High Performance Means More

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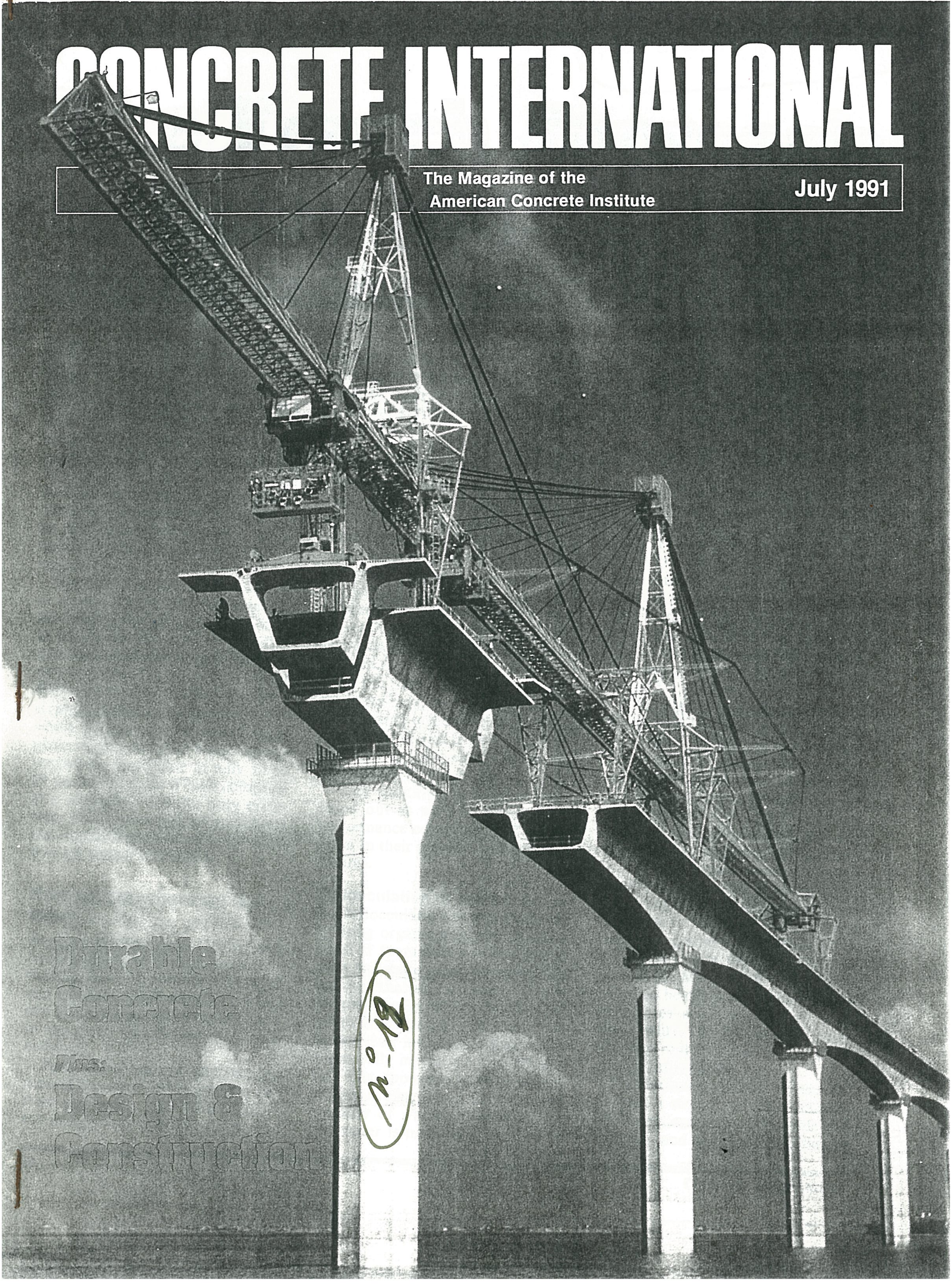

Durable
Concrete

Plus:
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n°-18

High Performance Means More Than High Strength

TITRE CHOISI ET IMPOSÉ PAR L'A.C.I !

The French Approach to Using HPC

by Yves Malier

From the beginning, traditional concrete has been characterized essentially by its compressive strength. But as concrete strengths have climbed as high as 140 MPa (20,000 psi), many other concrete properties have improved as well. Many of the methods for obtaining high-strength concrete also improve such qualities as durability, workability, shear strength, and abrasion and impact resistance.

