterized by a high silica content, generally greater than 98%, ensuring excellent chemical stability and compatibility with the cement paste. A low water absorption coefficient is also required in order to control the effective water-to-binder ratio and avoid undesirable variations in rheology and mechanical performance.

High grain hardness is essential to ensure a strong aggregate–paste interface capable of efficiently transferring stresses and limiting localized damage under loading.

These sands may be of natural alluvial origin, offering a more rounded morphology favorable to workability, or crushed sands from massive or detrital rocks, which are more angular and may improve mechanical interlocking at the expense of slightly reduced workability. The choice of sand therefore results from a compromise between mechanical performance, fresh concrete rheology, and specific UHPFRC placement requirements.

3.3.3. *Fibers*

The use of fibers in UHPFRC is essential because they act as obstacles to crack initiation and propagation, which cause structural damage. Moreover, fibers are incorporated to obtain ductile tensile behavior and, if possible, to reduce or eliminate the need for passive reinforcement. However, the fiber content is limited by workability criteria.

a. Types of Fibers

- Organic Fibers: Polypropylene (Figure 3.4)

Fibers are incorporated at dosages between 500 g and 2 kg per cubic meter, corresponding to a very low volume fraction between 0.05% and 0.2%.

In the fresh state, the concrete exhibits improved workability and reduced shrinkage. In the hardened state, it shows increased cohesion and improved resilience. Fire resistance is also enhanced.

This type of concrete is mainly used for thin shells and sprayed concrete for repair works. It is also used for slabs and precast elements requiring rapid demolding.



Figure 3.4 : *Polypropylene*

- Mineral Fibers: Glass (Figure 3.5)

These fibers are incorporated at dosages between 25 and 50 kg/m³, corresponding to a volume fraction between 1% and 2%. However, since glass is sensitive to alkali attack from fresh cement, prior treatment of the fibers is required to ensure protection.

Glass fibers mainly improve tensile strength. Cement–glass composites are used for large but thin elements such as panels, cladding, and channels.

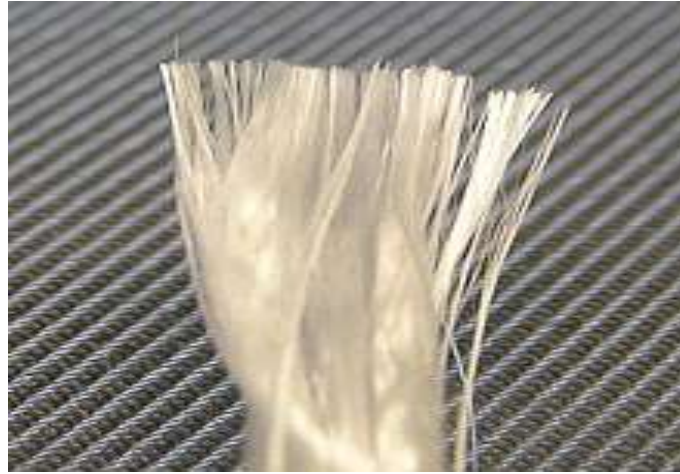


Figure 3.5 : Glass fibers

- Metallic Fibers: Steel (Figure 3.6)

In ordinary fiber-reinforced concrete, fiber content generally ranges between 20 and 40 kg/m³ (0.25%–0.5% by volume).

For structural fiber-reinforced concrete, dosages range between 40 and 80 kg/m³ (0.5%–1% by volume).

For UHPFRC, fiber contents are significantly higher, ranging from 100 to 160 kg/m³, corresponding to 2%–3% by volume.

Increasing the fiber content significantly improves ductility and post-cracking strength. However, it may reduce workability and increase the risk of segregation and placement difficulties. For UHPFRC, vibration is often avoided.

Fiber-reinforced concretes are commonly used in foundation piles, underground structures such as tunnels, and in precast elements subjected to high stresses.



Figure 3.6 : Metallic Fibers

- Natural (Plant) Fibers (Figure 3.7)

Plant fibers are natural fibers extracted from plants and used as discontinuous reinforcement in cementitious materials. They are mainly composed of cellulose, hemicellulose, and lignin, which provide good deformability and low density.

In concrete, these fibers bridge cracks, improving post-cracking behavior, toughness, and resistance to shrinkage cracking, while contributing to sustainability due to their renewable and biodegradable nature.

Common plant fibers used in concrete include hemp, flax, jute, sisal, coconut, bamboo, and agricultural waste fibers (straw, alfa, doum, sugarcane bagasse, palm fibers, or olive pomace). These fibers differ in mechanical properties, morphology, and local availability.

Long fibers (hemp, sisal, bamboo) are generally more effective in controlling macrocracking, while shorter or finer fibers are preferred for improving matrix cohesion and limiting microcracking.

Fiber lengths typically range from 5 to 50 mm, with diameters between 50 and 500 μm , corresponding to aspect ratios (L/D) between 20 and 200.

Fiber dosage is often expressed as a volume fraction between 0.25% and 2.0%, approximately 2 to 20 kg/m^3 depending on the fiber type. Higher contents may significantly reduce workability and increase the risk of segregation or fiber agglomeration.

Before incorporation, plant fibers generally require treatment to improve durability and bonding with the cement matrix. Common treatments include alkaline treatment (NaOH), mineral coating (lime, silica, cement slurry), or impregnation with polymers or hydrophobic agents. These treatments aim to reduce water absorption, limit alkaline degradation, and improve fiber–matrix anchorage.

Plant fiber-reinforced concretes are mainly used in non-structural or lightly loaded applications such as filling concretes, repair mortars, lightweight precast elements, insulating concretes, renders, and environmentally oriented or heritage structures. They are also increasingly used in eco-construction for panels, blocks, and bio-based concretes, where reducing carbon footprint and improving crack control are key objectives.



