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High Performances Concrete in Algeria, for a More Economical and More Durable Concrete (State of the Art Report)

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Abstract: This study is of general nature. It represents a state of art of High and Very High Performance concretes (HPC and VHPC). This type of concrete has been extensively studied during the last decade in many countries, mainly in France, Germany, Japan, Norway, Canada and US. Knowing that the field of construction in Algeria is in full expansion. The objective of this study, is to emphasize the various aspects of this type of concrete (formulation, mechanical properties, durability) and to show structural, economic and environmental advantages in order to encourage manufacture and the use of a local HPC.

Key words: High performance concrete, research on HPC in Algeria, superplasticizers, compressive strength, durability

INTRODUCTION

The HPC are concretes characterized by a compressive strength which can exceed the 100 MPa. They are manufactured under conditions similar to those of the traditional concretes whose essential components are cement, aggregates and water. Using high-performance concrete in structural elements, would allow reduction of the element's cross-section (Andrzej and Wojciech, 2002). The uses of supplementary cementitious materials (pozzolans) in low-water/cement ratio modify the microstructure of the traditional concrete resulting from a very compact matrix (better durability). To build with HPC helps to decrease the CO2 rate emitted in the atmosphere, since one uses less cement. Whenever economical, the concrete industry has replaced a part of the cement used in concrete production with a number of natural products or industrial by-products, known as pozzolans: Volcanic ash, trass, ground pumice, fly ash from power generators and blast furnace slag (Malhotra, 1987). Nowadays, several important works are realized by HPC like Viaduct of Millau in France, (2001-2005, fcm = 60 MPa Length: 2466 m, Width: 32 m), Kuala Lumpur City Centre in Malaysia (1996, fcm = 100 MPa, height 452 m), the highest building in the world at present, Japan Centre in Frankfurt am Main (1994, fcm = 105 MPa, height 115 m) (Flaga, 2000).

FORMULATION OF HPC

Contrary to cement, aggregates and water, supplementary cementitious materials are not necessary to make an Ordinary Concrete (OC), but for HPC, superplasticizers and supplementary cementitious materials represent essential components which characterize the formulation of HPC.

Superplasticizers: They are additives (polymeric) characterized by their great capacity reduction of water. They were first used essentially as concrete fluidifiers but it was also realized that it was possible to produce flowing concretes with the minimum amount of water required to hydrate cement particles completely (Aitcin, 1995). Basically sulfonated melamine, formaldehyde and sulfonated napthalene formaldehyde condensates which are specially synthesized for the concrete industry, are much more efficacious in neutralizing surface charges than their predecessors (Tanaka *et al*., 1999). Using a superplasticizer it is possible to make a flowing low-water/cement-ratio concrete in the 0.20-0.35 range by at the same time increasing the amount of cement and decreasing the amount of mixing water. This water and w/c reductions explain how compressive strength can be increased four-or fivefold. The greater dispersing action of superplasticizers eliminates the need to add water to provide sufficient workability and to deflocculate the agglomerations of cement particles. Through the use of superplasticizers, the minimum amount of water needed to hydrate all cement particles now serves not only to hydrate the cement, but also to ensure adequate workability. This improvement can be exploited in two different ways (Fig. 1), to make concrete with high workability or with high compressive strength.

Supplementary cementitious materials (Pozzolans): The developments in the use of pozzalans in low-

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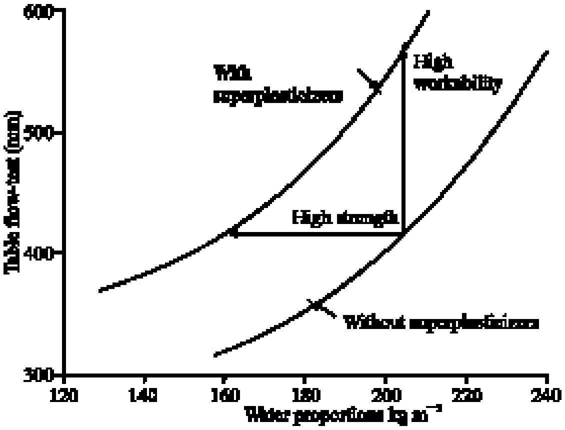