For some projects, improvement in qualities other than compressive strength can be an important factor in justifying the cost of building with what the French have come to call high-performance concrete (HPC). A review of about 100 HPC structures built throughout the world reveals that the use of high-performance concrete would be economically justifiable in only 15 to 25 percent of them if high compressive strength were the only criterion. Some examples of structures and crucial improved concrete qualities are shown in Table 1.

How we got where we are today

Smeaton (1756), Vicat (1818), and Apsdin (1825) all contributed to inventing modern concrete. Monier and Lambot (1848), Coignet (1852), and Hennebique (1880) put it to use in the first reinforced concrete buildings.

Then, for a century, concrete remained a mixture of aggregate, cement and water. This third ingredient played two essential roles: ensuring hydration of cement, and participating actively in the workability of fresh concrete by giving the material satisfactory rheological properties.

During the last 10 years, numerous scientific investigations have shown the detrimental effects of excess nonhydrated water on the strength and durability of concrete.[1,2] Nevertheless, for a long time, water was essential to obtaining effective rheological properties for placing, a requirement that pointed to the need to explore ways of reducing water content to improve the engineering properties of concrete.[3]

At the same time, other research scientists have been focusing on reconstituting a monolithic or solid, rock-like material from a very compact mix, placing emphasis on mix design.[4,5]

Very quickly, two approaches stood out as ways to obtain high performance concrete (HPC). They differ in their physical and chemical natures.

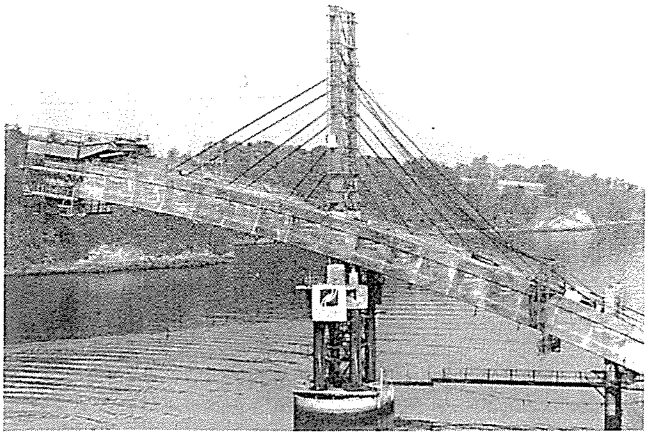
Deflocculation of cement grains — Deflocculation is accomplished by using organic products (condensates of formaldehyde and melamine sulfonate, and formaldehyde and naphthalene sulfonate). This is the process by which the cement grains in suspension in water can recover their initial grain size, which is generally between 5 and 50 μm. This first approach leads to an appreciable reduction in the necessary quantity of water, since much of this water is no longer trapped in the cement grain flakes as it would be in traditional concrete, so its contribution to workability becomes negligible.[6]

Widening the range of grain size — Extending the grain-size range is accomplished by adding extremely fine elements (e.g., silica fume,[4] calcareous fillers, and even black carbon[7]), chemically reactive or not, to fill the microvoids in grain packing, thus improving the compactness of the material while improving the rheological properties of the fresh mix. It follows that the quantity of water necessary for placing the concrete can be further reduced.[4]

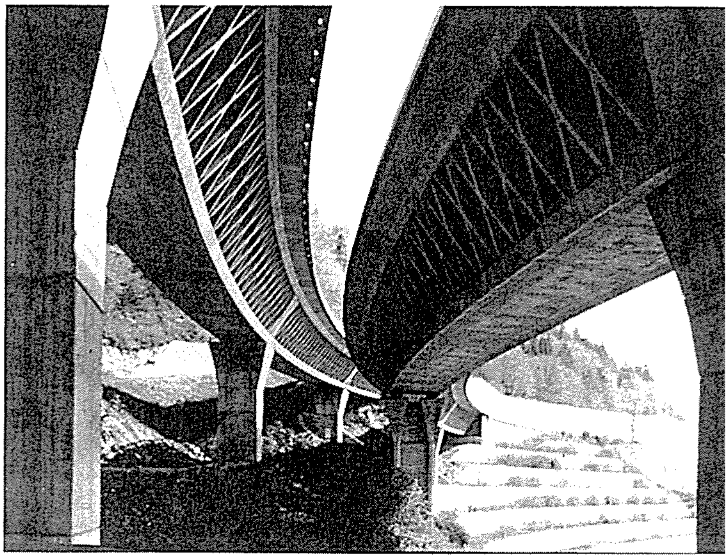
The first approach can be used alone and leads to gains in engineering properties, workability, and durability. Obviously, the second approach implies simultaneous use of the first, since it is useless to extend the grain-size range with very fine elements if priority has not been given to reducing flocculation.

