2. MIX DESIGN

2.1 Constituent materials for concrete composition

Concrete is the material formed by mixing cement, aggregates and water, with or without the incorporation of admixtures and additions, which develops its properties by hydration of the cement. The general concept for concrete mix design as presented herein is in full compliance with the most spread existing standards for concrete production, such as the *European Standard for concrete: EN 206* [12]. For the present application, a concrete volume is assumed that contains certain amounts of ***cement, additions (optional), aggregates, water, and admixtures (optional)*** *only*, see Fig. 2.1.1. To the above materials ***entrained or entrapped air*** should be added.

CONCRETE :

Cement:	main constituents: portland clinker, blast furnace slag, silica fume, pozzolanic materials (natural or natural calcined pozzolanas), fly ash (siliceous or calcareous), burnt shale, and limestone minor additional constituents: all main constituents except clinker calcium sulphate, additives

+

Additions:	type I (filler aggregate, pigments), type II (fly ash, silica fume)

+

Aggregates:	fine, coarse

+

Water:	mixing water

+

Admixtures:	retarder, accelerator, air-entraining, plasticizer, superplasticizer, etc.

+

Air:	entrained, entrapped

Figure 2.1.1 Constituent materials for concrete composition.

All these materials have to comply with the corresponding standards for the constituent materials, for instance in the case of European Standards: EN 197 (Cement), EN 450 (Fly ash for concrete), EN 13263 (Silica fume for concrete), EN 12620 (Aggregates for concrete), EN 1008 (Mixing water for concrete), EN 934-2 (Admixtures for concrete), etc.

More specifically and for the purposes of the present application for the approach of concrete service life, we define as follows:

2.1.1 Cement

Cement is a hydraulic binder, i.e. a finely ground inorganic material which, when mixed with water, forms a paste that sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water. General suitability for concrete production is established for cement conforming to EN 197-1 [13]. Cement conforming to this European Standard, termed CEM cement, shall, when appropriately batched and mixed with aggregate and water, be capable of producing concrete or mortar which retains its workability for a sufficient time and shall after defined periods attain specified strength levels and also possesses long-term volume stability.

Hydraulic hardening of CEM cement is primarily due to the hydration of calcium silicates but other chemical compounds may also participate in the hardening process, e.g., aluminates. The sum of the proportions of reactive calcium oxide (CaO) and reactive silicon dioxide (SiO_2) in CEM cement shall be at least 50% by mass when proportions are determined in accordance with EN 196. CEM cements consist of different materials that are statistically homogeneous in composition resulting from quality assured production and material handling processes. According to this standard, a cement may comprise of ***main constituents, minor additional constituents, calcium sulphate and additives***, see Table 2.1.1.

A ***main constituent*** is a specially selected inorganic material in a proportion exceeding 5% by mass related to the sum of all main and minor additional constituents. As main constituents are used portland cement clinker, blast furnace slag, silica fume, pozzolanic materials (natural or natural calcined pozzolanas), fly ashes (siliceous or calcareous), burnt shale, and limestone.

Table 2.1.1 Types of common cements according to European Standard EN 197-1*.

Main types	Nota-tion	Main constituents**									Minor addit. const.
		K	S	D	P	Q	V	W	T	L/LL	
PORTLAND CEMENTS											
CEM I	I	95-100	-	-	-	-	-	-	-	-	0-5
PORTLAND-COMPOSITE CEMENTS											
CEM II	II/A-S	80-94	6-20	-	-	-	-	-	-	-	0-5
	II/B-S	65-79	21-35	-	-	-	-	-	-	-	0-5
	II/A-D	90-94	-	6-10	-	-	-	-	-	-	0-5
	II/A-P	80-94	-	-	6-20	-	-	-	-	-	0-5
	II/B-P	65-79	-	-	21-35	-	-	-	-	-	0-5
	II/A-Q	80-94	-	-	-	6-20	-	-	-	-	0-5
	II/B-Q	65-79	-	-	-	21-35	-	-	-	-	0-5
	II/A-V	80-94	-	-	-	-	6-20	-	-	-	0-5
	II/B-V	65-79	-	-	-	-	21-35	-	-	-	0-5
	II/A-W	80-94	-	-	-	-	-	6-20	-	-	0-5
	II/B-W	65-79	-	-	-	-	-	21-35	-	-	0-5
	II/A-T	80-94	-	-	-	-	-	-	6-20	-	0-5
	II/B-T	65-79	-	-	-	-	-	-	21-35	-	0-5
	II/A-L	80-94	-	-	-	-	-	-	-	6-20	0-5
	II/B-L	65-79	-	-	-	-	-	-	-	21-35	0-5
	II/A-M	80-94	6-20								0-5
	II/B-M	65-79	21-35								0-5
BLASTFURNACE CEMENTS											
CEM III	III/A	35-64	36-65	-	-	-	-	-	-	-	0-5
	III/B	20-34	66-80	-	-	-	-	-	-	-	0-5
	III/C	5-19	81-95	-	-	-	-	-	-	-	0-5
POZZOLANIC CEMENTS											
CEM IV	IV/A	65-89	-	11-35					-	-	0-5
	IV/B	45-64	-	36-55					-	-	0-5
COMPOSITE CEMENTS											
CEM V	V/A	40-64	18-30	-	18-30			-	-	-	0-5
	V/B	20-38	31-50	-	31-50			-	-	-	0-5

