# An introduction to concrete

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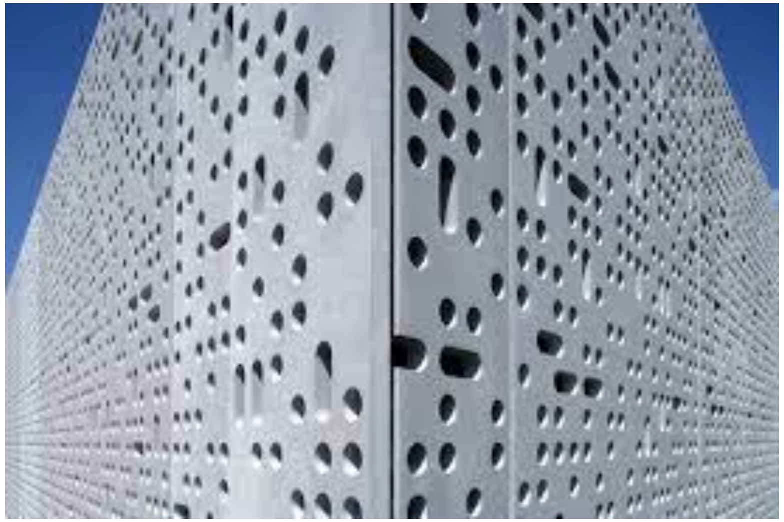
# CONTENTS



- Economics
- Cement and components of concrete
- Formulation
- Properties
- Pathologies, durability
- Fibres in concrete

Goal : to scan what is the « science of concrete », from its manufacturing to its long term behaviour.

*Bibliography : most of the information given in this lecture are coming from technical documents edited by the French « Centre d'Information sur le Ciment et ses Applications ».*

CIMbéton
CENTRE D'INFORMATION SUR LE CIMENT ET SES APPLICATIONS

# INTRODUCTION

KEY FIGURES

Concrete is a mouldable artificial stone.

It is the most intensive used material over the World. During one year, 1 m3 of concrete per capita of our planet is moulded; therefore more than **6 billion of m3**.

For that, **4.6 billions of tons of cement** are manufactured in cement factories, so producing **CO2 emission up to 4 billions tons**.

The cement production is boosted by the emerging countries among them, 60% only for China.

For comparison, the world wide demand in steel is 1.6 billions tons (200 millions m3), those of wood 200 millions m3.

# INTRODUCTION

In spite we usually speak of « concrete » as a single material, there are actually a lot of various concretes differing in their composition, use, mechanical strength, durability, density, rheology, resistance against chemical aggressions.

Most often, the concrete as a **brittle material**, is reinforced by steel-bars in construction, according the fact the bars are prestressed or not, the concrete is named **prestressed concrete** or **reinforced concrete**.

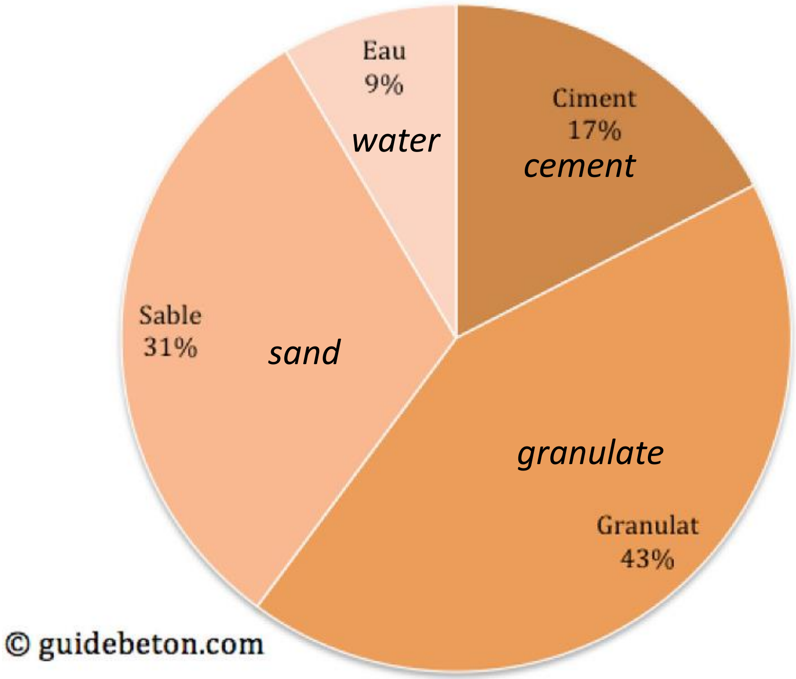
The reinforcement can also be obtained by use of fibres.

One should distinguish mortar and concrete.

- **Mortar** is devoted for gluing (bricks), hole-filling, sealing, chapping and rendering. It is made with sand.
- **Concrete** is used for structural bearing pieces of construction (columns, plates, wall, …). It is made with wider granulates.

Rule on the thumb in order to formulate a mortar : one part of cement, half a part of water, one part of sand (in mass).

# INTRODUCTION



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The typical composition in mass of a concrete is given bellow:

For one cubic metre of concrete, should be mixed:

- 300 to 350 kg of cement
- 175 to 185 litres of water
- 600 to 700 kg of sand
- 850 to 1000 kg of granulate

and, may be :

- water could include “adjuvants” (or “admixtures”) like plasticizer, accelerator or setting retarder, air-entrainer, etc…
- Some “additives” (lime, quartz, fly hashes, …) could be incorporated into the formula
- Fibres (polypropylene, cast iron, glass, carbon…) could be added.

Rule on the thumb for formulating a concrete: one part of cement, half a part of water, two parts of sand, three parts of granulates (in mass).

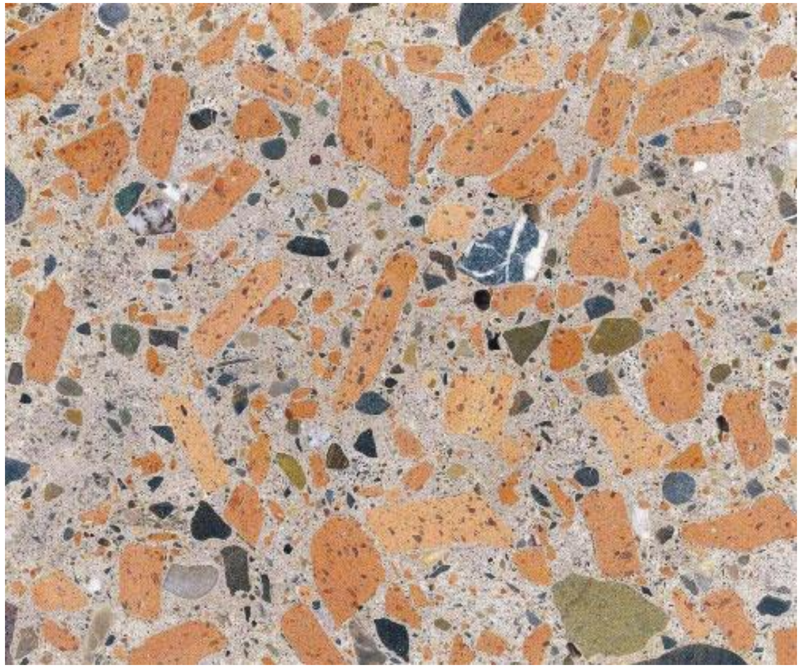
# INTRODUCTION

In this lecture, we are studying, one by one, the various components entering in the composition of a concrete.

We are examining then the main properties of the concrete, both at fresh state and at hardened state.

The issues of pathology and durability are being addressed afterwards.

A special focus on the fibres and what could be a research program on carbon fibres in concrete is closing the lecture.



# CEMENTS

The cement constitutes the glue which links the granulates (pebbles, gravels, sand)  together, the granulates forming the skeleton of the concrete.

The cement hardens in presence of water. The hardening results from the hydration of its anhydrous components (and not by ‘drying’ as we hear all too often).

Indeed, the cement harden in air as in water and the products of hydration remains insoluble. Therefore a cement is an “**hydraulic binder”**.

At the opposite, the “air binders” hardens solely in air, in presence of CO2 by carbonation. It is the case, for instance, of hydrated lime.

# CEMENTS

## CEMENT MANUFACTURING BY DRY WAY (MOST USED TODAY)

20% clay (various silicates and aluminosilicates)

80% limestone (calcium carbonate)

crushing → correction → grinding → **cement raw** → homogeneization → Firing 1450°C – 1h → Cooling → **clinker**

**clinker** → milling

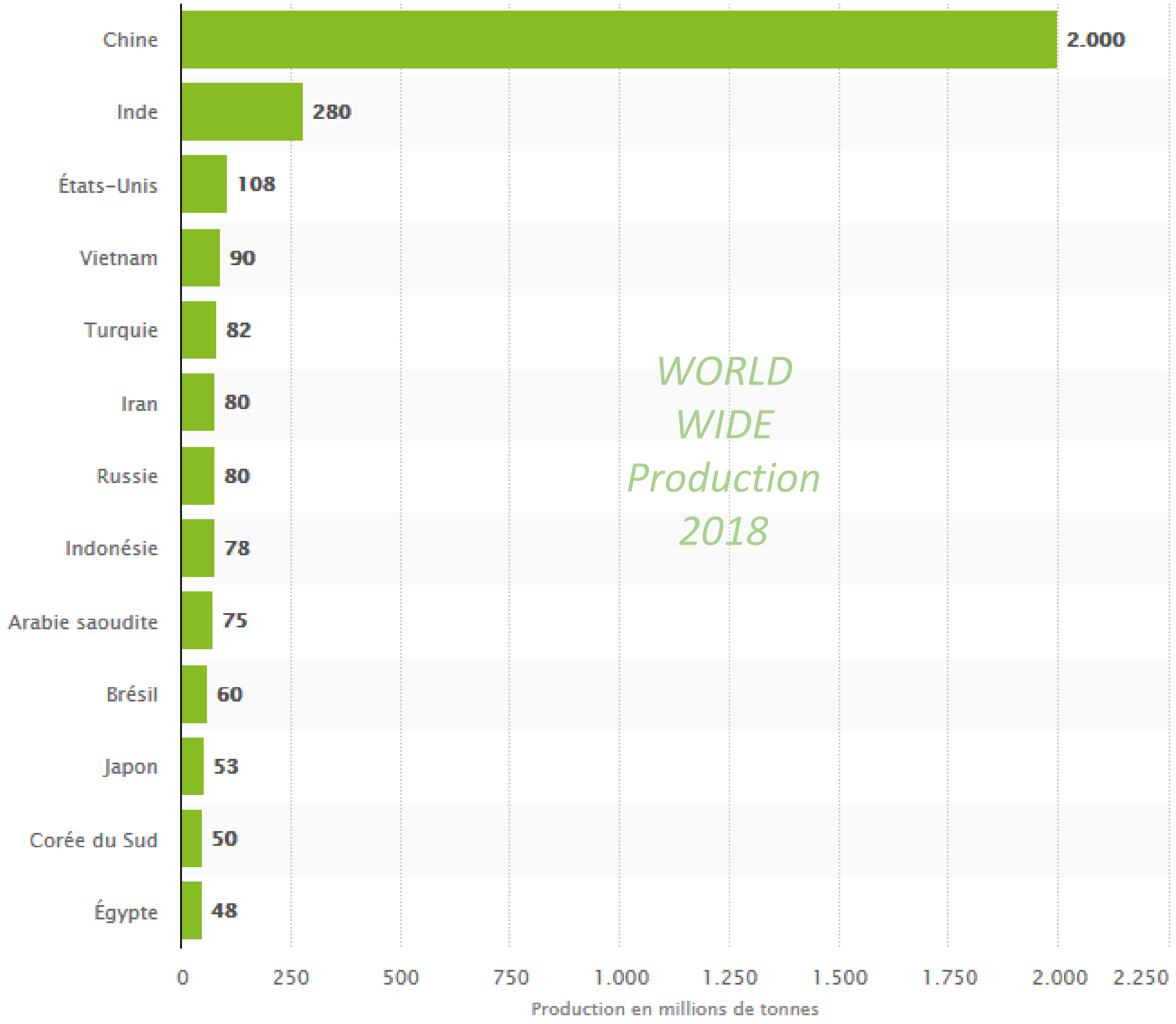
**gypsum** → milling

milling 0-100µm → **additions**

**additions** → bulk

**additions** → 35 kg bags

# CEMENTS



World wide cement production:
no European country in the top 10 !

For instance: France → 20 Mt/year only

# CEMENTS

## COMPOSITION OF ANHYDROUS CEMENT

Main anhydrous components of the **Portland clinker**, in the decreasing order of their amount.

| name | full name | chemical formula | cement notation | % in mass |
|---|---|---|---|---|
| Alite | tri-calcium silicate | $3CaO,SiO_2$ | $C_3S$ | 40 to 75 |
| Belite | di-calcium silicate | $2CaO,SiO_2$ | $C_2S$ | 10 to 35 |
| Celite | tri-calcium aluminate | $3CaO,Al_2O_3$ | $C_3A$ | 0 to 15 |
| - | tetra-calcium aluminoferrite (*) | $4CaO,Al_2O_3,Fe_2O_3$ | $C_4AF$ | 0(*) to 20 |

| oxide symbol | formula | oxide symbol | formula |
|---|---|---|---|
| **C** | CaO | **A** | $Al_2O_3$ |
| **S** | $SiO_2$ | **F** | $Fe_2O_3$ |
| **H** | $H_2O$ | Etc… | |

(*) The white cement does not contain iron oxide.

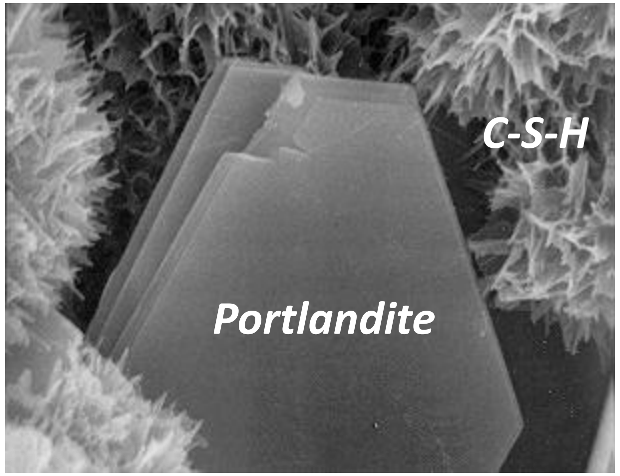
# CEMENTS

## HYDRATION OF SILICATES

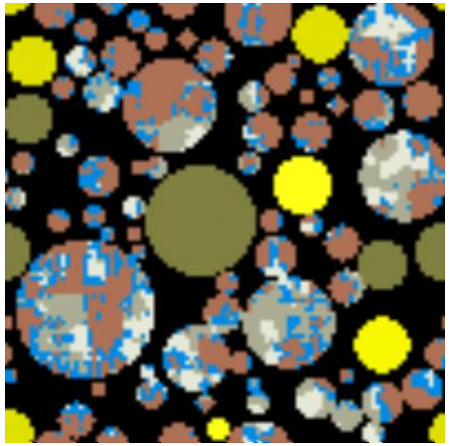
The chemical reactions between the anhydrous components of the clinker and the water lead to the setting then to the hardening of the cement paste.

When in presence of water, the anhydrous tri-calcium silicates $C_3S$ and bi-calcium silicates $C_2S$ gradually dissolve as ions then produce **hydrated calcium silicates** (C-S-H) and **portlandite** (CaO). These exothermic reactions accelerate the hydration. The hydration of the phase $C_2S$ is much slower and generates less portlandite. The phase C-S-H is not crystallin but forms a **gel** which composition is variable. The general formula of C-S-H is noted $C_xS_yH_z$ with an average around $C_{1.7}S_1H_4$ .

The entanglement of C-S-H gives the cement its strength: C-S-H develop at the surface of the anhydrous cement grains then progressively fill the capillarity gap between the grains. In few hours, the hydrate layer surrounding the cement grains becomes thick enough for slowing down the ions and the water diffusion towards the anhydrous component of the system. The global hydration slows down more and more but still goes on during months.



*CEMYHY3D – NIST/LMDC*



# CEMENTS

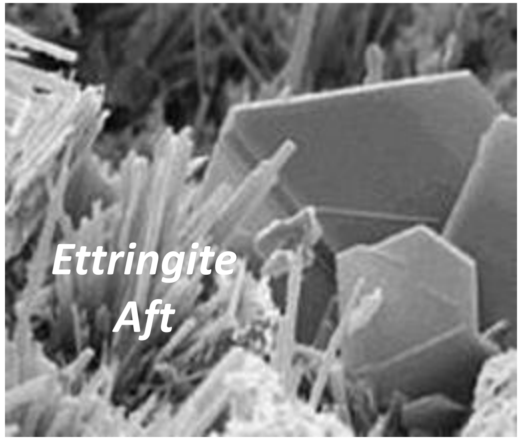
## ALUMINATES HYDRATION

Because of the high reactivity of the tri-calcium aluminate $C_3A$ with water, the cement manufacturers add **gypsum** to the clinker in order to mitigate the reaction.

