High Performance Concrete : Custom-Designed Concrete
A Review of the French Experience and Prospects for Future Development

Professor Yves MALIER, E.N.S. de Cachan (France)
Professeur Pierre RICHARD, Bouygues Group (France)

Synopsis Following a brief overview of the techniques employed in developing the first generation of High Performance Concrete (from 50 to 130 Mpa/19 000 psi), then the second generation and, most recently, the generation of Reactive Powder Concrete (from 200 to 800 Mpa/120 000 psi), the authors highlight the originality of the French approach as it has evolved, within the construction industry, over the past ten years. The basic principles underlying this originality are focused on :

- high peformance rather than high strengh, since improvements in other mechanical, physical and chemical properties have become, for many structural applications, crucial in the choice of construction materials,
- application beyond sophisticated structures exclusively to encompass more basic construction uses or even many small, pre-fabricated structural elements,
- a global analysis (design, development, maintenance) and a « systems » approach to construction that serves to emphasize the economic considerations behind High Performance Concrete.

The second, and most detailed, part of this paper provides specific examples of the French approach through a discussion of not only : bridges and tunnels sized for heavy loads, major building projects, industrial structural framework (nuclear plant, offshore platform, oil tanker, etc), but also : short and medium-span bridges, small-scale, prefabricated components used in construction and public works, foundation work and structural repairs, etc.

The third part, based on ten years of experience acquired through rather varied applications from French industry, provides an outlook on future development prospects and suggests new domains, both within or outside the field of construction.

Yves Malier is Professor of Civil Engineering (Ecole Normale Supérieure de Cachan and Ecole Nationale des Ponts et Chaussées Paris, France) and Associated Professor (Sherbrooke University, Canada). From 1984 to 1992 he was the head of the French National Applied Research on H.P.C. wich involves 30 different organisations (owners, firms, designers, research laboratories) and has supervised the construction of many experimental structures made of HPC.

Pierre Richard is Research Director Senior Vice President of Bouygues Group. Associated Professor at Sherbrooke University (Canada) and Lecturer at Ecole Centrale de Nantes (France). New materials and new kinds of structures are the subjects of his research works. He has been managed a lot of major projects in the world (nuclear plants, stadiums, cable stayed and suspended bridges, important buildings (like the Great Arch and Library of France in Paris, offshore structures, ...).

1. BRIEF OVERVIEW OF TECHNIQUES FOR DEVELOPING HPC

For a century, concrete remained a mixture of aggregate, cement and water. The essential roles played by water were in fact two-fold: to insure the hydration of the cement and to actively participate in the workability of fresh concrete by providing a satisfactory rheological behavior.

Over this past decade, a good deal of scientific work has demonstrated the harmful impacts, on both strength and durability, of excess non-hydrated water, which was nonetheless necessary to obtain the appropriate rheological characteristics at the time of pouring. With the objective then of improving concrete's construction-oriented properties, methods aimed at reducing the proportion of water have been explored.

In parallel, other researchers have focused on reconstituting solid rock after having obtained, during the composition of concrete, a mix exhibiting very high compactness and very low porosity.

As a result, two initial approaches with different physio-chemical features were developed to produce high performances (1):

- the deflocculation of cement grains resulting from the use of organic products allowing the cement grains suspended in water to return to their original granularity. The net effect permitted reduction in the proportion of water since a certain amount of water was no longer, in contrast with conventional concrete, trapped within the flocs of cement grains (and therefore of little use in handling and a source of future microcracking).
- the extension of the granular mix spectrum obtained by adding superfine, chemically reactive elements (silica fume, limestone filler, etc.) in order to fill the microcavities resulting from grain-stacking. The compactness of the

mix is thereby improved, and its rheological characteristics, so vital at the time of pouring, are further enhanced at the fresh concrete state. Consequently, the use of these elements gives rise to additional reductions in water content and therefore a significant additional improvement in terms of strength and durability.

The past few years have witnessed major developments in high performance concretes, most often characterized in engineering terms by a compressive strength varying between 60 and 130 MPa (between 8,500 and 19,000 p.s.i.) depending on the formula employed.