Fig. 1: Relation between table-flow test and water proportions of a concrete with or without superplasticizers (Mayer, 1979)

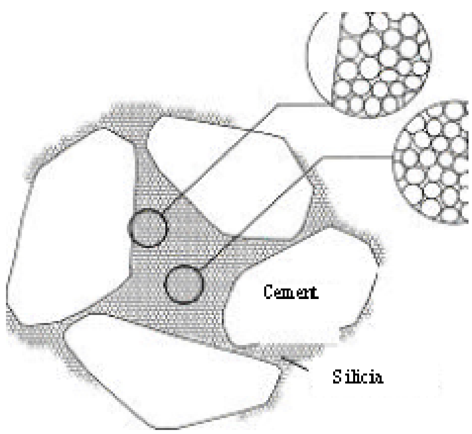

Fig. 2: Filler effect of silicia fume

water/cement-ratio concrete have also contributed in controlling the rheology of concretes with water/cementitious ratios between 0.25 and 0.35 that can be sticky and prone to lose their slump rapidly (Uchikawa *et al*., 1992). Pozzolans play an important role when added to Portland cement because they usually increase the mechanical strength and durability of concrete structures. Pozzolans, silica fume and ground rice husk ash have no intrinsic binding properties on their own; their latent potential must be developed through combination with Portland cement. In fact, pozzolans react with the lime liberated when di- and tricalcium silicates hydrate to form Calcium Silicate Hydroxide (C-S-H) that gives Portland cement its binding property (Dron and Voinovitch, 1982). The most important effects in the cementitious paste microstructure are changes in pore structure produced by

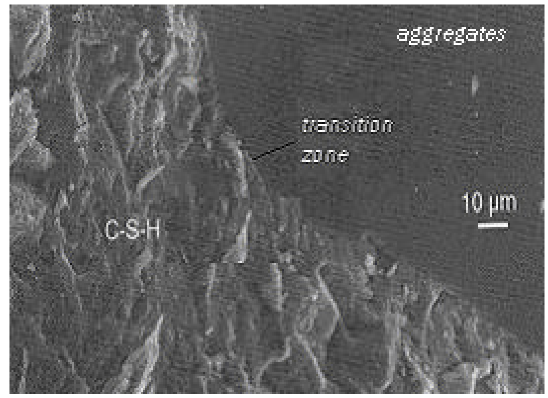

Fig. 3: Dense C-S-H around the aggregate in concrete with silica fume

the reduction in the grain size caused by the pozzolanic reactions Pozzolanic Effect (PE) and the obstruction of pores and voids by the action of the finer grains (physical or filler effect) (Fig. 2). According to Mehta and Aitcin (1990), the small particles of pozzolans are less reactive than Portland cement. When dispersed in the paste, they generate a large number of nucleation sites for the precipitation of the hydration products. Therefore, this mechanism makes the paste more homogeneous and dense as for the distribution of the finer pores, because of the pozzolanic reactions between the amorphous silica of the mineral addition and the calcium hydroxide produced by the cement hydration reactions.

In addition, the physical effect of the finer grains allows denser packing within the cement and reduces the wall effect in the transition zone between the paste and the aggregates (Fig. 3). This weaker zone is strengthened due to the higher bond between these two phases improving the concrete microstructure and properties (Durekovic, 1995).

In general, the Pozzolanic Effect (PE) depends not only on the pozzolanic reaction but also on the physical or filler effect of the smaller particles in the mixture. Therefore, the addition of pozzolans to cement results in increased mechanical strength and durability when compared to the plain paste because of the interface reinforcement. Thus, the PE on the paste microstructure depends not only on the pozzolanic reactions but also on the Filler Effect (FE) of the finer particles. The physical action of the pozzolans provides a denser, more homogeneous and uniform paste. The replacement of 15% of the cement mass by silica fume for example, will add approximately 2,000,000 particles to each cement grain (Isaia, 2003).

MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE

One feature of high performance concrete is high compressive strength, resulting from a very compact matrix. Other characteristics include almost no paste/ aggregate transition zone; a higher modulus of elasticity than conventional concrete (Aitcin, 2001).

Compressive strength: Concrete compressive strength is closely related to the compactness of the hardened matrix (Feret, 1892). In particular, in HPC, the coarse aggregate can be the weakest link in concrete when the strength of the hydrated cement paste is drastically increased by lowering its water/binder ratio. In such cases, concrete failure can start to develop within the coarse aggregate. In some areas, decreasing the water/binder ratio below a certain level is not practical from a mechanical point of view because the strength of the HPC will not significantly exceed the compressive strength of the aggregate. When the compressive strength is limited by the coarse aggregate, the only way to get higher strength is to use a stronger aggregate (Aitcin, 2003). Figure 4 represents the evolution of compressive strength in HPC made by De Larrarad. The material resists more than 60 MPa at 24 h. The behavior of this HPC at 12 h is that of an ordinary concrete at 28 days (Larrard, 1988).

Adherence steel-HPC: For reason of comparison between Adherence steel-HPC and Adherence steel-OC, several tests are realized by Lorrain. The results are presented in Fig. 5. It should well be noted that the tests took place at the three days age for each one of the two types of concrete (Lorrain, 1992).

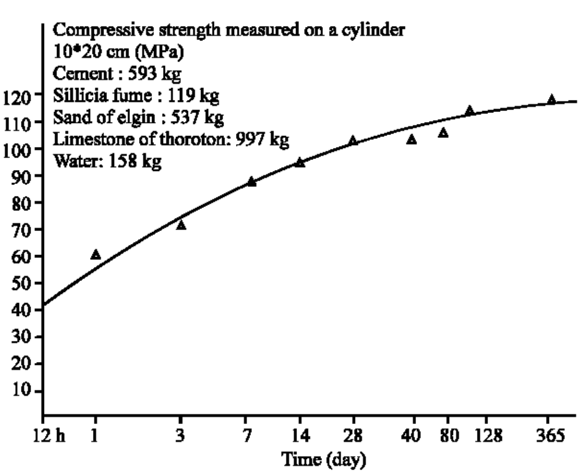

Fig. 4: Evolution of compressive strength according to time (Larrard, 1988)

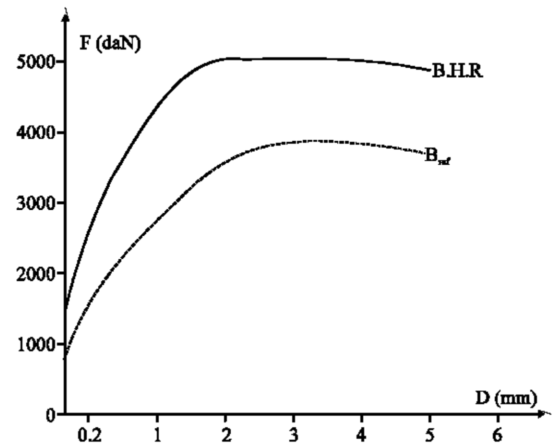

Fig. 5: Comparison between Adherence steel-HPC and Adherence steel-OC (Lorrain, 1992)

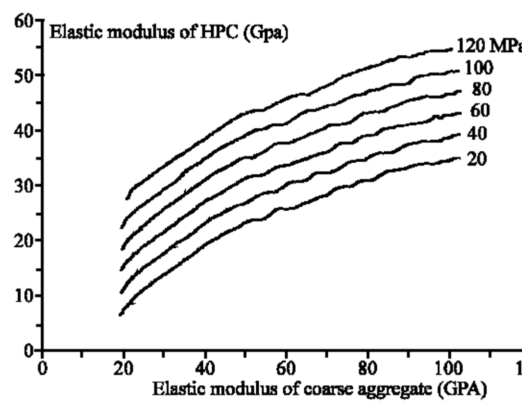

Fig. 6: Abacus predicting the value of the elastic modulus of a HPC according to the value of the elastic modulus of the coarse aggregate and the compressive strength of the HPC (Baalbak, 1997)

At the end of the tests, the author concluded that resistance to the appearance and to the propagation of the damage of adherence steel-HPC does not depend only on the mechanical resistance, but also of the microstructure of the concrete.

