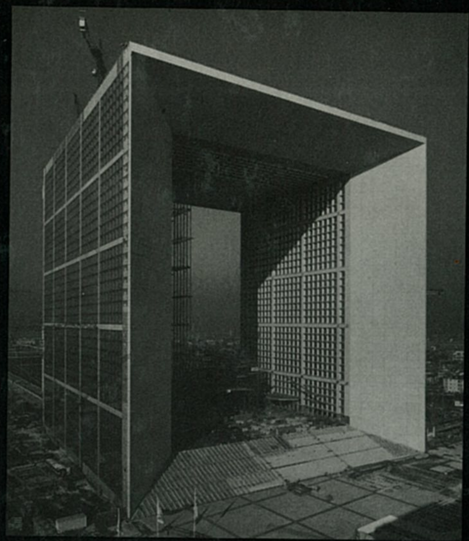
EDITED BY YVES MALIER

HIGH PERFORMANCE CONCRETE

From material to structure



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FOREWORD

By bringing together, in 1986, thirty partners from industry and research, all highly qualified, particularly responsible and justifiably ambitious, the Project 'New Ways for Concrete' has, from the outset, displayed four clear ambitions.

1. To decompartmentalize certain innovative processes by combining, in a single scientific policy, finalized research, experimentation on actual structures, and improvement of regulations and codes.
2. To treat our new materials at the same time microscopically, macroscopically, and according to how they are used in the structures, with the aim that each one of us should move beyond his specialization in one of these three areas, becoming involved in, participating in, and ultimately taking charge of work in the other two sectors, which formerly did not appear to concern him.
3. To bring about, among the partners, a fruitful pooling of a large number of research policies, studies and results.
4. To make available (in due course, and respecting everybody's interests) to all members of the profession (owners, architects, builders, inspectors, researchers, teachers, etc.) the greater part of the results of our work.

This collective publication presents contributions from the most highly qualified representatives of the thirty partners in the Project and by international experts with whom we regularly co-operate. It is to a large extent based on papers presented at seminars organized by the Project. It deals in turn with:

- the formulation and structural placing and use of different high performance concretes;
- the characterization and modelling of their mechanical behaviour, their durability with respect to internal changes and external aggressive agents;
- their application in very different structures (bridges, tunnels, offshore installations, industrial buildings, prefabricated components, etc.).

The publication also constitutes proof that, in the scientific field of high performance concretes there now exists a common language, a basis for dialogue, mutual recognition . . . in short, the foundations of common understanding between engineers and researchers.

We hardly need a crystal ball to predict that we have not yet completely evaluated all the consequences of such a frame of mind, including those for the economy and quality of our constructions.

I wish to express my sincere gratitude to all those who, over the past four years, have maintained their enthusiasm for what seemed, to so many others, merely a pleasing Utopian.

My gratitude is also especially due to those of our partners and overseas colleagues who have contributed to the realization of this first publication on high performance concretes. It is also due to Lysiane Alasluquetas, without whom this work could certainly never have been achieved.

Yves Malier
Cachan

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INTRODUCTION

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1 Ways to obtain high performance

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 aggregates, 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 ten years, numerous scientific investigations have shown the detrimental effects of excess non-hydrated water on the **strength** and **durability** of concrete. Nevertheless, water is essential to obtain effective rheological properties for placing. This requirement therefore points to the need to explore ways of **reducing the water content** so as to improve the engineering properties of concrete.

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

So, very quickly, two approaches stood out as ways to obtain high performance. They differ in their physical and chemical nature:

(a) Deflocculation of cement grains

Deflocculation is achieved by using organic products (condensates of formaldehyde and sulphonate melamine or of formaldehyde and naphthalene sulphonate). This is the process by which the cement grains in suspension in water can recover their initial grain size (between 5 and 50 µm for the most part). This first approach leads to an appreciable reduction in the quantity of water necessary, since quite a lot of this water is no longer trapped in the cement grain flakes (as it would be in traditional concrete where its contribution to workability is then negligible).