* The composition is expressed as % by mass of the main and minor additional constituents.

** Notation **exclusively** for the present table: portland clinker (K), blast furnace slag (S), silica fume (D), pozzolana (natural, P or natural calcined, Q), various fly ashes (siliceous, V or calcareous, W), burnt shale (T), and limestone (L or LL).

Portland cement clinker is the main constituent that all cement types contain (CEM I to CEM V). It is made by sintering a precisely specified mixture of raw materials (raw mill, paste or slurry) containing elements, usually expressed as oxides, CaO, SiO_2, Al_2O_3, Fe_2O_3 and small quantities of other materials. It is a hydraulic material which shall consist of at least 2/3 by mass of calcium silicates (3CaO. SiO_2 and 2CaO. SiO_2), the remainder consisting of aluminium and iron containing clinker phases and other compounds. The ratio by mass CaO/SiO_2 shall be not less than 2.0. The content of magnesium oxide (MgO) shall not exceed 5.0% by mass.

All other main constituents (except clinker), defined only in the present work as *supplementary cementing materials (SCM)*, may be divided into *natural materials* and *artificial* ones. To the former belong natural pozzolanic materials and limestone. To the second category belong granulated blast furnace slag, silica fume, calcined pozzolanas, fly ashes, and burnt shale. In EN 197 these materials defined as follows:

Granulated *blast furnace slag* is made by rapid cooling of a slag melt of suitable composition, as obtained by smelting iron ore in a blast furnace slag and contains at least 2/3 by mass of glassy slag and possesses hydraulic properties when suitably activated. It shall consist of at least 2/3 of the sum of ($CaO+MgO+SiO_2$), the remainder contains Al_2O_3 together with small amounts of other compounds. The ratio by mass of (CaO+MgO)/(SiO_2) shall exceed 1.0.

Silica fume originates from the reduction of high purity quartz with coal in electric arc furnaces in the production of silicon or ferrosilicon alloys and consists of very fine spherical particles containing at least 85% by mass amorphous SiO_2.

In EN 197, *pozzolanic materials* are defined the *natural substances* of siliceous or silico-aluminous composition or a combination thereof (in general, however, pozzolanic materials are also fly ash and silica fume). Pozzolanic materials do not harden in themselves when mixed with water but, when finely ground and in the presence of water, they react at normal ambient temperature with dissolved calcium hydroxide, $Ca(OH)_2$, to form strength-developing calcium silicate and calcium aluminate compounds. These compounds are similar to those which are formed in the hardening of hydraulic materials. They consist essentially of reactive SiO_2 (>25.0 % by mass) and Al_2O_3, the remainder contains Fe_2O_3 and other oxides.

These materials may be *natural pozzolanas* (materials of volcanic origin or sedimentary rocks) or *natural calcined pozzolanas* (materials of volcanic origin, clays, shales or sedimentary rocks, activated by thermal treatment).