The reaction of the aluminates proceeds in three stages:

Étape 1 : Formation of ettringite (phase AFt)

The aluminates react with the sulphate of the gypsum $Ca0,SO_3$ (cement notation: $C\bar{S}$) and form **ettringite** or hydrous calcium sulphate $C_6A\bar{S}_3H_{32}$. This reaction is extremely exothermic. A layer of acicular hydrates surrounds the aluminates.



| oxide symbol | Formula |
|---|---|
| $\bar{S}$ | $SO_3$ |

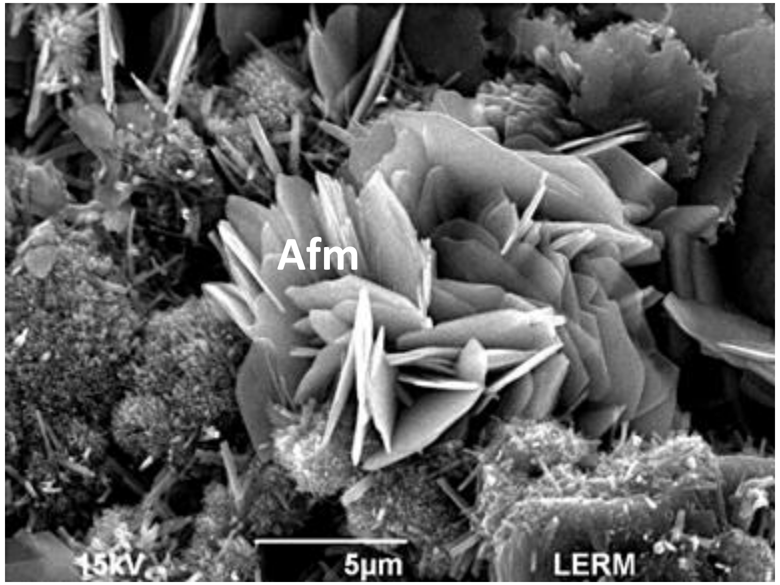
# CEMENTS

## ALUMINATES HYDRATION

Stage 2 : Transformation of the ettringite in calcium mono-sulphate hydrate

When the gypsum is totally consumed, the sulphate concentration decreases in the solution. The ettringite therefore becomes unstable, dissolves and forms calcium mono-sulpho-aluminate hydrate, called “Afm”, which formula is $(CaO)_3(Al_2O_3)(CaSO_4), 12H_2O$

→ Chemical reactions accelerate.

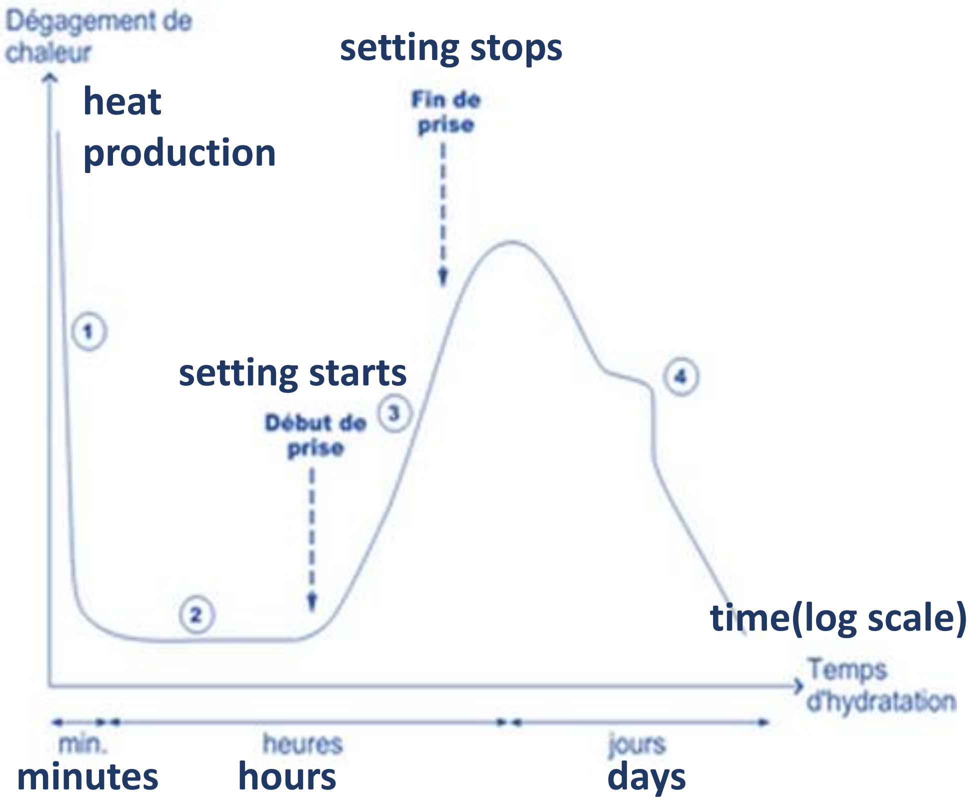


Stage 3 : Hydration of the other aluminates

Finally, all the ettringite transforms into mono-sulpho-aluminate. After one month, the reactions slowly go on with the aluminate (C3A) and the aluminoferrite ($C_4AF$) forming calcium aluminoferrite hydrates. The reactions have some similarity with the C3A reactions but the tetra-calcium aluminoferrite ($C_4AF$) reactions are much slower and appear only when the gypsum has totally disappeared.

# CEMENTS

## HYDRATION KINETICS



The hydration of cement can be summarized as followed:

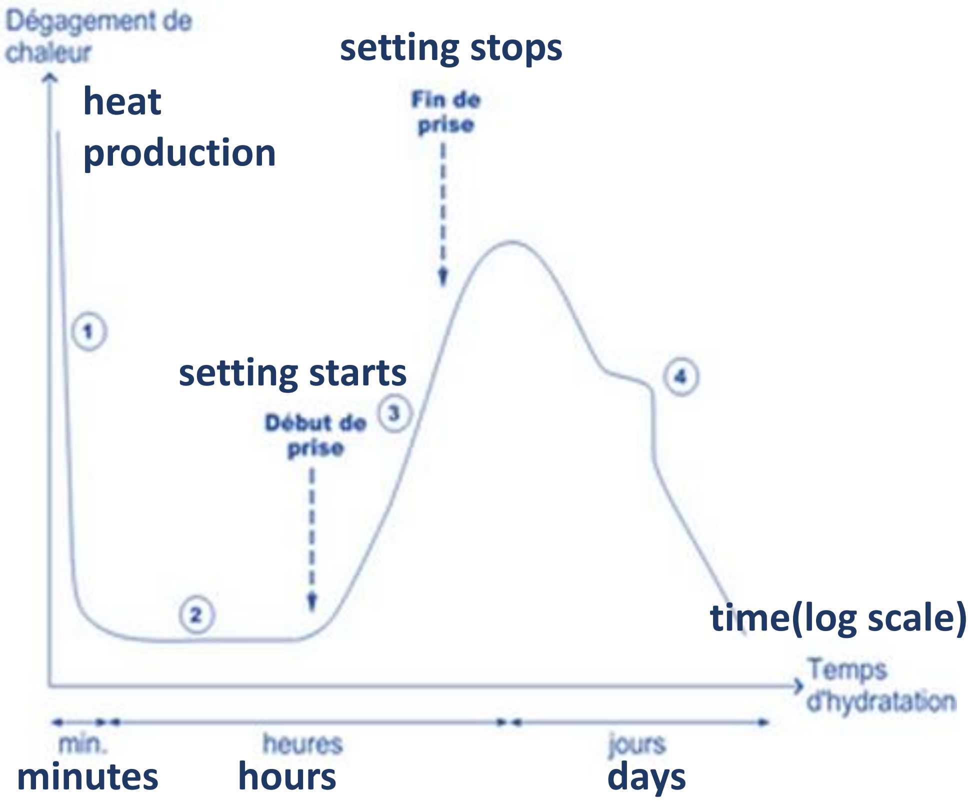
Stage 1: The contact between cement and water initiates the early reactions which last only few minutes. C3S and C3A contained in the cement grains immediately react with water, forming ettringite and the first C-S-H: ions dissolve and migrate in the solution.

Stage 2: dormant period
The heat emission is weak. There is no obvious manifestation of any evolution of the cement paste. However, ions solution is increasing during this stage (calcium ions, silicates ions, hydroxide and sulphate ions).

Starting of the setting: When the mixing water is saturated in ions, the beginning of the setting occurs. The pH of the solution gradually increases. The further dissolution of the cement components slows down.

# CEMENTS

**CINETIQUE D'HYDRATATION**



Stage 3: accelerating period

When the concentration in ions $Ca^{2+}$ et $OH^{-}$ becomes high, the electric conductivity reaches its maximum. The oversaturation leads to the precipitation of the portlandite. Mechanisms of dissolution, de seeding and precipitation of the various components allow the formation of the hydrates (ettringite, portlandite, C-S-H). This chemical activity, highly exothermic, provokes the entanglement of the hydrates and, therefore, the hardening.

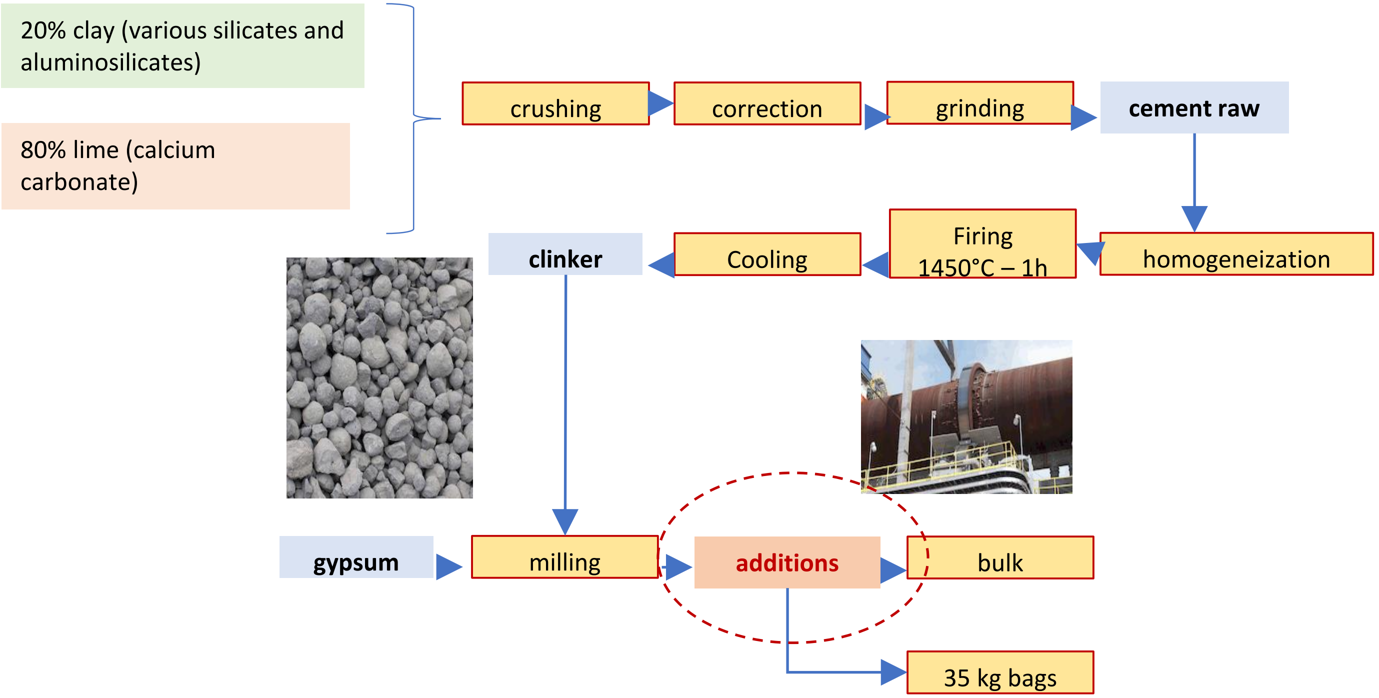
Stage 4: slowdown period

The anhydrous grains of cement are covered by an hydrate layer which thickens more and more. In order to continue the hydration process, water has to permeate through the gel porosity. The heat production decreases.

If the pore network is closed, a part of the cement will never hydrate. During the slowdown period, the ettringite type AFt dissolves and transforms into the type AFm.

The conventional end of setting is 28 days.

# CEMENTS



- **D = silica fumes** come form the silica industry in electric arc furnaces. Provide small particles ~1µm very rich in amorphous silica.
- **Z = pozzolans.**
  Natural volcanic stones or artificial stones, rich in amorphous silica with pozzolanic properties.

## OTHER COMPONENTS (additions)

Manufacturers add other components to the Portland clinker in order to provide a wide range of cement qualities:

- **S = blast furnace slag** brings more aluminates and magnesium oxides finely distributed and very reactive. Ratio C/S~3 against C/S~1.2 for the clinker.
- **V/W = fly hashes.** come from the smoke filtering from the coke combustion in thermoelectric factories. They mainly contain vitreous silica giving their pozzolanic reactivity.
- **L/LL = lime.** finely ground, contains more than 75% of CaCO$_3$ and must not contain organic carbon. It is a “filler”.
- **T = burnt shale.** Contains SiO$_2$ with pozzolanic properties and C$_2$S et CA with hydraulic properties.

# CEMENTS

## WHAT IS POUZZOLANICITY?

Pozzolans are silica-based or aluminosilicateous fines (<100µm). They do not have any intrinsic hydraulic properties but they chemically react with the calcium hydroxide $Ca(OH)_2$ in water, at ordinary temperature. They form components having hydraulic abilities:

Pozzolan + lime + water → binder

Natural pozzolans contain 60 to 85% of silica ($SiO_2$) and alumina ($Al_2O_3$). In presence of water and lime, they form calcium silicate hydrates, similar to those occurring when tri-calcium silicate hydrates (remember that $C_3S$ is the main compound of the Portland cement):

$CaO + SiO_2 + H_2O \rightarrow C\text{-}S\text{-}H$ (pozzolanic reaction)

$3CaO.SiO_2 + H_2O \rightarrow C\text{-}S\text{-}H + CH_2$ (hydraulic reaction of C3S for comparison)

NOTE: It is necessary for silica to be reactive that it comes in amorphous vitreous form. For instance, crystallized quartz is not pozzolanic at all and remains inert.

# CEMENTS

<table>
<tr><th>Family</th><th>Notation</th><th>Clinker<br>K</th><th>Slag<br>S</th><th>Silica fume<br>D</th><th>Pozzol.<br>Z</th><th>Fly ashes<br>V/W</th><th>Burnt shales<br>T</th><th>Limestone<br>L/LL</th><th>Second. compon</th></tr>
<tr><td>Portland Cement</td><td>CEM-I</td><td>95-100</td><td colspan="7"></td><td>0-5</td></tr>
<tr><td rowspan="2">Composed Portland Cement</td><td>CEM-II/A</td><td>80-94</td><td colspan="8">6-20</td></tr>
<tr><td>CEM-II/B</td><td>65-79</td><td colspan="8">21-35</td></tr>
<tr><td rowspan="3">Blast Furnace Cement</td><td>CEM-III/A</td><td>35-64</td><td>36-65</td><td colspan="5"></td><td>0-5</td></tr>
<tr><td>CEM-III/B</td><td>20-34</td><td>66-80</td><td colspan="5"></td><td>0-5</td></tr>
<tr><td>CEM-III/C</td><td>5-19</td><td>81-95</td><td colspan="5"></td><td>0-5</td></tr>
<tr><td rowspan="2">Pozzolanic Cement</td><td>CEM-IV/A</td><td>65-90</td><td></td><td colspan="3">10-35</td><td colspan="2"></td><td>0-5</td></tr>
<tr><td>CEM-IV/B</td><td>45-64</td><td></td><td colspan="3">36-55</td><td colspan="2"></td><td>0-5</td></tr>
<tr><td rowspan="2">Slag and fly ashes Cement</td><td>CEM-V/A</td><td>40-64</td><td>18-30</td><td></td><td colspan="2">18-30</td><td colspan="2"></td><td>0-5</td></tr>
<tr><td>CEM-V/B</td><td>20-39</td><td>31-50</td><td></td><td colspan="2">31-50</td><td colspan="2"></td><td>0-5</td></tr>
</table>

27 “common cements” are available (standard EN 197-1).

# CEMENTS

## STRENGTH CLASSES

The cements are classified according three classes of compressive strength: 32,5 / 42,5 et 52,5 (MPa). The “class” corresponds to the minimal value of the “characteristic” strength of a cement after a 28-day period of hardening. The strength is measured on 4x4x16 cm samples made in a “standard mortar” according to EN 196-1. Each class is accompanied by a velocity attribute, either “N” for normal setting, either “R” for rapid setting. This attribute characterises the 2-day strength at young-age.

| Class | Compressive strength | | |
|---|---|---|---|
| | At 2 days | At 28 days | |
| | Limite inf. | Limite inf. | Limite sup. |
| 32,5 | -- | 32.5 | 52.5 |
| 32,5 R | 13.5 | | |
| 42,5 | 12.5 | 42.5 | 62.5 |
| 42,5 R | 20.0 | | |
| 52,5 | 20.0 | 52.5 | -- |
| 52,5 R | 30.0 | | |

# CEMENTS

## OTHER CEMENTS (without Portland clinker)

| name | Standard (France) | Comment |
|---|---|---|
| Natural Prompt Cement<br>CNP | NF P15-314 | Cooking at ~1000°C of an argillaceous lime stone. Contains $C_2S$, $CA$, $CA\bar{S}$ highly reactive → cement which sets and hardens in few minutes (for sealings). |
| Alumina Cement<br>CA | NF P15-315 | More than 30% alumina. Applications : refractory concrete(up to 1300°C), grounds subjected to shocks or to heavy traffic, concrete pipes, sanitations facilities, repairing mortars… |
| Slag and lime Cement<br>CLX | NF P15-306 | |
| Masonry Cement<br>CM | NF P15-307 | Mix of clinker, slag (<50%), pozzolans and fillers at low ration of $SO_3$ < 3,5%. 2 strength classes are available: 16 et 25 MPa. |
| Natural Cement<br>CN | NF P15-308 | |

# CEMENTS

## STANDARD SUPPLEMENTARY CHARACTERISTICS

| Marking | standard (France) | characteristic | Concerned types of cements | Comment |
|---|---|---|---|---|
| PM | NF P15-317 | Cements for sea works | CEM-I, CEM-II, CEM-III/C, CEM-V, CNP, CA | Limited content in $C_3A$ |
| ES | NF P15-319 | Cements for works in high sulphate ratio water | CEM-I, CEM-II, CEM-III/C, CEM-V, CA | Limited content in $C_3A$ |
| CP | NF P15-318 | Cements at limited content in sulphides | CEM-I, CEM-II, CEM-III, CEM-V | Prestressed concrete |

# CEMENTS

## DESIGNATION OF A CEMENT

Cements are named by a series of symbol, according their origin, composition and properties:

1. TYPE (Roman digit from I to V followed by a letter A,B,C according the content in clinker, followed by a letter giving the type of addition among: S, D, P, Q, V, W, T, L, LL, M)
2. Strength class
3. Setting velocity : letter “R” (rapid), “N” (normal), “L” (slow)
4. In case or supplementary characteristic, it appears between parenthesis
5. If the cement is conformed to the article 7 of the standard EN 197-2 → mark “CE”
6. In France, if conform to  standards NF P15-XXX → mark “NF”

## EXAMPLE

*CEMI = Cement with more than 95% of Portland clinker*
*42,5 = Resistance strength = 42,5 MPa à 28 j*
*R = Minimal strength at 2 days = 20,0 MPa*
*PM = Sea setting*
*NF = Conform to French standards.*

# GRANULATES

The granulates constitute the skeleton of the concrete (~70% in volume). They must conform to the standards NF P18-540 (France) and EN 12620.

