7. COST CALCULATION AND DESIGN OPTIMIZATION

7.1 Concrete production cost

As a common basis, the volume unit of 1 m^3 of fresh concrete will be considered. *The total production cost* of this volume unit, KT (€/m^3), from the materials purchase until concrete delivery, can be analyzed into the following terms:

$$KT = K_P + K_M + K_B + K_G \qquad (7.1.1)$$

where:

K_P: *purchase cost* of materials, €/m^3

K_M: *mixing cost* for concrete production, €/m^3

K_B: cost of concrete *transportation and delivery*, €/m^3

K_G: *other fixed and operational costs*, €/m^3. They include the fixed cost of purchase and establishment of equipment (depreciation values), labor and administration costs and general operational costs.

7.1.1 Purchase cost

The cost that represents the value of the raw materials (including transportation to the plant premises) can be estimated as follows:

$$K_P = C\,U_C + S\,U_S + F\,U_F + A\,U_A + W\,U_W + D\,U_D \qquad (7.1.2)$$

where:

U_C: cement value, €/kg

U_S: silica fume value, €/kg

U_F: fly ash value, €/kg

U_A: aggregate value, €/kg

U_W: water value, €/kg

U_D: total admixture value, €/kg

7.1.2 Mixing cost

The cost of material mixing and preparation of the fresh concrete, K_M, can be estimated by:

$$K_M = P_M \; t_M \; U_E \tag{7.1.3}$$

where:

P_M: mixing power / m^3 of concrete, J/s.m^3,

U_E: cost of energy, €/J

t_M: the mixing time, s

Parameters P_M and t_M depend on concrete workability and density and, therefore, on concrete composition parameters (CCP: C, S, F, A, W and D).

7.1.3 Transportation and delivery cost

The cost of transportation, K_T, primarily depends on the distance between project location and plant, and consequently is independent of concrete compositional parameters. At the project location, the cost is burdened with pumping and application expenses and thus the total cost can be estimated by:

$$K_B = K_T + (P_B / Q) \, U_E \tag{7.1.4}$$

where:

P_B: pumping power, J/s

Q: concrete flow, m^3/s

Parameter P_B depends on concrete compositional parameters, through workability and density.

7.2 Mix design optimization

The most important *properties* regarding concrete production are three: strength, durability and cost (dependent variables). All of them are functions of the *concrete compositional parameters* (*CCP*: independent variables, primarily C, P, A, W and D contents).

The strength, f_c, in general, is a function of CCP, time (t) and curing conditions, i.e.:

$$f_c = f_c \{CCP, curing, t\} \qquad (7.2.1)$$

From the beginning of 20th century, many efforts have been made to approach this dependence by analytical expressions based on concepts of porosity, degree of hydration, etc. (e.g., Abrams' law, Feret and Bolomeys' relationships, etc., see chapter 4. At a specified time, strength depends mainly on W/C ratio, cement content and standard strength class, additions activity and content, quality of aggregates, air-content, and the curing procedure. The Eqs. (4.2.5) or (4.3.1) can be applied as a first approximation.

The durability, expressed as service lifetime of structure, Z, is also a function of CCP, curing conditions, concrete cover, and environmental conditions (deterioration mechanism):

$$Z = Z \{CCP, curing, concrete\ cover, environmental\ conditions\} \qquad (7.2.2)$$

For carbonation and chloride-induced deterioration mechanisms, the lifetime can be predicted accurately, using the relationships given in chapters 5 and 6, respectively.

The total production cost, KT, depends on CCP and other parameters (see, section 7.1.1):

$$KT = (C\ U_C + S\ U_S + F\ U_F + A\ U_A + W\ U_W + D\ U_D) + K_M + K_B + K_G \qquad (7.2.3)$$

To the above equations, the *mass balance equation* must be added:

$$C/d_C + S/d_S + F/d_F + A/d_A + W/d_W + D/d_D + \varepsilon_{air} = 1 \quad (7.2.4)$$

Thus, for a total optimization these relationships (7.2.1)-(7.2.4) have to be taken into account. The following conditions must also be fulfilled:

$$CH \geq 0, \quad W \geq H \quad (7.2.5)$$

In other words, the SCM content must not exceed P_{max} in order sufficient calcium hydroxide to exist for completion of pozzolanic activity, and the W content must not be lower than the minimum required water (H) for completion of both hydration and pozzolanic activity, see chapter 3.

An **optimization strategy** could be as follows:

Optimization target: Determination of the optimum CCP values that give a minimum cost (KT_{min}), for a required strength (f_c*) and service lifetime (Z*).

Parameters for optimization: n (e.g., C, S, F, A, W, etc.)

Equations: f_c*= f_c {CCP, for given curing and time)
Z*= Z {CCP, for given curing, cover and environment}
Eq. (7.2.4)
Fulfillment of Eq. (7.2.5)

Using the above equations, all n-1 parameters may be expressed as a function of one parameter, say cement content, C (as the most fundamental of all concrete properties). Thus, the optimum value for this parameter can be calculated from the following equation:

$$\partial KT / \partial C = 0 \Rightarrow$$
$$U_C + U_S \partial S/\partial C + U_F \partial F/\partial C + U_A \partial A/\partial C + U_W \partial W/\partial C + U_D \partial D/\partial C = 0$$
$$\Rightarrow \; C_{opt} \text{ and then } CCP_{opt}.$$

and then knowing the dependence of the other n-1 parameters on C, their optimum values can be estimated. If the dependence is not known, iteration methods of optimization may be followed.