Different experimental programs involving large-scale projects using locally available materials have confirmed that high-performance concrete, defined in terms of compressive strength values of between 60 and 80 MPa (8700 and 11,600 psi), can be obtained if these simple principles are respected.[8-11] And these values can be obtained without any real increase in the basic cost of the concrete.

Furthermore, a more precise approach, a stricter choice of materials, accepting a more noticeable cost increase, and absolute obligation to



Compression, short-term strength, and workability were major considerations in designing Rance Bridge in France.



France's Sylans Bridge required high strength, deferred deformation, short-term strength, and workability.

using the two approaches described make it possible, using industrial production methods, to obtain strengths between 90 and 140 MPa (13,000 and 20,000 psi), which the designer may consider essential for a particular project.[12]

A different approach, calling upon carefully selected materials (cements and aggregates of exceptional quality, polymers, etc.); new production processes (compaction, autoclaving, etc.); and new structural design (constraint, etc.), can ensure mechanical strengths of several hundred MPa for projects in which the designer is allowed to exceed the usual costs.[4]

This is the way to open the field to new applications of hyperperpormance concretes, especially in other industrial sectors where their relative low cost will often be very competitive with that of the materials usually chosen.

Characteristics of high-performance concretes

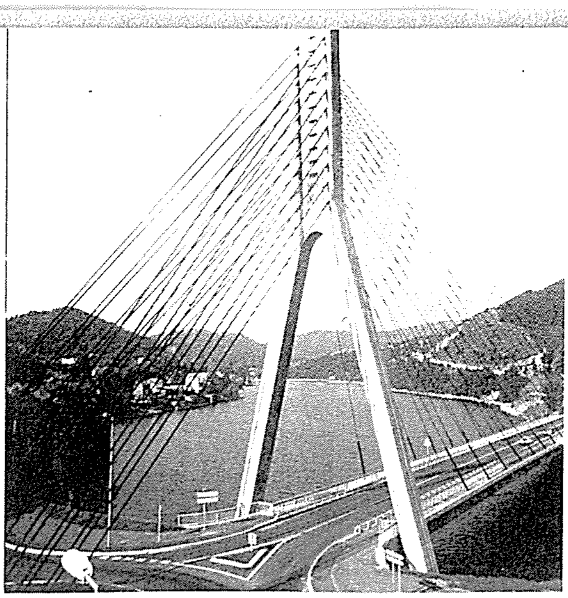
Microstructure

Research undertaken within the framework of the French National Project and by others has clearly defined the links between improving concrete performance and densifying the matrix and the cement paste-aggregate interface.[13-15] Observation of microstructure has confirmed two points:

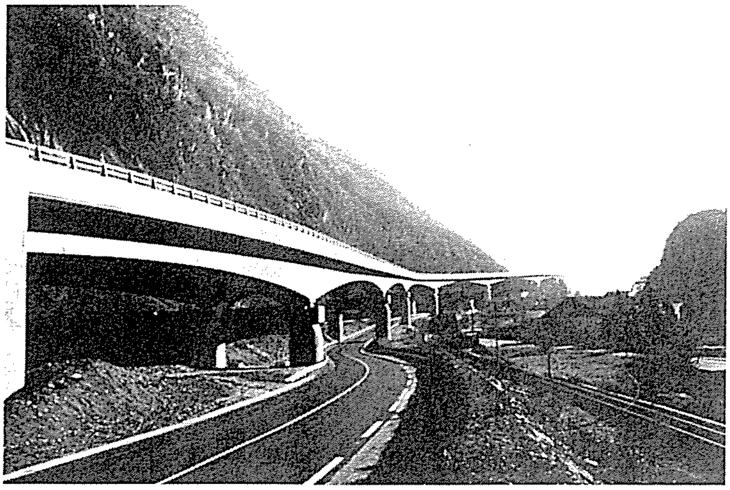
- In the 65-MPa (9400-psi) concrete with no silica fume in Joigny Bridge, the capillary porosity is lower than that of an ordinary con-

