High strength and reliable concretes

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INTRODUCTION

High strength concretes, and in particular early high strength concretes, are very important from a practical point of view especially for the precast concrete industry.

The early strength of concrete substantially depends on (a) curing temperature, (b) type of cement and (c) water/cement (w/c) ratio. A systematic research in the field of the first two parameters has been performed since the late fifties and a recent review of the literature concerning these subjects was shown in the last International Congress on Chemistry of Cement (1,2).

On the other hand it is well known that a reduction in the w/c ratio improves all the properties of concrete and in particular increases its strength (3). Unfortunately, the w/c ratio cannot be lowered under a certain value as the workability of concrete becomes so low that, for a given method of compaction, the concrete cannot be completely compacted. If one excludes some particular and sophisticated methods of compaction, the stiffest concrete that is generally placed is the « no-slump » concrete, that is a concrete with a slump lower than 1 inch (4).

However a no-slump concrete is very difficult to place especially if the concrete is prepared on a job-site or if a highly reinforced precast element must be obtained. If the vibration of fresh concrete is not fully and carefully performed in all the parts of the structure, macroscopic voids and in some cases honeycombs can be found in the elements.

When this happens there is some difference between the strength of the well compacted concrete of the specimens and the strength of the real concrete locally placed in the elements, the difference being higher, for stiffer concretes. We shall assume that when this difference is low the concrete is « reliable ».

In Fig. 1, for example, three groups of concretes are shown with different reliability.

The higher the workability, the lower the difference between unvibrated and fully vibrated specimens and the greater is the reliability of concrete.

Reliability depends on (a) efficiency, care and time of compaction, (b) the density of reinforcement and the geometry of elements, and (c) fresh concrete workability.

Only the last parameter concerns intrinsically the quality of concrete and will be examined in this paper.

The workability can be improved by increasing w/c ratio, by using richer mixes and by adding water-reducing admixtures. However, if high-strength and reliable concretes must be prepared, w/c ratio must be decreased, and only very strong water-reducing agents (superplasticizer admixtures) added to relatively rich mixes must be taken into account.

Superplasticizer additives are substantially based on sulphonated naphtalene-formaldehyde polymers, or sulphonated melamine-formaldehyde polymers (5), and they can be used either by reducing the w/c ratio in order to increase its strength or by raising the workability.

In this paper superplasticizer additives, based on sulphonated naphtalene-formaldehyde polymers, have been utilized both by reducing w/c ratio and by raising workability so that high-strength and reliable concretes could be obtained.

EXPERIMENTAL : MATERIALS AND PROCEDURE

A) Materials

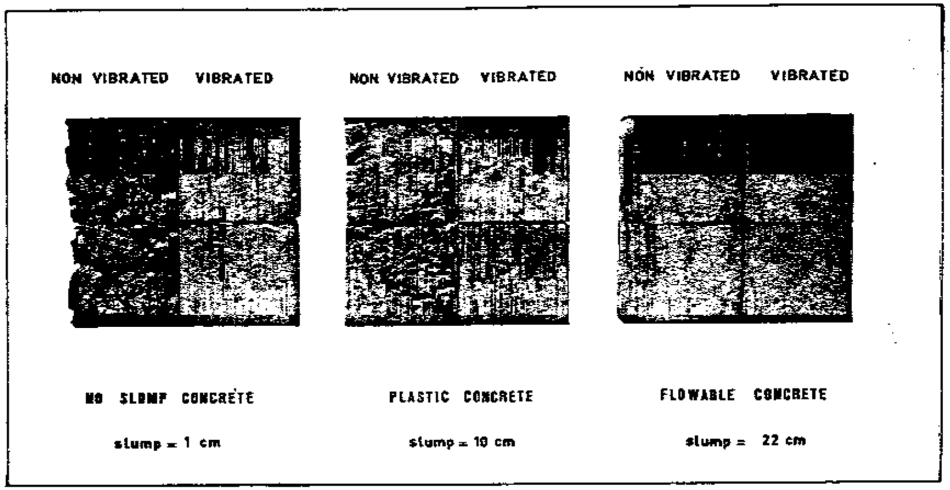

Fig. 1. — Concrete aspect as a function of workability and vibration.

