COMPUTERIZED MIX DESIGN FOR READY MIXED CONCRETE

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ABSTRACT

A computerized mix design has been developed in order to take into account some specific factors which affect the amount of mixing water (w), at a given consistency class, for ready mixed concrete: transportation time and weather temperature, as well as type of cement, chemical admixture and aggregate (natural or crushed).

Moreover the water-cement ratio (w/c) and the corresponding strength class are adopted by taking into account not only the 28-day compressive strength but even the exposure class in order to manufacture durable concrete. Additional data for determining the w/c can be considered such as watertightness, flexural or tensile strength and early compressive strength in cold or hot weather.

The total amount of aggregate is determined by volume balance by knowing the amount of water (w) and cement (c) in one cubic meter of concrete. Finally, fine and coarse aggregate are combined by taking into account a reference particle size distribution such as Fuller or Bolomey curve.

1. INTRODUCTION

The mix-design is a technique developed (1) to relate the concrete required performances to the mix composition by taking into account the available ingredients. In other words, this method is able to design a tailor-made concrete mix on the basis of the required performances and the available ingredients. The advantage of using the mix-design method for RMC companies is double:

a) on one hand it is possible to calculate the most economical composition of the concrete mix on the basis of the most important required technical specifications: workability and compressive strength;
b) on the other hand a distinguished RMC company can suggest alternative concrete mixes with improved performances for the specific job by taking into account additional requirements such as durability, watertightness, thermal stress, shrinkage, etc.

The flow-chart of a simple mix-design is shown in Fig. 1 where the required performances are the 28-day compressive strength (f_{c28}) and the slump (S), whereas the other parameters affecting the concrete composition are:

A) type and strength class of the available cement for the relationship between f_{c28} and the water-cement ratio (w/c);
B) maximum size ($M.S.$) of the natural or crushed aggregate for the relationship between S and the amount of mixing water (w);
C) $M.S.$ of the coarse aggregate to determine the volume of entrapped air (V_{air});

By knowing the w/c and the amount of w, the cement content (c) is determined and transformed into cement volume (V_c) through its specific gravity (3.1 kg/l). The total volume of aggregate (V_a) is calculated by a balance through the volume of water (V_w), cement (V_c) and entrapped air (V_{air}) in 1 m^3 of concrete mix (V_{CON}).

Then the total volume of aggregate is divided into the volumes of the individual aggregates (V_s = volume of sand, V_g = volume of gravel, etc.) by taking into account the required particle size distribution of the combined aggregate (Fuller, Bolomey, etc.) and that of the available individual aggregates.

Finally the weight of the aggregate (in kg/m^3) is determined by taking into account the specific gravity (2.6-2.7 kg/l for ordinary aggregates).

2. A NEW MIX-DESIGN METHOD: CMD-RMC

There are many limits in the traditional mix-design method schematically shown in Fig. 1, particularly for a RMC production. For instance, the required mixing water (w) does not take into account many parameters such as transportation time, cement type, temperature, type and dosage of chemical admixtures. All these parameters strongly affect the slump loss and consequently the required additional water to compensate slump loss.

In other words, according to a realistic mix-design for RMC, the amount of mixing water should be more related to the required slump at the time of placing concrete on the job site rather than to the slump at the batching plant just after mixing.

Moreover, there are performances for the hardened concrete, in addition to the 28-day compressive strength, which can significantly affect the w/c of the concrete mix. These additional performances include durability, watertightness, early compressive strength, flexural or tensile strength.

Finally, the curing temperature can strongly affect the strength development and in particular early strength. Therefore, cold and hot weather should be taken into account to determine the right mix composition through a more realistic and sophisticated mix-design method.

In the present paper the principles for a new mix-design method particularly devoted to the ready-mixed concrete will be illustrated. Such a method is based on a software program and it is called CMD-RMC (Computerized Mix Design for Ready Mixed Concrete). In the following section the most important changes with respect to a traditional mix-design method will be examined.

3. THE AMOUNT OF WATER IN A RMC MIX

Table 1 shows the amount of mixing water (in kg/m^3) as a function of the required workability (consistency class from *S1* to *S4*) for concrete mixes with natural or crushed aggregates in a dry surface saturated condition (*DSS*) with maximum size of 8, 16 and 32 mm. The values of mixing water of this specific table have been determined on experimental basis for concrete mixes manufactured on the job site without any significant slump loss between mixing and placing by working in the following conditions:

i) the time between mixing and placing was less than 15 min;
ii) the cement adopted was CE II/B-L 32.5;
iii) no chemical admixture has been used;
iiii) the temperature was in the range of 5-9°C.

Should the mix be manufactured on the batching plant with a transportation time longer than 15 min and with different cement types and/or at different temperatures, the amount of mixing water can significantly vary due to the extra-water required to compensate the slump loss. The higher is the slump loss, the higher is the amount of mixing water and therefore the higher must be the slump at the batching plant for the same slump on the job site. Figure 2 schematically shows the influence of the transportation time, temperature, cement type and chemical admixture on both the mixing water and the slump at the batching plant for a given slump on the job site (120 +/- 25 mm) with a given crushed aggregate (maximum size of 25 mm).