Figure 3.7 : Natural Fibers

b. Principle of Fiber Use

Consider a fiber of diameter D and length L , with a tensile strength R_T . The tensile force F_T that it can carry is equal to:

$$F_T = R_T \cdot \pi \cdot D^2 / 4$$

If ψ is the bond coefficient of the fiber, the bond force F_A acting on it is proportional to its surface area, such that:

$$F_A = \psi \cdot \pi \cdot D \cdot L$$

The equilibrium of these forces corresponds to:

$$R_T \cdot D / 4 = \psi \cdot L$$

From which we obtain:

$$L/R_T = D/(4 \cdot \psi)$$

In order to obtain the smallest possible length-to-strength ratio, the diameter D must be small and/or the bond coefficient ψ must be as large as possible.

Thus, fiber efficiency is achieved when the fiber cross-section is as small as possible.

c. Problems Related to the Use of Fibers

Fibers may locally accumulate and form arches, thereby hindering the movement of other fibers and aggregates, which can lead to segregation phenomena. This type of disorder is generally observed in confined areas where the spacing between reinforcing bars is smaller than or only slightly greater than the fiber length.

When the fiber content is high, fiber entanglement may create, around the vibrating needle, a rigid envelope that prevents the viscous matrix from properly filling the cavity left by the withdrawal of the needle. It is therefore recommended to avoid internal needle vibration for UHPFRC containing a high percentage of fibers.

Moreover, another segregation mechanism may occur in very fluid UHPFRC, particularly in structural elements of significant height.

Conversely, a fiber depletion phenomenon may occur in the case of sprayed concrete. During projection using a nozzle, fibers acquire significant kinetic energy and, upon impacting a generally rigid surface, tend to rebound, leading to a reduction in their effective content in the placed concrete.

3.4. Formulation of UHPFRC

The adopted mix design approach aims to reduce material porosity and increase the compactness of the granular skeleton. To achieve this, the water-to-binder ratio (W/B) is reduced to values lower than 0.2 through the optimized use of superplasticizers, allowing effective deflocculation of fine particles.

Optimization of the granular skeleton is carried out at two levels. The first consists of reducing aggregate size to obtain a more homogeneous mixture and to limit intergranular porosity. The second aims to improve overall compactness by increasing the binder content, which fills the voids between particles.

Additionally, the possible application of heat treatment can further enhance the mechanical performance of the material. Finally, the incorporation of fibers contributes to improving the ductility of the concrete.

3.4.1. Maximum Density Method (Optimized Particle Packing)

The most fundamental and widely used method for formulating UHPFRC is based on the principle that their exceptional performance stems from an extremely dense microstructure. This density is

achieved by optimizing the packing of solid particles across multiple size scales, including cement, fillers, silica fume, and fine sand. The primary objective is to maximize solid compactness, minimize capillary porosity, and reduce the amount of water required for hydration to the strict minimum, thereby ensuring both high mechanical strength and enhanced durability.

3.4.2. Method Based on the Modified Andreasen and Andersen Model

This method is a mathematical formalization of maximum packing density. The target particle size distribution is given by:

$$p(D) = \left(\frac{D}{D_{max}} \right)^q$$

where:

- $p(D)$: passing percentage,
- D : particle diameter,
- D_{max} : maximum particle diameter,
- q : distribution coefficient (often between 0.20 and 0.30 for UHPFRC).

A lower q value increases the proportion of fines, resulting in a denser matrix but a higher water demand.

3.4.3. Empirical or Semi-Empirical Method

This method relies on reference formulations from the literature, complemented by gradual adjustments through experimental trials. A typical UHPFRC formulation includes a water-to-binder ratio of 0.20 or less, the incorporation of silica fume representing 20–30% of the cement mass, the use of fine sand with a maximum particle size of 2 mm, and the addition of fibers at 2–3% by volume.

3.5. Conclusion :

High-performance fiber-reinforced concretes (HPFRC) represent a major advancement in cementitious materials, combining a very dense matrix with the addition of fibers that significantly improve their mechanical behavior. The incorporation of fibers notably increases tensile strength, ductility, and energy absorption capacity, while limiting crack opening and propagation.

Thanks to these properties, HPFRC provides improved performance in terms of durability, resistance to mechanical loads, and post-cracking behavior. They therefore represent a particularly suitable solution for structures subjected to severe conditions or requiring a high level of reliability.

3.6. Exercises

Exercise 1:

A UHPFRC is formulated with:

- Cement: 800 kg/m³
- Silica fume: 200 kg/m³
- Water: 180 kg/m³

Questions:

1. Calculate the water-to-binder ratio E/LL.
2. Check if it is compatible with a UHPFRC.

Solution:

Total binder:

$$B = 800 + 200 = 1000 \text{ kg/m}^3$$

Water-to-binder ratio:

$$W/B = 180/1000 = 0.18$$

Compatible with a UHPFRC, since $E/B \leq 0.20$.

Exercise 2:

Application of the Andreasen Model

We want to design a UHPFRC with:

- $D_{\max} = 2 \text{ mm}$
- $q = 0.25$

Question:

Calculate the theoretical passing percentage for $D = 0.2 \text{ mm}$.

Solution:

Using the Andreasen formula:

$$p(D) = \left(\frac{0.2}{2}\right)^{0.25} \approx 0.56$$

$P(D) \approx 56\%$

This highlights the importance of fine particles in the formulation of UHPFRC.

Exercise 3 :

Formulate an ultra-high performance fiber-reinforced concrete (UHPFRC) by optimizing the granular packing using the modified Andreasen and Andersen model, in order to improve workability, pumpability, and durability.

The following constituents are available:

Material	minimum particle size (mm)	maximum particle size (mm)
Limestone filler	0,001	0.063
Cement CEM 52.5	0.001	0.100
Fine siliceous sand	0.100	2.000
Silica fume	0.0001	0.010

- No coarse aggregates (specific to UHPFRC)
- Continuous particle size distribution
- Grain shape assumed to be spherical
- Effect of fibers not considered in the particle size curve
- Distribution exponent: $q = 0.23$

Modified Andreasen and Andersen Model

The theoretical curve is given by:

$$p(D) = \left(\frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \right)$$

With :

- $P(D)$: cumulative passing fraction
- D : considered particle diameter (mm)
- $D_{min} = 0.0001$ mm
- $D_{max} = 2$ mm
- $q = 0.23$

Questions :

1. Write the expression of the target particle-size distribution curve for the UHPC (BFUP).
2. Calculate $P(D)$ for the following particle diameters:
 - 0.01 mm
 - 0.063 mm
 - 0.10 mm
 - 1 mm
 - 2 mm
3. Propose a coherent mass distribution of the constituents.
4. Comment on the influence of the parameter q on the UHPC formulation.