Table 1 — Types of HPC structures and important improved concrete properties

Structure type	Improved concrete properties	Practical examples
Bridges	Short-term strength Workability Durability Deferred deformation Strength	Joigny Bridge, France Rance Bridge, France Perthuiset Bridge, France Champs du Comte Bridge, France Sylans Bridge, France
Offshore structures	Durability Compression & shear Workability Abrasion & impact resistance	Gullfaks B & C, Norway Terre Nueve, Canada Terre Adelie, France
High-rise buildings	Compression & shear Workability Short-term strength Constraint	Scotia Plaza, Toronto, Canada 311 South Wacker Tower, Chicago 2 Union Square, Seattle, U.S. Grande Arche, Paris, France
Tunnels	Durability Compression Short-term strength	Villejust Tunnel, France English Channel Tunnel La Baume Tunnel, France
Highways	Abrasion & impact resistance Freeze-thaw durability Shear Durability Workability	Valerenga, Oslo, Norway Highway E18-E6, Norway Highway 86, Paris, France Paris Airport, France
Precast structural members	Short-term compression Compression Shear Workability Lightness	Precast joists, France Precast floor slabs, France
Steel-concrete composite construction	Shear Compression Workability Constraint	La Roize, France 2 Union Square, Seattle, U.S.
Drainage	Durability Abrasion resistance Compression Workability	Paris, France
Special foundation underpinnings	Compression Workability Short-term strength Deferred deformation	Hassan Mosque, Morrocco
Nuclear	Durability Strength Tightness	Civeaux (research), France



Durability and short-term strength were important factors in designing Perthuiset Bridge in France.



Durability, abrasion resistance, and freeze-thaw durability essential properties of the HPC in the Champs du Comte Bridge.

crete, but the texture of the hydrates remains the same, and the cement paste-aggregate interface is still somewhat porous and crystallized.

- In a 105-PMa (15,200-psi) concrete containing silica fume, the matrix is perfectly homogeneous and apparently amorphous. The silica fume particles, evenly distributed between the cement grains, become the loci of hydrate nucleation.[7] Capillary porosity is diminished and discontinuous, unlike that of other concretes in which it is interconnected. The silica fume particles act as filler or exert pozzolanic reaction, densifying the cement paste-aggregate interface.[15,16]

Consequently, failure occurs across the grains rather than between or around them, as in other concretes.[14] Moreover, silica fume adsorbs the excess water molecules, which no longer migrate toward the aggregate. There is no bleeding, and thus no transition zone at the cement paste-aggregate interface.

Placing

Eliminating the shear threshold in the fresh cement paste by adding a plasticizer leads to a concrete that flows easily, although it appears viscous. Placing and pumping operations are made much easier.[17]

Furthermore, precise investigations have been carried out on creep of high-strength concrete loaded at early ages. These demonstrate that the high strength obtained during the first hours and first days can lead to a very different approach to the scheduling of site work. Formwork removal and prestressing can be undertaken very rapidly, resulting in important savings and simplification.[18]

In certain cases, it can be useful to retard setting for several hours. This can be done without detrimental effect, thanks to the very high thixotropy of the paste, which also avoids any segregation, as in Joigny Bridge.[25]

On the other hand, absence of bleeding water leads to early and intense surface desiccation. Careful curing is essential, since it is the only way to avoid surface cracking due to plastic shrinkage.

Mechanical behavior

Apart from compressive strength gain, emphasis must be given to such advantages brought about by increases in tensile and shear strength with respect to resistance of beams to lateral shear, crosswalls, and problems of point loading and impact.[19]

The designer must analyze the increase in elastic modulus in light of maintaining, or even increasing, fracture toughness and consider the extensive improvement in the quality of bond between the steel and the concrete. Provided the quantities of passive reinforcement remain more or less the same (i.e., greater in percentage of volume), this will result in improved resistance to cracking and better ductility of the reinforced concrete composite in the structure under normal service conditions.

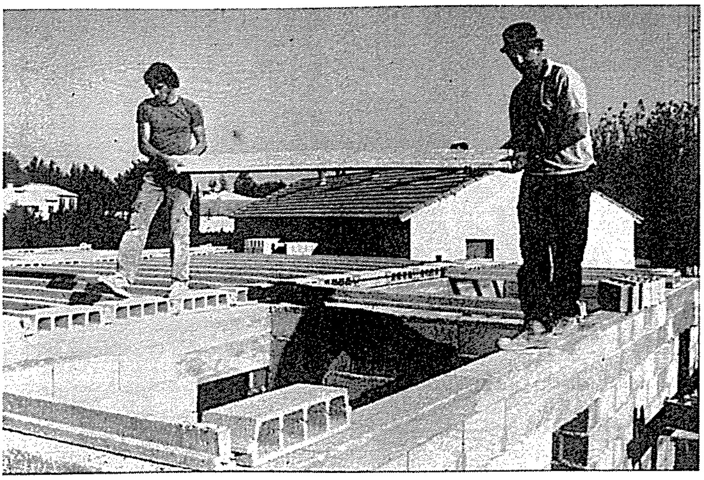
Additionally, creep is appreciably reduced in HPCs when the grain-size range is widened.[20]