For instance, for a given temperature (15°C) and a given transportation time (30 min), the change of the cement from CE II/B-L 32.5 (Fig. 2, A) to CE II/A-L 42.5 R (Fig. 2, B), causes an increase in the mixing water (from 220 to 225 kg/m^3) and consequently in the slump at the batching plant (from 150 to 170 mm) to guarantee the same slump of 120 mm at the job site.

By increasing the temperature from 10 to 25°C (C and D in Fig. 2) the amount of water increases from 225 to 235 kg/m^3, and the slump at the batching plant goes from 180 to 240 mm for the same required slump of 120 mm at the job site after a transportation time of 60 min.

On the other hand, the use of an adequate chemical admixture can reduce the required mixing water for a given slump at the batching plant as well as the slump loss during the transportation to the job site. For instance, by using a retarding superplasticizer (RET/WR in Fig. 2, F) the amount of mixing water is reduced from 235 to 190 kg/m^3, whereas the slump at the batching plant goes from 230 to 160 mm to attain to the same required slump on the job site (120 mm) after a transportation time of 90 min at 20°C (E and F in Fig. 2).

A change in the mixing water (w) for one of the above mentioned reasons related to the slump loss (Fig. 2), must be combined with a proportional change in the cement content (c) in order to keep the w/c at the designed level required by the concrete performances in service (strength, durability, etc.).

Therefore the CMD-RMC program calculates the amount of mixing water by taking into account two main factors:

i) the amount of mixing water (w_1) as a function of the consistency class without transportation (and therefore without slump loss) for natural and crushed aggregates with maximum size varying from 8 to 160 mm: Table 1 is just an example for maximum size of 8, 16 and 32 mm;

ii) the amount of additional water (w_2) required to compensate slump loss (ΔS), so that the slump at the batching plant (S_{BP}) is automatically designed in order to place the concrete mix on the job site at the scheduled slump (S_{JS}):

The slump loss values (ΔS), which are needed to transform the scheduled slump on the job site (S_{JS}) into the designed slump on the batching plant (S_{BP}), have been measured by field tests (like these shown in Fig. 2) where the following parameters have been changed:

- transportation time: 0-15 min; 16-30 min; 31-45 min; 46-75 min; 76-105 min; 106-120 min;
- temperature: 0-4°C; 5-9°C; 10-16°C; 17-23°C; 24-30°C; 31-37°C;
- cement type: I (Portland cement); II (Blended Portland cement); III (Slag cement); IV (Pozzolanic cement); V (Composite cement);
- cement strength class: 32.5; 32.5 R; 42.5; 42.5 R; 52.5; 52.5 R;
- chemical admixture: retarder, plasticizer, superplasticizer of different chemical family (naphtalene, melamine, acrylic) at different dosages up to 2.5% by weight of cement.

Through the combination of these factors the CMD-RMC program is able to determine ΔS, and then the scheduled slump on the job site (S_{JS}) is transformed into the required slump at the batching plant (S_{BP}).

$$S_{BP} = S_{JS} + \Delta_S \qquad [1]$$

The amount of the total water (w) is then estimated as a function of the designed S_{BP} by taking into account both the mixing water (w_1) without slump loss and the additional water (w_2) to compensate the slump loss:

$$w = f(S_{BP}) = w_1 + w_2 \qquad [2]$$

The amount of the total water (w), referred to aggregates in a *DSS* condition, can be finally transformed into gauging water by taking into account, in the usual way, the absorption of the individual aggregates and their actual water contents.

4. THE W/C IN A RMC MIX

Figure 3 schematically shows the different (w/c) requirements to produce concrete mixes with pre-determined characteristic strength (f_{ck}), early compressive strength (f_{ce}), flexural (f_f) or tensile (f_t) strength, watertightness and durability level for the corresponding environmental exposure class. The corresponding w/c value for these requirements are indicated in Fig. 3 as $(w/c)_1$, $(w/c)_2$, $(w/c)_3$, $(w/c)_4$ and $(w/c)_5$ respectively, according to the ENV 206 European norm (2) for reinforced concrete structures. The CMD-RMC mix design method chooses the minimum water/cement - *(w/c)min* - which is able to guarantee all the above pre-determined performances when at least two of these performances are required. This always occurs after the ENV 206 requirements. According to this norm, with the exception of plain concrete structures in exposure class *1* (interior of buildings), all concrete structures - plain, reinforced, prestressed - besides f_{ck}, should meet the durability criterion based on a limit in the maximum value of the water-cement ratio - $(w/c)_5$ in Fig. 3 - as a function of the environmental exposure class. This means that the $(w/c)_5$ value designed by durability requirements should be compared with that - $(w/c)_1$ - needed to attain to the required f_{ck}. Incidentally, the $(w/c)_1$ designed for a scheduled f_{ck} depends on the type and strength class of cement as it is schematically shown in Fig. 3.

If, for a given cement, f_{ck} and durability requirements do not give the same water-cement ratio - in other words if $(w/c)_1 > (w/c)_5$ or $(w/c)_1 < (w/c)_5$ - the only way to overcome this incongruous situation is to adopt the smallest *w/c* between the two values.