They differ by:

- their size or "granularity"
- their shape more or less flat
- their mineralogic and physicochemical properties
- their own porosity
- their cleanness
- their mechanical properties (wear resistance)
- their origin: natural rolled granulate or crushed
- their density

| designation | granularity |
|---|---|
| filler | D<2mm whose 85% < 1,25 mm and 70% < 63µm |
| fine sand | D<1mm and less than 10% < 63µm |
| sand | D<4 mm |
| gravel | D<6.3 mm |
| pebble | $d_{moy}$=2mm & D < 63mm |
| ballast | $d_{moy}$=31.5mm & D < 63mm |

# GRANULATES

## EN 12620  STANDARD’S REQUIREMENTS

❑ cleanness : limitation of the organic part and the clay content

❑ frost resistance : limitation of the porosity of the granulate

❑ strength resistance (“Los-Angeles” trial)

❑ harmlessness : limitation of the
  ❖ sulphates (risk of swelling by secondary ettringite apparition)
  ❖ chlorates (risk of reinforcement corrosion)
  ❖ amorphous silica (risk of damages by alkali-silica reactions)

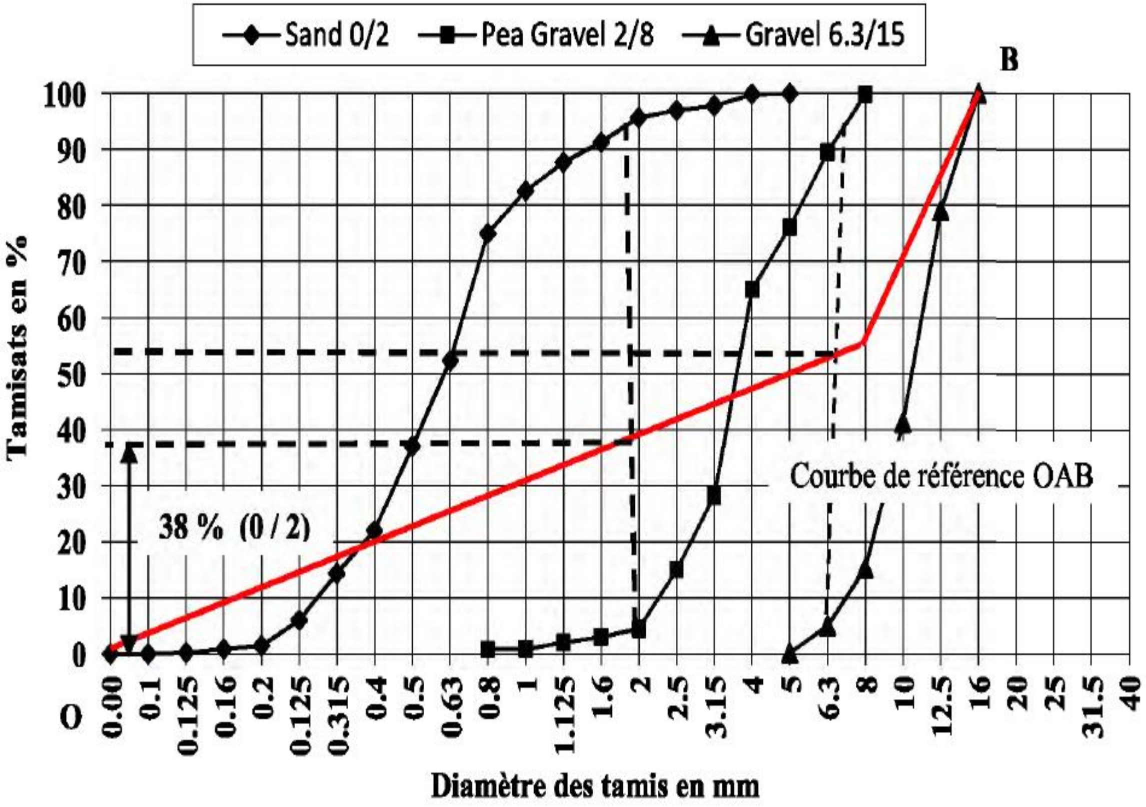
❑ swear resistance ( “micro-Deval” coefficient)

*Rotative drum used for the “Los Angleles” trial of fragmentation by chocks*

# GRANULATES

## GRADING CURVE

The grading curve characterises the repartition of the grain sizes in % of the mass. This curve is obtained thanks a series of standard sieves. The grading curve of a concrete results from the combination of the grading curves of the mixed granulates.



The normalised series of sieves, expressed in mm, is:

**0,063-** 0,08 - 0,10 - **0,125** - 0,16 - 0,20 - **0,25** - 0,315 - 0,40 - **0,50** - 0,63 - 0,80 - **1** - 1,25 - 1,60 - **2** - 3,15 - **4** – 5 - 6,30 **- 8** – 10 - 12,50 – 14 - **16** – 20 – 25 **- 31,50** – 40 – 50 **- 63** – 80 – 100 – **125**

(according EN 12620).

# WATER

## ROLE OF THE WATER IN CONCRETE (standard EN 1008)

The water entering in the formulation of a concrete plays two roles:

1. At the fresh state, it contributes to the plasticity of the concrete required for its moulding;
2. When hardening, it participates to the hydration mechanisms already described.

## Importance of the "W/C" water on cement ratio

The amount of water incorporated in the concrete is expressed relatively to the cement mass thanks to the W/C ratio. The minimal content of water required for the hydration of the cement is around 25% but the "workability" necessitates a quite higher ratio around 50%. An excess of water contributes to pernicious effects such that the bleeding, the retractation, the creeping, the porosity increase and, therefore, to the weakening of both the strength and the durability.

# WATER

## ORIGINE OF THE WATER

- ☐ tap water: OK
- ☐ recycled water from concrete factory: after trials
- ☐ underground water: after trials
- ☐ recycled water from industry: after trials
- ☐ sea water: only in non-reinforced concrete!
- ☐ sewage water: forbidden

## EN 1008 REQUIREMENTS

- ☐ aspect (odour, colour, oily residues and small particles)
- ☐ limited content in:
  - ❖ chlorates, sulphates, alkalis
  - ❖ sugar, Pb/Zn salts, phosphates (act as setting retardants)
- ☐ mechanics
  - ❖ setting start < 1h and gap <25% with respect to distilled water
  - ❖ setting end < 12h and gap <25% with respect to distilled water
  - ❖ strength at 7 days at least equal to 90% than get with distilled water

*Vicat needle*

EN 196-3 → measure of setting start and end thanks to the "Vicat needle".

# ADMIXTURES

The standard EN 934-2 defines an “admixture” (or chemical additive) as a product incorporated in the concrete formula with a light content (less than 5% of the cement mass) in order to bring or to improve a property of the concrete either in its fresh state, either in its hardened state.

3 great categories exist:

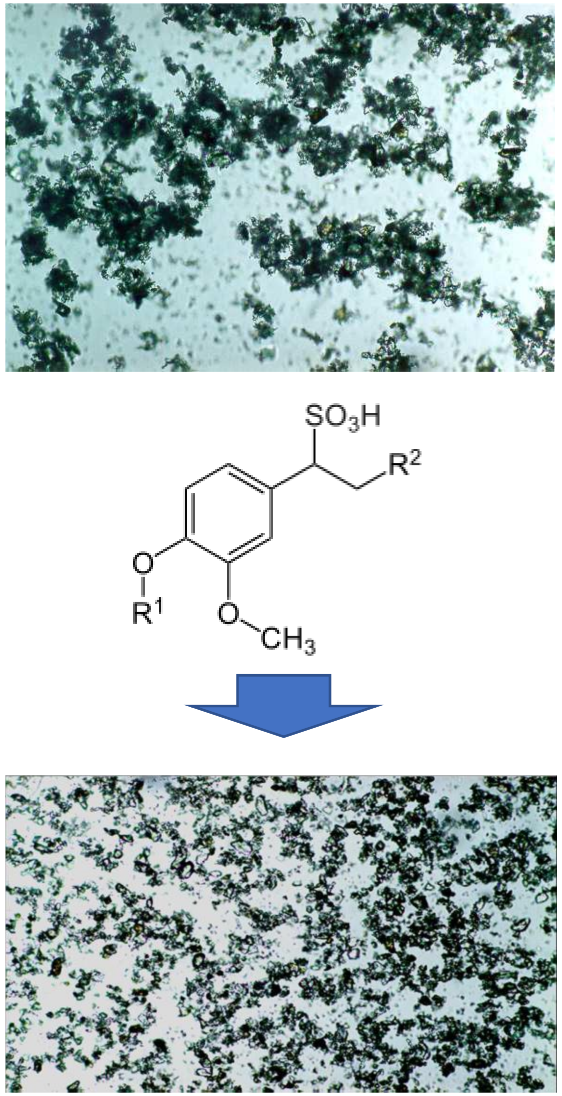
1. Modification of the workability (rheology): plasticizer, super-plasticizers;
2. Modification of the setting or the hardening: set accelerators and set retardants;
3. Modification of the properties when concrete is hard: air entraining agent, waterproofing, colouring, …

See the site of the French SYNAD : [http://www.synad.fr](http://www.synad.fr) for instance.

# ADMIXTURES

## PLASTICIZERS

- Allow the reduction of the water content (down to 6%) keeping the same fluidity.
- Chemistry : surfactants (hydrophobic/hydrophilic) **ligno-sulphonates**, acidic salts, sulphonate melamine, polycarboxylates (PC), polyacrylate (PA), polyoxymethylene (POE).
- Effect : deflocculation, dispersion of the cement particles, reduction of the porosity, quick demoulding.
- Use : civil engineering structures, sliding formworks
- Dosage : 0.5 to 3% of the cement mass



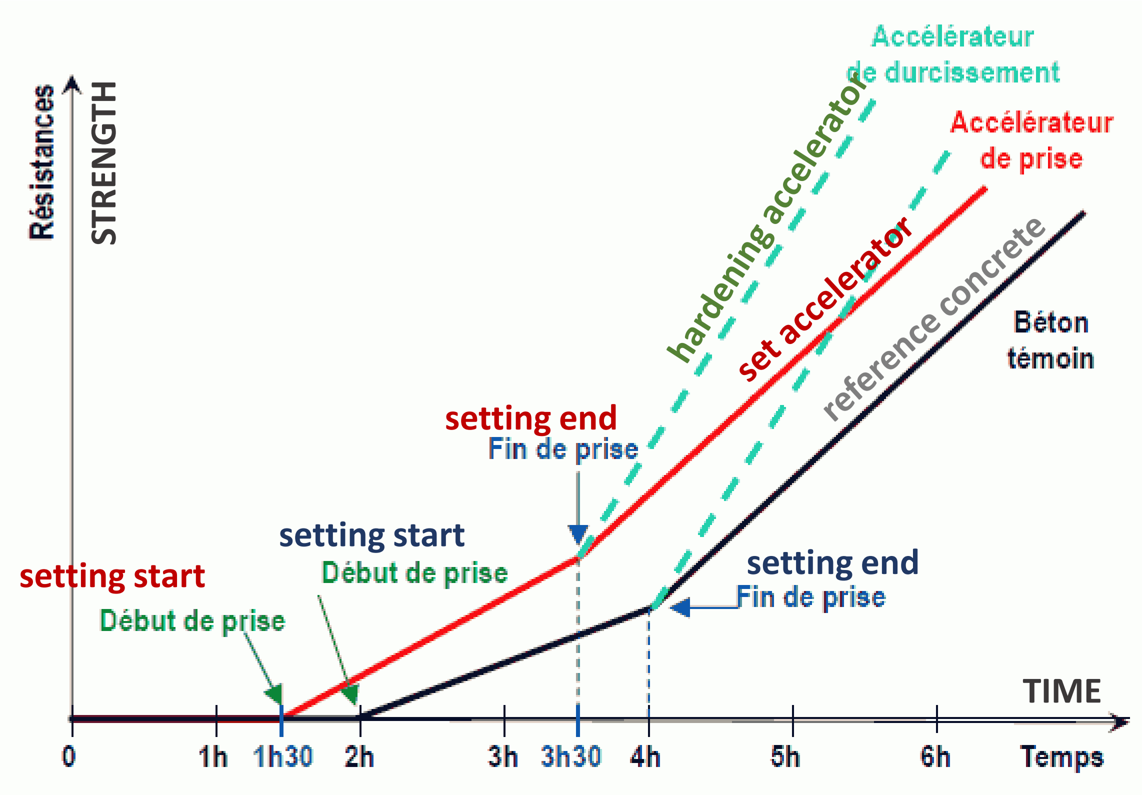
## SUPER-PLASTICIZERS (SUPER WATER-REDUCERS)

- Substantially improve the workability.
- Chemistry : lignosulfonates, vinyl copolymers, polycarboxylic ethers
- Effect : porosity reducer, quick demoulding
- Use : high performance concrete (HPC)
- Dosage : less than 0.5% at the end of the mixing

# ADMIXTURES

## SET ACCELERATOR / HARDENING ACCELERATOR

- Reduces the times of starting and ending of the setting or/and the hardening.
- Chemistry : calcium or sodium nitrates.
- Effect : Enable strength at young age.
- Use : concreting by cold weather, quick demoulding, works under water, prestressed concrete.
- Dosage : 1 to 3% of the cement mass.



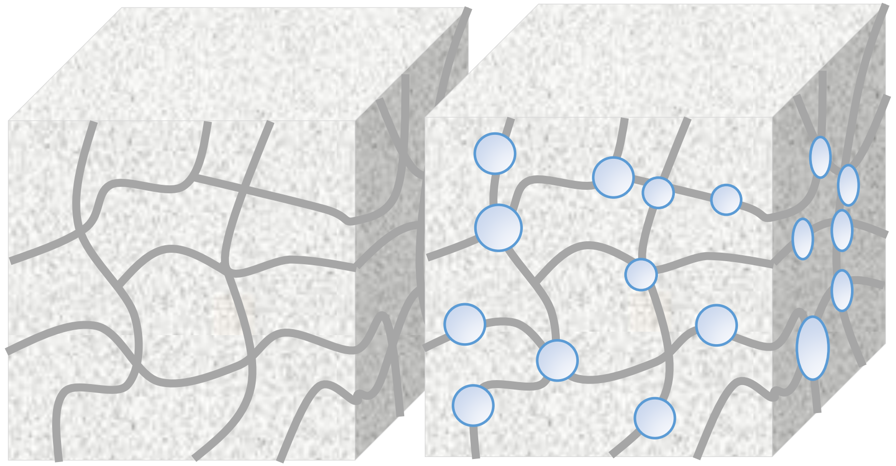
## SET RETARDANT

- Increases the times of starting and ending of the setting.
- Chemistry : hydroxycarboxylic acids (RCOOH), fluorides (NaF), phosphates (Na3PO4, Na4P2O7).
- Effect : slowdown of the lime diffusion.
- Use : concreting by hot weather; enables to win several hours.
- Dosage : 0.1% to 1.0% of the cement mass.

# ADMIXTURES

## AIR ENTRAINERS

- Create an uniform distributed set of air microbubbles.
- Chemistry : ligno-sulphonates, ethanolamine salts, alkyl-sulphonates.
- Effect : traps air in the fresh concrete, makes the concrete less sensitive to frost (the porosity – normally around 2% -- can reach 8%).
- Use : works exposed to the frosts (mountains), area where de-icing salts are used.
- Dosage : 0.01 % to 0.50 % of the cement mass – often used in combination with a plasticizer.



*reduction of the intern stresses thanks to the volume brought by the buble distribution*

## WATERPROOFING ADMIXTURES

- Reduce the capillary absorption of the hardened concrete (typically down to 50% at 7 days and 60% after 90 days).
- Chemistry : stearates (calcium, aluminium, butyl).
- Effect : The stearates combine with the free lime and form crystals covering the capillary and the porosity, such decreasing the possible progression of the external water.
- Use : Reservoirs, water tower.
- Dosage : 0.1 % to 1.0 % - combined with a plasticizer.