	Cement N.1	Cement N.2	Cement N.3
CaO	63,08%	63,60%	62,92%
SiO_2	22,25%	20,80%	21,43%
Al_2O_3	3,71%	5,51%	5,31%
Fe_2O_3	4,58%	2,99%	2,68%
MgO	2,46%	0,85%	1,63%
SO_3	2,10%	2,95%	3,37%
Na_2O	0,08%	0,19%	0,12%
K_2O	0,14%	0,38%	0,14%
Insoluble residue	0,10%	0,15%	0,22%
Loss of ignition	1,50%	2,00%	2,22%
C_3S	50,2%	56,9%	44,2%
C_2S	25,9%	19,3%	28,1%
C_3A	2,1%	9,8%	9,5%
C_4AF	13,9%	9,8%	8,1%
Initial set (h)	2h 20'	3h 08'	1h 45'
Final set (h)	4h 35'	4h 23'	2h 40'
Blaine cm²/g	3763	3855	5160

TABLE I
Characteristics of cements used

a) Cement

Three different types of Portland cements have been used. Table 1 shows the chemical analysis, the fineness and the setting time of these cements. Cement no. 1 and no. 2 are « high-strength » cements according to the Italians standard specification (compressive strength at 28 days ⩾ 425 kg/cm² for a mortar 1:3 with a w/c ratio of 0.5).

Cement no. 3 is a « rapid-hardening » and « high-strength » cement (compressive strength ⩾ 175 kg/cm² at 1 day and ⩾ 525 kg/cm² at 28 days).

Cement no. 1 and no. 3 can be roughly classified as type V° and type III° respectively according to ASTM specification.

b) Aggregates

Ordinary natural aggregates (sand and gravel) and expanded clay have been used to prepare

ordinary and lightweight concretes. The particle size distribution of single and mixed aggregates are shown respectively in Fig. 2 and Fig. 3 for ordinary (specific gravity = 2500 kg/m³) and lightweight concretes (specific gravity = 1600 ÷ 1800 kg/m³).

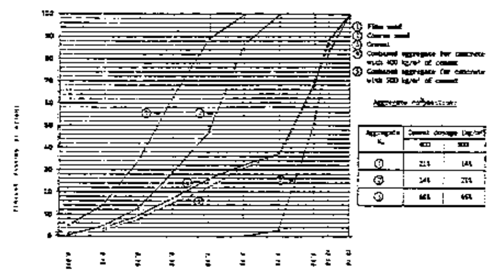

Fig. 2. — Particle size distribution for normal concretes (sp. gr. = ≃ 2500 kg/m³

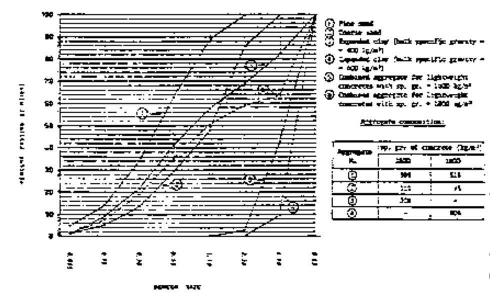

Fig. 3. — Particle size distribution for lightweight concretes (sp. gr. = 1600-1800 kg/m³)

c) Admixture

A chloride-free superplasticizer admixture based on sulphonated naphtalene-formaldehyde polymer has been used. The normal dosage rate of the admixture is 1,5 liters per 100 kg of cement, and the total solid of sulphonated naphtalene-formaldehyde polymer is about 0,4 % by weight of cement.

B) Procedure

a) Cement pastes

Heat evolution as a function of time was measured by a procedure similar to the one described by Gragg and Skalny (6). The 3-gram cement samples are weighed and placed in the calorimeter cells, which are closed with rubber caps and placed in a constant temperature bath for thermal equilibration. The reactant liquids containing pure water or aqueous solutions containing the admixture are injected by a hipodermic needle through the rubber caps into the cells containing the cement samples.

During the injection the cells are mechanically vibrated for 30 seconds to assure a full mixing of cement pastes.