In general, with the exception of high strength concretes, the $(w/c)_5$ value for durability requirements is lower than that designed for f_{ck} in the range of 20-30 N/mm^2, the difference being higher with cements of higher strength class.

For instance in the case of a reinforced concrete structure exposed to a sea water environment (exposure class *4a*) a $(w/c)_5$ not higher than 0.55 should be adopted for durability reasons. On the other hand, for a characteristic strength (f_{ck}) of 25 N/mm^2 (cube specimen) a $(w/c)_1$ of 0.62 is required with a cement CE II-L 32.5 (Fig. 4). Therefore the *w/c* of 0.55 should be adopted in order to guarantee both durability and characteristic strength. However, with a *w/c* of 0.55 the actual characteristic strength is 30 N/mm^2 by using the same cement type CE II/B-L 32.5 (Fig. 4). Therefore a strength class of *C 24/30* ($f_{ck/cyl}$ = 24 N/mm^2; $f_{ck/cube}$ = 30 N/mm^2) should be specified in order to meet the requirements for both durability and characteristic strength.

By changing the cement type from CE II/B-L 32.5 to CE II/A-L 42.5 with the same exposure class (*4a*), the strength class becomes *C 32/40* (Fig. 5), since the f_{ck} value corresponding to a *w/c* of 0.55 with a cement CE II/A-L 42.5 is 40 N/mm^2 (cube specimen). Incidentally one can observe that a *w/c* as high as 0.70 is required to attain to a cube characteristic strength of 25 N/mm^2 with this cement. Therefore, the higher is the strength class of the cement, the higher is the difference between the water-cement ratio determined by durability requirements, $(w/c)_5$, and that, $(w/c)_1$, designed by f_{ck} values in the range of 20-30 N/mm^2.

The mix design method CMD-RMC is able to determine the actual strength class corresponding to the exposure class by taking into account all the available cements in Europe (150 different cements) and even to compare this value with the f_{ck} (required by structural reason only) in order to choose the adequate concrete strength class which is able to meet the requirements of both durability and characteristic strength.

An other important requirement by ENV 206 norm concerns watertight concrete structures such as tunnels, reservoirs, etc. independently of the exposure class input. The water-cement ratio required for watertight concrete - $(w/c)_4$ - should not be higher than 0.55 (Fig. 6).

The $(w/c)_4$ value can become more restrictive than that required by durability reasons - $(w/c)_5$ - in the exposure class *2a*. In such a case the watertightness requirement ($w/c < 0.55$) should be compared with those related with the f_{ck} value for a given cement. For instance, the $(w/c)_4$ requirement for watertight concrete (0.55) is more restrictive than that required by f_{ck} of 35 N/mm^2 with a cement CE II/A-L 42.5 (w/c = 0.60). On the other hand, with a cement such as CE II/B-L 32.5 the same strength requirement (35 N/mm^2) determines a *w/c* ratio (0.50) lower than that needed for the watertightness requirement.

Besides the f_{ck}, watertightness and durability performances specified by ENV 206, sometimes there are additional requirements for early compressive strength (f_{ec}) of RMC due to demoulding or pre-tensioning reasons at 1 to 7 days. In such a case, the CMD-RMC method determines the water-cement ratio - $(w/c)_2$ in Fig. 3 - corresponding to the scheduled f_{ec} value by taking into account all the following factors such as:

- the specific time corresponding to the required early age (from 1 to 7 days);
- the temperature range during this period of time (from 0-4°C to 31-37°C);
- the cement type (from I to V);
- the cement strength class (from 32.5 to 52.5 R).

When a relatively high early strength is required, particularly in cold weather, the designed $(w/c)_2$ can become more restrictive than those required by f_{ck} or durability reasons. In such a case, through the CMD-RMC method an adequate cement strength class and/or a chloride-free accelerating admixture can be adopted in order to reduce the gap between the $(w/c)_2$ determined by the f_{ec} requirement and those required by f_{ck} and durability reasons, $(w/c)_1$ and $(w/c)_5$ respectively.

In any case the CMD-RMC method is able to find an adequate concrete strength class to meet f_{ec} and f_{ck} as well as the durability requirements.

On the basis of the same above principle, the CMD-RMC method is able to design the water/cement - $(w/c)_3$ - required for a scheduled flexural (f_f) or tensile (f_t) strength (Fig. 3): in many cases, concrete structures, such as for instance a concrete floor or a bridge deck are more loaded by a flexural stress rather than a compressive one. However, hardly ever a RMC company is able to design a concrete mix based on f_f or f_t requirements.

The CMD-RMC method is able to determine the mix composition and in particular the $(w/c)_3$ as a function of the available aggregate (natural or crushed) which strongly affects the relationship between flexural or tensile strength and water-cement ratio.

Finally, the CMD-RMC method is able to evaluate the water-cement ratio adjustments for f_{ck}, f_{ec}, f_f and f_t when a required air-volume entrainment is specificed for frost-resistant concrete in exposure classes *2b*, *3* and *4b*. In Fig. 7, for instance, it is shown that for a scheduled f_{ck} of 30 N/mm^2, the water-cement ratio of 0.55 (for ordinary non air-entrained concrete) should be reduced to 0.47 (for a frost resistant air-entrained concrete) in order to compensate the strength loss due to air-bubbles by a stronger cement matrix.