Over the last two years, a new generation of HPC, Reactive Powder Concretes (2), has come to the fore in France, thanks mainly to Pierre Richard, Scientific Director of the Bouygues Group. This type of concrete is the outcome of a remarkable synthesis of ideas that serves to complement the two previous approaches mainly through:

- a new vision of the role of water and a better understanding of the cement-admixtures-aggregate interactions,
- a more thorough study of the scaling effects and the consequences on the optimal geometry of "aggregates",
- the "physical" role of the cement grain in grain-stacking and the optimization of the chemical reactions in hydration, that includes modifying fabrication processes (pressure, steam curing, etc.),
- the association of adapted fibers, or fibers with geometric configurations that also respect the scaling laws previously mentioned.

This second generation (3) of concrete will dramatically alter the future of the construction industry. The material properties already obtained (over 800 MPa (116,000 p.s.i.) in compression, over 100 MPa (14,500 p.s.i.) in tension, 0.5 to 0.8% elongation at tension failure, etc.) demonstrate a strong potential for future applications to construction-related activities as well as, undoubtedly, to many other industrial sectors. It's from this perspective that a radical evolution in the use of concrete will be spurred at the beginning of the 21st century.

Nonetheless, let's stay, for the remainder of this presentation, within the framework of "conventional" HPC, those that have been successfully adapted to a variety of projects.

2. THE ORIGINALITY OF THE FRENCH APPROACH FROM 1982 ONWARDS

In opting for new types of concrete (high strength concrete), the major construction firms of some countries (United States, Canada, Norway, Japan) have been electing, in general, to favor higher strength; the use of this type of concrete has been almost exclusively reserved for very tall buildings (in

Chicago, Seattle, Toronto, etc.) and for some offshore construction work.

In France (4), over the same period, particularly within the framework of the "New Ways for Concrete" National Project, three fundamental ideas were selected as priorities:

- beyond strength alone, many other inherent properties must be emphasized (wherein lies the concept of High Performance Concrete, "HPC", as opposed to High Strength Concrete, "HSC", that we've insisted on over this period) since these properties are determinant in selecting: the best-suited material for the structure to be built, the construction method, the project owner's desired level of durability, etc. As a consequence, reference is no longer made to "concrete" in the singular but to "concretes" in the plural.
- HPC is not exclusively reserved for major projects, but, quite to the contrary, can prove to be the optimal material choice for the most economic fabrication of many concrete-based products, even smaller-sized products.
- the application of HPC requires a "systems approach", a very common method employed in industrial sectors but as of yet rarely encountered in the field of civil engineering. The "systems approach" represents a tight mix of: the choice of material (strength, delayed effects, thermal effects, ductility, cracking), the construction element's fabrication process (rapid removal of formwork, early prestressing, long-distance pumping, continuous casting, etc.), the structural shape (triangulated and lightened structures, funicular structural loading, thin shells, etc.), the type of structural operations (coupling with external prestressing, new generation of mixed-material construction, etc.), durability parameters with respect to external attack (deicing salts, cracking, thermal gradients, etc.) and internal alterations (alkali-aggregate reactions, corrosion, etc.). The objective of such a "global" analysis is to develop an approach that is also itself "global" in nature to obtain a true costing of construction work carried out with HPC, rather than confining the approach to one simple calculation of the added value resulting from the transformation of the structure's material composition, while neglecting other parameters (shape, fabrication process, technology, operations, etc.). The real attractiveness of using HPC appears from the findings of this global analysis that very often reveal a particularly advantageous position for HPC.

3. A FEW EXAMPLES OF FRENCH CONSTRUCTION PROJECTS USING H.P.C.

Let's list briefly herein some examples that serve to highlight the three guiding principles detailed in the previous paragraph (high performance rather than high strength; ordinary, and not only exceptional, structures; a "systems approach" towards the art of concrete construction as opposed to the simple replacement of ordinary concrete by HPC). Without claiming to be exhaustive, the following examples can be cited:

1. Major Bridge Projects (1), (4), (5), (6), (8), (10), (11) :

- Ré Island Bridge (BOUYGUES): the world's first major prefabricated structure using HPC, 34,000 m3, 10-hour resistance required, 15 MPa for formwork removal of the voussoirs (deck: 3,000m in length). (Fig. 1)
- Pertuiset Bridge (BOUYGUES): cable-stayed bridge, 2,500 m3, 16-hour compressive strengh: 33 MPa, slump: 20 cm, required compressive strength: 60 MPa, average strength: 80 MPa, HPC used for short-term tensioning of the stays and ease of concreting successive cantilevers. (Fig. 2)
- Champ du Comte Bridge (G.T.M. - SOGEA): 37,000 m3 of HPC by means of a ready-to-use concrete network, HPC used for meeting requirements of 14-hour, 20-MPa resistance and severe durability problems related to the site (freezing-thawing, salts, etc.). (Fig. 3)
- Sylans Bridge and Glacières Viaduct (BOUYGUES): very long, magnificent structure (3 km) with triangulated voussoirs and prestressed exterior, 12-hour, 25-MPa compressive strengh, slump: 20 cm, average strength: 68.5 MPa (13,000 m3, 5,500 prefabricated voussoirs, lightened by their x-shape). (Fig. 4)
- Arc de la Rance (CAMPENON BERNARD): an arch with a 261-meter span, progressively cast in-situ by successive cantilevers; 20-hour, 3-day and 28-day strengths: 25, 58 and 82 MPa, respectively (3,000 m3). (Fig. 5)

Following these pioneer projects of the 1980's, many other, more recent examples could also be mentioned, as the following selection attests:

- Elorn Bridge (RAZEL): cable-stayed bridge with a central span of 400m and four types of structural concretes: 40 MPa for the deck outside the central zone, 60 MPa and 80 MPa for the towers, and lightweight 35 MPa for the central span (Fig. 6)
- Garabit Bridge (DUMEZ): a segmented-cantilever bridge with inclined piers and a 195-m long main span (64 MPa) (Fig. 7)

This list would certainly not be complete without the Normandy Bridge (BOUYGUES, CAMPENON BERNARD, S.G.E.): 35,000 m3, average strength: 78 MPa, inaugurated in 1995; with a central span length of 857m, the Normandy Bridge holds the world record for cable-stayed bridges. (Fig. 8)

2. Short and Medium-Span Bridges (9), (10) :

- Joigny Bridge (DALLA VERA): 3 spans of approximately 40m, no major city located nearby, local aggregate, B.P.E. power station at a distance of 18 km, designed at 60 MPa with an average strength of 78 MPa, prestressed at 6 days, specific constraints imposed on the quality of the bridge's cladding, a large number of sensors comprising the structure's measurement system (2),(3). (Fig. 9)

- Roize Bridge at Vorreppe (CAMPENON BERNARD, SCETAUROUTE): prestressed mixed-material bridge with triangulated metallic frame and 90-MPa HPC, spans: approximately 40m, particularly original design as the first mixed-material structure in HPC (2). (Fig. 10)
- Auzon Bridge at Monteux (CAMPENON BERNARD): HPC used for power station in ready-to-use concrete (25 km), 1,200 m3, average strength: 75 MPa.
- Arroux Bridge at Autun (Dijon-based contractor): gantry crane with a 20-m opening, designed at 60 MPa, average strength: 69.2 MPa, 600 m3.
- Louhans Bridge (SOTRAMINE): undoubtedly still the smallest bridge in HPC in the world, 8.5-m span, prefabricated beams with bonded wires and 70-MPa compression slabs. (Fig. 11)
- and a very large number of more recently-built structures (Lille, Mâcon, Toulouse, Nevers, etc.).