# ADMIXTURES

## WATER RETENTION ADMIXTURES

- Improve the retention of the water in concrete.
- Chemistry : very small particles ~10 µm chemically inert, colloid, products derived from cellulose
- Effect : reduction of the bleeding (-50%), less evaporation of the water during the first hours, improvement of the cohesion at fresh state, increase of the shear threshold, reduce the segregation of the granulates.
- Use : Self-compacting concrete, colloidal concrete, slope concrete, concreting under water.
- Dosage : < 0.5% of the cement mass in combination with a plasticizer.

## CURING PRODUCT (not an admixture because applied after moulding or demoulding)

- Avoid the desiccation at young age.
- Chemistry : water based resin, wax, chlorinated rubber.
- Effect : constitutes a shield limiting the diffusion of the water steam towards outside of the concrete.
- Use : Application on fresh concrete (pavement) or after demoulding (concrete slab and walls)
- Dosage : ~200 g/m². Must be removed before application of any coating (paint for instance).

# MINERAL ADDITIONS

A mineral addition, finely crushed, can be incorporated to the concrete formulation for the purposes of improving its behaviour or the performances or to reduce the price. It is possible to add or to substitute:

- Fly ashes,
- limestone fillers,
- quartz fillers,
- silica fumes,
- slag,
- colloidal silica,
- metakaolin,
- pigments

The additions fall in the scope of the standards NF P18-50X (France) and EN 206-1 (Europe).

Two kind of additions:

- ✓ The inert additions just act as fillers and complete the stone skeleton of the concrete;
- ✓ The active additions of type II, either hydraulic, either pozzolanic, can be used in partial substitution of cement and are characterized by a coefficient of equivalence k. The equivalent content of binder is equal to $L = C + kA$ (L=binder, C=cement, A=addition).

# FIBRES

In concrete, fibres have a length comprised between 1 to 60 mm. Because they oppose to the opening and the propagation of cracks, they support the role of the reinforcements in concrete. They are rarely used alone (there is no known method of calculation). They contribute to make the concrete more ductile.

General benefits :

- ☐ better cohesion of the fresh concrete
- ☐ Much better ductility
- ☐ Better resistance to the chocks
- ☐ Better fatigue strength (in case of alternate solicitations)
- ☐ Better shear resistance
- ☐ Improvement of the young age strength
- ☐ Limitation of the shrinkage cracking

Nature :

- ❖ Natural: *asbestos(**),* cellulose
- ❖ Synthetic mineral: glass, steel, cast iron, carbon,
- ❖ Synthetic organic: polyamides, polypropylene, acrylic, Kevlar™

# FIBRES

## SOME CHARACTERISTICS

| Nature | shape | Long. mm | thick. µm | vol. mass g/cm³ | Module GPa | strength GPa | dilat. (*) µdef/°C | Dosage kg/m³ |
|---|---|---|---|---|---|---|---|---|
| steel | Irregular<br>Cylindrical<br>Waves in<br>Omega | 6-60 | 250-600 | 7.8 | 20 | 2.5 | 11 | 25-160 |
| cast iron | strip | 30-60 | 25 | 7.2 | 14 | 2 | 10 | 25-160 |
| *asbestos* (**) | Cylindrical | *5* | *~2* | *2.6* | *100* | *0.8* | *10* | |
| Cellulose | Variable | | | 0.5-0.8 | | | | |
| Polypropylene | Cylindrical | 10-30 | 15-250 | 0.9 | 5 | 0.6 | 90 | 0.5-2.0 |
| Glass | Cylindrical | 10-20 | 5-20 | 2.6 | 80 | 3 | 9 | |
| **Carbon** | **Cylindrical** | **3-15** | **7-20** | **2.0** | **400** | **>2** | **1** | |
| Aramid (Kevlar™) | Cylindrical | 1-10 | ~12 | 1.2 | 15 | 1 | 60 | |

(*) concrete: ~10 µdef/°C – note : 1 µdef =1 µm/m

(**) forbidden in France since 1997.

# POLYMERS

## USE OF POLYMERS OVER AND IN THE CONCRETE

3 types of use of the polymers in the realm of concrete:

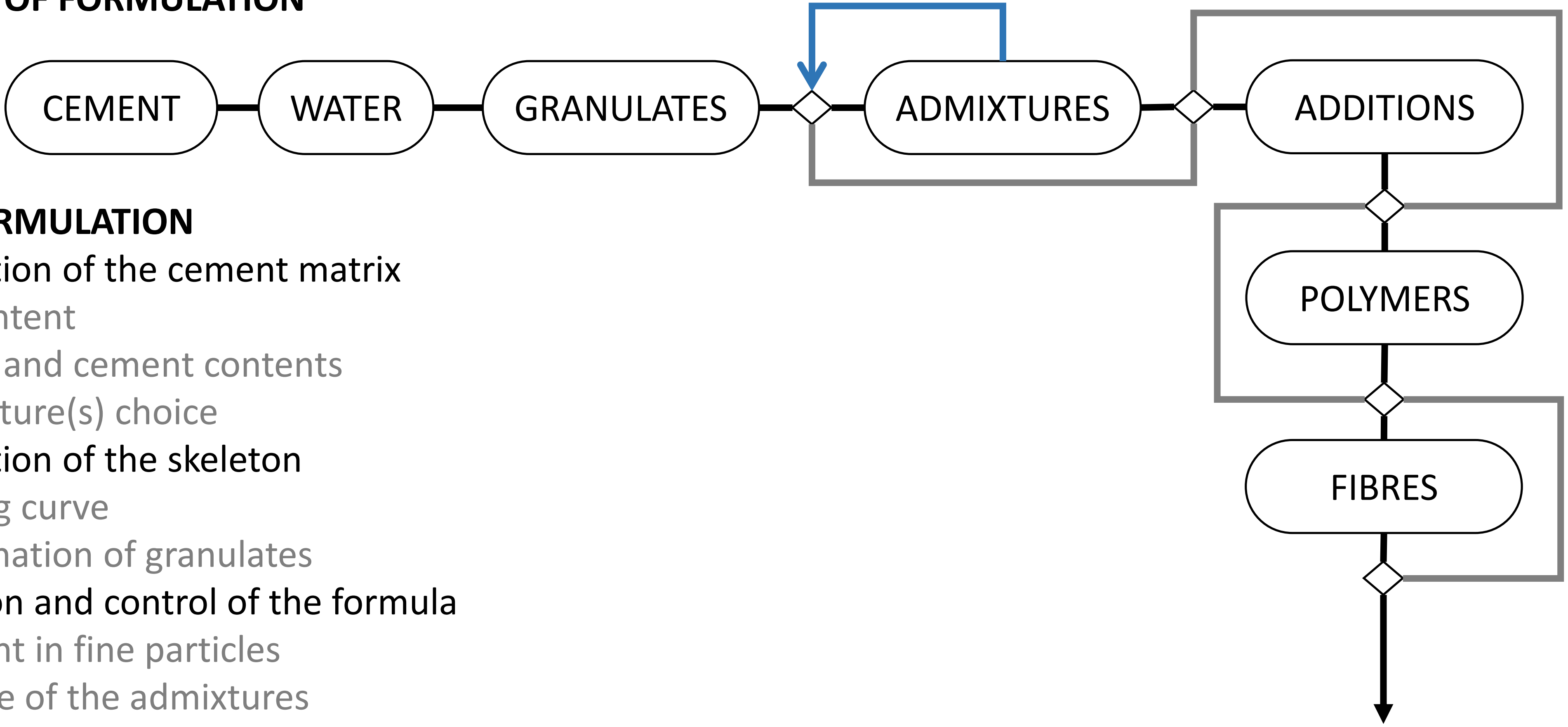
1. impregnation or injection
   Enables to improve the characteristics of the skin of the concrete, to modify the energy surface, to bring some new **surface properties** (colour, waterproofing, anti-graffiti, depolluting, …).

2. polymer concrete
   **Without any cement**, the binders of "polymer concretes" are polyester resins. The resulting material is lighter, has a higher compressive and tensile strength and becomes waterproof and even totally sealed. The main application of this kind of concrete is the manufacturing of construction blocs or pipes (see www.aco.com ).

3. modification of the cement-based matrix
   Some resins (polyvinyl acetate, vinyl acetate, vinyl ester, styrene butadiene, acrylates, …) **added** from 5% to 25% of the cement mass, form a film during the formation of the porous porosity and modify the products of the hydration of the cement. Microcracks are bridged by the polymers. Resulting properties: better adherence; lower permeability, better ductility, better durability, better resistance to frost and chemical aggressions.

# CONCRETE

## GENERAL RULES OF FORMULATION



## STAGES OF FORMULATION

1. determination of the cement matrix
   - air content
   - water and cement contents
   - admixture(s) choice
2. determination of the skeleton
   - grading curve
   - combination of granulates
3. optimisation and control of the formula
   - content in fine particles
   - dosage of the admixtures
   - control of the chlorates and the alkalis
   - workability
   - strength

# CONCRETE

## RUDIMENTS OF FORMULATION

The **Féret law** establishes the relationship between the averaged compressive strength $f_c$ , the amount od cement and the ratio water/cement. This law is expressed in volume (with lowercase symbols) :

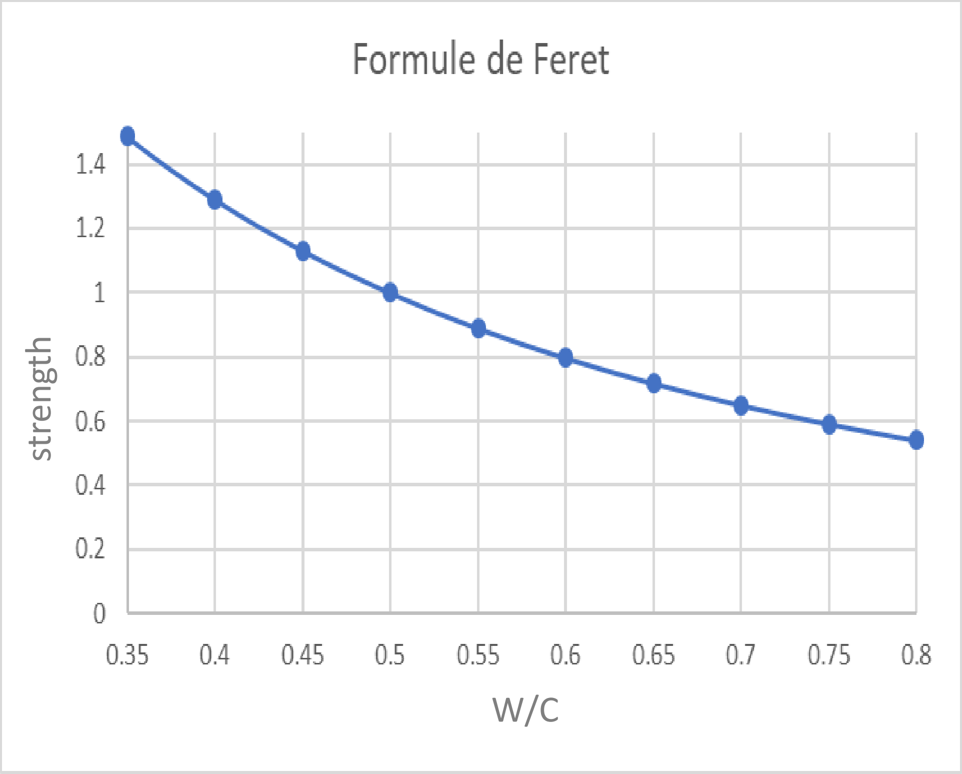
$$f_c = K.\left(\frac{1}{1+\frac{w+a}{c}}\right)^2$$

w=% water, a=% air, c=% cement, s= % granulate,
with $w + a + c + s = 1$,
K=factor depending on the amount of cement.

If the air content is neglected, the law, expressed inmass (uppercase) becomes:

$$f_c \; = K.\left(\frac{1}{1+\rho_c.\frac{E}{C}}\right)^2$$

with $\rho_c = 3.1 \mid 3.0 \mid 2.9 \frac{kg}{l}$ for the cements CEM-I, CEM-II, CEM-III, respectively.



# CONCRETE

## RUDIMENTS OF FORMULATION

The **Bolomey-Fuller** law targets the optimisation of the grading curve of the granulate skeleton when reducing the risk of segregation. The initial idea is to maximise the compacity and, in the same time, to take into account the constrain of workability:

$$Y = A + (100 - A)\sqrt{\frac{d}{D}}$$

**Y** is the residue on the sieve with diameter **d**.

| granulate | « stiff » concrete | « plastic » concrete | « fluid » concrete |
|---|---|---|---|
| roulé | 4-8 | 8-10 | 10-12 |
| concassé | 6-10 | 10-12 | 12-14 |

*table : values for A according the targeted workability*

# CONCRETE

## RUDIMENTS OF FORMULATION

Actual methods of formulation enable to study mixes of various components in order to get the right concrete responding to any prescription. Modern tools (years 2020) incorporate a wide range of mineral additions and admixtures (for instance, for an entrained air concrete). They allow to predict and to simulate most of the targeted properties: mixing time,  bleeding, alkali content, swelling, creeping, strength, hydration heat production, etc…. Some models enable to predict the rheological properties at the fresh state of the simulated concrete. Of course, European rules are taken into account.

A method of formulation is described by the “Ecole Normale Supérieure Paris-Saclay” at the address: https://eduscol.education.fr/sti/sites/eduscol.education.fr.sti/files/ressources/pedagogiques/10328/10328-formulation-dun-beton-ordinaire-ensps.pdf

These methods have been programmed in softwares, for instance **BetonlabPro** has been developed in France by the team of François DE LARRARD (LCPC). A light and free version **BetonlabFree** is downloadable at the address: http://betonlabpro.ifsttar.fr/betonlabfree/telecharger-betonlabfree/ .

# BEHAVIOUR OF THE CONCRETE

**BEHAVIOUR AT FRESH STATE (before setting)**

The workability is one of the criterion of the formulation of concrete; it characterises the "plasticity", namely the ability of the concrete to fill its mould with the appropriate tools. It is measured by various ways :

— Degree of consistency (slump) according EN 12350-2 ;
— Consistency "VEBE" according EN 12350-3 ;
— Degree of compacity according EN 12350-4;
— Degree of spreading according EN 12350-5 ;
— or other specific methods.

According its consistency, measured with the Abrams cone (slump test), concretes are classified in accordance to the standard EN 206-1.

| plasticity class | slump cm | comment |
|---|---|---|
| S1 | 10-40 | stiff, for road |
| S2 | 50-90 | plastic |
| S3 | 100-150 | very plastic |
| S4 | 160-210 | fluid |
| S5 | >220 | self compacting |

# BEHAVIOUR OF THE CONCRETE

## SHORT TERM MECHANICAL BEHAVIOUR

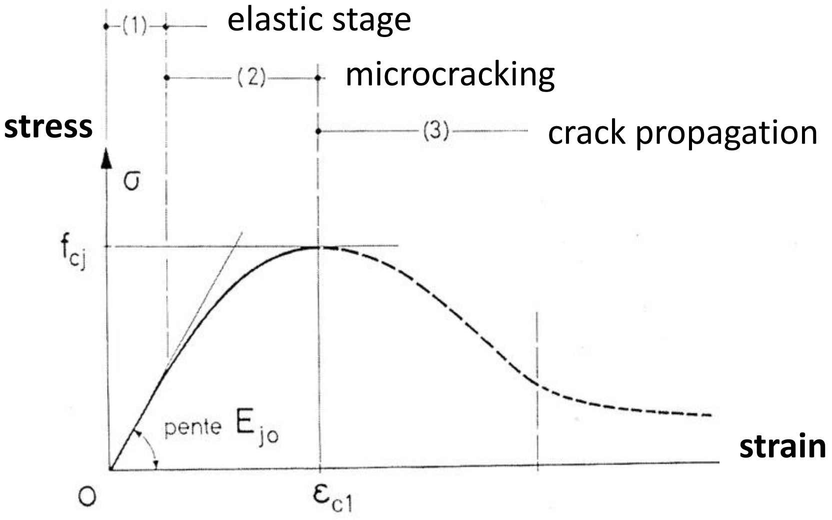
### Uniaxial (unconfined) compression test

Most often, the unconfined compression test is performed on cylindrical samples It can also be done on cubic samples.

☐ If the test is driven by the compressive stress, the behaviour is plotted until the specimen breaks.