5 CONCLUSIONS

A modified mix design method has been developed which is based on the same principle of a traditional one (Fig. 1) with the following changes:

a) the amount of mixing water is designed by taking into account transportation time, temperature, type of cement, type and dosage of chemical admixture in addition to the type of aggregate (crushed or natural) and its maximum size;

b) the *w/c* of the concrete mix is choosen as the minimum among five different values corresponding to characteristic strength, early compressive strength, flexural or tensile strength, watertightness and durability level corresponding to the exposure class.

The volume of the aggregate is then determined by volume balance, whereas fine and coarse aggregates (up to 6 individual aggregates) are combined by taking into account a reference particle size distribution (according to Fuller, Bolomey, etc.) as in the traditional mix design method.

When the mix-design of the concrete has been definitely established on the basis of all the above inputs, other performances of the concrete in service (such as shrinkage, specific creep, modulus of elasticity, thermal change in massive placements due to cement hydration, etc.) are finally determined as additional outputs.

REFERENCES

(1) ACI Committee 211, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete (ACI 211.1-91), ACI Manual of Concrete Practice 1994, Part 1.

(2) European Prestandard ENV 206, Concrete-Performance, production, placing and compliance criteria.

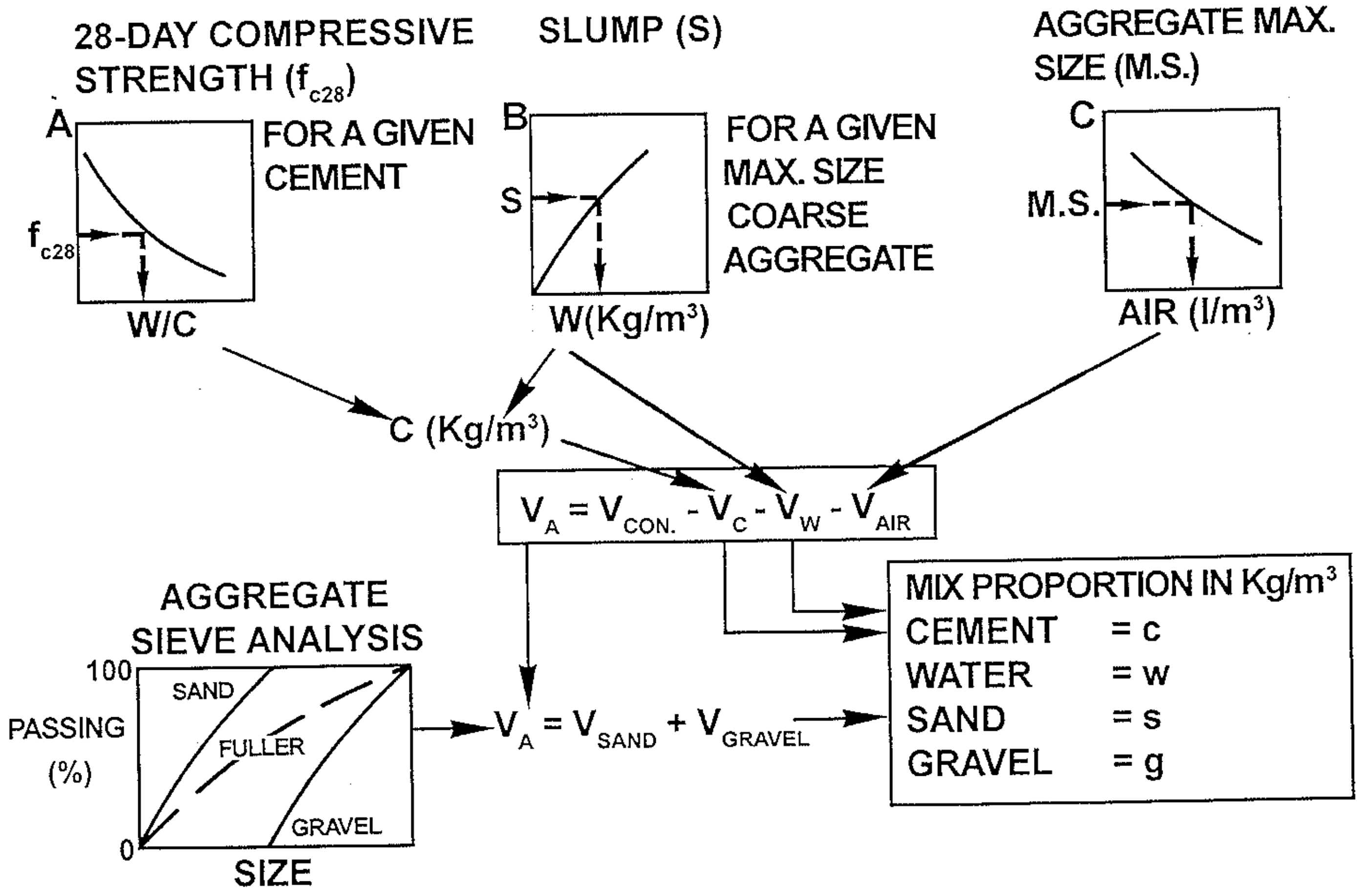

Fig. 1 - Flow chart of a simple concrete mix design (slump measurement just after mixing).