Durability

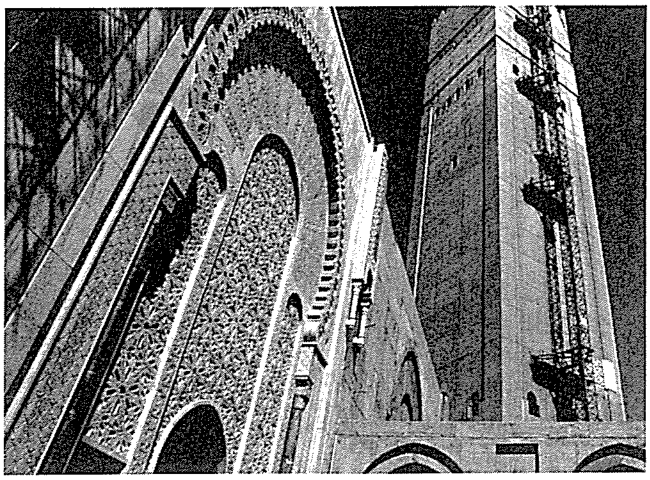
Concrete is a porous material that is characterized by its range of pore sizes and the types of connections between them, by such discontinuities in the microtexture as joints in grains, and by the crystalline nature of hydrates. This porosity implies permeability, which allows movement of fluid that is likely to cause expansion, cracking, and corrosion of reinforcement.

HPCs and very high performance concretes (VHPCs) show better resistance to chemical attack than traditional concretes. They are also recommended in the case of potential reaction between the alkalies of the pore solution and reactive aggregate. Silica fume content is generally about 10 percent.

Carbonation can destroy the passivation film on steels, and the rate of corrosion of reinforcement depends on the electrical resistivity of concrete. Carbonation was studied closely during testing for Joigny Bridge, but its influence is negligible compared with reactions on ordinary concrete. VHPC containing silica fume shows very good performance as regards accelerated carbonation, and Norwegian research confirms that silica fume increases the electrical resistivity of concrete, which restricts the galvanic current, and therefore steel corrosion.[16]



HPC's lightness make it a logical choice for precast joists for small homes in France.



Morocco's Hassan Mosque required short-term strength, deferred deformation, and compression.

Satisfactory behavior of HPC and VHPC subjected to freeze-thaw cycles has also been confirmed in French National Project research. The pore structure of these concretes is so fine that ice cannot form during freezing, even if the concrete is saturated with water. These results confirm those obtained by Canadian scientists[21] indicating that HPC and VHPC containing 5 to 10 percent silica fume and a plasticizer have a network of air bubbles which remain stable under vibration.[22] The concretes also resist scaling when subjected to deicing salts.[23]

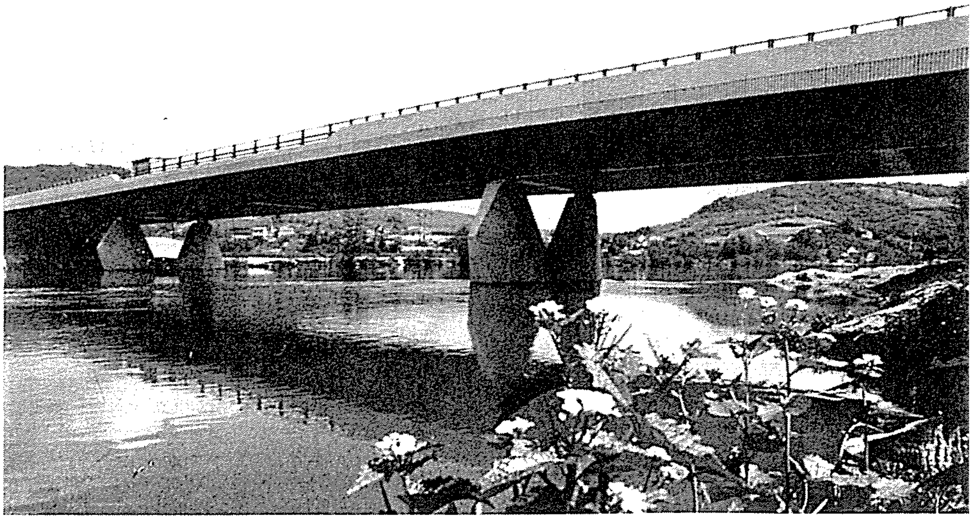
The durability of silica fume concrete in construction practice is reported in a recent survey published by the FIP.[24]