☐ If the test is driven by the strain, the “post-pic” behaviour is obtained as well. 3 stages are distinguished :

- quasi-elastic stage
- microcracks development
- crack propagation



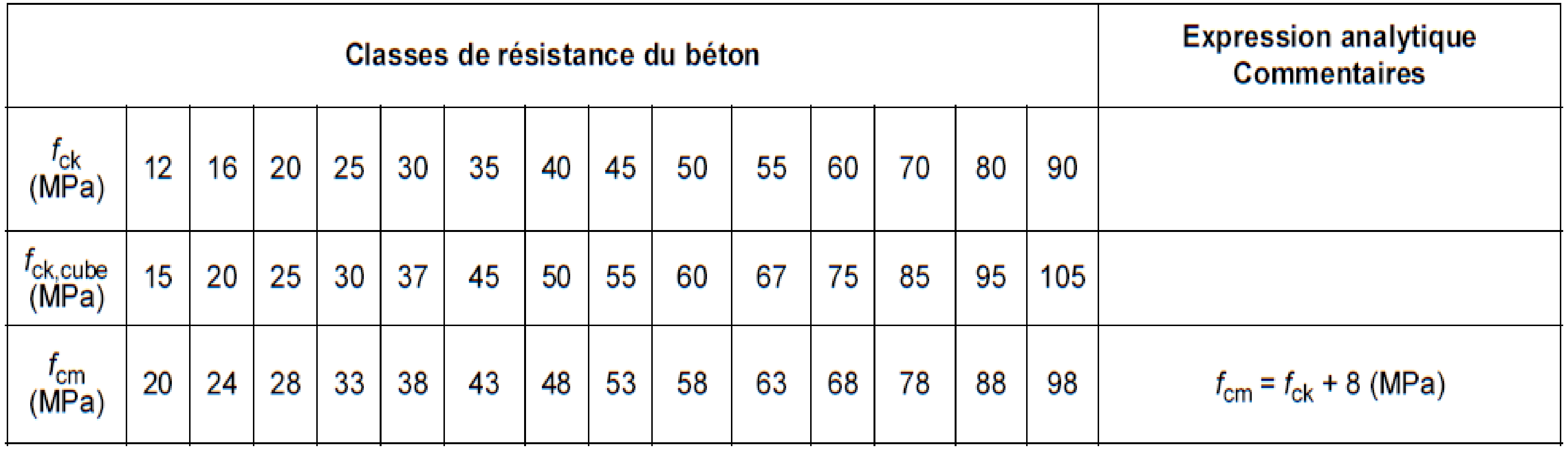
strain-stress curve got in a unconfined compressive test on concrete

*300 kN hydraulic press*

# BEHAVIOUR OF THE CONCRETE

## Characteristic strength in compression

(according EN 1992-1-1:2004)



| Classes de résistance du béton | | | | | | | | | | | | | | | Expression analytique<br>Commentaires |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_{ck}$ (MPa) | 12 | 16 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 70 | 80 | 90 | |
| $f_{ck,cube}$ (MPa) | 15 | 20 | 25 | 30 | 37 | 45 | 50 | 55 | 60 | 67 | 75 | 85 | 95 | 105 | |
| $f_{cm}$ (MPa) | 20 | 24 | 28 | 33 | 38 | 43 | 48 | 53 | 58 | 63 | 68 | 78 | 88 | 98 | $f_{cm} = f_{ck} + 8$ (MPa) |

$fck$ = class (on cylinder)
$fck\ cube$ = class (on cube)
$fcm$ = average strength

The probability that a test gives a value lower than the characteristic strength is less than 5%.

The compressive strength:

- increases quickly then slowly with the concrete aging (hardening due to the hydration)
- it decreases if the stresses are applied at early age. Indeed, when the concrete is submitted to a sustainable force, microcracks appear and develop, damaging and weakening the material.
- it decreases in case of cyclic loading because of the fatigue effect.

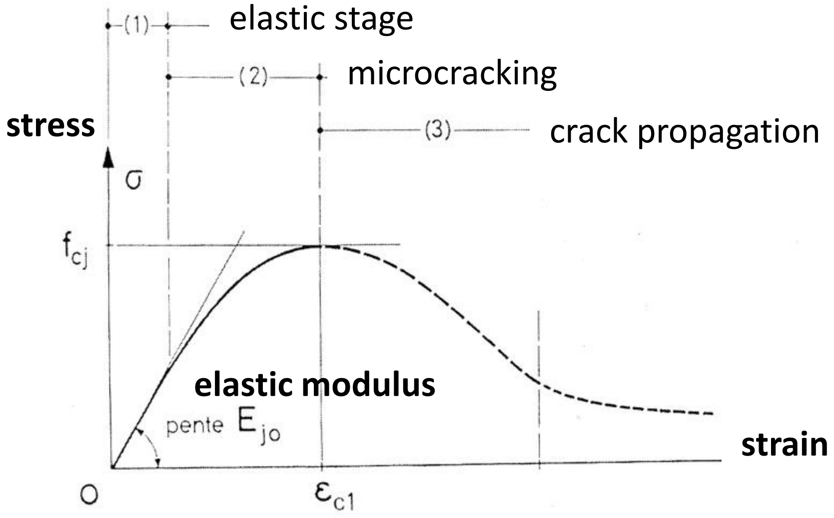
# BEHAVIOUR OF THE CONCRETE

## ELASTICITY MODULUS

The instantaneous modulus is correlated to the compressive strength according the standard EN 1992 (Eurocode 2):

$$E_{ij} = 11000\, f_{cj}^{1/3}$$

*Example : if $f_{cj}$=25 MPa, then: $E_{ij}$=32000 MPa*



strain-stress curve got in a unconfined compressive test on concrete

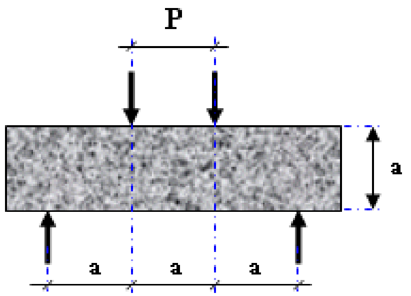
## TENSILE STRENGTH OF CONCRETE

The tensile strength $f_{tj}$ can be obtained thanks to 3 types of trials: bending test, splitting test and direct tensile test. A correlation can be established with $f_{cj}$ :

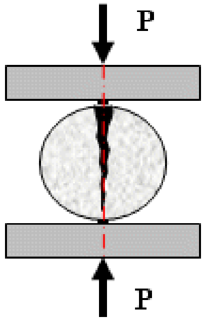
$$f_{tj} = \psi . f_{cj}^{2/3} \quad \text{with} \ \psi = 0.3$$

In fact, the order of magnitude of the tensile strength is around the tenth of the compressive strength:

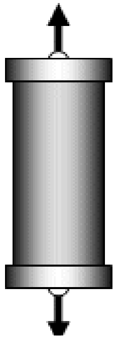
$$f_{tj} \cong \frac{1}{10} f_{cj}$$



bending test



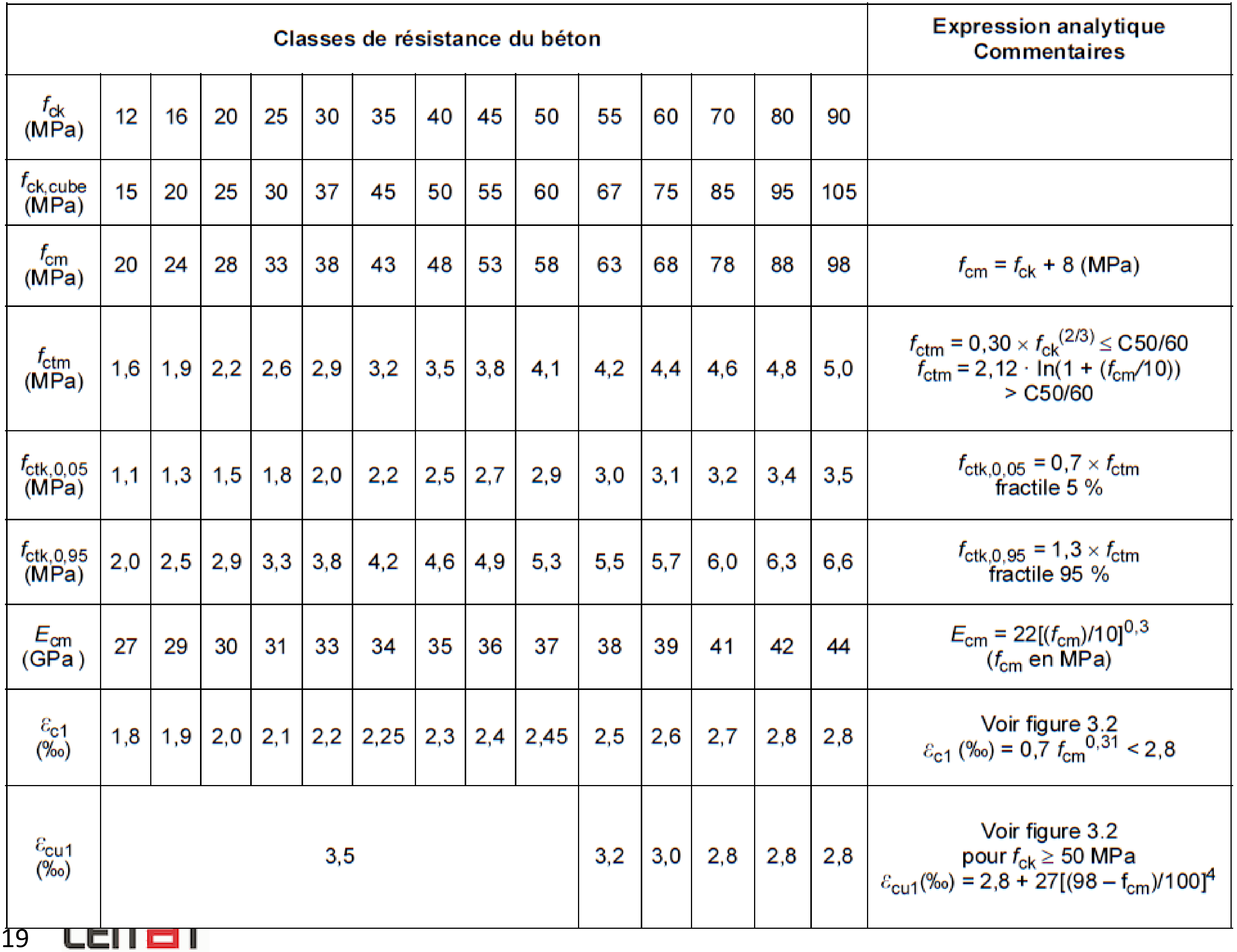
splitting test



direct tensile test

# BEHAVIOUR OF THE CONCRETE

**EXTRACTION FROM THE EUROCODE 2**



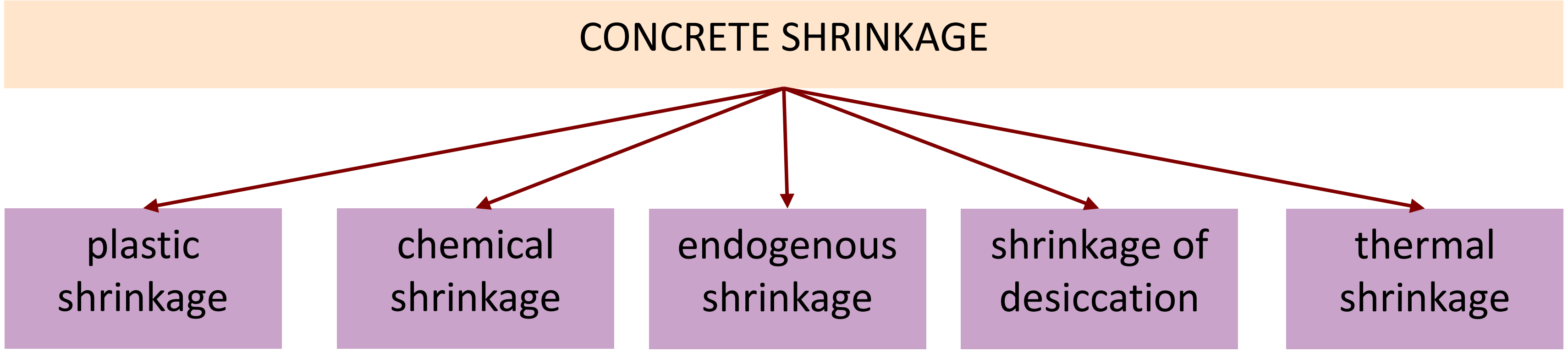
| Classes de résistance du béton | | | | | | | | | | | | | | | Expression analytique<br>Commentaires |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_{ck}$ (MPa) | 12 | 16 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 70 | 80 | 90 | |
| $f_{ck,cube}$ (MPa) | 15 | 20 | 25 | 30 | 37 | 45 | 50 | 55 | 60 | 67 | 75 | 85 | 95 | 105 | |
| $f_{cm}$ (MPa) | 20 | 24 | 28 | 33 | 38 | 43 | 48 | 53 | 58 | 63 | 68 | 78 | 88 | 98 | $f_{cm} = f_{ck} + 8$ (MPa) |
| $f_{ctm}$ (MPa) | 1,6 | 1,9 | 2,2 | 2,6 | 2,9 | 3,2 | 3,5 | 3,8 | 4,1 | 4,2 | 4,4 | 4,6 | 4,8 | 5,0 | $f_{ctm} = 0,30 \times f_{ck}^{(2/3)} \leq$ C50/60<br>$f_{ctm} = 2,12 \cdot \ln(1 + (f_{cm}/10))$<br>> C50/60 |
| $f_{ctk,0,05}$ (MPa) | 1,1 | 1,3 | 1,5 | 1,8 | 2,0 | 2,2 | 2,5 | 2,7 | 2,9 | 3,0 | 3,1 | 3,2 | 3,4 | 3,5 | $f_{ctk,0,05} = 0,7 \times f_{ctm}$<br>fractile 5 % |
| $f_{ctk,0,95}$ (MPa) | 2,0 | 2,5 | 2,9 | 3,3 | 3,8 | 4,2 | 4,6 | 4,9 | 5,3 | 5,5 | 5,7 | 6,0 | 6,3 | 6,6 | $f_{ctk,0,95} = 1,3 \times f_{ctm}$<br>fractile 95 % |
| $E_{cm}$ (GPa) | 27 | 29 | 30 | 31 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 41 | 42 | 44 | $E_{cm} = 22[(f_{cm})/10]^{0,3}$<br>($f_{cm}$ en MPa) |
| $\varepsilon_{c1}$ (‰) | 1,8 | 1,9 | 2,0 | 2,1 | 2,2 | 2,25 | 2,3 | 2,4 | 2,45 | 2,5 | 2,6 | 2,7 | 2,8 | 2,8 | Voir figure 3.2<br>$\varepsilon_{c1}$ (‰) $= 0,7\ f_{cm}^{0,31} < 2,8$ |
| $\varepsilon_{cu1}$ (‰) | 3,5 | | | | | | | | | 3,2 | 3,0 | 2,8 | 2,8 | 2,8 | Voir figure 3.2<br>pour $f_{ck} \geq 50$ MPa<br>$\varepsilon_{cu1}$(‰) $= 2,8 + 27[(98 - f_{cm})/100]^4$ |

# BEHAVIOUR OF THE CONCRETE

## LONG TERM BEHAVIOUS: SHRINKAGE

The shrinkage is the deformation over time of the concrete without any external loading It is produced by different causes : hydration, hydric variation, thermal variation.

The causes are decomposed in **5 main mechanisms**.

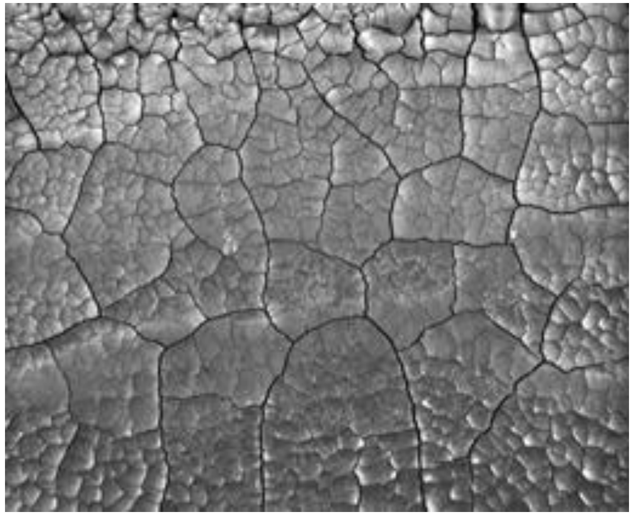


CONCRETE SHRINKAGE

- plastic shrinkage
- chemical shrinkage
- endogenous shrinkage
- shrinkage of desiccation
- thermal shrinkage

# BEHAVIOUR OF THE CONCRETE

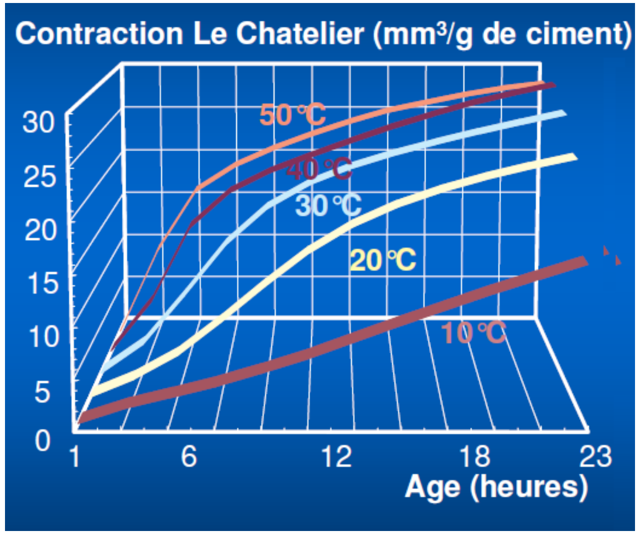
## 1/5. PLASTIC SHRINKAGE



This shrinkage affects the concrete when it loses water being still plastic (before and during the setting). This water either evaporates, either is absorbed by the surrounding porous material (for instance, road repair).

→ A "curing" of the concrete (protection against evaporation) can limit the plastic shrinkage.

## 2/5. CHEMIC SHRINKAGE



The cement hydration produces a reduction of the initial volume (8 to 12 %). It is the **Le Chatelier** contraction. The corresponding lineic strain reaches 3-4% → The volume of the hydrated phase is lower than the total of the initial anhydrous phase and the water. The contraction process occurs at the very beginning of the hydration. During the stage of chemical shrinkage, the bridges formed by the hydrates are not stiff enough for avoiding the contraction which is free.

# BEHAVIOUR OF THE CONCRETE

## 3/5. ENDOGENOUS SHRINKAGE

When hydration progresses, the hydrates progressively form a network more and more stiff. This stiffness opposes to the movement between the grains. It the same time the water is consumed.