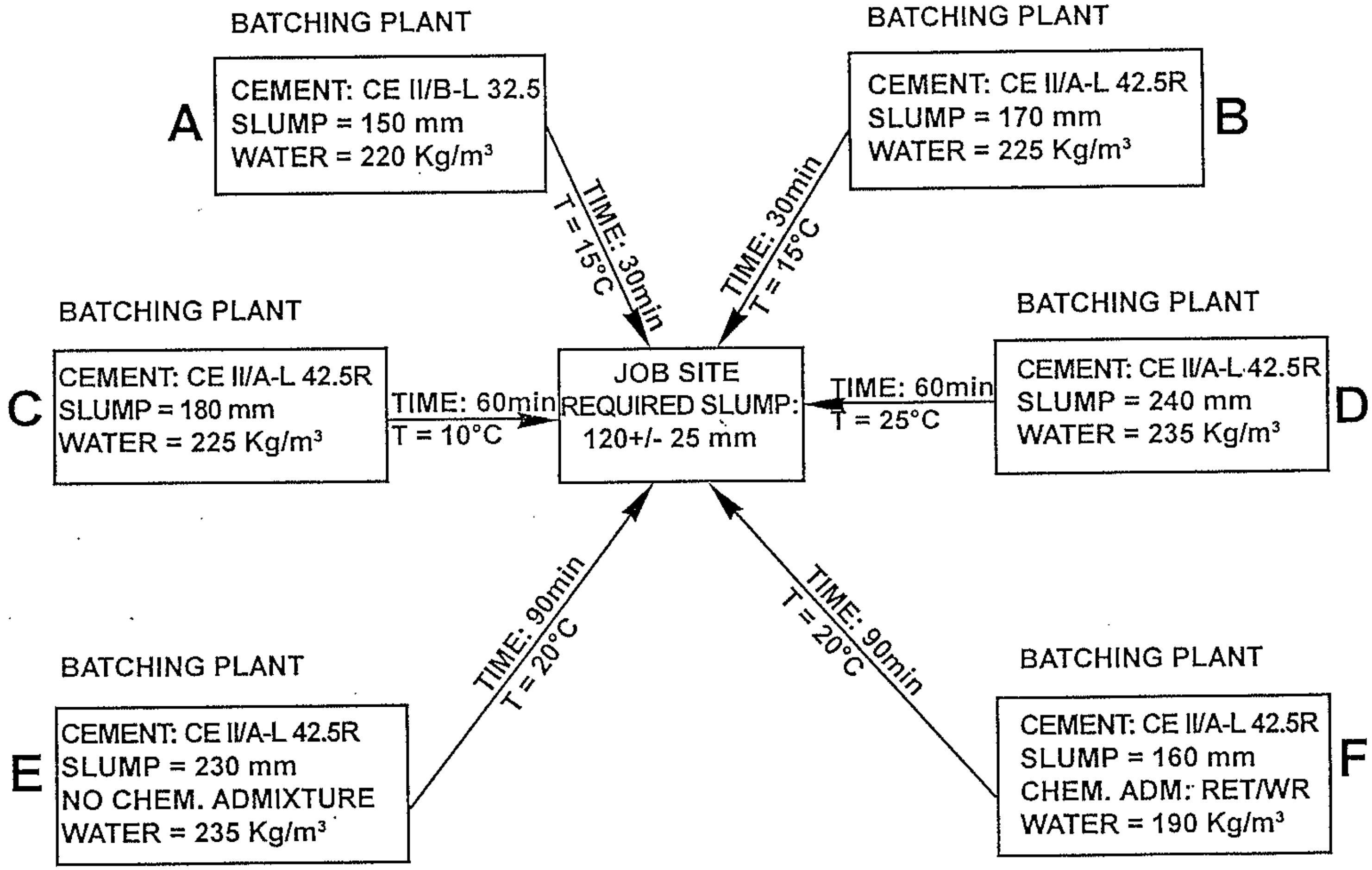

Fig. 2 - Examples of the influence of transportation time, temperature, cement type and chemical admixture on the required mixing water for a given slump on the job site. Max size of crushed aggregate = 25 mm.

DURABILITY

Exposure class	1	2a	2b	3	4a	4b	5a	5b	5c	Watertightness
Maximum W/C	0.65	0.60	0.55	0.50	0.55	0.50	0.55	0.50	0.45	0.55