Solution:

$$p(D) = \left(\frac{D^{0.23} - 0.0001^{0.23}}{2^{0.23} - 0.0001^{0.23}} \right)$$

D (mm)	$D^{0.23}$	P(D)
0.01	0.35	0.44
0.063	0.53	0.67
0.10	0.59	0.74
1.00	1.00	0.97
2.00	1.17	1.00

The curve is continuous and very rich in fines, which is characteristic of UHPFRC.

Proposed UHPFRC mix design (granular phase).

Constituents	Mass proportion
Fine Sand	45%
Cement	25%
Limestone fillers	20%
Silica fume	10%
Total	100%

This combination allows:

- optimal filling of voids
- reduction of capillary porosity
- improvement of pumpability

Exercise 4

Consider a cylindrical fiber with diameter **D** and length **L**, characterized by a tensile strength **R_T**. The maximum tensile force **F_T** that the fiber can sustain is given by:

$$F_T = R_T \cdot \pi D^2 / 4$$

The fiber is anchored in the cementitious matrix. The bond force **F_A** developed at the fiber–matrix interface is proportional to the lateral surface area of the fiber and is expressed as:

$$F_A = \psi \cdot \pi D L$$

Where **ψ** is the fiber–matrix bond coefficient.

Questions

1. Establish the equilibrium condition between fiber rupture and fiber pull-out.
2. Deduce a relationship linking the ratio **L/R_T** to the fiber diameter **D** and the bond coefficient **ψ**.
3. Physically interpret this relationship and identify the parameters influencing fiber efficiency.

Solution

1/ Equilibrium condition

At the ultimate state, two failure modes are possible:

- tensile rupture of the fiber
- pull-out of the fiber due to loss of bond

Equilibrium is reached when the two forces are equal:

$$F_T = F_A$$

Thus:

$$R_T \cdot \pi D^2 / 4 = \psi \cdot \pi D L$$

By simplifying by πD , we obtain:

$$R_T \cdot D / 4 = \psi \cdot L$$

2/ Relationship between **L/R_T**, **D** and **ψ**

Rearranging the previous expression:

$$L / R_T = D / 4 \psi$$

3/ Physical interpretation

This relationship shows that the ratio L/R_T , which characterizes the mechanical efficiency of the fiber, depends directly on the fiber diameter and inversely on the bond coefficient.

Thus:

- a smaller diameter D improves the efficiency of the fiber
- a higher bond coefficient ψ improves anchorage and limits pull-out

Consequently, optimal fiber efficiency is obtained with the smallest possible cross-section combined with high fiber–matrix adhesion. This explains the interest in thin fibers with rough surfaces or optimized geometries in fiber-reinforced concrete and UHPC (Ultra-High Performance Concrete).

Exercise 5

Consider a steel fiber used in fiber-reinforced concrete with the following properties:

- Fiber diameter
 $D=0,20$ mm
- Tensile strength of the fiber
 $R_T=1\,200$ MPa
- Fiber–matrix bond coefficient
 $\psi=5$ MPa

Question

Determine the minimum fiber length L required so that fiber rupture occurs before pull-out.

Solution

The previously established relationship is:

$$L/R_T = D/4\psi$$

Thus:

$$L = R_T \cdot D/4\psi$$

Substituting the numerical values:

$$L = (1,2 \times 10^9 \times 2,0 \times 10^{-4}) / (4 \times 5 \times 10^6)$$

$$L = 1,2 \times 10^{-2} \text{ m} = 12 \text{ mm}$$

The minimum fiber length required to ensure tensile rupture rather than pull-out is 12 mm.

For shorter lengths, the fiber–matrix bond is insufficient and pull-out becomes the dominant failure mode.

Exercise 6

Consider a UHPC (Ultra-High Performance Concrete) with a compressive strength $f_c=130$ MPa.

In UHPC, the fiber–matrix bond coefficient is often correlated with the matrix strength.

A commonly used assumption is:

$$\psi = 0,1 f_c$$

Thus:

$$\psi = 0,1 \times 130 = 13 \text{ MPa}$$

- Fiber diameter
 $D=0,20$ mm
- Tensile strength
 $R_T=2\,000$ MPa

- Bond coefficient
 $\psi = 13 \text{ MPa}$

Determine the minimum fiber length L required to ensure fiber rupture rather than pull-out in UHPC.

Solution

The general relationship is:

$$L = R_T \cdot D / 4\psi$$

Substituting the numerical values:

$$L \approx 7.7 \text{ mm}$$

For a UHPC with a compressive strength of 130 MPa, a fiber with a diameter of 0.20 mm requires a minimum length of approximately 8 mm to fully mobilize its tensile strength.

Chapter 4: Smart and Self-Healing Concretes

4.1. Definitions of Smart and Self-Healing Concretes:

A smart concrete is a cementitious material capable of detecting changes in its environment (cracking, humidity, stress), reacting autonomously or semi-autonomously, and adapting its properties in order to limit damage or improve its durability.

Among these functions, self-healing is currently one of the most studied and most promising for civil engineering applications.

Self-healing concretes are innovative cementitious materials capable of spontaneously sealing cracks that appear during their service life, without external human intervention (Figure 4.1). This capability relies on internal mechanisms that are generally activated in the presence of water or after cracking, allowing the reduction of permeability, the improvement of durability, and the extension of the service life of structures.

Depending on the mechanism involved, self-healing may be either autogenous, resulting from the continued hydration of cement and the precipitation of calcium carbonate, or autonomous, involving specific agents such as bacteria, chemical compounds, or microcapsules embedded in the cementitious matrix.