→ The liquid phase does not fill all the interstitial volume.

→ A cavitation begins: The liquid water transforms in vapor, creating an interface gaz-liquid. High capillary tensions take place that provokes the endogenous (self-desiccation) shrinkage.

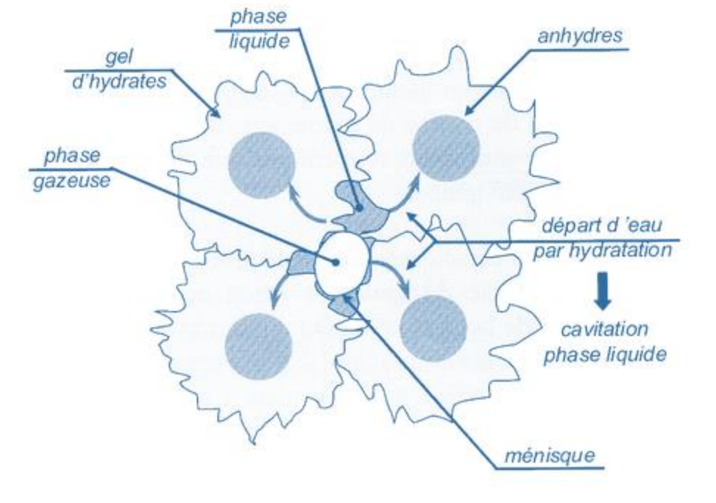


**Figure 7.3.** *Cavitation de la phase liquide et création de ménisques du fait de la poursuite de l'hydratation lors de la prise*

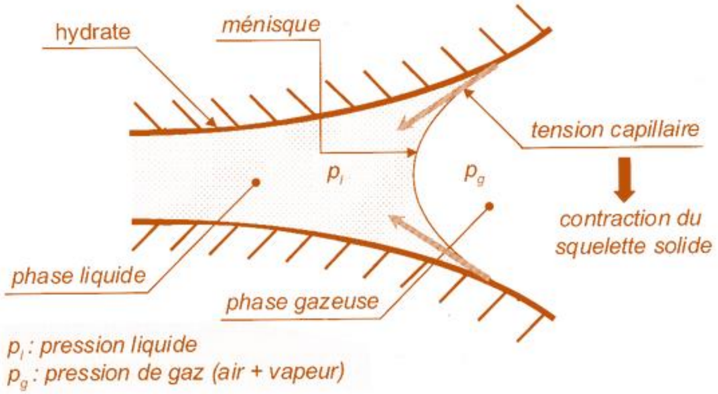


**Figure 7.4.** *Rapprochement de deux feuillets d'hydrates sous l'effet de tensions capillaires*

# BEHAVIOUR OF THE CONCRETE

## 4/5. DESICCATION SHRINKAGE

The desiccation shrinkage is due to the departure of the water when the concrete is submitted to a drying. This departure induces a variation of the internal content of water which is the cause of stresses and a contraction.

Water migrates towards the exterior of the concrete because of the difference between the initial hygrometry of the material (80 to 100% HR) and the environment (~60% HR). The kinetics of drying is slow: 10 years are necessary for a 16x32cm concrete cylinders). The duration increases like the square of the dimensions of the concrete piece.

The non-uniform distribution of the drying creates differential strains between the core and the peripheral zones → the resulting stresses initiate a cracking process.

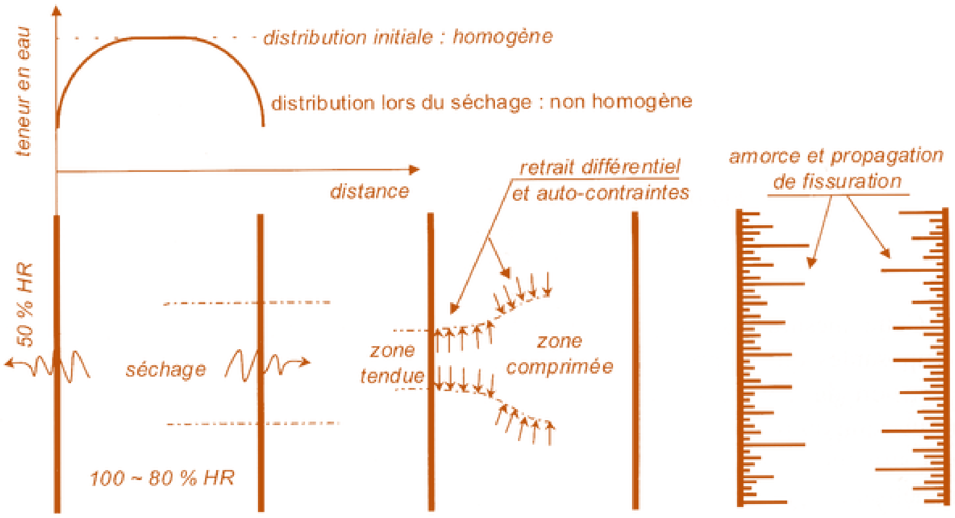


**Figure 7.5.** *Effet structural du retrait de dessiccation induit par un séchage*

# BEHAVIOUR OF THE CONCRETE

## 5/5. THERMAL SHRINKAGE

The hydration reaction is exothermic (150 to 450 J/g of cement). This heat provokes a raise of the temperature that can reaches 50°C when concrete pieces are massive.

This temperature enables the vaporisation of the interitial water which migrates and, therefore, provokes a thermal shrinkage. The shrinkage strain can reach up to 500µdef depending on the cement type and the concrete composition.

→ The cooling is quicker at the periphery of the concrete piece: there is a temperature gradient and, consequently, a stress gradient. The cracking occurs.

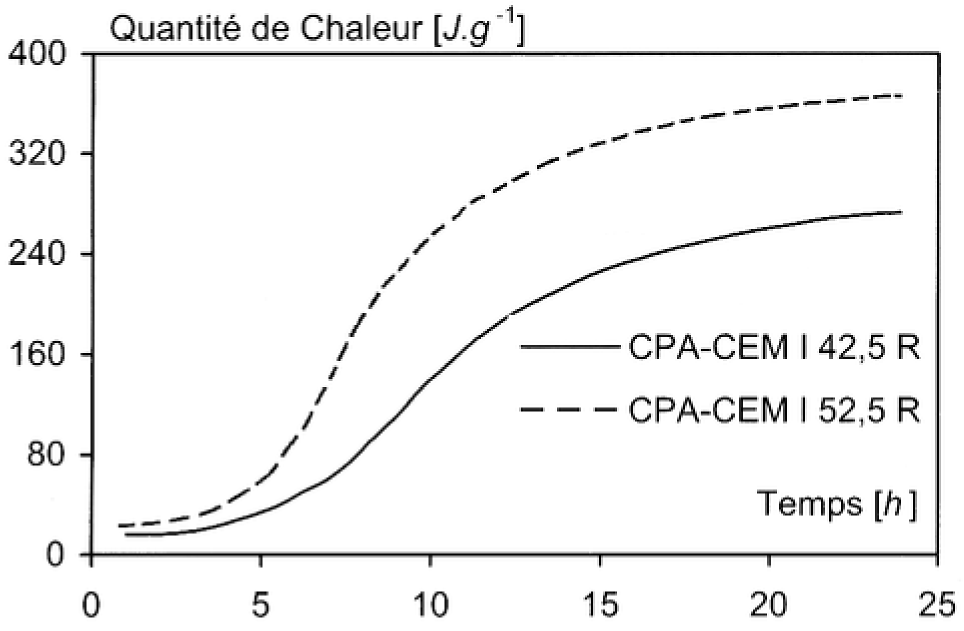
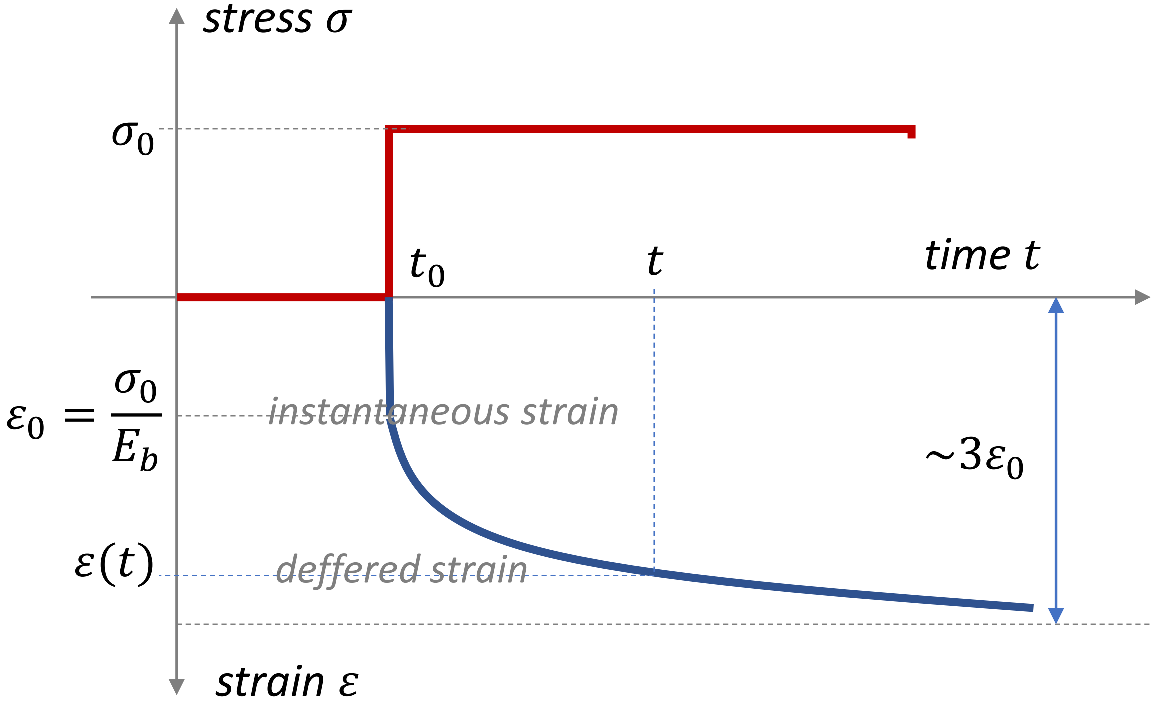


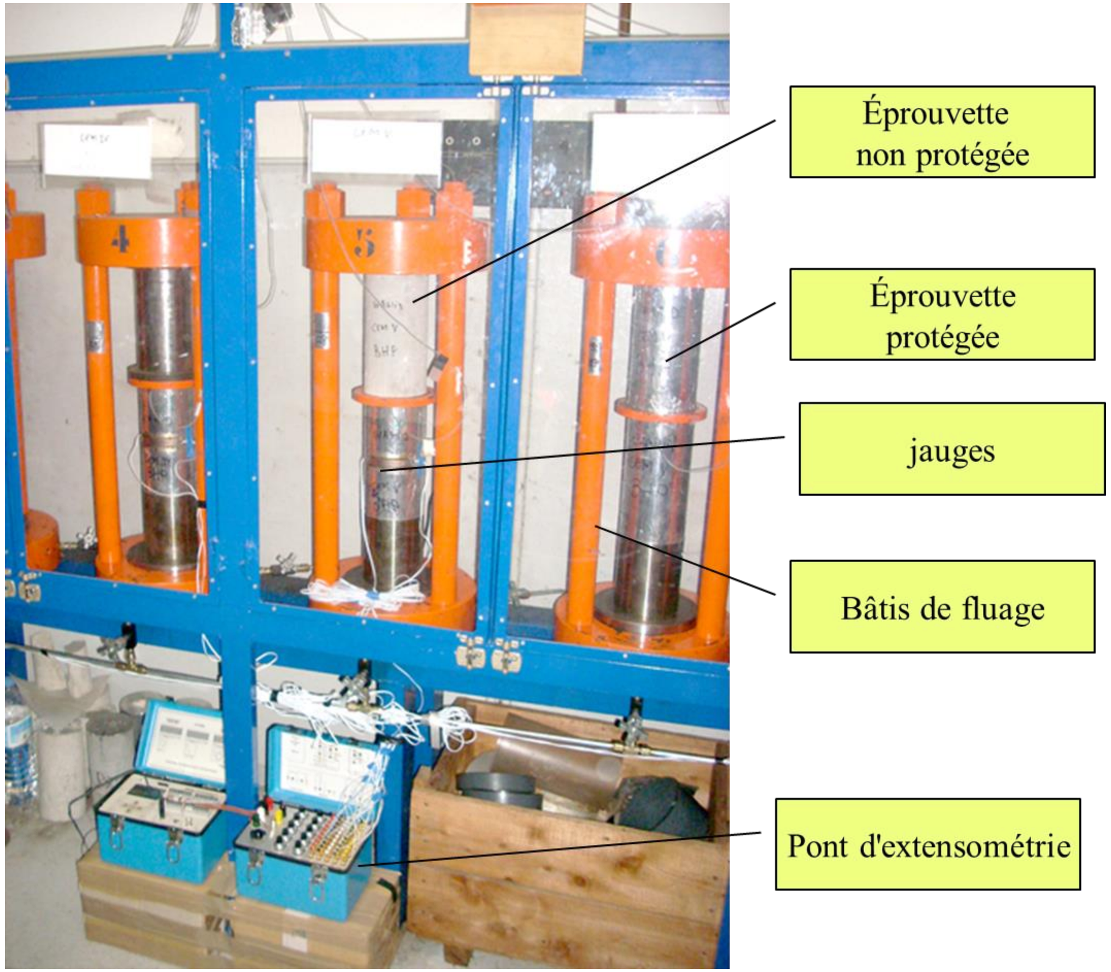
**Figure 7.8.** *Evolution de la chaleur d'hydratation d'un CPA – CEM I mesurée selon la norme NF P 15-436 [BARO 97]*

# BEHAVIOUR OF THE CONCRETE

## LONG TERM BEHABIOUR: CREEP

The creep if the dimensional variation due to a sustainable loading applied on concrete. Once again, this phenomenon is tightly linked to the migration of water inside the material.





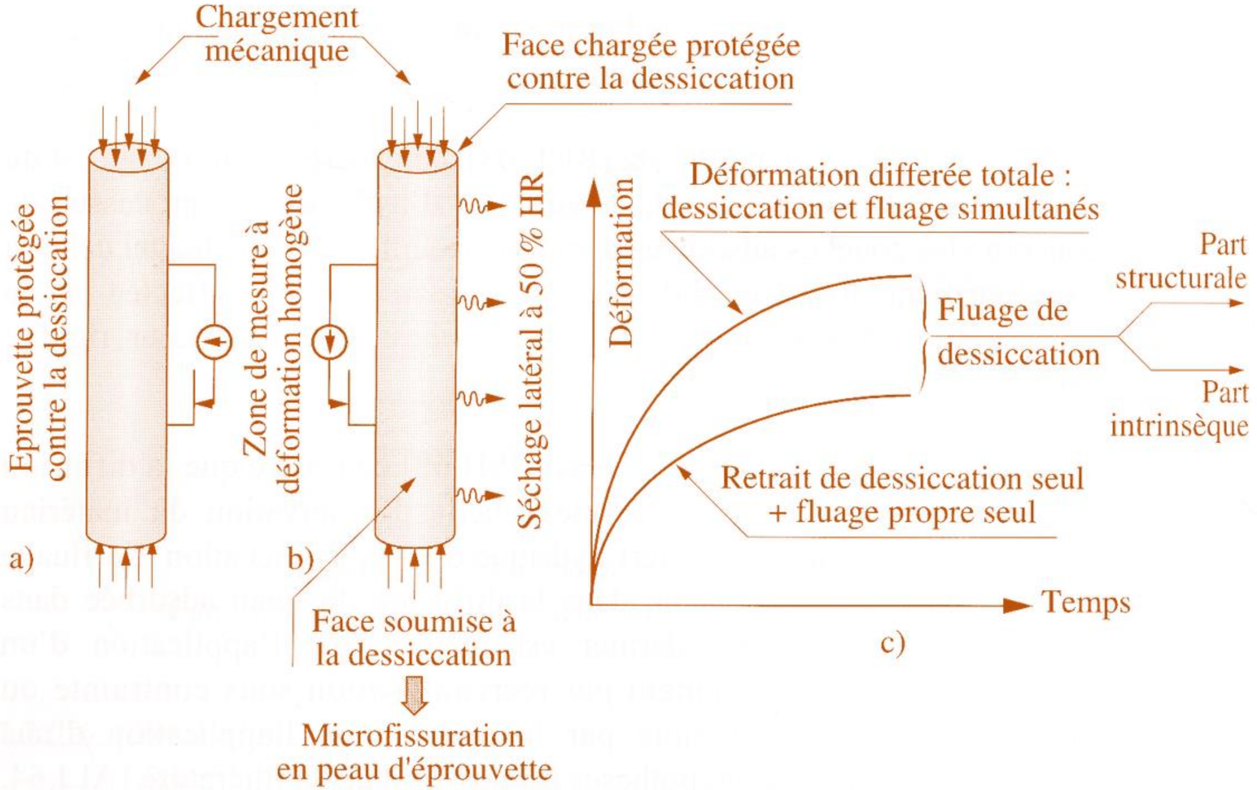
# BEHAVIOUR OF THE CONCRETE

## CREEP

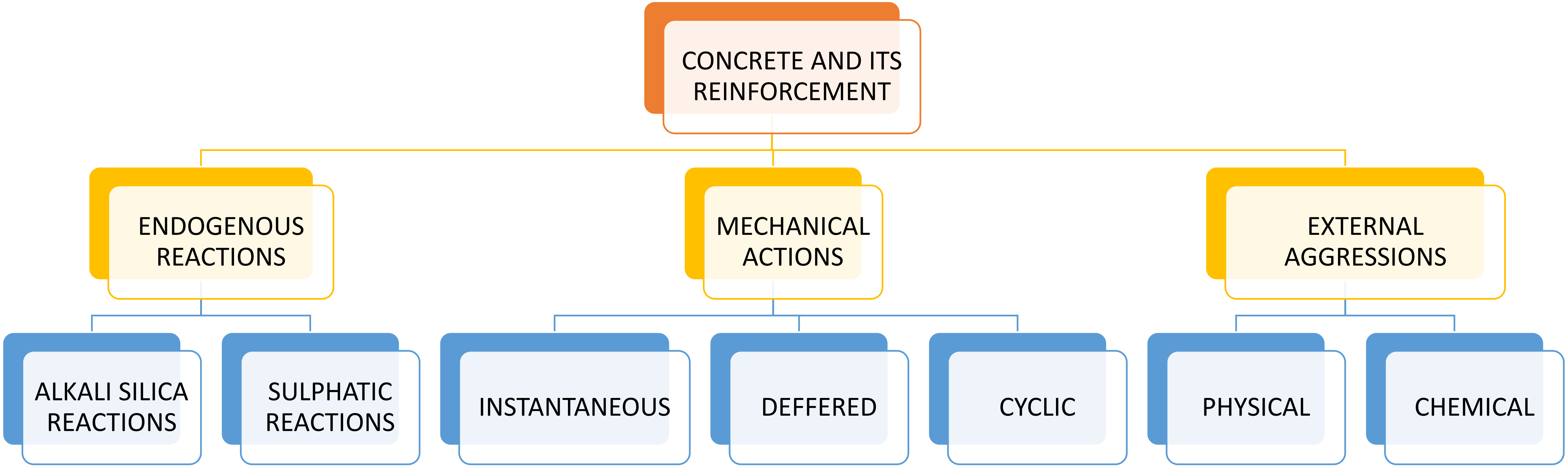
The creep is decomposed into two parts:

1. **endogenous creep**: strain of a concrete sample without moisture exchange with the environment.