3. <u>Major Building Projects</u> (1), (7), (8) :

- "Grande Arche" Paris (BOUYGUES): 25,000 m3 of HPC chosen for purposes of workability, capacity to be pumped over sizable distances and elevation differences, high initial strength for rapid prestressing (in the case of upper and lower horizontal mega-beams), quality of cladding and productivity gains thanks to ease of application (2),(6). (Fig. 12)
- "Grande Bibliothèque de France" in Paris (BOUYGUES): 7,000 m3 at 70 MPa and 50 m3 at 94 MPa, use of HPC vital especially for the quality of the cladding, homogeneity of the color, workability and application to very large structural elements as well as for its strength. This project of 380,000 m2 comprises four 90-meter high towers. HPC was used for the construction of the supporting columns of these towers. Since this concrete remains visible, stringent requirements were specified concerning the clarity and uniformity of the color, thereby preventing silica fume from being used. For the columns bearing the heaviest loads, very high strength concrete was necessary. White silica fume, obtained from the zinc industry, was used to maintain consistent color. (Fig. 13)
- Société Générale Tower in Paris (CAMPENON BERNARD, S.G.E.): This building comprises two main towers constructed on an eight-level basement occupied by car parks; the towers are 160m in height for a total of 38 storeys. All vertical elements (walls and columns) are made of HPC pumped at a rate of 20 m3 per hour; concrete was obtained from a mix of fine cement and silica fume (10,800 m3, average strength at 28 days: 73 MPa, slump: 22 cm, formwork removal in 7 hours). (Fig. 14)
- Amphitheater for the Mining School at Aläs (BOUYGUES): 80 MPa and 100 MPa concrete, structure with triangulated beams and shells. (Fig. 16)
- and a good number of other structures such as the Japan Tower in Paris (Fig. 15), the train station in Rennes, the Lyons Theater, etc.

4. Small-Scale Components used in Construction and Public Works

- prefabricated joists prestressed with bonded wires (RECTOR or SARETE PPB): concrete flooring components for single-family houses and buildings, 60 MPa, 80 MPa and sometimes 100 MPa HPC, provides increases in design load, span length, stiffness, shear resistance forces, bonding of corrugated reinforcement and productivity (related to the high initial strength that facilitates prestressing and therefore speeds up fabrication). (Fig. 18)
- prefabricated beams and poles (prestressed by strands) for construction of industrial buildings, shopping centers, etc. (SARETE, RECTOR, etc.): the same advantages as in the previous category along with the simplification of structural shapes (possibility of maintaining inertia constant over zones with bending moment and maximum shearing force). (Figs. 19 and 20)
- prefabricated pipes (BONNA, etc.) for buried networks and micro-bored pipes using the centrifugal process: 85-MPa HPC; among the numerous examples, the record was set by the 165-m length, 800-mm diameter tunnel micro-bored at Chatenay-Malabry thanks to the use of HPC, the only concrete that allows producing the axial thrusts necessary for the boring operation. (Fig. 21)
- prefabricated micro-components: sidewalk curbs, plinths, railings, fence components, small cladding panels, interlooking paving stones are but some examples of elements becoming increasingly fabricated in HPC, for the combined reasons of improved productivity, weight reduction, durability, ease of surfacing, abrasion resistance, etc.

5. Major Structural Frames (industrial or other) (1), (6), (7), (8) :

- the offshore platform Hibernia in Newfoundland (DUMEZ - GTMI - DORIS): 160,000 m3 of HPC, 28-day strength: 84 MPa (47 MPa at 3 days); compressive strength, shock resistance, abrasion resistance, durability in a marine environment and workability were the primary reasons for choosing HPC. (Fig. 23)
- the nuclear power plant at Civaux (FOUGEROLLE, BALLOT, CHAGNAUD): 20,000 m3 of a special HPC formulation (60 MPa at 28 days) containing a high silica fume content (40 kg/m3) and a low cement content (266 kg/m3). In-situ casting (pumping up to a height of 70 m) was controlled with a superplasticizer to give a slump of 180 to 200 mm on a discharge into the forms. The suitability of HPC for thick prestressed concrete constructions with improved water or air tightness was thus demonstrated, as HPC is less subject to cracking (reduced restrained thermal shrinkage), having a very low autogenous shrinkage (due to a high water/cement ratio of about 0.6) and a very low creep, while still maintaining a greater durability (2). (Fig. 24)
- Elf's concrete offshore platform N'Kossa (BOUYGUES OFFSHORE): large-scale (220m long x 46m wide x 16m high), this platform has

specifically been designed for its resistance (bending, shocks, etc.), watertightness, workability and durability; HPC was used in order to minimize the total weight and the resulting draft, a more economic solution than conventional solutions using metal (HPC: 2,700 m3, 79 MPa).