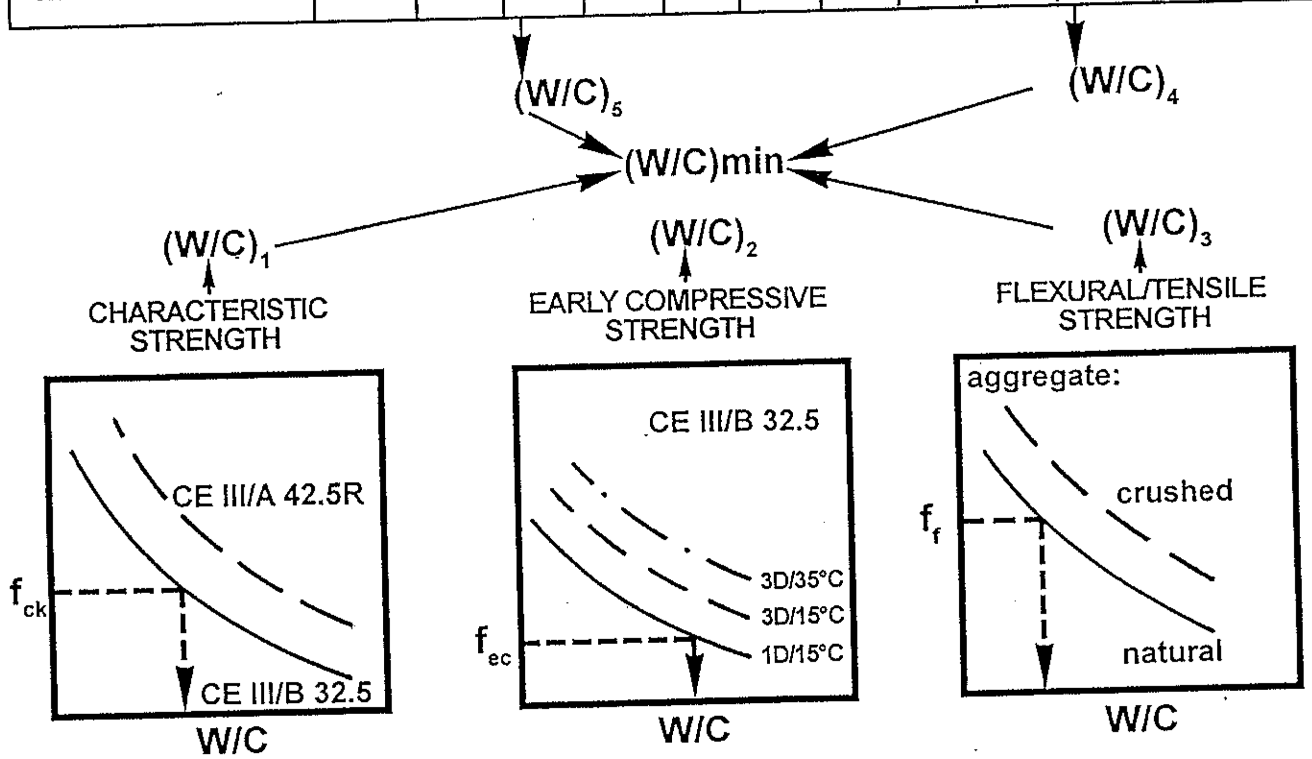

Fig. 3 - How to adopt the w/c to meet all the different requirements.