New material calls for new structural design

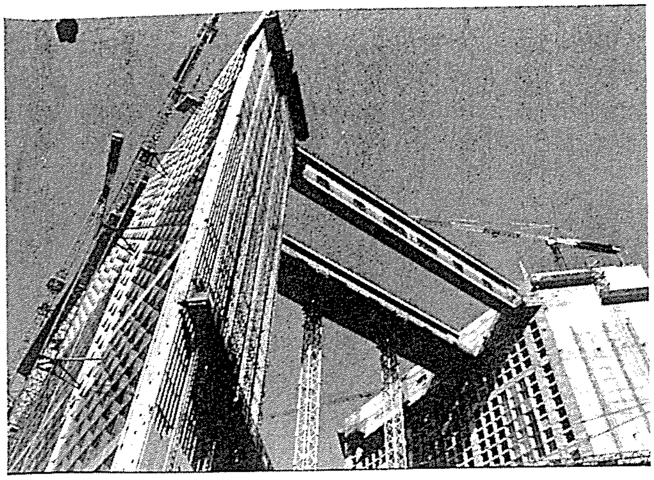
It is quite common to dismiss the advantage of increased concrete strength, claiming that the cross sections used in structural design for normal concretes lead to dimensions quite compatible with the space needed to accommodate reinforcing steels, cables, vibrating needles, etc. In the past, similar negative remarks about using a new material in traditional design raised difficulties for Freyssinet and Magnel when they introduced prestressed concrete, or even earlier for Hennebique and Coignet for reinforced concrete.

In fact, there is a need for a completely new and resolute approach to structural design. It is the author's opinion that the approach must be global to be effective.[27] Certainly, it must integrate data concerning:

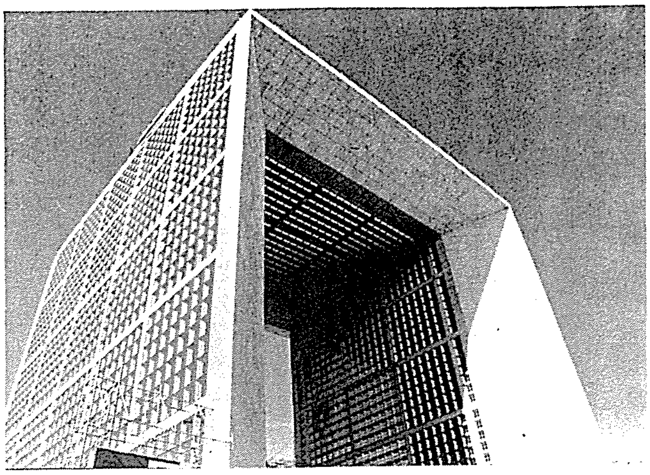
- Materials — including possible use of HPC, fiber-reinforced HPC, light-aggregate HPC, reinforcement with improved elastic limits, and improved cables.
- Technology — including enhancing external prestressing to obtain more slender sections of higher strength and lighter weight, developing composite construction with a new approach to connections with HPC, reviving the use of precast structures with new devices for assembly and connection, and using constraint to multiply the strength of certain members.[25]
- Work process — including proper use of the outstanding workability of this concrete to fully develop pumping technology and, from the economic point of view, more efficient use of formwork and precasting, and using the possibilities of partial prestressing at very short term.
- Induced effects — for example, care in the quality of curing as soon as the HPC is placed, and addressing the prestressing diffusion that results from external prestressing of HPC.
- Shape of structures — reviving the use of funicular arch loading, research on lowering weight using steel construction models such as trusses, and seeking advances in light-weight bolted structures.[25]
- Specific conditions — considering such conditions as chemically aggressive environments, locations with total impermeability to air, and resistance to friction and impact.



Workability and durability were two important HPC properties for Joigny Bridge.



The roof of the Grande Arche in Paris required lightness, high strength, and workability.



HPC also provided the workability and quality of surface required in building the Grande Arche.

Consideration of all of these parameters and their interactions is necessary in selecting the appropriate concrete for a project.

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