Modulus of elasticity: The simple empirical relations binding the modulus of elasticity E and the Compressive strength fc which can be establishedforusual concretes do not apply for the HPC. The values of the elastic modulus of High-performance concretes which have the same compressive strength and which are made with various types of aggregate can varied because aggregates using in material have different elastic modulus (Aitcin, 2003). Following the results obtained on Concretes manufactured with aggregates of various origins, proposed the following simple formula (Baalbaki, 1997):

$$Ec = -52 + 41.6 \log (Ea) + 0.2\ fc\ (GPa) \qquad (1)$$

Ec represents the modulus of elasticity of the HPC, Ea represents the modulus of elasticity of coarse aggregate. Baalbaki proposes also an abacus (Fig. 6) to predict the elastic modulus of any type of concrete as soon as one knows the elastic modulus of the coarse aggregate and the compressive strength of the HPC.

DURABILITY OF HIGH-PERFORMANCE CONCRETE

The experience gained with ordinary concrete has taught us that concrete durability is mainly governed by concrete permeability and the harshness of the environment. With its dense microstructure and very low permeability, HPC should obviously be more durable that ordinary concrete.

Carbonation: Following tests on Ordinary Concrete (OC) and HPC, Levy (1992) could obtain the results exposed in Table 1. The carbonic penetration of the molecules tends towards the zero in the case of HPC, concrete whose compactness is much better than ordinary concrete.

Chloride-ion permeability: The rapid chloride-ion test (AASHTO T-277) also reveals that the connectivity of the pore system decreases drastically as the W/C ratio

Table 1: Depth of carbonation for HPC and usual concrete (Lèvy, 1992)

Conservation 28 days in wet room	Type of concrete	dx (mm)	Dx max (mm)
(100 % HR)	OC	5	0.0
	HPC	0	0.0
(50 % HR)			
	OC	8.7	22.9
	HPC	1.6	1.6

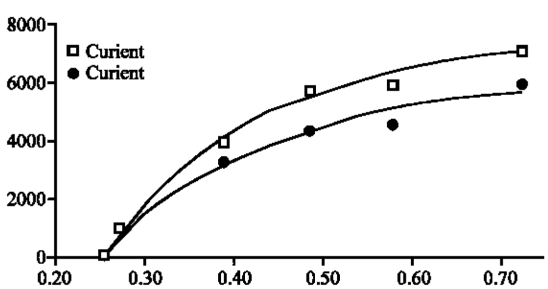

Fig. 7: Chloride-ion permeability according to water/binder ratio (Wierig, 1984)

decreases, making the migration of aggressive ions or gas more difficult in HPC than in ordinary concrete (Fig. 7) (Wierig, 1984).

In HPC, the penetration of aggressive agents is quite difficult and only superficial. High-performance concretes that have a water/binder ratio between 0.30 and 0.40 are usually more durable than ordinary concrete not only because they are less porous, but also because their capillary and pore networks are somewhat disconnected due to the development of self-desiccation (Aitcin, 2003).

COMPARATIVE STUDY BETWEEN ORDINARY CONCRETE, HPC AND STEEL

Resumption of a compressive strength: The difference of the cost of sectionsmadeby steel, usual concrete andHPC during the resumption of the same compressive strength is presented in Table 2 (Larrard, 1988).

Б max represents the strength max in the material, ζ: density, c: the price of kg. The cost of the section which can take a compressive strength unit will be thus ζ c/б max. Following the found results this study goes in favor of the HPC.