Fly ash is the combustion residue (coal mineral impurities) in coal-burning electric power plants, which flies out with the flue gas stream and is removed by electrostatic or mechanical precipitation. Ash obtained by other methods shall not be used in cement that conforms the EN 197-1. Fly ash may be siliceous or calcareous in nature. The former has pozzolanic properties; the latter may have, in addition, hydraulic properties. *Siliceous fly ash* is a fine powder of mostly spherical particles having pozzolanic properties. It consists essentially of reactive SiO_2 and Al_2O_3, the remainder contains Fe_2O_3 and other compounds. The proportion of reactive CaO shall be less than 10.0% by mass and the content of free CaO shall not exceed 1.0% by mass. The reactive SiO_2 content shall not be less than 25.0% by mass. *Calcareous fly ash* is a fine powder having hydraulic and/or pozzolanic properties. It consists essentially of reactive CaO, reactive SiO_2 and Al_2O_3, the remainder contains Fe_2O_3 and other compounds. The proportion of reactive CaO shall not be less than 10.0% by mass and the content of free CaO shall not exceed 1.0% by mass. The reactive SiO_2 content shall not be less than 25.0% by mass, if the reactive CaO is between 10-15% by mass; if the reactive CaO is greater than 15% by mass certain strength levels should be required.

Burnt shale, specifically burnt oil shale, is produced in a special kiln at temperatures of approximately 800 ^{o}C. Owing to the composition of the natural material and the production process, burnt shale contains clinker phases, mainly dicalcium silicate and monocalcium silicate. It also contains, besides small amounts of free calcium oxides and calcium sulphate, larger proportions of pozzolanically reacting oxides, especially SiO_2. Consequently, in a finely ground state burnt shale shows pronounced hydraulic properties like Portland cement and in addition pozzolanic properties.

Limestone shall meet the following requirements: The $CaCO_3$ content shall be at least 75% by mass, the clay content shall not exceed 1.20% by mass, and the total organic carbon content shall conform to one of the following criteria, LL: shall not exceed 0.20% by mass, L: shall not exceed 0.50% by mass

In general, but not accepted in EN 197, to the above SCM may be added slags from metallurgical furnaces producing steel, copper, nickel and lead, bottom ashes, ashes from incinerators and waste treatment sludge, metakaolin, red mud from alumina production, etc. These materials may, in some future revised edition of the standards, be included as cement constituents. However, either experimentally or at industrial scale all the the above additions are extensively used the recent years especially as ingredients in blended cements and at a lower degree as separately batched constituents in concrete [14-21]. *Almost only silica fume and siliceous fly ash are used as separately additions in concrete (see below: concrete additions).* However, all these materials, whatever is their origin in concrete, besides the effect on usual structural properties, such as strength and volume stability, *the concrete durability should seriously be considered.*

A ***minor additional constituent (mac)*** is a specially selected inorganic material used in a proportion not exceeding 5% by mass related to the sum of all main and minor additional constituents. As minor additional constituents can be used inorganic natural materials, inorganic mineral materials derived from the clinker production process or main constituents as specified earlier unless they are included as main constituents in the cement. Inert materials, such as limestone and dust derived from the clinker production process (materials known as fillers) are usually used. Thus, mac affect only the physical properties of concrete, such as workability and water retention. However, they shall not increase the water demand of the concrete appreciably, impair the resistance to deterioration or reduce the corrosion protection of the reinforcement.

Calcium sulphate (between 3 % and usually 5% by weight of cement) in the form of gypsum or anhydrite is added to the above constituents to control the clinker flash setting.

Various ***additives*** may also be added (up to 1% by weight of cement) to improve either the cement production or cement properties. They shall not promote the corrosion of the reinforcement or impair the properties of cement, mortar or concrete.

By studying Table 2.1.1, and of the purpose of understanding the various cements' behaviour, we can distinguish herein *five different categories of cement*, according to the SCM type that cement contains [16]:

1. **CEM I.** This is the type CEM I of cement, containing no additional SCM more than that in mac. An older name in the literature was ordinary Portland cement (OPC).
2. **CEM II/D.** This is the type CEM II/A-D of cement, containing a highly pozzolanic material (silica fume) at 6-10 % in cement (minus calcium sulphate).
3. **CEM II/ V,P,Q,M.** This covers the cement types CEM II/A-V, CEM II/B-V, CEM II/A-P, CEM II/B-P, CEM II/A-Q, CEM II/B-Q, CEM II/A-M, CEM II/B-M of cement, containing a normal pozzolanic material ([16], siliceous fly ash and natural or artificial pozzolanic materials) at 6-20 % (A) or 21-35% (B) in cement (minus calcium sulphate). This cement category can also cover the **CEM IV** cement types, whereas mostly normal pozzolanic materials are contained at higher contents: 11-35% (A) and 36-55% (B). The **CEM V** cement type requires a more detailed composition information; however as a first approximation it may be covered by this cement category, when burnt furnace slag is calculated almost as Portland clinker and normal pozzolanic materials are contained at 18-30 % (A) or 31-50% (B) in cement.
4. **CEM II/W,S,T.** This covers the cement types CEM II/A-W, CEM II/B-W, CEM II/A-S, CEM II/B-S, CEM II/A-T, CEM II/B-T of cement, containing a pozzolanic material with latent hydraulic properties ([16], calcareous fly ash, blast furnace slag and burnt shale) at 6-20 % (A) or 21-35% (B) in cement (minus calcium sulphate). This cement category can also cover the **CEM III** cement types, whereas a cementitious-pozzolanic material (blast furnace slag) is contained at higher contents: 36-65% (A), 66-80% (B), and 81-95% (C).
5. **CEM II/L.** This covers the cement types CEM II/A-L (or LL) and CEM II/B-L (or LL) of cement, containing a mineral admixture of low reactivity (limestone, L or LL) at 6-20 % (A) or 21-35% (B) in cement (minus calcium sulphate).

The ***standard strength of a cement*** is the compressive strength determined in accordance with EN 196-1 at 28 days and shall conform to the requirements in Table 2.1.2. *Three classes of standard strength are included; class 32,5, class 42,5 and class 52,5.* The *early strength* of a cement is the compressive strength at either 2 days or 7 days. Two classes of early strength are induced for each class of standard strength, a class with *ordinary early strength (N),* and a class with *high early strength (R).*

Table 2.1.2 Mechanical and physical requirements for common cements according to European Standard EN 197-1.

Strength class	Compressive strength (MPa)				Initial setting time (min)	Soundness (expansion) (mm)
	Early strength		Standard strength			
	2 days	7 days	28 days			
32,5 N	-	≥ 16.0	≥ 32.5	≤ 52.5	≥ 75	≤ 10
32,5 R	≥ 10.0	-	≥ 32.5	≤ 52.5	≥ 75	≤ 10
42,5 N	≥ 10.0	-	≥ 42.5	≤ 62.5	≥ 60	≤ 10
42,5 R	≥ 20.0	-	≥ 42.5	≤ 62.5	≥ 60	≤ 10
52,5 N	≥ 20.0	-	≥ 52.5	-	≥ 45	≤ 10
52,5 R	≥ 30.0	-	≥ 52.5	-	≥ 45	≤ 10

The initial setting time and expansion of cement shall conform to the requirements in Table 2.1.2. In EN 197, chemical requirements for the cements have also been specified.

Regarding ***durability requirements*** it is stated that, in many applications, particularly in severe environmental conditions, the choice of cement has an influence on the durability of concrete, mortar and grouts, e.g., frost resistance, chemical resistance and protection of the reinforcement. The choice of cement, particularly as regards type and strength class for different applications and exposure classes shall follow the appropriate standards and/or regulations for concrete or mortar valid in the place of use.

CEM cements shall be identified by at least the notation of the *cement type* as specified in Table 2.1.1 and the figures 32,5, 42,5 or 52,5 indicating the *standard strength class*, see Table 2.1.2. In order to indicate the *early strength class* the letter N or the letter R shall be added, see Table 2.1.2. ***The cement shall be selected*** from those for which the suitability is established, taking into account the execution of the work, the end use of concrete, the curing conditions, the dimensions of the structure (the heat development), the environmental conditions and the potential reactivity of aggregate to the alkalis from the constituents.

In the present work, we suppose that the cement belongs to one of the **CEM types** presented in Table 2.1.1, with strength class and early strength class as presented in Table 2.1.2. The total cement content in concrete is denoted by **C (kg cement / m^3 of concrete)**. The particle density (EN 196) of cement is denoted by **d_C (kg/m^3)**.