Self-healing concretes can be combined with all types of concrete, particularly self-compacting concrete, high-performance concrete, and fiber-reinforced concrete.

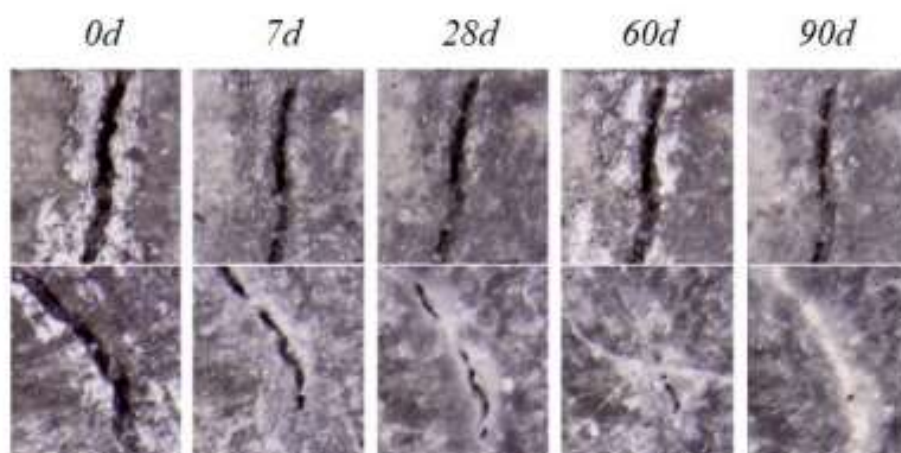


Figure 4.1 : *Concrete healing as a function of time*

Self-healing concretes have attracted increasing attention in recent years due to their potential to significantly enhance the service life and sustainability of civil engineering structures. Their main implication lies in the ability to autonomously seal cracks and partially restore mechanical and durability properties, thereby reducing maintenance costs and extending the lifespan of infrastructure.

This technology is particularly relevant for structures exposed to aggressive environments such as marine facilities, bridges, tunnels, and water-retaining structures, where crack formation can lead to rapid ingress of harmful agents. Various self-healing mechanisms have been developed, including bacterial-induced mineral precipitation, encapsulated healing agents, and intrinsic autogenous healing. Among these, bacterial self-healing systems have shown promising results in improving crack closure efficiency and reducing permeability (Jonkers, 2011; De Belie et al., 2018). Overall, self-healing concretes represent a key innovation toward more durable and sustainable construction materials, aligning with modern requirements for resilience and reduced life-cycle environmental impact (Li & Herbert, 2012).

4.2. Properties of Self-Healing Concretes

Self-healing concretes differ from conventional concretes by their ability to actively respond to cracking, resulting in specific properties affecting mechanical, physical, and durability aspects.

4.2.1. Mechanical Properties

a. Compressive strength

Self-healing concretes generally exhibit compressive strength comparable to that of conventional concretes (30 – 45 MPa) (Yehia et al. 2025). However, a slight reduction in early-age strength may be observed, particularly when self-healing agents (bacteria, microcapsules) are incorporated.

b. Tensile and flexural behavior :

Self-healing enables partial recovery of mechanical performance after cracking, especially in flexure, due to the sealing of cracks by healing products such as calcium carbonate or hydration products.

c Crack control :

When combined with fibers, self-healing concretes exhibit better control of crack openings, which enhances the efficiency of the healing mechanism.

4.2.2. Physical Properties

a. Crack sealing and closure

Self-healing concretes are mainly characterized by the natural sealing of cracks, typically for crack widths ranging from 0.2 to 0.8 mm. Consequently, crack sealing leads to a significant reduction in permeability to water and gases, thereby improving the effectiveness of the self-healing process.

b. Local densification of the matrix

Healing products fill cracks and pores, resulting in a reduction of connected porosity.

4.2.3. Durability Properties

a. Significant improvement in durability

Self-healing concretes limit the penetration of chlorides, sulfates, and carbon dioxide, thereby reducing reinforcement corrosion, carbonation, and chemical attacks. By slowing down these degradation mechanisms, self-healing contributes to the long-term durability of concrete structures.

b. Repeatable self-repair

Some self-healing concretes, particularly bacterial concretes, may be capable of several healing cycles as long as activation conditions are satisfied.

The self-healing mechanism is mainly activated in the presence of water, allowing a targeted reaction at the cracked zones.

4.3. Classification of Self-Healing Mechanisms

Self-healing mechanisms can be classified into two main categories: autogenous **and** autonomous.

4.3.1 Autogenous Self-Healing

Autogenous self-healing is a natural phenomenon already present in conventional concretes. It corresponds to the ability of concrete to repair or heal its cracks in the absence of tensile stresses and in the presence of moisture. The autogenous self-healing process relies solely on the original constituents of the material, which, under favorable environmental conditions, promote healing due to their specific chemical and reactive nature.

It mainly relies on:

- the continued hydration of unhydrated cement particles,
- the precipitation of calcium carbonate (CaCO_3) within cracks.

Physical factors include the expansion of the cementitious matrix around the crack opening, resulting from water absorption by the hydrated cement matrix, which leads to crack tightening. Chemical mechanisms are mainly related to two processes: the continuation of Portland cement hydration and the precipitation of calcium carbonate around the cracks. The mechanical effect of autogenous self-healing corresponds to the filling of open cracks by fine particles originating from the surface of the damaged concrete or transported to the crack by water.

This mechanism is generally effective for very fine cracks (≤ 0.2 mm) and requires the presence of water. However, its efficiency remains limited over time, especially for wider cracks.

In general, the causes of autogenous self-healing can be classified into three categories: physical, chemical, and mechanical.

4.3.2 Autonomous Self-Healing

Autonomous self-healing relies on the introduction of specific healing agents into the cementitious matrix, capable of being activated after cracking (Figure ...).

Among these agents, the following can be distinguished:

- chemical and mineral agents,
- polymeric microcapsules,

- functional fibers,
- bacteria.