Cement paste hydration experiments were performed with a w/c ratio of 0.3 and a dosage rate of 1,5 liter of admixture per 100 kg of cement was used.

b) Concretes

Twenty different concretes have been designed and each of them has been cured both at room temperature (20°C), and at steam curing, testing in this way a total of 40 concretes.

The steam cycle was as follow :

4 hours at 20°C, from 20°C to 70°C in 3 hours time, and 6 hours of steam curing at 70°C, then cooling at room temperature in two hours time.

Concretes with a nominal dosage of cement of 400 and 500 kg/m² have been tested for each cement.

The actual dosage of cement, calculated from the specific gravity and the air content is shown in Table 2 and 3.

Concretes without admixtures have been mixed at plastic consistency (slump about 10 cm). Although concretes containing admixture (1,5 liters per 100 kg of cement) were prepared at very flowable consistency (slump ⩾ 20 cm) the w/c ratio was lower than that of the corresponding concretes without admixture (Table 2-3).

In spite of the very high workability, concretes with admixture were very cohesive, pratically unsegregable and bleeding was negligible (in any case lower than 2 cm³ of water per concrete liter), so that « rheoplastic » concretes (7) were obtained.

TABLE II

Characteristics of normal concretes

Cement type	Nominal dosage (kg/m³)	Effective dosage (kg/m³)	Admixture	w/c ratio	Slump (cm)	Specific Gravity (kg/m³)
N. 1	400	418	no	0,43	10	2500
		423	yes	0,32	22,5	2550
	500	485	no	0,39	10	2512
		502	yes	0,30	22	2537
N. 2	400	411	no	0,46	11	2462
		417	yes	0,35	21	2525
	500	477	no	0,42	10,5	2487
		498	yes	0,34	21	2537
N. 3	400	426	no	0,47	10	2475
		413	yes	0,36	22	2525
	500	469	no	0,43	11	2450
		498	yes	0,29	22	2512

TABLE III

Characteristics of lightweight concretes

Cement type	Nominal dosage (kg/m³)	Effective dosage (kg/m³)	Admixture	w/c ratio	Slump (cm)	Specific Gravity (kg/m³)
N. 3	400	410	no	0,64	10	1780
		416	yes	0,56	20	1850
	500	524	no	0,50	10	1840
		514	yes	0,44	21	1890
N. 3	400	386	no	0,66	11	1540
		397	yes	0,59	20	1640
	500	494	no	0,50	10	1590
		497	yes	0,45	20	1675

Structural lightweight concretes (specific gravity = 1600-1800 kg/m³) were also prepared by using sand and expanded clay (Fig. 3) and Portland cement no. 3. The composition of lightweight concretes is reported in Table 3.

The compressive strength of both ordinary and lightweight concretes were tested on cubic specimens (10 by 10 by 10 cm) at 1-7-28 days. In some cases tests were performed at 90 days too. All the above mentioned specimens were fully compacted independently of the workability of concrete.

In a second series of tests 50 specimens of both ordinary and lightweight concrete were prepared with cement no. 2 and placed with different times of vibration (0-5-10-20-30 sec), in order to examine the influence of workability on the reliability, and then they were all cured at room temperature for 7 days.

The composition of these concretes is reported in Table 4.

TABLE IV

Characteristics of concretes subjected to different vibration. Specific gravity concerns fully compacted concrete to constant weight

Dosage of cement (kg/m³)*	w/c ratio	Slump (cm)	Type of aggregate	Specific Gravity (kg/m³)
418	0,33	1	normal	2525
411	0,46	10	normal	2460
417	0,35	22	normal	2520
405	0,48	1	lightweight	1780
432	0,52	8	lightweight	1835
401	0,48	21	lightweight	1750

(*) = Cement N. 2 as been used

Finally, in another series of tests the influence of superplasticizer admixture on steel-concrete bond was examined. Smooth and twisted steel bars (2 cm in diameter) were dipped in concrete cylindrical specimens and steel-concrete bond was determined by pull-out at 7 and 28 days.