We also denote as **p_K (%)** the percentage of clinker (including the various additives) in the cement (minus calcium sulphate), **p_{CS} (%)** the percentage of calcium sulphate in the cement, **p_{MAC} (%)** the percentage of minor additional constituents in the cement (minus calcium sulphate), and **p_{SCM} (%)** the percentage of SCM in the cement (minus calcium sulphate). Obviously, we have:

$$[(p_K/100) + (p_{MAC}/100) + (p_{SCM}/100)]\ C\ (100-p_{CS})/100 + (p_{CS}/100)\ C = C \qquad (2.1.1)$$

Using Eq. (2.1.1) we can calculate p_{SCM} content when all other cement composition parameters are known:

$$p_{SCM} = 100 - p_K - p_{MAC} \qquad (2.1.2)$$

In the case of cement type CEM V, these composite cements contain, apart the clinker, certain amounts of both slag and other pozzolanic materials. The p_{SCM} (%) percentage of the total SCM in the cement (minus calcium sulphate) is separated in **p_{SL} (%)**, referring to slag percentage in cement, and **p_{PO} = (p_{SCM} – p_{SL})**, referring to the other pozzolanic materials.

2.1.2 Additions

Addition is a finely divided material used in concrete in order to improve certain properties or to achieve special properties. The EN 206 deals with two types of inorganic additions:

- *nearly inert additions **(type I)***
- *pozzolanic or latent hydraulic additions **(type II)***

General suitability as type I addition is established for *filler aggregate* conforming to EN 12620 and *pigments* conforming to EN 12878. General suitability as type II addition is established for ***fly ash*** conforming to EN 450 and ***silica fume*** conforming to EN 13263. However, EN 206 notes that certain constituents no conforming to some European Standard may be used in concrete; the establishment of suitability may result from: a European Technical Approval, or a relevant national standard or provisions. In general, type II additions may by all the above called supplementary cementing materials (SCM).

Type I additions may be calculated in the aggregate content. In the present work, we suppose that only fly ash and/or silica fume may be used as separate additions of type II in concrete. The fly ash content in concrete is denoted by **F (kg fly ash / m^3 of concrete)**. There is the possibility to use a specific **fly ash type**: siliceous (SIL) or calcareous (CAL). The silica fume content in concrete is denoted by **S (kg silica fume / m^3 of concrete)**. The particle densities of fly ash and silica fume are denoted as **d_F (kg/m^3)** and **d_S (kg/m^3)**, respectively.

We suppose also that *when these type II additions are used directly in concrete, a cement type CEM I is used as cement.* If however an other cement type is used we have to separate the pure portland clinker from all the other main constituents of cement. This portland clinker with the gypsum and mac is further considered as the only real cement; see further, portland cement in chapter 3. The other main constituents (SCM) have to be added, if they are active, to the above SCM content or, if they are inert, to the aggregates content.

2.1.3 Aggregates

Aggregate is a granular mineral material suitable for use in concrete. Aggregates may be natural (natural collected or just natural, and natural crushed), artificial or recycled from material previously used in construction. General suitability is established for:

- *normal and heavy-weight aggregates* conforming to EN 12620. Normal-weight aggregate has an oven-dry particle density between 2000 – 3000 kg/m^3, when determined according to EN 1097-6. Heavy-weight aggregate has an oven-dry particle density $\geq$ 3000 kg/m^3, when determined according to EN 1097-6.

- *light-weight aggregates* conforming to EN 13055-1. Light-weight aggregate of mineral origin has an oven-dry particle density ≤ 2000 kg/m^3 when determined according to EN 1097-6 or a loose oven-dry bulk density ≤ 1200 kg/m^3 when determined according to EN 1097-3.

Aggregate type, grading and categories, e.g., flakiness, freeze/thaw resistance, abrasion resistance, fines, ***shall be selected*** taking into account the execution of the work, the end use of the concrete, the environmental conditions and any requirements for exposed aggregate. The *maximum nominal upper aggregate size* (D_{max}) shall be selected taking into account the concrete cover to reinforcement and the minimum section width. When aggregates contain varieties of silica susceptible to attack by alkalies (Na_2O and K_2O originating from cement or other sources) and the concrete is exposed to humid conditions, actions shall be taken to prevent deleterious alkali – silica reaction using procedures of established suitability.