The highest possible column and the maximum length between two supports: The maximum height h of a tower is calculated from the following theoretical formula (without external strength):

$$\zeta g h = б\ max \qquad (2)$$

g is the acceleration of gravity, h = б max/ ζg.
From the formula:

$$L_{max} = 4\ r\lambda / \zeta g \qquad (3)$$

We deduce the maximum length Lmax between two supports. λ is the twinge given and r represents the geometrical output of section, taken conventionally equal to 0.6. The results are presented in the following Table 3.

The results show that the constructive values of the HPC are much better than OC.

Table 2: Cost of three materials during the resumption of the same compressive strength

	Steel E36	OC	HPC
б max (MPa)	0.66*360=238	0.5*35=17.5	0.5*90= 45
ζ (t m^{-3})	7.85	2.5	2.6
c (F kg^{-1})	10	0.18 (armé)	0.24 (armé)
Cost of the element (F m^{-1}.MPa)	330	26	14

Table 3: The maximum height and the maximum length between two supports for the three materials

	Steel E36	OC	HPC
h (m)	3090	710	1730
L_{max} (m)	371	48	123

COMPOSITION OF SOME HPC

There are not fixed rules to make HPC; the original formulation has to be adapted to local materials. Many compositionsfound in the literature gave satisfaction.

Reactive Powder Concrete (RPC): These cementitious materials have originally been developed in France by Bouygues some years ago. The principles of RPC mix composition have been published by Richard and Cheyrezy (1995) but the original formulation has to be adapted to local materials. However, selection criteria of the type of cement and the nature of silica fume seem to be very important in order to obtain the mechanical performances of the Reactive Powder Concrete RPC (target compressive strength: 180 Mpa) with good rheological properties (Staquet and Espion, 1990). Table 4 gives a standard mixture composition for RPC. The expected mechanical properties are listed in Table 5 (Richard and Cheyrezy, 1995).

HPC made by Wang: The following Table 6 represents an example of formulation of HPC made by Wang. The levels of Compressive strengthat 28 days is 116.3 MPa on cubes of 100 mm and 109,7 MPa on cubes of 150 mm.

Table 4: Original RPC formulation According to Richard and Cheyrezy (1995)

RPC composition	Mass/volume ratio (kg m^{-3})	Material/cement ratio
Cement	693.0	1.000
Silica fume	225.0	0.324
Silica sand	991.0	1.430
Crushed quartz	208.0	0.300
Steel fibers	151.0	0.218
Superplasticizer (dried up)	14.4	0.021
Water	159.0	0.230

Table 5: Mechanical properties of RPC according to Richard and Cheyrezy (1995)

RPC properties	Curing at 20°C	Curing at 90°C
Compressive strength (MPa)	18	230
3-points flexural strength (MPa)	40 to 50	50 to 60
Young's Modulus (GPa)	55 to 60	55 to 60

Table 6: HPC Formulation

HPC composition	Mass/volume ratio (kg m^{-3})
Portland cement	490
Fly ash	140
Microsilice dries	70
Gravel 10 mm	1045
Fine river sand	450
Superplasticizer (Napthalene)	20 L
Retarder	1-2

CONCLUSION

The exceptional rigidity characteristic of high-performance concrete is a considerable construction advantage for buildings subject to lateral stress due to winds. High-performance concrete opens the door to more slender structural elements, more audacious designs and the service life of HPC should exceed that of ordinary concrete in the same environment. As the formulation of HPC can be adapted to the local products, especially blast furnace slag which represents industrial by-products (factory of EL Hadjar, Annaba), there are no severe materials or technological obstacles to produce and develop HPC in Algeria. The need to improve the performances of ordiary concrete and durability of concrete structures, endorses technically and economically the use of HPC. The principal fields of Algerian research must be directed towards the following points:

- Esearch on mix design,
- Testing on the mechanical characteristics
- Research on thermal effects.

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