- launching pad for Ariane 5 at Kourou in Guyana (DUMEZ): a rocket launch generates a temperature on the order of 1,800°C during 17 seconds and constitutes a significant thermal shock whose impacts are magnified by the abrasion due to the exposure to gas passing at a speed of Mach 3. Obviously, the evaporation of free water contained in the combustion chambers of the launching pad increases deterioration, which has led to the application of an HPC following preheating up to 200°C (2-day strength: 51 MPa). (Fig. 25)

6. Tunnels (1), (6), (8) :

- the TGV Atlantique (high-speed train) tunnels at Villejust (SPIE BATIGNOLLES): 110,000 m3 of concrete, 50,000 voussoir segments stripped from their molds at 9 hours (10 MPa required) (2).
- the Channel Tunnels (BOUYGUES, SPIE BATIGNOLLES, SGE, DUMEZ): durability, watertightness, strength, rapid mold stripping (10 MPa at 6 hours) and special workability conditions (the liner segments were cast horizontally with a concrete having an almost nonexistent slump) have all necessitated the use of a B60 concrete (500,000 m3, 226,000 segments produced on the French side) (2),(3). (Fig. 26)

7. Underpinnings and Foundations

- many building aprons.
- the underpinnings of the Minaret of the Casablanca Mosque (BOUYGUES): the heavy structural work had already been completed when it was decided to raise the height of the Minaret another 25m to reach 200m. This decision created the need for major reinforcement work for the lower section and the replacement of load-bearing, very large cross-section structural elements (4m x 4m poles). The use of HPC as a substitute for ordinary concrete enabled increasing the strength along with, owing to a remarkably well-mastered technique introduced by the contractor, the resumption of delayed effects (with very limited impact thanks to the HPC) without modifying the verticality of the structure. This project will undoubtedly retain the world record for underpinnings for a long time to come (average strength: 95 MPa). (Fig. 27)

8. Other, more specialized applications could still be presented as the results of efforts carried out with experimental structures, or with some sizable pre-industrial or industrial constructions. Among these applications are, of

course, military structures subjected to shocks, storage facilities subjected either to very low temperatures or to strict impermeability constraints for specific gases, and, for more ordinary uses, roadway surfacing, airport runways, industrial buildings subjected to strong abrasive forces, high water deviation channels, etc.

4. FUTURE DEVELOPMENT PROSPECTS

It is admittedly still early, after only ten years of construction experience with HPC, to set out future prospects. Nonetheless, a few accomplishments can already be highlighted:

1. HPC can now be used throughout France; almost 90% of the country is "covered" by a network delivering ready-to-use concrete with a design strength of 60 MPa (8,700 p.s.i.) directly to work sites.

2. At the present time, the major users of HPC are already utilizing its wide range of advantages, far beyond just the 28-day strength, that are related to: improved productivity; durability; cladding quality; speed for removing formwork, loading and prestressing; mechanical property variability (delayed effects, cracking, bonding, thixotropy, shearing threshold, thermal effects, etc.); design of new shapes; use of more productive processes, and the list goes on. A complete economic assessment is then conducted once all these characteristics have been taken into account.

3. The HPC approach and the improved level of work site control it fosters are a sign of progress in terms of construction quality even when the use of ordinary concrete is required on the very same work sites.

4. The size of the HPC market devoted to small and medium-scale components is bound to grow over the near future, thereby leading to new methods in prefabricated construction that will certainly more closely resemble the existing approaches within many other industrial sectors, such as mechanical and automotive engineering, etc.

5. The examples presented earlier of the offshore platform N'Kossa, the small HPC components used in the manufacturing of (upscale) household appliances, new types of street furniture, the assembly of machine tools, etc. provide the first real proof that HPC - and to an even greater extent RPC (reactive powder concrete) - is going to dominate markets in which the use of concrete, up until a short time ago, had been considered impossible.

6. With respect to the material itself, keep in mind that we've only just begun to seriously explore HPC/fiber and HPC/light aggregate combinations and that new construction properties will continue to be developed. In addition, major efforts still remain to be carried out in the area of reinforcing and

fibers (yet, RPC has already made great strides therein).