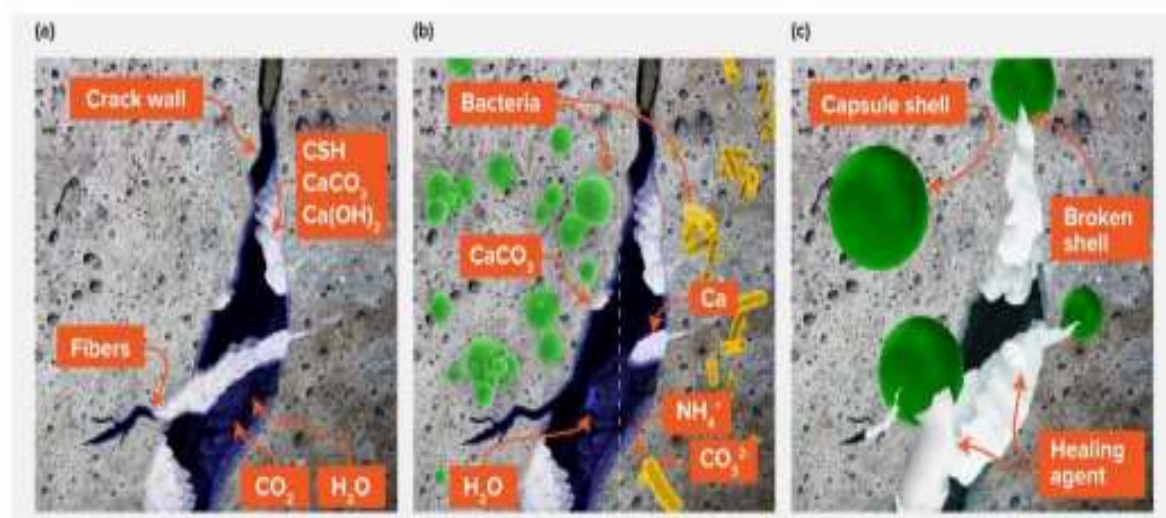


Figure 4.2. Self-healing mechanisms:

(a) autogenous, (b) autonomous bacteria-based, and (c) autonomous capsule-based

4.4. Constituents of Self-Healing Concretes

In addition to the basic constituents of conventional concrete—namely cement, aggregates, water, and admixtures (superplasticizers,...)—self-healing concretes may also include the following components:

4.4.1 Expansive or Reactive Agents

Expansive agents (EA) are characterized by their expansive behavior within the cementitious matrix. As soon as the constituents come into contact with water, an initial bonding is established between the aggregates within the cementitious matrix, while the expansive agents simultaneously initiate crystal formation. These crystals progressively grow within the microstructure, leading to the rupture of the initial bonds between aggregates and the formation of new connections. During this growth process, the crystals generate crystallization pressures which, when the available pore space becomes insufficient, transform into swelling pressures. This mechanism induces an expansion of the cementitious matrix.

Several types of expansive agents are commercially available, such as calcium oxide, magnesium oxide, and calcium sulfoaluminate.

4.4.2. Calcium Oxide

The production of calcium oxide (CaO) from limestone represents one of the oldest known chemical transformations. Calcium oxide appears as a white crystalline solid obtained by the calcination of limestone, chalk, shells, or corals rich in calcium carbonate (CaCO_3) at temperatures between 750 and 900 °C.

The reactivity of CaO strongly depends on the calcination temperature of CaCO_3 . When CaO reacts with water, it forms portlandite, which progressively crystallizes and exerts stresses within the

cement paste matrix. The delayed formation of these crystals in a confined environment generates an expansion of the cementitious matrix.

4.4.3. Magnesium Oxide (MgO)

Expansive agents based on magnesium oxide (MgO) are generally obtained by the calcination of magnesium carbonate minerals. The reactivity of MgO can be easily controlled by calcination conditions such as temperature and duration.

During hydration, MgO first dissolves, increasing the concentration of Mg^{2+} ions in the pore solution. The formation of brucite crystals is induced by the supersaturation of Mg^{2+} ions in this solution. The growth of these crystals—restricted by the pore network of the matrix—generates crystallization pressures that enlarge the internal spaces of the matrix and consequently produce expansion.

4.4.4. Calcium Sulfoaluminate

Expansive agents based on calcium sulfoaluminate can be produced from natural calcite as well as industrial by-products and wastes such as $\text{Al}(\text{OH})_3$ and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The raw materials are mixed and then heated successively at 20, 400, 600, and 1200 °C for one hour before being rapidly air-cooled.

The hydration of calcium sulfoaluminate reacts with water and $\text{Ca}(\text{OH})_2$ produced during the hydration of free lime and/or present in the cement matrix. A solid solution is then formed which reacts with anhydrite to produce ettringite.

4.4.5. Polymers Involved in the Self-Healing of Concrete

a. Poly(Phenol-Formaldehyde) Resin (PF)

Poly(phenol-formaldehyde) resin is used in the form of microcapsules embedded within the cementitious matrix. When a crack propagates, it causes the mechanical rupture of the microcapsules, releasing the PF resin. This resin then polymerizes in situ upon contact with air or moisture, enabling crack sealing and partial restoration of the concrete's watertightness.

This mechanism is particularly effective for early-age cracks with small openings, thereby contributing to extrinsic self-healing of the material.

b. Superabsorbent Polymers (SAP)

Superabsorbent polymers (SAP) play a key role in self-healing due to their high water absorption and retention capacity.

In cementitious materials, SAP particles swell when water penetrates into cracks, producing an immediate physical sealing effect. In addition, the stored water promotes secondary hydration of unhydrated cement phases, strengthening the autogenous self-healing process and reducing the permeability of the material.

c. OXE-CHI-PUR Polymer (Oxetane-Modified Chitosan–Polyurethane)

The OXE-CHI-PUR polymer is a hybrid polymer obtained from the combination of chitosan, polyurethane, and oxetane groups. Although initially studied for asphalt binders, its principle can be applied to cementitious materials.