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(b) Widening the range of grain size
This extension is achieved by using extremely fine chemically reactive materials (silica fume, calcareous fillers even black carbon, etc), so that they fill the microvoids in grain packing, thus improving the compactness of the material and at the same time improving the rheological properties of the fresh mix. It follows that the quantity of water necessary for placing the concrete can be further reduced.

Table 1 The two ways to obtain H.P.

REDUCE THE FLOCCULATION OF CEMENT GRAINS	WIDEN THE RANGE OF GRAIN SIZE
PLASTICIZERS : - FORMALDEHYPE AND SULPHONATE MELAMINE - FORMALDEHYDE AND SULPHONATE NAPHTHALENE	CEMENT ADDITIVES : - SILICA FUME - CALCAREOUS FILLERS - ETC

The first approach can be used alone and leads to interesting gains in engineering properties, workability and durability. Obviously, the second approach implies simultaneous recourse to the first, since it is naturally useless to complete the grain size range of the granular material towards very fine elements if priority has not been given to reducing flocculation.

As parts of large-scale projects, different experimental programmes have confirmed that, where materials available locally are used, respecting these simple principles offers the possibility of obtaining high performance concrete, measured in terms of characteristic compressive strength, with values between 60 and 80 MPa (as used in the Joigny bridge). 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 basic ingredients, acceptance of a more noticeable increase in cost, absolute obligation to use the two approaches already described, can even now make it possible, using industrial production methods, to obtain strengths between 90 and 140 MPa (Seattle 118 MPa) which the designer may consider essential for a project.

Finally, a different type of approach calling upon carefully selected ingredients (cements and aggregates of exceptional quality, inclusion of polymers, etc), new production processes (compaction, autoclaving, etc), new structural design (constraint, etc) can ensure mechanical strengths of several hundred MPa for new applications for projects where the designer can exceed the usual costs.

This is the way to open the field to new applications of these hyper-performance concretes, especially in other industrial sectors where their relatively low cost will often be very competitive with that of the more noble materials usually chosen.

2 High performance (H.P.C.) rather than high strength (H.S.C.)

From the very beginning, traditional concrete was characterized essentially by its compressive strength. But this must now change with new concretes since many other properties are improved and can therefore become decisive in the choice of solutions made in engineering projects.

Let us briefly analyse the progress accomplished over the last few years in our knowledge of high strength concrete.

(a) Microstructure

The research undertaken within the framework of the French National Project has clearly defined the links between the improvement of concrete performance and the densification of the matrix and the cement paste-aggregate interface.

Observation of microstructure has confirmed two aspects:

- in a 65 MPa HPC with no silica fume (Joigny bridge) the capillary porosity is lower than that of an ordinary concrete. The texture of the hydrates however remains the same and the cement paste-aggregate interface is still somewhat porous and crystallized,

- in a 105 MPa VHPC containing silica fume, the matrix is perfectly homogeneous, apparently amorphous. The particles of silica fume, evenly distributed between the cement grains, become the loci of hydrate nucleation. The capillary porosity is diminished and discontinuous, contrary to that of other concretes where it is interconnected. The silica fume particles play the role of filler or exert pozzolanic reaction densifying the cement paste-aggregate interface. Failure then occurs across the grains and not between or around them as in other concretes. Moreover, silica fume adsorbs the excess water molecules which no longer migrate towards the aggregate. There is no bleeding, therefore no transition zone at the cement paste-aggregate interface.

(b) Placing

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

Furthermore, precise investigations have been carried out on creep of HPC loaded at early age. These demonstrate that the high strength obtained during the first hours and first days leads to a very different approach to the scheduling of site work. Formwork removal and prestressing can be undertaken very rapidly, implying important saving and simplification.

In certain specific cases, it can be interesting to retard setting for several hours. This can be done whithout detrimental effect thanks to the very high thixotropy of the paste which also avoids any segregation (cf. Joigny bridge).

On the other hand, the fact that there is no bleeding water leads to early and intense surface desiccation. Careful curing is therefore essential since it is the only way to avoid surface cracking due to plastic shrinkage.