2. **desiccation creep**: part of shrinkage due to the desiccation because of the hydric exchanges with the exterior.



# DURABILITY



- CONCRETE AND ITS REINFORCEMENT
  - ENDOGENOUS REACTIONS
    - ALKALI SILICA REACTIONS
    - SULPHATIC REACTIONS
  - MECHANICAL ACTIONS
    - INSTANTANEOUS
    - DEFFERED
    - CYCLIC
  - EXTERNAL AGGRESSIONS
    - PHYSICAL
    - CHEMICAL

FOR A SERVICE LIFE OF 100 TO 120 YEARS

# DURABILITY

## TOWARD THE ENVIRONMENT

The standard EN 206-1 defines 6 **classes of exposition**, each of them being accompanied by a digit expressing the seriousness of the exposition to external agents.

| | **class of exposition** | |
|---|---|---|
| risk of corrosion | X0 | no risk of corrosion or attack |
| | XC1 to XC4 | corrosion induced by carbonation |
| | XD1 to XD3 | corrosion induced by chlorates other than coming from the sea water |
| | XS1 to XS3 | corrosion induced by chlorates coming from the sea water |
| chemical attacks | XF1 to XF4 | freeze-thaw cycles with or without de-icing salts |
| | XA1 to XA3 | chemical attacks |

Example :
XF4 = concrete submitted to a severe attack due to freeze-thaw cycles while it is wet with a water saturated in de-icing salt.

Several classes of exposition can be combined.
The Eurocode 2 (EN 1992) requires specific supplementary constructional features for reinforced concrete.

# DURABILITY

*Extrait de l'EN 206-1*

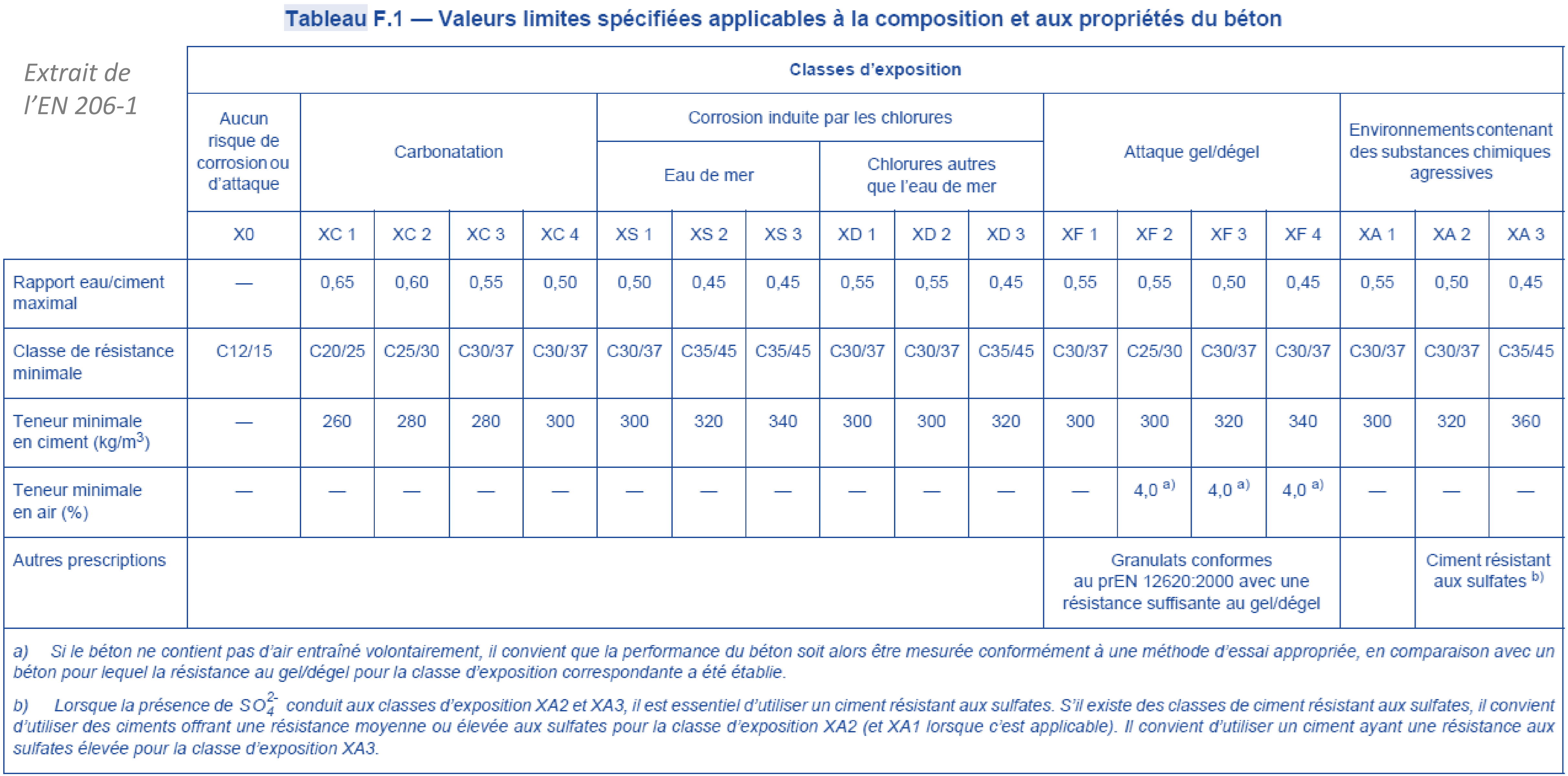


**Tableau F.1 — Valeurs limites spécifiées applicables à la composition et aux propriétés du béton**

| | Classes d'exposition | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aucun risque de corrosion ou d'attaque | Carbonatation | | | | Corrosion induite par les chlorures | | | | | | Attaque gel/dégel | | | | Environnements contenant des substances chimiques agressives | | |
| | | | | | | Eau de mer | | | Chlorures autres que l'eau de mer | | | | | | | | | |
| | X0 | XC 1 | XC 2 | XC 3 | XC 4 | XS 1 | XS 2 | XS 3 | XD 1 | XD 2 | XD 3 | XF 1 | XF 2 | XF 3 | XF 4 | XA 1 | XA 2 | XA 3 |
| Rapport eau/ciment maximal | — | 0,65 | 0,60 | 0,55 | 0,50 | 0,50 | 0,45 | 0,45 | 0,55 | 0,55 | 0,45 | 0,55 | 0,55 | 0,50 | 0,45 | 0,55 | 0,50 | 0,45 |
| Classe de résistance minimale | C12/15 | C20/25 | C25/30 | C30/37 | C30/37 | C30/37 | C35/45 | C35/45 | C30/37 | C30/37 | C35/45 | C30/37 | C25/30 | C30/37 | C30/37 | C30/37 | C30/37 | C35/45 |
| Teneur minimale en ciment (kg/m$^3$) | — | 260 | 280 | 280 | 300 | 300 | 320 | 340 | 300 | 300 | 320 | 300 | 300 | 320 | 340 | 300 | 320 | 360 |
| Teneur minimale en air (%) | — | — | — | — | — | — | — | — | — | — | — | — | 4,0 a) | 4,0 a) | 4,0 a) | — | — | — |
| Autres prescriptions | | | | | | | | | | | | Granulats conformes au prEN 12620:2000 avec une résistance suffisante au gel/dégel | | | | | Ciment résistant aux sulfates b) | |

*a) Si le béton ne contient pas d'air entraîné volontairement, il convient que la performance du béton soit alors être mesurée conformément à une méthode d'essai appropriée, en comparaison avec un béton pour lequel la résistance au gel/dégel pour la classe d'exposition correspondante a été établie.*

*b) Lorsque la présence de $SO_4^{2-}$ conduit aux classes d'exposition XA2 et XA3, il est essentiel d'utiliser un ciment résistant aux sulfates. S'il existe des classes de ciment résistant aux sulfates, il convient d'utiliser des ciments offrant une résistance moyenne ou élevée aux sulfates pour la classe d'exposition XA2 (et XA1 lorsque c'est applicable). Il convient d'utiliser un ciment ayant une résistance élevée aux sulfates pour la classe d'exposition XA3.*

# DURABILITY

The French standard NF P18-011 gives supplementary prescriptions with respect to cements

| medium | XA1 weakly aggressive | XA2 moderatly aggressive | XA3 strongly aggressive | XA4 very strongly aggressive |
|---|---|---|---|---|
| $SO_4^{2-}\ (mg/l)$ | 200<content<600 | 600<content<3000 | 3000<content<6000 | 6000<content |
| pH | 5.5<pH<6.5 | 4.5<pH<5.5 | 4<pH<4.5 | pH<4 |
| $CO_2(mg/l)$ | 15<content<40 | 40<content<100 | 100<content | -- |
| $NH_4^+(mg/l)$ | 15<content<30 | 30<content<60 | 60<content<100 | 100<content |
| $Mg^{2+}(mg/l)$ | 300<content<1000 | 1000<content<3000 | 3000<content | -- |
| sulphates | -- | CEM I/PM, CEM II/PM, CEM III/A, CEM III/B, CEM IV/C, CEM V/A, CEM V/B | CEM I (C3A<5%), CEM II (C3A<5%), CEM III/A, CEM III/B, CEM III/C, ciments alumineux | idem XA3+supplementary protection |
| acidic | CEM I with low rate of C2A et C3S, some CEM II | CEM I with low rate of C2A et C3S, some CEM II, CEM V, CEM III | CEM III/A, CEM III/B (with slag >60%), CEM V/A, CEM V/B with CaO cement < 50% | idem XA3+supplementary protection |

# DURABILITY

## ALKALI SILICA REACTIONS (ASR)

These reactions occur between the reactive silica contained in the granulates and the alkalis ($Na_2O$, $K_2O$) present in the entirely components of the concrete or coming from outside (sea water, salty water, de-icing salts). The ASR reactions produce an **expansive gel** which provoke high stresses and therefore damages.

$$Na_2O + H_2O \rightarrow 2\ NaOH \text{ (soluble calcium hydroxide)}$$
$$2\ NaOH + SiO_2\ \rightarrow Na_2SiO_3H_2O$$
$$Na_2SiO_3 \cdot H_2O + n\ H_2O \rightarrow Na_2SiO_3 \cdot (n+1)\ H_2O$$

*Photo SEM LMDC – SAR gel*

The kinetics of reaction depends on:

- ✓ the reactivity of the silica (amorphous form is more reactive);
- ✓ the mobility of the alkali ions (diffusion in the hardened cement);
- ✓ the diffusion of the water towards the expansive gel.

The SAR gel attracts is hydrophile: it attracts the water and swells. If there is space enough for the expansion, the internal stresses develop and provoke the cracking of the concrete.

# DURABILITY

**ALKALI SILICA REACTIONS (ASR)**

For preventing the ASR :

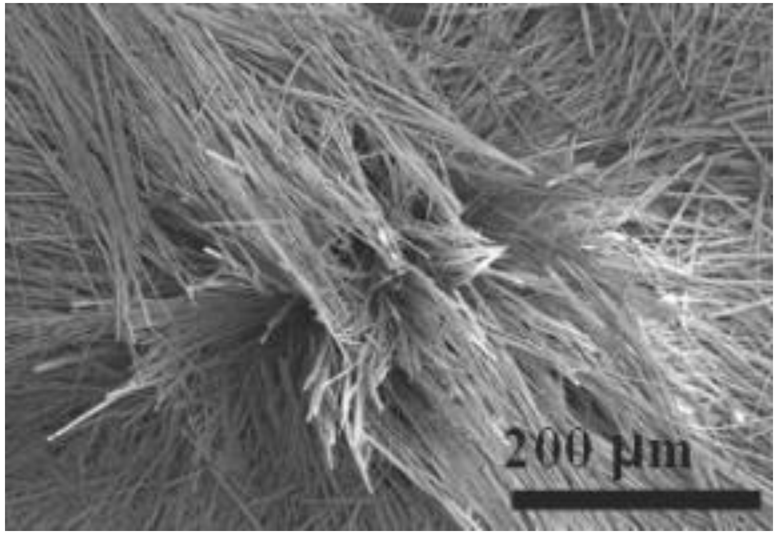
- ☐ limit the total content of alkalis (for instance, preferring cement with slag or fly ashes).
- ☐ use mineral additions (slag, fly ashes)
- ☐ use non-reactive granulates (NF P18-542 and 589)
- ☐ limit the water saturation of the concrete.

*Damages due to the ASR at macroscopic scale*

# DURABILITY

## INTERNAL SULPHATIC REACTION (ISR)

Sulphatic reactions lead to the formation of ettringite (hydrous calcium sulphate $C_6A\bar{S}_3H_{32}$) which, in turn, can have a advantageous or pathologic effects in respect to its origin.



*Ettringite needles.*

- ☐ Positive impact: when the cement hardens, the gypsum plays a role of setting regulation in the hydration of $C_3A$, producing **primary ettringite**. This ettringite develops in the cement structure before it is convert into calcium mono-sulpho-aluminate hydrate $C_4A\bar{S}H_{12}$ ;
- ☐ Negative impact: The **secondary ettringite** develops when the concrete has hardened in presence of sulphate coming from external sources (gypseous water, fertilizer residues, sea water, chemistry factory water, …). This secondary ettringite expands and damages the concrete;
- ☐ In case there is an excess of sulphates in the components of the concrete, because of its heating and the moisture (massive pieces, heat-cured concrete), sulphatic reactions producing secondary ettringite could initiate. The ettringite develops in a hardened structure generating internal stresses, swelling of the concrete, cracking and finally severe damages.

# DURABILITY

**INTERNAL SULPHATIC REACTION (ISR)**

The look of the damages provoked by ISR is very similar to that due to ASR with a bidirectional cracking with a 10-30 cm mesh.

**Prevention**

Control of the favourable conditions of the ISR which are:

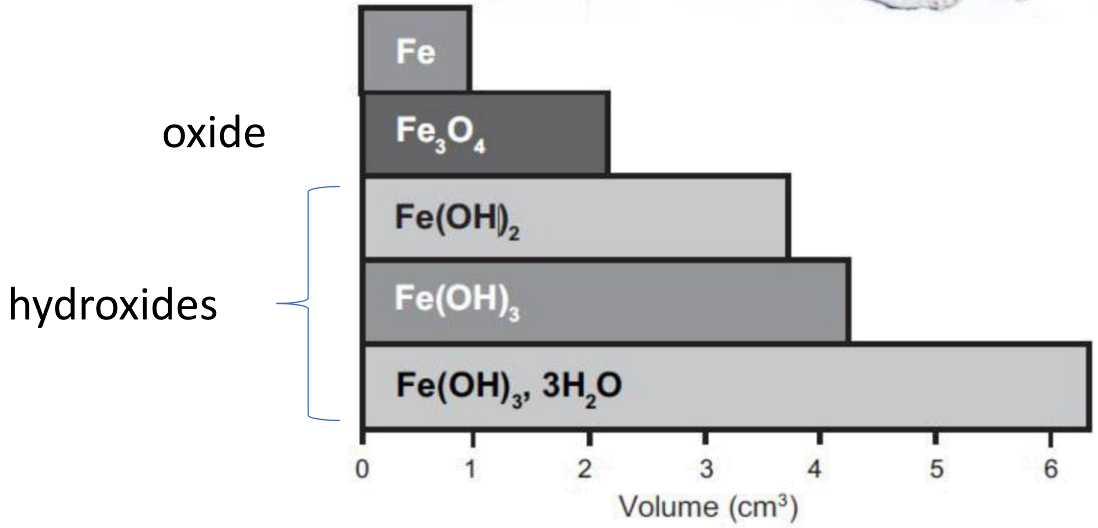
- the moisture (permanent or cyclic)
- the heating of the concrete during its hardening
- the high content of alkalis
- the high content of sulphates
- the high content of aluminates

# DURABILITY

## REINFORCED CONCRETE CORROSION

The corrosion of the reinforced bars in concrete constitutes the main subject of concern for the building owners.