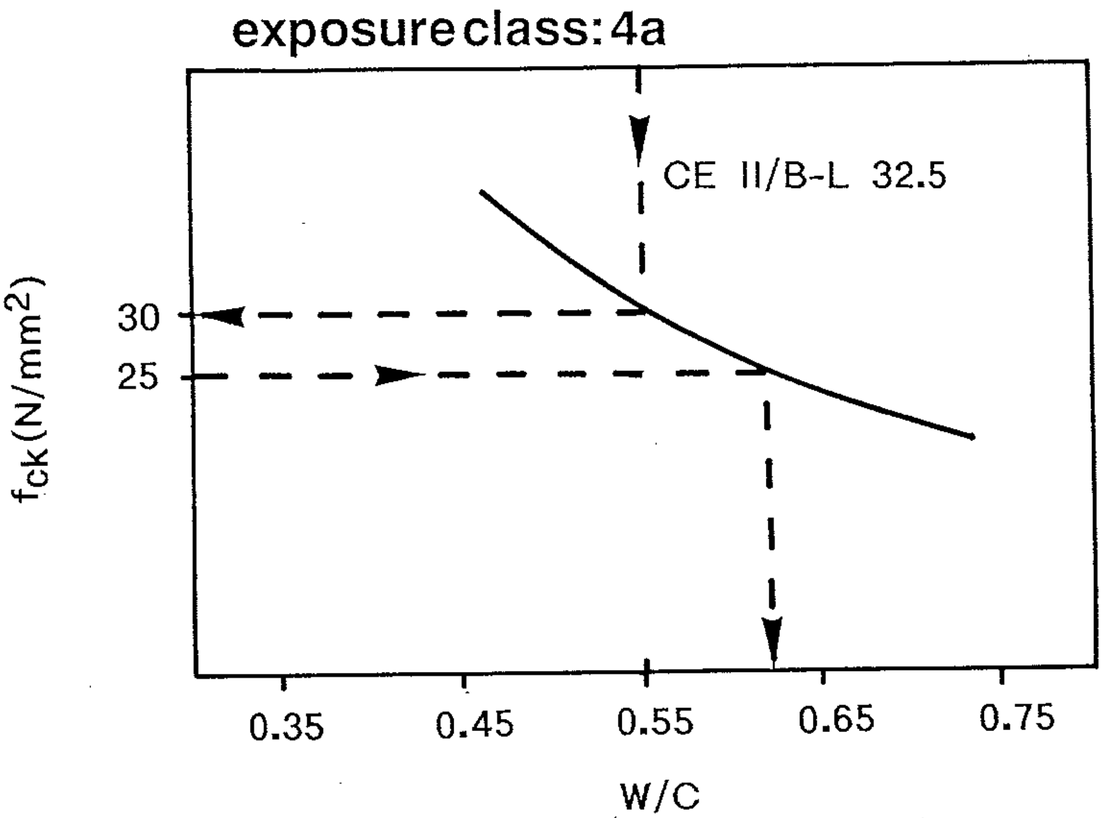

Fig. 4 - Water/cement requirements for f_{ck} only (w/c = 0.62) and for exposure class 4a in addition to f_{ck} (w/c = 0.55). Cement: CE II/B-L 32.5.

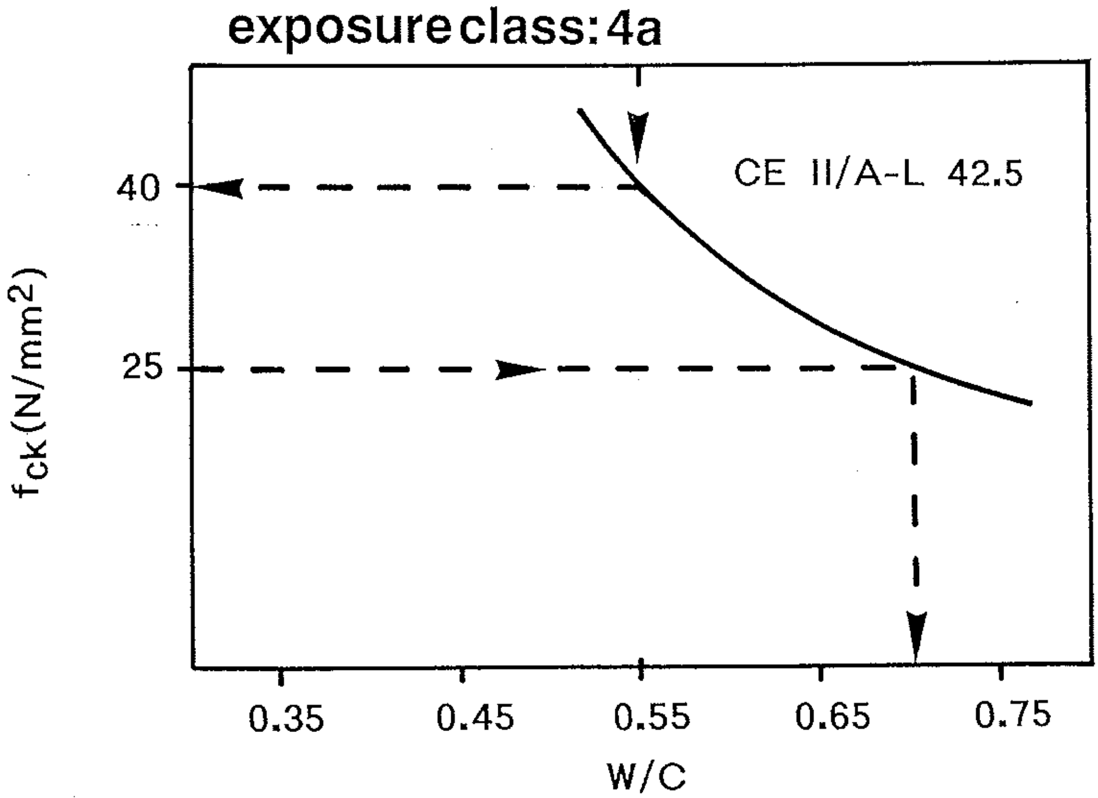

Fig. 5 - Water/cement requirements for f_{ck} only (w/c = 0.70) and for exposure class 4a in addition to f_{ck} (w/c = 0.55). Cement: CE II/A-L 42.5.