This polymer possesses a molecular self-reorganization capability, allowing the repair of microcracks under repeated mechanical loading. In concrete, such polymers may be used as additives or internal coatings, improving fatigue resistance and extending structural durability.

d. Repeatable Self-Healing Polymers

Repeatable self-healing polymers rely on reversible bonds (hydrogen bonds, ionic interactions, or dynamic covalent bonds). In smart concretes, these polymers can be incorporated in the form of films, fibers, or additives.

When a crack forms, the broken bonds spontaneously reform under the effect of external stimuli such as heat, humidity, or mechanical stress, enabling multiple healing cycles without the addition of new healing agents.

e. Polyurethane-Based Photo-Healing Polymers

Photo-healing polymers, generally based on modified polyurethane, are activated by UV light exposure. In these systems, UV irradiation induces controlled breaking of certain polymer bonds and the formation of free radicals, which trigger a re-crosslinking reaction of the polymer at the microcrack location.

When applied to concrete as smart coatings or protective layers, these polymers allow rapid self-repair of surface cracks and improve resistance to environmental degradation.

4.4.6 Biological Agents Involved in Concrete Self-Healing

a. Calcifying Bacteria – *Bacillus subtilis*

Bacillus subtilis is one of the most commonly used microorganisms in self-healing concrete. These bacteria are encapsulated or incorporated in the cementitious matrix in the form of spores.

When a crack forms and moisture penetrates, the spores germinate and produce enzymes such as urease. This reaction leads to the precipitation of calcium carbonate (CaCO_3), which fills the cracks and improves the watertightness and durability of the concrete.

These bacteria remain stable over long periods due to their spore form, which is resistant to the highly alkaline conditions of concrete.

b. Bacteria of the Species *Bacillus sphaericus*

Bacillus sphaericus is also widely studied for its role in biomineralization. It uses nitrogen and calcium sources present in the concrete to produce CaCO_3 .

The bacteria can be encapsulated in microcapsules or absorbent aggregates to protect them during mixing and hardening of the concrete. This biomineralization process can seal cracks up to 0.5 mm and restore part of the mechanical strength of the material.



Figure 4.2: *Bacteria of the Species Bacillus sphaericus*

c. Ureolytic Heterotrophic Bacteria

Certain heterotrophic bacteria, such as *Sporosarcina pasteurii*, are capable of degrading urea to release carbonate ions and precipitate calcium carbonate (CaCO_3). In concrete, they can be activated by water penetrating into cracks, triggering the biochemical self-healing mechanism. These bacteria are particularly effective in repairing fine cracks and reducing the permeability of concrete.

d. Calcifying Algae or Cyanobacteria

Some cyanobacteria (for example *Synechococcus* or *Chlorella*) can precipitate calcium carbonate through photosynthesis by using dissolved CO_2 and calcium from the surrounding environment. When incorporated into porous concretes or mortars, they can contribute to the formation of a mineral deposit within superficial cracks, thereby participating in the self-healing process, particularly in areas exposed to light and moisture.

• Methods for Introducing Bacteria into Concrete

Bacteria cannot be directly introduced into cement paste because this generally leads to their rapid destruction. For this reason, bacteria are introduced in the form of **spores**, which can remain dormant for long periods and are activated only when water penetrates into a crack.

Bacterial spores are encapsulated or incorporated into porous carriers such as:

- expanded clay
- perlite
- vermiculite
- hydrogels or microcapsules

These carriers:

- protect the spores during mixing
- store nutrients
- release the bacteria when water penetrates cracked concrete

4.5. Nutrients and Healing-Promoting Agents

4.5.1. Bacterial Nutrients

Bacteria require a nutrient substrate to produce calcium carbonate. The most commonly used nutrient is **calcium lactate** because:

- it is compatible with concrete
- it directly provides Ca^{2+} ions
- it does not degrade mechanical properties

The biological reaction leads to the formation of calcium carbonate (CaCO_3), which is the main crack-sealing agent and also reduces permeability.

4.6. Factors Influencing Healing Efficiency

Several factors may influence the efficiency of self-healing in concrete.

4.6.1. Crack Width

The initial crack width is a determining factor for the success of self-healing. Very fine cracks (less than 50 μm) generally heal more slowly, whereas wider cracks (200–500 μm) may fill more rapidly due to better access to water and external CO_2 , which promotes CaCO_3 precipitation or C–S–H formation.

4.6.2. Type and Concentration of Biological Agents

The efficiency strongly depends on the bacterial species used (e.g., *Bacillus subtilis*, *Bacillus sphaericus*) and the concentration of incorporated spores. An insufficient quantity of bacteria may limit calcium carbonate formation, while an excessively high concentration may lead to excessive expansion and secondary cracking.

4.6.3. Curing Conditions

Water availability and relative humidity are essential to activate bacteria and enable calcium carbonate precipitation. Self-healing concretes under dry conditions exhibit limited healing, whereas water curing promotes the formation of healing products.

4.6.4. Influence of Concrete Composition

- The presence of free lime $\text{Ca}(\text{OH})_2$ and other cementitious compounds influences the ability of bacteria to produce calcium carbonate. Concretes rich in C_3S and C_2S allow better formation of portlandite, which is a key component for the biological reaction.
- The lower the water-to-cement ratio, the more significant the self-healing phenomenon through hydration of anhydrous particles becomes. Effective healing has been obtained for w/c ratios between 0.3 and 0.4.

- Healing capacity increases when supplementary binders partially replace cement. The most effective proportions are 30% slag or 40% fly ash, with an optimal sand proportion of 33%.
- The nature of aggregates has no direct effect on self-healing, although limestone aggregates may increase the calcium available for calcium carbonate precipitation. Porous aggregates can serve as carriers for calcifying bacteria, promoting healing of larger cracks, while aggregate size and shape influence crack geometry and water flow within them.
- Fibers crossing cracks appear to increase the self-healing capacity of concrete because they create zones where water flow is slower and provide anchorage points for healing products.