In the present work, the total aggregate content in concrete is denoted by **A (kg aggregate / m^3 of concrete)**. The particle density of aggregates is denoted as **d_A (kg/m^3)**. Aggregate/cement ratio (**A/C**) is the ratio of the aggregate content to cement content by mass in the fresh concrete.

2.1.4 Water

Suitability is established for ***mixing water*** and for recycled water from concrete production conforming to EN 1008. *Total water content* is the added water plus water already contained in the aggregates and on the surface of aggregates plus water in the admixtures and in additions used in the form of a slurry and water resulting from any added ice or steam heating. *Effective water content* is the difference between total water present in the fresh concrete and the water absorbed by the aggregates.

In the present work this ***effective water*** content is denoted by **W (kg water / m^3 of concrete)**. The water density is denoted as **d_W (kg/m^3)**. Water/cement ratio (**W/C**) is the ratio of the effective water content to cement content by mass in the fresh concrete.

2.1.5 Admixtures

Admixture is a material (usually organic) added during the mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete. General suitability is established for admixtures conforming to EN 934-2.

In general, the admixtures for concrete can be divided into:

- admixtures modifying set and hardening:
  - accelerators
  - retarders
- admixtures modifying the mix rheology and the air content:
  - water-reducing admixtures (superplasticizers, plasticizers)
  - water-retaining admixtures
  - thickening admixtures
- admixtures entraining air into the mixes:
  - air-entraining and air-detraining admixtures
  - gas-forming admixtures
  - foam-forming admixtures
- admixtures modifying the resistance to physical and chemical actions:
  - frost-resisting and anti-freezing admixtures
  - water-repelling admixtures
  - permeability-reducing admixtures
  - corrosion-inhibiting admixtures
  - improving resistance to chemical actions

However, the most largely used products are *retarders* (0.2-0.4% by mass of cement), *accelerators* (0.5-6% by mass of cement), *air-entraining admixtures* (0.05-0.2% by mass of cement), *plasticizers* (0.3-0.5% by mass of cementitious materials), and *superplasticizers* (0.8-1.5% by mass of cementitious materials). These representative dosages refer to the total solution of admixtures (as supplied: solids plus solvent water).

The total amount of admixtures, if any, shall not exceed the *maximum dosage* recommended by the admixture producer and not exceed 50 g of admixture (as supplied) per kg cement unless the influence of the higher dosage on the performance and durability is established. If the total quantity of liquid admixtures exceeds 3 l/m^3 of concrete, its water content shall be taken into account when calculating the water/cement ratio.

In the present work, we suppose that one or more admixtures may be used, and the total admixture content in concrete is denoted by **D (kg of admixture solids / m^3 of concrete)**. The solids' density of admixtures is denoted by **d_D (kg/m^3)**. There is the possibility to use a specific **admixture type** (retarder, accelerator, air-entraining, plasticizer, superplasticizer, etc.) or a combination of them.

2.1.6 Entrained or entrapped air

Entrained air are the microscopic air bubbles intentionally incorporated in concrete during mixing, usually by use of a surface active agent; typically between 10 – 300 µm in diameter and spherical or nearly so. ***Entrapped air*** are voids in concrete which are not purposely entrained.

The total entrained and entrapped air content of concrete, when compacted in accordance with the procedure given in EN 12350-6, is denoted by **ε_{air} (m^3 of entrained or entrapped air / m^3 of concrete)**. It mainly depends on maximum aggregate size and the air-entraining agents' content. It shall be measured in accordance with EN 12350-7.

2.2 Basic calculations

As the **basis** for concrete composition, the volume unit of **1 m^3** of the fresh concrete is selected. By assuming negligible expansion this volume unit represents also hardened concrete. It must be emphasized that if *a material is added* to this unit, *then an equal volume of another component must be removed* in order to keep the same total volume and a common comparison basis. The composition of 1 m^3 of fresh concrete is given in Table 2.2.1. The following mass balance equation has to be fulfilled:

$$C/d_C + S/d_S + F/d_F + A/d_A + W/d_W + D/d_D + \varepsilon_{air} = 1 \quad (2.2.1)$$

This Eq. (2.2.1) may be used to calculate the *aggregate content* if all other composition parameters are known:

$$A = (1 - C/d_C - S/d_S - F/d_F - W/d_W - D/d_D - \varepsilon_{air})\, d_A \quad (2.2.2)$$

The *water to cement ratio (W/C)* is calculated as the ratio of the effective water content to cement content by mass in the fresh concrete. The *aggregate to cement ratio (A/C)* is calculated as the ratio of the aggregate content to cement content by mass in the fresh concrete. The *fresh concrete density*, d_{CON} (kg/m^3), is given by:

$$d_{CON} = C + S + F + A + W + D \quad (2.2.3)$$

Table 2.2.1 Composition of 1 m^3 volume of concrete.