RESULTS AND DISCUSSION

A) Influence of the admixture on the Cement paste hydration

Heat evolution versus time is shown in Fig. 4. Two heat evolution peaks were always observed during the 30 hours of hydration : the first one, during the first 30 minutes, is mainly due to the first rapid C_3A hydration forming predominantly ettringite (8), and secondarily to the early calcium silicates hydration before the induction period (9-11).

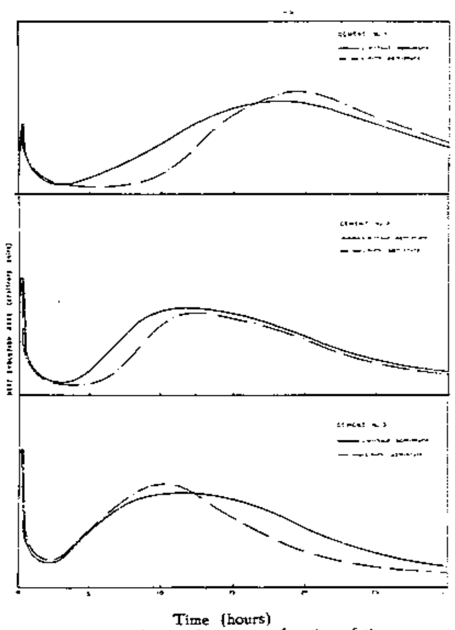

Fig. 4. — Heat evolution as a function of time

It was very difficult to evaluate the effect of the admixture on the first peak because of the low reproducibility of this heat evolution. Only strong effect such as that due to lower C_3A content could be observed : in fact the first peak was quite lower with cement no. 1 than with the other cement richer in C_3A. The second peak is mainly due to C_3S hydration during the acceleratory period or stage III according Kondo (9).

Indipendently of the type of cement the addition of the admixture causes a longer induction period, particularly with a low C_3A cement such as cement no. 1.

The hydration rate in the acceleratory period increases particularly with cement no. 1 and 3 while it is not substantially modified with cement no. 2.

The influence of the admixture on the time corresponding to the second peak depends on the two above mentioned effects.

For example with the cement no. 3 the time of the second peak is anticipated of about 1,5 hours in the presence of the admixture because the induction period is only slightly prolonged and the hydration rate in the acceleratory period is increased. On the contrary, by adding the admixture to a low C_3A cement (no. 1), although the hydration rate increases remarkably during the acceleratory period, the time of the second peak is prolonged of about 2,5 hours because of the longer induction period.

B) Influence of the admixture on the strength of concrete

Fig. 5-7 shows compressive strength at 1 to 90 days of ordinary concretes with and without admixture.

For all the three types of cement, in the presence of admixture the strength increases remarkably although the workability too raises from plastic (slump $\simeq$ 10 cm), to flowing consistency (slump $\geqslant$ 20 cm). In all the cases, strength increase is higher at early curing than at longer one. For example in the concrete prepared with cement no. 3 (400 kg/m³ and cured at 20°C, strength increase is about 90 % at 1 day and about 40 % at 90 days (Fig. 7). If we assume that the degree of hydration is not substantially modified by the addition of admixture, a greater increase in the strength of early age could be ascribed to a greater influence of the w/c ratio on the gel/space ratio at earlier age. This can be demonstrated by the empirical Power's equation (12) relating the compressive strength (δ) with the gel/space ratio and therefore with the

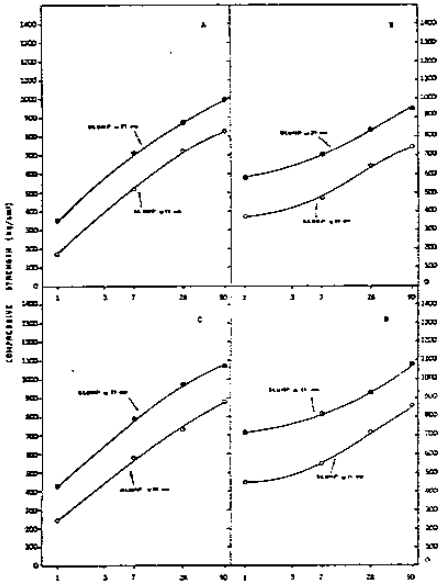

Fig. 5. — Compressive strength as a function of time for cement no. 1 and normal aggregate.