4.6.5. pH and Chemical Environment

Calcifying bacteria require an alkaline environment (high pH) to survive and precipitate calcium carbonate. Therefore, the chemical composition of concrete, as well as salts and additives, may directly influence the efficiency of the healing process.

4.6.6. Carbonation State

Carbonation reduces the self-healing capacity of concrete by transforming portlandite and C–S–H products into calcite, which is much less soluble, thereby limiting calcium carbonate precipitation within cracks. Consequently, concretes exposed to air, where carbonation is favored, show a slightly lower self-healing rate.

4.6.7. Temperature Effect

An increase in temperature accelerates the self-healing process in concrete by promoting faster crack closure and reducing specimen permeability. This is explained by the acceleration of chemical reactions and increased precipitation of calcium carbonate, whose solubility decreases with temperature.

4.7. Formulation of Self-Healing Concrete

4.7.1. Formulation of Autogenous Self-Healing Concrete

The main recommendations for designing autogenous self-healing concretes are:

- Increasing the amount of free lime $\text{Ca}(\text{OH})_2$ available in the concrete to promote calcium carbonate precipitation in cracks.
- Reducing the water–cement ratio to improve matrix density while maintaining some free water for later hydration.
- Using cements rich in C_3S and C_2S to prolong hydration and produce additional C–S–H.
- Adding mineral admixtures such as silica fume or fly ash to stimulate the formation of additional C–S–H gels.

4.7.2. Formulation of Autonomous Self-Healing Concrete (via Incorporated Agents)

These concretes must incorporate healing agents (agents + nutrients) capable of autonomously sealing cracks.

Main recommendations include

- Bacteria-based systems
 1. Incorporation of spores in the dry mix or in encapsulated form.
 2. Addition of a calcium source and nutrients for germination.
 3. Concrete placement similar to conventional concrete.
- Polymer Capsules or Microcapsules
 1. Encapsulate the healing product in microcapsules resistant to the alkaline environment of concrete.
 2. Mix the capsules with the concrete during formulation.
 3. Capsules rupture when cracks form, releasing the healing agent and filling the cracks.
- Expansive Mineral Agents
 1. Incorporate the expansive agent in the concrete mix (generally **5–10% of cement weight**).
 2. Adjust the water–cement ratio to control expansion and avoid secondary cracking.

4.7.3. Formulation Procedure (Depending on the Desired Concrete Type)

1. Aggregate volumes
 - $V_{\text{fine}} + V_{\text{coarse}} = \text{total aggregate volume}$
 - Partial replacement of fine aggregates with porous aggregates to host bacteria or microcapsules.
2. Cement dosage
 - Calculated according to total volume and water–cement ratio to reach the target strength while allowing further hydration.
3. Addition of self-healing agents
 - Bacteria: encapsulated spores or spores incorporated in porous aggregates.
 - Microcapsules: PF resin, polyurethane, or OXE-CHI-PUR.
 - Expansive agents: CaO, MgO, or CSA (quantity depending on crack width to be sealed).
4. Adjustment of water and admixtures
 - Water: sufficient for hydration and activation of bacteria or resins.
 - Admixtures: superplasticizers or retarders if required.
5. Verification of total volume

Cement + water + aggregates + admixtures + capsules/agents = total concrete volume.

6. Curing and control

Moist curing is recommended to promote bacterial reactions or expansive agent activation.

4.8. Characterization of Self-Healing Concretes

4.8.1. Microscopy

Microscopy techniques, particularly optical microscopy and scanning electron microscopy (SEM), are widely used to visually evaluate crack self-healing by observing crack closure and calcite crystal

formation. More advanced techniques such as polarized light microscopy, fluorescence microscopy, and SEM coupled with EDS allow identification of healing products and highlight the reduction in porosity associated with the self-healing process.

4.8.2. X-Ray Diffraction (XRD)

X-ray diffraction allows the identification of crystalline phases present in cementitious materials by analyzing the diffraction of X-rays by atomic planes. This makes it possible to identify healing products, particularly in autonomous healing systems. It has been used to detect healing agents and reaction products formed in modified cement pastes, such as **ettringite or calcium carbonate**.

4.8.3. Permeability

Liquid permeability tests represent a key method for evaluating the efficiency of self-healing because they directly reflect the ability of cracks to close and limit fluid flow.

After controlled pre-cracking of specimens, the progressive reduction in fluid flow (water or other low-reactivity liquids) over time is interpreted as an indicator of healing product formation, particularly calcium carbonate.

Gas permeability tests are complementary because they are more sensitive to pore and crack connectivity than liquid tests. Comparing permeability values before cracking, immediately after cracking, and after a healing period allows quantification of the self-healing efficiency. A significant reduction in gas permeability confirms partial or total crack closure and restoration of durability properties.

4.8.4. Absorption

Absorption (or sorptivity) tests represent a faster alternative to permeability tests for evaluating the self-healing of cracked concrete. They measure the amount of water absorbed by capillary action, which significantly decreases when cracks are partially or fully sealed by healing products. These tests also show that the reduction in absorption can be directly correlated with crack closure.

Self-healing concretes generally exhibit a significant reduction in water absorption compared to conventional concretes due to their ability to seal cracks and refine the pore structure. When cracks form, self-healing mechanisms—such as bacterial precipitation of calcium carbonate or the release of encapsulated healing agents—contribute to blocking capillary pathways, thereby limiting fluid ingress. As a result, both sorptivity and water permeability are reduced over time, especially after healing activation. Experimental studies have shown that healed specimens can recover a substantial portion of their initial resistance to water penetration, which directly enhances durability in aggressive environments (Jonkers, 2011; De Belie et al., 2018). However, the effectiveness of absorption reduction strongly depends on crack width, environmental conditions, and the availability of moisture required to trigger the healing process.

4.8.5. Acoustic Techniques

Methods based on the propagation of ultrasonic waves are widely used to evaluate self-healing in concrete because partial or complete crack closure enhances wave transmission across the crack

faces. Several studies have shown that a decrease in transit time or an increase in wave velocity after healing is consistent with visual crack closure and reflects both an improvement in mechanical properties and a reduction in permeability. Among these techniques, Ultrasonic Pulse Velocity (UPV) is the most commonly used; it generally increases progressively during the healing process, indicating a partial restoration of material stiffness, although its accuracy remains limited for precise quantification.