7. The decision to use HPC does not depend on the decision of one contractor alone, except when the contractor happens to be, scientifically speaking, well-advanced in the field. In general, it would be necessary to enlist the full support of the project's owner and team of designers and architect/engineers as well as the inspecting authority.

8. With respect to research conducted on HPC, a strong body of work has already been concentrated on material properties. Additional efforts must now be oriented towards structural properties: the use of reinforcement exhibiting improved mechanical qualities, fire resistance, ductility of reinforced concrete components, flexibility and cracking, dynamic behavior of structures, shock resistance, etc.

ACKNOWLEDGEMENTS

I would like to thank all the companies cited herein and, especially, all those having actively participated in the National Project entitled "New Applications for Concrete Materials", launched in 1984 at the behest of the French Ministries of Public Works and Research.

TECHNICAL NOTE TO CLARIFY THE TEXT'S USE OF THE TERM STRENGTH

1. Throughout the text, we've been referring, in general, to design strength (28 days, 160mm x 320mm cylindrical test specimens); values correspond to a level of confidence of 95% of being reached or exceeded. On rare occasions, average strength is given instead.

2. These details are important, particularly from the perspective of international comparisons. In this respect, the experimental bridge in Joigny provided the opportunity to determine, for the same concrete materials, the various strength measures associated with a large number of different countries' testing criteria. As an illustration, it should simply be pointed out that a design strength (according to French rules: 28 days, 160mm x 320mm cylinders, 95% level of confidence) of 68MPa did correspond, for the same material, to an average strength, for a cube with a side length of 100mm tested at 90 days, of 88Mpa.

REFERENCES

(1) "High Performance Concrete - From Material to Structure", Malier Y. Ed., 560 p., E and F.N. Spon, Chapman and Hall, London, Van Nostrand Inc., New York, 1992. (ISBN 0442 31618 6).

(2) Richard P., Cheyrezy M.H., "Reactive Powder Concrete with High Ductility and 200-800 MPa Compressive Strength", A.C.I. Spring Convention, San Francisco, April 1994.

(3) Richard P., Cheyrezy M.H., Duget J., "Pretensioned Beam without Conventional Reinforcing", XIIth F.J.P. Congress, Washington D.C., May 1995.

(4) Malier Y., "The French Approach to Using HPC", ACI "Concrete International", July 1991, pp. 28-32.

(5) Malier Y., De Larrard F., "French Bridges with High Performance Concrete", Third Conference on High Strength Concrete, F.I.P.-A.C.I.-R.I.L.E.M., Lillehammer, 1993, pp. 534-544.

(6) Brocherieux J.M., Chardin G., Costaz J.L., Malier Y., Moranville-Regourd M., Richard P., Valenchon M., PCA and ACI Workshop on Achievements of HPC in France, Aitcïn P.C. and Malier Y. Ed., Montréal, 1990.

(7) Cheyrezy M.H., "Development of HPC in France", ACI Workshop on HSC, Zia P. Ed., Bangkok, 1994.

(8) "Les Bétons à Hautes Performances - Caractérisation, Durabilité, Applications", 672 p., Malier Y. Ed., 2nd Ed., Presses des Ponts et Chaussées, Paris, 1992.

(9) Malier Y., Moranville-Regourd M., "Construire en Béton à Hautes Performances", Annales de l'ITBTP, 502, March 1992, pp. 138-169.

(10) Malier Y., Brazillier D., Roi S., "The Joigny Bridge: an Experimental High-Performance Bridge", A.C.I. "Concrete International", May 1991, pp. 39-42.

(11) Le Bris J. and al., « H.P.C. in the Elorn Bridge », Symposium on High Performance Concrete in Severe Environments, A.C.I. SP-140, Paul Zia Ed., pp. 73-93

(12) Ithurralde G.J.B., Costaz J.L., « H.P.C. for the Improvement of Tightness of Nuclear Reactor Containments in Case of Severe Accidents », Symposium on High Performance Concrete in Severe Environments, A.C.I. SP-140, Paul Zia Ed., pp. 227-237.