A Nominal cement content = 400 kg/m³ ; cured at 20°C
B Nominal cement content = 400 kg/m³ ; steam cured
C Nominal cement content = 500 kg/m³ ; cured at 20°C
D Nominal cement content = 500 kg/m³ ; steam cured

● with admixture
o without admixture

w/c ratio and the degree of hydration (α).

$$\delta = k\,x^n = k\left(\frac{0.6790\,\alpha}{0.3175\,\alpha + w/c}\right)^n$$

where x is the gel/space ratio, k represents the strength of the cement gel, and n is a constant having a value usually between 2.6 and 3, depending on the characteristic of the cement. By assuming that n is 2.7 that the w/c ratio is 0.36 or 0.47 for concrete respectively with or without admixtures, (Table 2) and that α is substantially that same for both the concretes, the increase in the compressive strength caused by reduction of w/c ratio from 0.47 to 0.36 is 87 % when $\alpha = 0.2$ and only 56 % at longer curing when $\alpha = 0.8$.

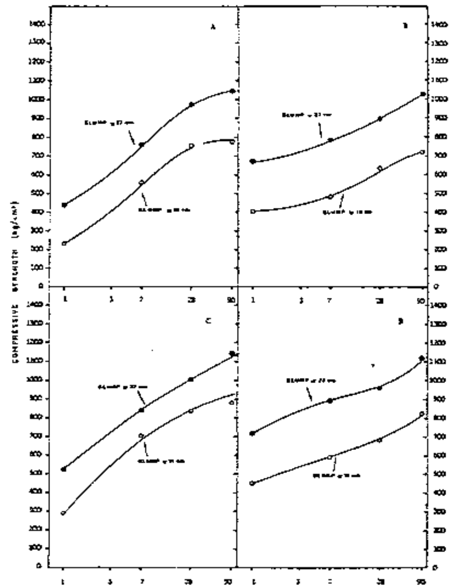

Fig. 6. — Compressive strength as a function of time for cement no. 2 and normal aggregate.

A Nominal cement content = 400 kg/m³ ; cured at 20°C
B Nominal cement content = 400 kg/m³ ; steam cured
C Nominal cement content = 500 kg/m³ ; cured at 20°C
D Nominal cement content = 500 kg/m³ ; steam cured

● with admixture
o without admixture

By taking into account the incertainty of the above mentioned assumptions we may deduce that values calculated for $\alpha = 0.2$ and 0.8 are in a good agreement with the experimental data at 1 and at 90 days concerning the strength increase caused by admixture. Anyhow the Power's equation, or other similar empirical equations, show that, for the same degree of hydration, the earlier the age, the higher the increase in the strength caused by the reduction of w/c ratio.

The increase in the compressive strength due to the reduction of w/c ratio caused by admixture is generally higher for concretes cured at room temperature than for the steam cured ones.

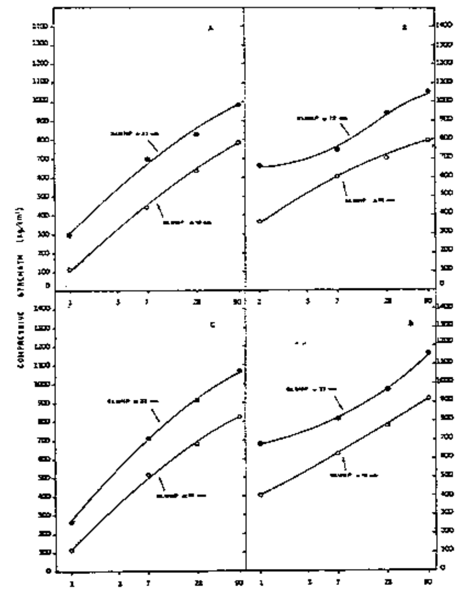

Fig. 7. — Compressive strength as a function of time for cement no. 3 and normal aggregate.