C:	kg cement / m^3 of concrete	d_C:	cement density (kg/m^3)
S:	kg silica fume / m^3 of concrete	d_S:	silica fume density (kg/m^3)
F:	kg fly ash / m^3 of concrete	d_F:	fly ash density (kg/m^3)
A:	kg aggregates / m^3 of concrete	d_A:	aggregate density (kg/m^3)
W:	kg effective water / m^3 of concrete	d_W:	water density (kg/m^3)
D:	kg admixtures (solid) / m^3 of concrete	d_D:	admixture density (kg/m^3)
ε_{air}:	m^3 of entrained and/or entrapped air / m^3 of concrete		

2.3 Design strategy

The *concrete mixture composition* and the *constituent materials* for designed or prescribed concrete shall be chosen to satisfy the requirements specified for fresh and hardened concrete, including consistence, density, strength, durability, protection of embedded steel against corrosion, taking into account the production process and the intended method of execution of concrete works [12]. As *designed concrete* called the concrete for which the required properties and additional characteristics are specified to the producer who is responsible for providing a concrete conforming to the required properties and additional characteristics. As *prescribed concrete* called the concrete for which the composition and the constituent materials to be used are specified to the producer who is responsible for providing a concrete with the specified composition. Where not detailed in the specification, the producer shall select types and classes of constituent materials from those with established suitability for the specified environmental conditions.

In all specifications regarding concrete production, among the main design parameters are the *cement content (C)* and the *water-to-cement ratio (W/C).* Thus, minimum values of cement content and maximum values of W/C ratio are specified according to the *aggressiveness class* of the surrounding environment. Despite the exposure classes, in all cases, the *total equivalent cement content* should be taken into account [12].

After having specified the *fresh concrete composition (mix design: C, S, F W, A, D, and* ε_{air}*)* that fulfils the strength expectations and standard requirements (e.g., minimum C, maximum W/C ratio, etc.), the *concrete durability* should be examined. *Let us suppose that the* ***designed service life is Z years****.* Thus, this specific concrete composition must be examined if it ensures service life greater than the designed one, as regards the possible deterioration environment in which the concrete will be exposed.

First the case of **concrete carbonation**, if any, must be taken into account. The ***concrete cover, c,*** must be higher than the expected carbonation depth within the lifetime Z. An accurate prediction of this carbonation depth can be obtained using the equations presented in section 5. If an *unacceptable* (due to various technical or economic reasons) cover is predicted then either a different concrete composition (e.g., lower W/C ratio, higher cement content, etc.) or a protective coating application shall be proposed. Then the calculation must be repeated until satisfaction.

Having specified the concrete composition and cover as above, the case of **chloride penetration**, if any, must then be considered. The equations presented in section 6 have to be solved using the corresponding parameters, in order to predict the chloride profile into the concrete as a function of time. Using the Cl-profile at the time equal to Z, the *minimum concrete cover* can be found at which and onwards the chloride concentration takes lower values than the *critical threshold* for corrosion. If an unacceptable cover is predicted then again either a denser concrete composition or a coating application should be considered and the calculations are repeated.

If any other deterioration mechanism could take place, e.g., a specific **chemical attack** (section 7), it has to be considered in a similar way. Finally, the ***cost of concrete production*** has to be estimated.

For the initially selected concrete composition the most essential properties have been predicted, such as ***strength, service life and cost***. The *specifier* can then alter accordingly the concrete composition and/or the protection measures to improve further every desired property.

- The design parameters that ensure *full protection* (the higher concrete cover and the denser concrete composition or the best protection measures) among them predicted for resistance against carbonation and chloride penetration, chemical attack, etc., at the lowest cost, *must be finally proposed*.