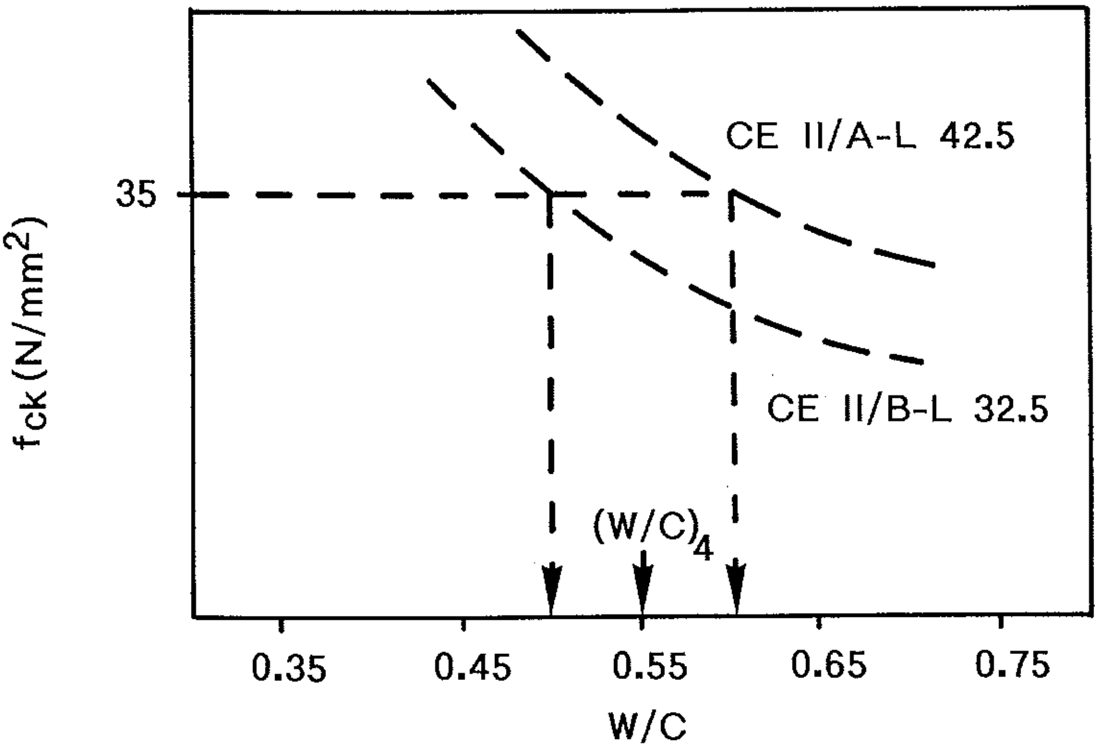

Fig. 6 - Water/cement requirement for watertight concrete: $(W/C)_4$ = 0.55. This value is more or less restrictive than that required by f_{ck} of 35 N/mm^2 depending on the cement strength class.

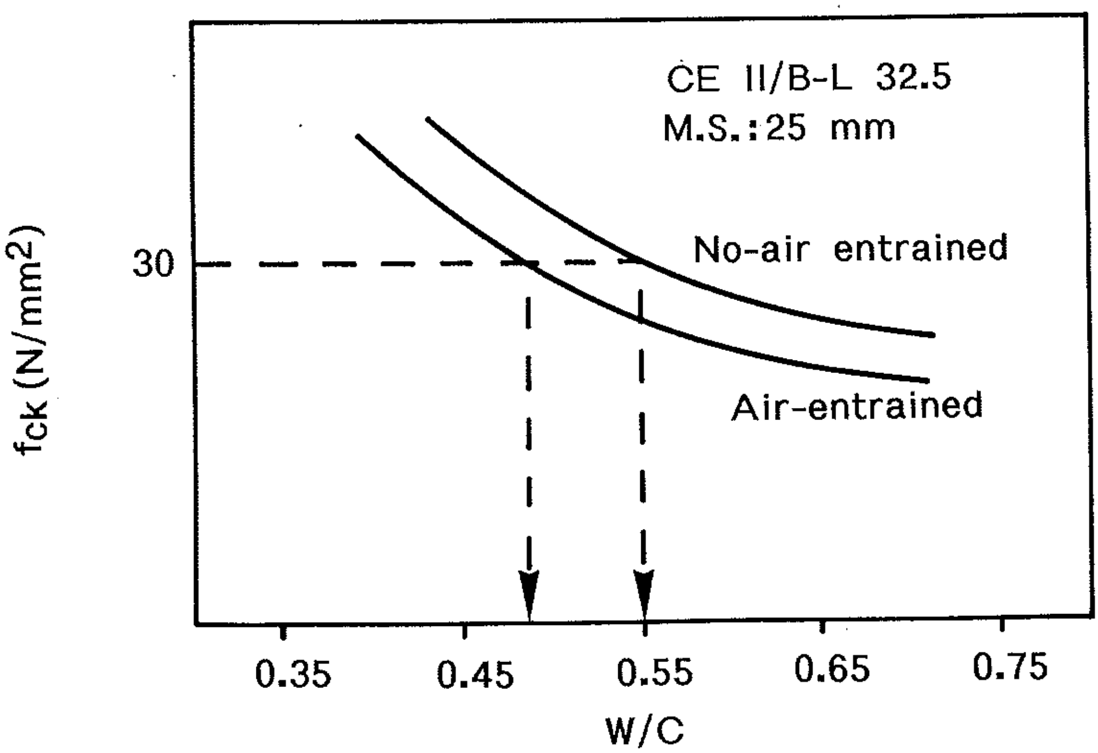

Fig. 7 - Water/cement requirements for given f_{ck} (30 N/mm^2) and maximum size (25 mm) in the absence or in the presence of air-entrainment: 0.55 and 0.47 respectively.

COARSE MAXIMUM SIZE (mm)	AMOUNT OF MIXING WATER (Kg/m³) FOR THE FOLLOWING CONSISTENCY CLASSES:							
	S1		S2		S3		S4	
	C*	N**	C	N	C	N	C	N
8	205	185	220	200	240	220	260	240
16	195	175	210	190	230	210	250	230
32	175	155	190	170	210	190	220	200

* C = Crushed aggregate ** N = Natural aggregate

Table 1 - Mixing water for different consistency classes (S1 to S4) in concretes with crushed (C) or natural (N) aggregates.