A Nominal cement content = 400 kg/m³ ; cured at 20°C
B Nominal cement content = 400 kg/m³ ; steam cured
C Nominal cement content = 500 kg/m³ ; cured at 20°C
D Nominal cement content = 500 kg/m³ ; steam cured

● with admixture
o without admixture

For example, in the concrete prepared with cement no. 1 (400 kg/m³) the increase in strength at 1 day due to the admixture is 165 % at room temperature curing and 78 % at steam curing (Fig. 5). At longer age the difference in strength increase caused by the admixture between normally and steam cured concrete tends to equalize and becomes about 30 % at 90 days. Moreover, in the presence of the admixture concretes are more flowable and at room temperature they have approximately the same early strength (1-3 days) of steam cured concretes without admixture.

Longer aged (7-90 days) concretes containing admixture and cured at room temperature are remarkably stronger than steam cured concretes without admixture.

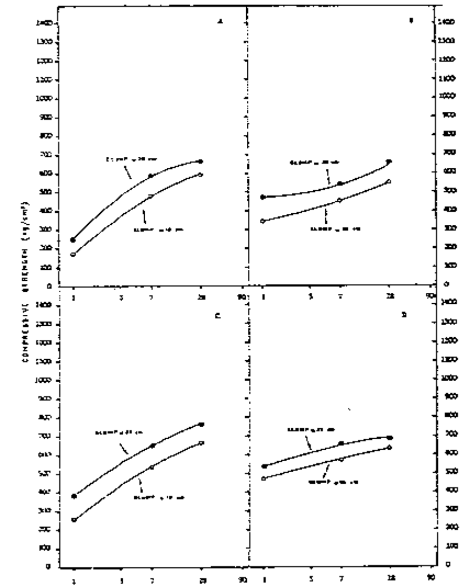

Fig. 8. — Compressive strength as a function of time for cement no. 3 and lightweight aggregate (sp.gr. = 1800 kg/m³).

A Nominal cement content = 400 kg/m³ ; cured at 20°C
B Nominal cement content = 400 kg/m³ ; steam cured
C Nominal cement content = 500 kg/m³ ; cured at 20°C
D Nominal cement content = 500 kg/m³ ; steam cured

● with admixture
o without admixture

Fig. 8-9 show compressive strength at 1 to 28 days of structural lightweight concrete with and without admixture.

Also in this case, concretes containing admixture are stronger although they are more flowable. The increase in the compressive strength due to the reduction in the w/c ratio caused by the admixture is lower for lightweight concretes (Fig. 8-9) than for ordinary ones (Fig. 5-7).

For example, the increase in concrete strength prepared with cement no. 3 (400 kg/m³) with a specific gravity of about 1800 kg/m³ is 44 % at 1 day and 13 % at 28 days at room temperature (Fig. 8).

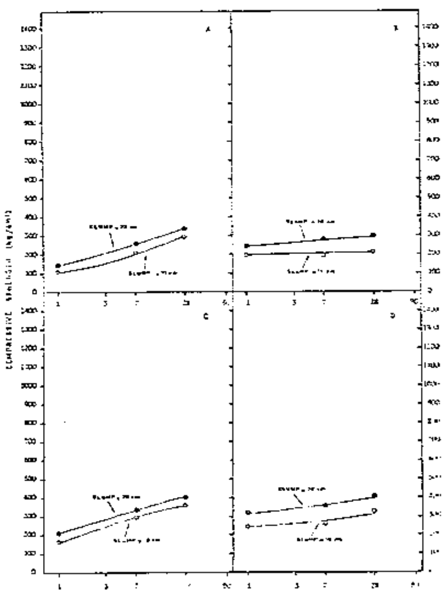

Fig. 9. — Compressive strength as a function of time for cement no. 3 and lightweight aggregate (sp.gr. = 1600 kg/m³).

A Nominal cement content = 400 kg/m³ : cured at 20°C
B Nominal cement content = 400 kg/m³ : steam cured
C Nominal cement content = 500 kg/m³ : cured at 20°C
D Nominal cement content = 500 kg/m³ : steam cured

● with admixture
o without admixture

Strength increase of the corresponding ordinary concrete with a specific gravity of about 2500 kg/m³ is 92 % at 1 day and 37 % at 28 days (Fig. 7). This is probably due to the fact that if lightweight and therefore weaker aggregates are used instead of ordinary and stronger aggregates, the improvement of quality of cement paste, caused by w/c ratio reduction, does not correspond to an equal increase in the strength of concrete.