The products of the corrosion are expansive and this expansion provokes major damages in the constructions and even their ruin.



*Swelling of the iron rust in regards to the initial volume of steel*

# DURABILITY

**The corrosion is an electrochemical process**

When corroded, the iron releases metallic ions in the interstitial solution of the concrete. There are two reactions:

1. an anodic reaction (oxidation) which provides metallic ions and electrons:

$$Fe \rightarrow Fe^{n+} + n\ e^-$$

2. a cationic reaction corresponding to the reduction of the ionized water.

$$O_2 + 2\ H_2O + 4\ e^- \rightarrow 4\ OH^-$$
$$O_2 + 4\ H_3O^+ + 4\ e^- \rightarrow 6\ H_2O$$

**The sound concrete protects the reinforced bars**

At the early age of the concrete the PH in the interstitial solution if very high (between 13.5 and 14.0) and the pH decreases with the aging of the concrete.

# DURABILITY

Two factors could favour the corrosion of the reinforced bars in concrete:

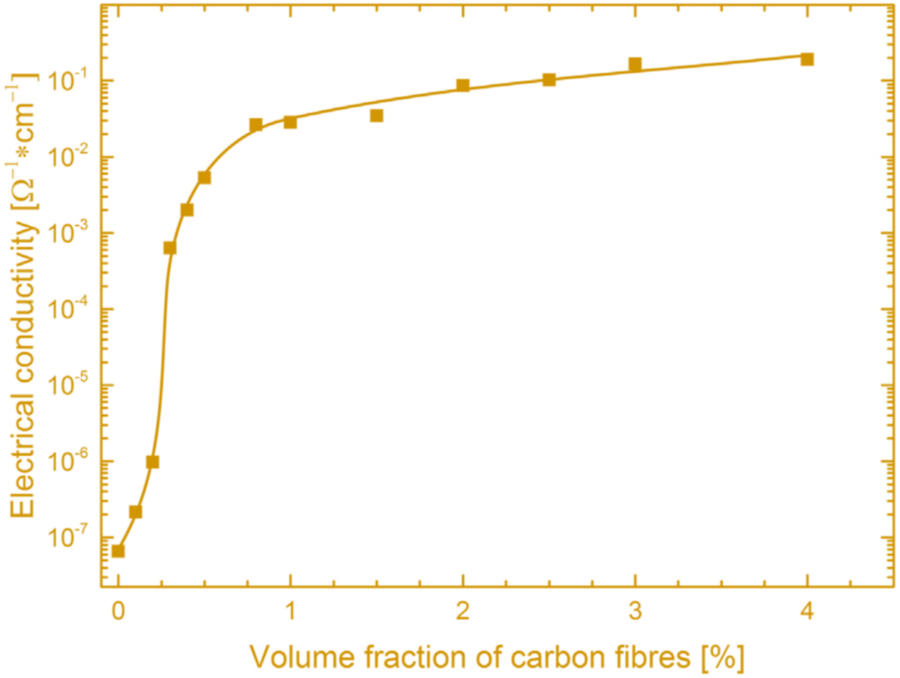
- ☐ The carbonation : induced by the penetration of the $CO_2$ of the atmosphere into the concrete. The carbonation is accompanied by a propagation front of the decrease of the pH which initiates the accelerates the corrosion as soon as the bars are reached;
- ☐ The chlorination: induced by the penetration of chlorate ions in the concrete when it is exposed to salt air and/or salt water.

# CARBON FIBRES IN CONCRETE

Examples of papers found in the scientific literature:

*Carbon fibre reinforced cement-based composites as smart floor heating material, Manuel Hambach et al, Composite Part B, vol.90, 2016, p.465-470.*

→ systematic development of an **electrically heatable cement-based composite**, prepared by admixing a few volume percent of **chopped carbon fibres** without a need of adding further heating elements, is reported. The optimal volume content of carbon fibres is determined to range from 1 to 2 volume percent, if 3 mm long and 7 mm thick carbon fibres are being used. By applying an electrical current to the composite material, a temperature rise suitable for heating rooms and walls can be induced. Mechanical tests show that the flexural strength of carbon fibre reinforced composite is not decreasing during electrical heating at 60°C for 4 weeks. For electrical heating purposes, graphite or silver is found to be the best electrode material.

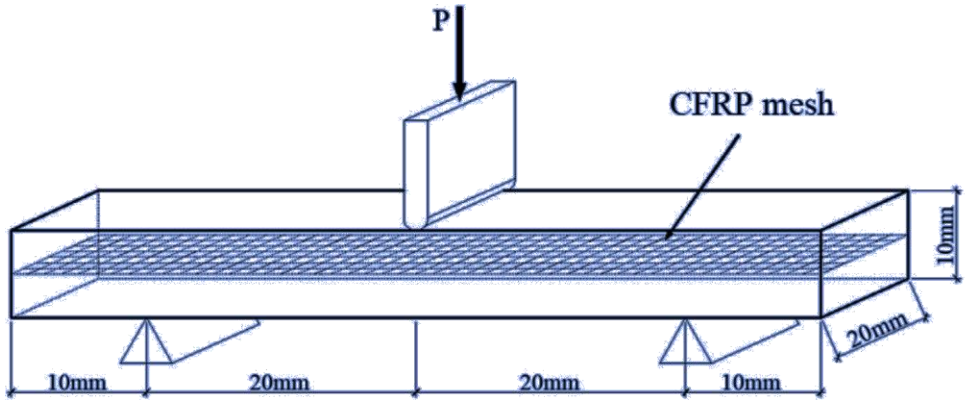


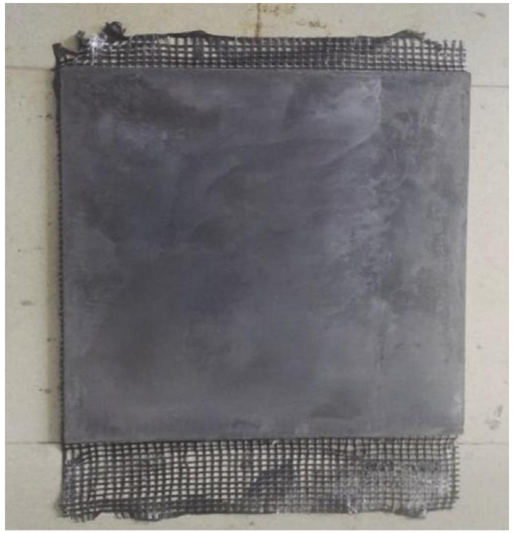
Innovations in Carbon Fibres and Composite Materials Recycling

# CARBON FIBRES IN CONCRETE

*Evaluation of carbon fiber reinforced cementitious matrix as a recyclable strengthening material, Wan-qian Li et al, Journal of Cleaner Production, vol. 217, 2019, pp.234-243*

In the research presented in this paper, a **new cement-based material was developed introducing chopped carbon fiber**. The carbon-fiber-reinforced cementitious matrix (C-FRCM) containing a cement-based matrix and embedded carbon-fiber mesh is an alternative solution to FRPepoxy resin, addressing cost, durability, and reversibility issues. The flexural performance **of carbonfiber-reinforced cementitious matrix plates** with chopped carbon fibers was explored in this study. […]. The results also show that the carbon fiber mesh is effective in strengthening the carbon-fiber-reinforced cementitious matrix.



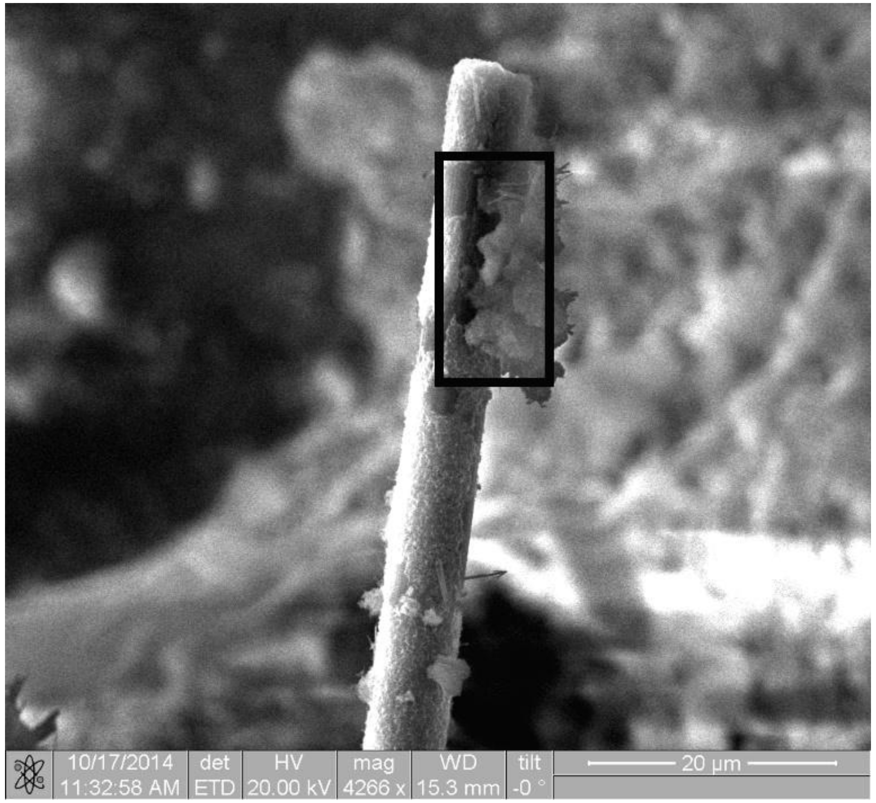


(b) C-FRCM plate

# CARBON FIBRES IN CONCRETE

*Improvement of cement concrete strength properties by carbon fiber additives, Andrey Nevsky etal, AIP Conference Proceedings 1698, 070005 (2016), published Online: 15 January 2016.*

The paper presents the results of studies of **fiber-reinforced concrete with carbon fibers**. The effectiveness of carbon fibers **uniform distribution in the concrete** was obtained as a result of its preliminary mechanical mixing in water solution with chemical additives. Additives are to be used in the concrete technology as modifiers at initial stage of concrete mix preparing. The technology of preparing of fiber-reinforced concrete mix with carbon fibers is developed. The superplasticizer is based on ether carboxylates as a separator for carbon fibers. The technology allows **increasing of concrete compressive strength up to 43.4% and tensile strength up to 17.5%** as well as improving stability of mechanical properties.

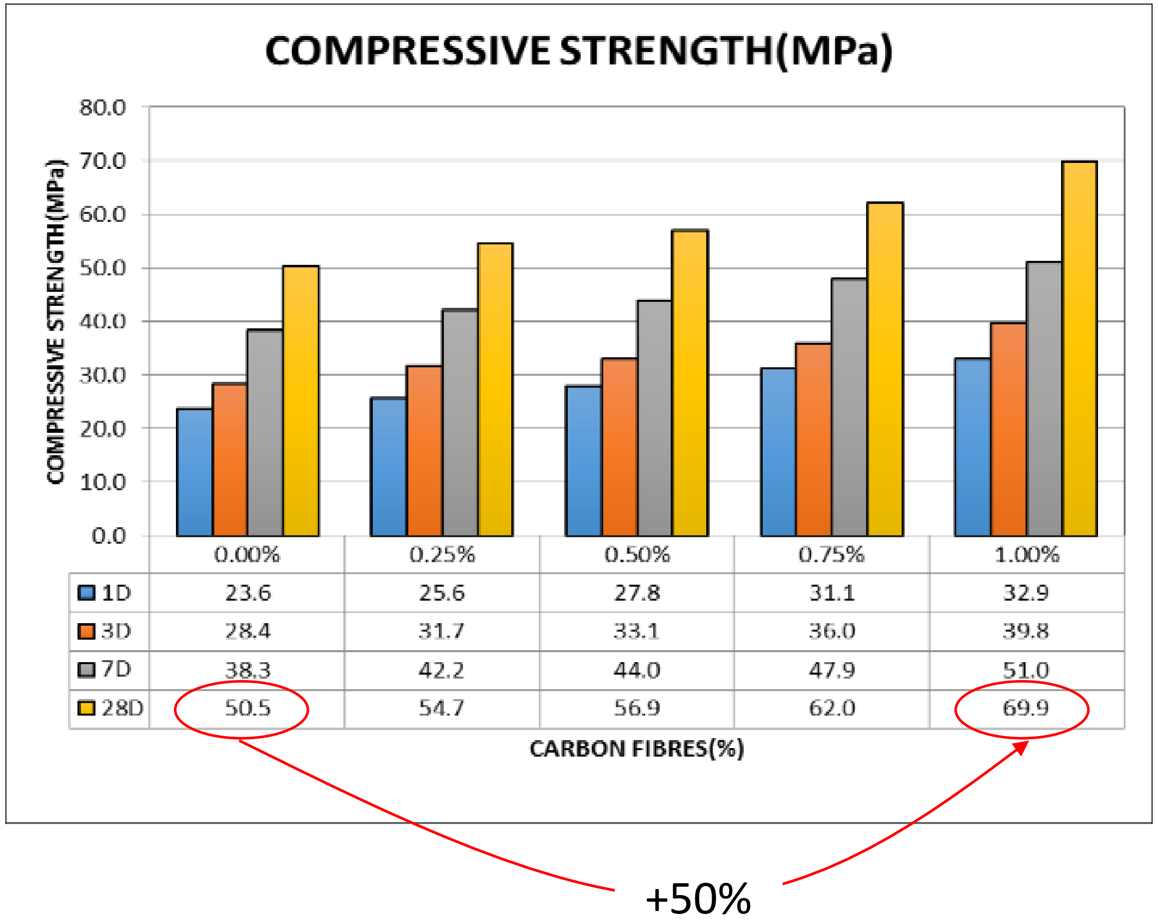


*Micrograph of carbon fiber in concrete*

# CARBON FIBRES IN CONCRETE

*Chopped Carbon Fibers Innovative Material for Enhancement of Concrete Performances , Prashant Muley et al., International Journal of Scientific Engineering and Applied Science (IJSEAS) - Volume-1, Issue-4, July 2015.*

[..] investigation of the use of short fibres in structural concrete to enhance the mechanical properties of concrete. [...]. The investigation was carried out using several tests, which included **workability test**, **compressive test**, **split tensile test** and **flexural test**. A total of five mix batches of concrete containing 0%, 0.25%, 0.5%, 0.75% and 1.0% fibre volume dosage rate on **carbon fibres** were tested to determine the enhancement of mechanical properties of concrete. [...]. Results of compressive strength test indicated that the **use of fibre in concrete increases the strength and help in early strength gain**. In flexural and split tensile test showed specimens with fibres that drastic increase in strength from specimens without fibres. ...



| | 0.00% | 0.25% | 0.50% | 0.75% | 1.00% |
|---|---|---|---|---|---|
| 🟦 1D | 23.6 | 25.6 | 27.8 | 31.1 | 32.9 |
| 🟧 3D | 28.4 | 31.7 | 33.1 | 36.0 | 39.8 |
| ⬜ 7D | 38.3 | 42.2 | 44.0 | 47.9 | 51.0 |
| 🟨 28D | 50.5 | 54.7 | 56.9 | 62.0 | 69.9 |

+50%

# CARBON FIBRES IN CONCRETE

What could be an experimental program involving carbon fibres in concrete?

1. **What are the intrinsic properties of carbon fibres in regards with their origin?**
    1. strength
    2. elasticity
    3. sensitivity to heat and moisture
    4. stress relaxation
    5. morphology (dimensions, shape and surface texture)
2. **What improvement of the final material is expected?**
    1. mechanical properties
        1. rheology
        2. short term strength (compressive, tensile)
        3. long term behaviour
        4. ductility?
        5. crack bridging
        6. shrinkage
        7. creep
        8. fatigue
        9. chock resistance
    2. physical properties
        1. electric conductivity
        2. heat conductivity
        3. air and water permeability
        4. entrained air
        5. specific mass
        6. porosity and connectivity
        7. sound wave propagation
        8. behaviour under fire
    3. chemical properties
        1. resistance to external aggressions
        2. carbon and alkali silica reactions
        3. carbon and sulphatic reactions
        4. combustion by-products

# CARBON FIBRES IN CONCRETE

What could be an experimental program involving carbon fibres in concrete?

1. **How to mix concrete/mortar and carbon?**
   1. sizing nature?
   2. compatibility with high pH, alkaline medium
   3. use of admixtures
   4. dispersion of the fibres
   5. dosage
   6. demand in water
   7. spatial organisation of fibres in a cement-mix

2. **What kinds of applications are targeted?**
   1. pipes, sewer, sanitation
   2. flooring
   3. decorative slabs, ceilings, cladding panels
   4. roof tiles
   5. structural concrete
   6. repairing mortars, sealing

3. **Environmental issues**
   1. safeness of the use of carbon fibres (workers, users, owners, nature)
   2. product lifecycle

4. **Economical issues**
   1. Pricing
   2. Marketing

**And after ?**

➔ modelling
➔ writing rules for calculation
➔ getting some agreements from official agencies

Example : *Avis technique 3.3/17-926 “lamelles LANKOSTRUCTURE CARBO et CARBOPUL” – groupe PAREXLANCO* (reinforcement of concrete structures by carbon lamellas bonded with an epoxy glue).

# An introduction to concrete

THANK YOU FOR YOUR KIND ATTENTION

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