To obtain a more comprehensive evaluation of self-healing efficiency, ultrasonic monitoring is usually combined with direct mechanical and durability-based tests. After an initial controlled cracking stage, specimens are subjected to specific healing conditions such as water immersion or wet-dry cycles, and their properties are periodically assessed. In addition to UPV measurements, recovery of flexural or splitting tensile strength, water permeability, sorptivity, and chloride ion penetration resistance are commonly used to quantify the functional recovery of the material. Furthermore, microstructural techniques such as Scanning Electron Microscopy (SEM) and X-ray computed tomography (CT) are employed to observe and characterize healing products formed within cracks, including calcium carbonate precipitates. Overall, the combination of these complementary methods provides a more complete understanding of both crack closure mechanisms and the recovery of mechanical and transport properties in self-healing concretes.

4.9. Conclusion

Self-healing concrete represents an important advancement in the field of cementitious materials, providing an intrinsic ability to repair microcracks. Through different mechanisms, such as natural autogenous healing, the use of reactive mineral additions, bacteria, or capsules containing healing agents, these concretes can partially restore their mechanical properties and watertightness over time. This healing capacity helps to limit crack propagation, reduce the penetration of aggressive agents, and consequently improve the durability of structures. Therefore, self-healing concretes constitute a promising solution for extending the service life of structures while reducing maintenance costs and the environmental impact of construction.

4.9. Exercises

Exercise 1

The objective is to design 1 m³ of self-healing concrete intended for structures exposed to water, capable of healing cracks $\leq 300 \mu\text{m}$, using an enhanced autogenous self-healing mechanism reinforced by a calcium sulfoaluminate (CSA) expansive agent.

- Target strength class: C30/37
- Workability: S3
- Cement: CEM I 42.5 (density $\rho = 3.15$)
- Aggregates:
 - Sand 0/4 mm ($\rho = 2.65$)
 - Gravel 4/12 mm ($\rho = 2.70$)
- Maximum water–cement ratio (W/C): 0.45
- Expansive agent CSA: 8% of the cement mass
- Entrapped air : 2%
- Non air-entrained concrete
- Moist curing is planned (favorable condition for self-healing)

Solution

1. Selection of the Water–Cement Ratio

For:

- Strength class C30/37
- Good durability
- Activation of the self-healing process

We adopt:

$$W/C=0.45$$

2. Cement Content

According to the Dreux–Gorisse method, for C30/37 concrete:

$$\text{Cement} \approx 350 \text{ kg/m}^3$$

3. Water Content

$$W = 0.45 \times 350 = 157.5 \approx 160 \text{ kg/m}^3$$

4. Absolute Volume Calculation

Cement Volume

$$V_c = 350 / 3150 = 0.111 \text{ m}^3$$

Remaining Volume for Aggregates

$$V_g = 1 - (0.111 + 0.160 + 0.02) = 0.709 \text{ m}^3$$

5. Sand–Gravel Distribution

For conventional concrete ($D_{\text{max}} = 12 \text{ mm}$), the Dreux–Gorisse method recommends:

- Sand: 40%
- Gravel: 60%

Sand Volume

$$V_s = 0.40 \times 0.709 = 0.284 \text{ m}^3$$

Gravel Volume

$$V_g = 0.60 \times 0.709 = 0.425 \text{ m}^3$$

6. Conversion to Mass

Sand Mass

$$M_s = 0.284 \times 2650 = 753 \text{ kg}$$

Gravel Mass

$$M_g = 0.425 \times 2700 = 1148 \text{ kg}$$

7. Dosage of the Expansive Agent (CSA)

$$\text{CSA} = 8\% \times 350 = 28 \text{ kg/m}^3$$

CSA can be added as a mineral addition or partially replace cement, depending on the selected formulation strategy.

Exercise 2

Design 1 m³ of self-healing semi-self-compacting concrete (SSCC) capable of healing cracks $\leq 300 \mu\text{m}$ through enhanced autogenous self-healing using MgO.

- Strength class: C40
- Target slump-flow: 450–500 mm
- Maximum aggregate size: $D_{\text{max}} = 12 \text{ mm}$
- Cement: CEM I 42.5
- Mineral addition: limestone filler
- Total binder: 500 kg
- Self-healing agent: MgO = 8% of cement mass
- Water-to-binder ratio: $W/B = 0.38$
- Target paste volume : $V_p = 360 \text{ l/m}^3$

Solution

Paste Volume

$$V_p = 0.36 \text{ m}^3$$

This volume includes:

- water
- cement
- mineral additions
- MgO
- chemical admixtures

Selection of Total Binder Content

For SSCC:

$$\text{Binder} \approx 500 \text{ kg/m}^3$$

Typical distribution:

- Cement = 420 kg/m³
- Limestone filler = 80 kg/m³

Mixing Water

$$W = 0.38 \times 500 = 190 \text{ kg} = 190 \text{ liters}$$

Absolute Paste Volume

Cement :

$$V_c = 420/3150 = 0.133$$

Filler :

$$V_f = 80/2700 = 0.030$$

Total paste volume:

$$V_{\text{paste}} = 0.353 \text{ m}^3 \approx 0.36 \text{ m}^3$$

Aggregate Volume

$$V_g = 1 - 0.36 = 0.64 \text{ m}^3$$

Typical SSCC distribution:

- Sand = 50%
- Gravel = 50%

Aggregate Masses

Sand

$$V_s = 0.32 \Rightarrow M_s = 0.32 \times 2650 = 848 \text{ kg}$$

Gravel

$$V_g = 0.32 \Rightarrow M_g = 0.32 \times 2700 = 864 \text{ kg}$$

Self-Healing Agent (MgO)

$$MgO = 8\% \times 420 = 34 \text{ kg}$$

MgO can be added to the binder or used as partial cement replacement.

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