However it is interesting to observe that, very flowable and usegregable lightweight concretes with a strength of about 650 kg/cm² and a specific gravity at about 1800 kg/m³ can be only obtained by using this type of admixture.

C) Influence of the admixture on the reliability of concrete

All the data discussed in the previous section concern concretes fully compacted independently of their workability. In the present section the results of ordinary and lightweight concretes with different workability and differently compacted are discussed.

Table 4 shows the composition of stiff concretes without admixture, plastic concretes without admixture, and flowable concretes with admixture. The w/c ratio of stiff and flowable concretes is approximately the same, and both these mixes have a w/c ratio lower than that of plastic concrete.

Each of these mixes was placed with a vibration time of 0-5-10-20-30 seconds, in order to obtain concretes with a different degree of compaction.

Fig. 10 shows the frequency as a function of compressive strength for ordinary concrete. Because of the same w/c ratio (~ 0,34), the highest compressive strength for both stiff and flowable concrete is 700 ± 25 kg/cm² and this value corresponds to the most fully compacted concretes. The compressive strength of the fully compacted plastic concrete is at most 500 ± 25 kg/cm² and this is due to the higher w/c ratio in comparison with the other two concretes.

However 75 % of the specimens prepared with flowable concrete have a strength of 700 kg/cm², while only 15 % of the stiff concrete specimens reach this value, and 40 % of the plastic concrete specimens attain to 500 kg/cm². Moreover, the lowest strength corresponding to the unvibrated concrete, is 150 ± 25 kg/cm² for plastic concrete and only 100 ± 25 kg/cm² for stiff concrete.

Finally, the average compressive strength is 679, 403 and 405 kg/cm² for flowable, plastic and stiff concrete respectively while the standard deviation is 44, 98, and 200 kg/cm² for flowable, plastic and stiff concrete respectively.

Similar consideration can be extended to lightweight concrete (Fig. 11).

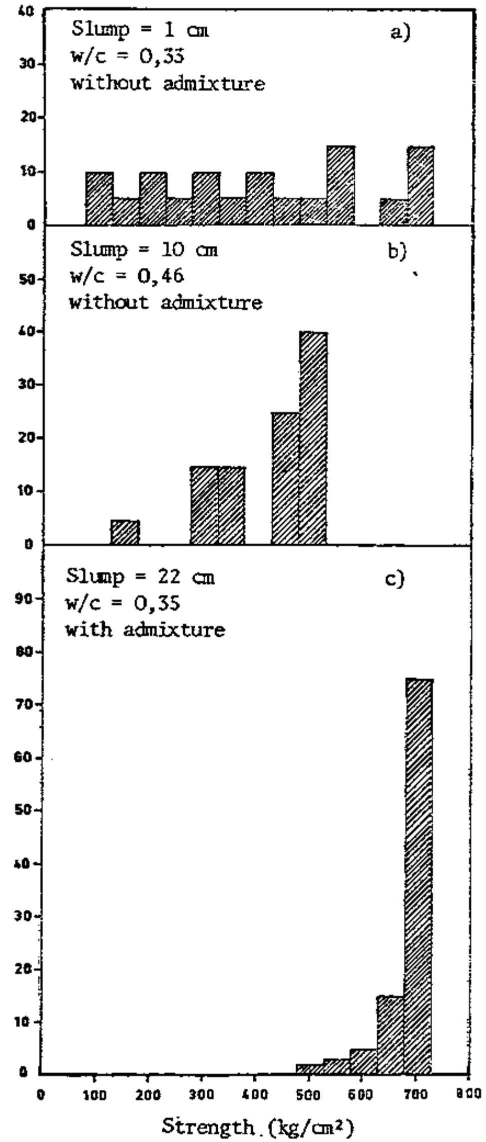

Fig. 10. — Frequency as a function of strength for normal concretes with different workability and vibrated for different time (0-30 sec).

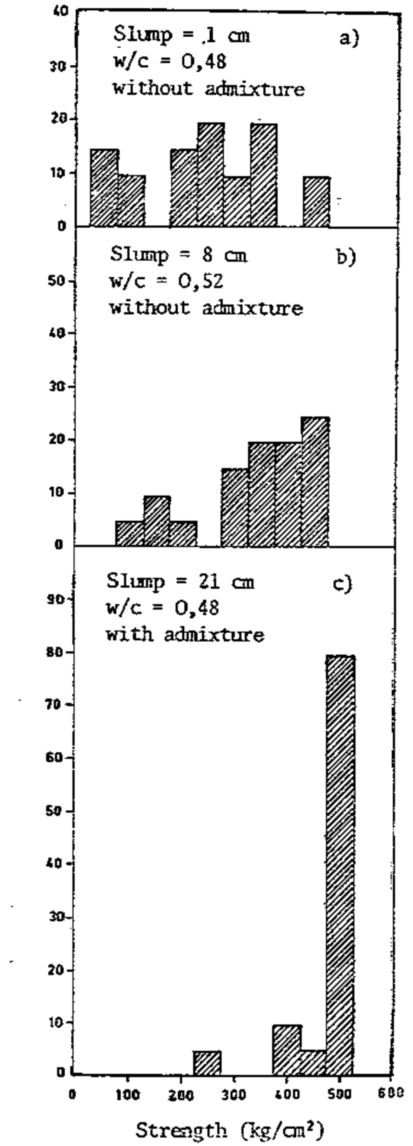

Fig. 11. — Frequency as a function of strength for lightweight concretes with different workability and vibrated for different time (0-30 sec).

All the above mentioned data (Fig. 10-11) demonstrate that flowing concretes containing the admixture are very reliable and this means that the strength obtained in well compacted laboratory specimens can also be achieved very easily in the structural elements. In other words, for very flowable concretes containing this type of admixture, and therefore made with a relatively low w/c ratio, the quality, and in particular the strength, are much less dependent on the density of reinforcement and geometry of element, and on the efficiency, care and time of compaction on a job-site.

D) Influence of the admixture on steel-concrete bond

Table 5 shows steel concrete bond at 7 and 28 days for smooth and twisted bars. The addition of the admixture improves the adhesion between steel and concrete for both ordinary and lightweight mixes.

TABLE V

Steel-concrete bonding

Concrete N.	Characteristics of concrete	Workability Slump (cm)	BONDING (kg/cm²) 7 d		28 d	
			Smooth	Twisted	Smooth	Twisted
1	400 kg/m³ of cement N. 1 without admixture	10	12	150	13	152
2	400 kg/m³ of cement N. 1 with admixture	22	35	275	40	285
3	300 kg/m³ of cement N. 2 without admixture, lightweight concrete (1800 kg/m³)	10	4	66	6	92
4	300 kg/m³ of cement N. 2 with admixture, lightweight concrete (1800 kg/m³)	21	9	212	21	210

For example, by using the admixture in the ordinary concrete the steel concrete bond at 7 days goes from 12 kg/cm² to 35 kg/cm² for smooth bars and from 150 kg/cm² to 275 kg/cm² for twisted bars. Similar improvements are observed for lightweight concrete. In this case, by using the admixture, the steel-concrete bond of a lightweight concrete becomes substantially the same as that of an ordinary plastic concrete without admixture, although the lightweight concrete is much more flowable.

CONCLUSIONS

The results of the present work show that, by using the admixture described in this paper and based on the sulphonated naphtalene-formaldehyde polymer, high strength and reliable concrete can be obtained.

The compressive strength of this concrete is substantially the same of a well compacted no-slump concrete with the same low w/c ratio. On the other hand, in the fresh state the concrete is very flowable but at the same time very cohesive and pratically unsegregable.

Because of its high workability and low segregation the strength of this concrete locally placed into the formworks is very little dependent on the efficiency, care and time of compaction, or on the density of reinforcement and geometry of elements. It has been proposed to define reliable such a concrete. Reliability is also due to the remarkable increase of the steel-concrete bond caused by the presence of the admixture.

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