(c) Mechanical behaviour

Apart from the gain in compressive strength, emphasis must be given to the advantage of the increase in tensile and shear strength in all the situations enhancing these properties (resistance of beams to lateral shear, crosswalls, problems of point loading and impact, etc).

The increase in the elastic modulus must be analysed by the designer in the light of maintaining, even increasing fracture toughness and with 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 or volume), this will result in improved resistance to cracking and better ductility of the "reinforced concrete composite" in normal service conditions in the structure.

Finally, the creep HPCs obtained with the second approach (widening the grain size range)is appreciably reduced.

(d) Durability

Concrete is a porous material: it is characterized by the range of pore sizes and their type of connections, by the discontinuities in the microtexture such as joints in grains, and by the crystalline nature of hydrates. This porosity implies permeability which allows movement of fluid liable to cause expansion, cracking and corrosion of reinforcement.

HPCs and VHPCs show better resistance to chemical attacks than traditional concretes. They are also recommended in the case of a potential reaction between the alkalis of the pore solution and reactive aggregate (alkali-silica reaction for example). The most usual silica fume content is around 10 %. Scandinavians and Icelanders have near 20 years experience of using such concretes. Now carbonation can destroy the passive film on steels: the rate of corrosion of reinforcement then depends on the electrical resistivity of the concrete. Carbonation was studied closely during testing for the 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. Norwegian research parallel to work in our teams confirms that silica fume increases the electrical resistivity of concrete, which restricts the galvanic current and therefore steel corrosion.

Our research team has also obtained confirmation of satisfactory behaviour of HPC and VHPC subjected to freeze-thaw cycles. 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 - HPC and VHPC containing 5 - 10 % silica fume and a plasticizer have a network of air bubbles which remain stable under vibration. They resist scaling when subjected to deicing salts.

3 A new material calls for new structural design

It is quite common to dismiss the advantage of increased strength of concrete 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 pokers, 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 our opinion that if this is to be effective, the approach must be global. It must especially integrate data concerning:

- the materials (possible use of HPC, fibre-reinforced HPC, light-weight aggregate HPC, reinforcement with improved elastic properties, improved cables etc);

- the technology (enhancement of external prestressing to obtain more slender sections of higher strength and lighter in weight, development of composite construction where the problems of connections are different with HPC, revival of precast structures with new devices for assembly and connection, use of constraint multiplying the strength of certain members, etc);

- the construction processes (proper use of the outstanding workability of this concrete to fully develop pumping technology, use of short-term strength for a new approach, from the economic point of view, to formwork and precasting, use of the possibilities of partial prestressing at very short term, etc);

- the induced effects: to take two examples of different types - care in the quality of curing as soon as the HPC is placed, or emphasis on the specific characteristics of problems of prestressing diffusion resulting from the association of HPC and external prestressing, it being established that in certain conditions they lead to specific technological solutions, transverse prestressing for example);

- the shape of structures (a revival of funicular arch loading, research on lowering weight using steel construction models such as trusses, advances in light-weight bolted structures, etc);

- the specific conditions (a chemically aggressive environment, a location with total impermeability to air, resistance to friction and impact).

- stages in maintenance: the high durability of HPC will allow for the integration right from the start of the replacement of prestressing cables who technology will certainly evolue in the next two decades. Such a concept will make it possible to reconcile in a structure the lifetime of concrete and the permanence of the characteristics of cables.

Before choosing the appropriate concrete, a designer must endeavour to distinguish all the interactions between these different groups of parameters, rather than concentrating exclusively on just some of them.

4 Lessons from the recent past and future prospects

Examining about one hundred HPC structures built throughout the world will confirm the reality of this analysis. However, observing them through the sole criterion of high compressive strength alone would certainly only justifiy the choice of HPC for about 15 - 25 % of them from the economic point of view (examples in Table 2).

In other words, and to conclude, it must never be forgotten that the cost of a structure certainly includes the cost of the basic constituent materials, but also the amortization of the equipment essential for the building and the sum of the maintenance and the adaptations needed during service life.

The true advantage of HPC can only be judged in the light of the sum of these different costs.

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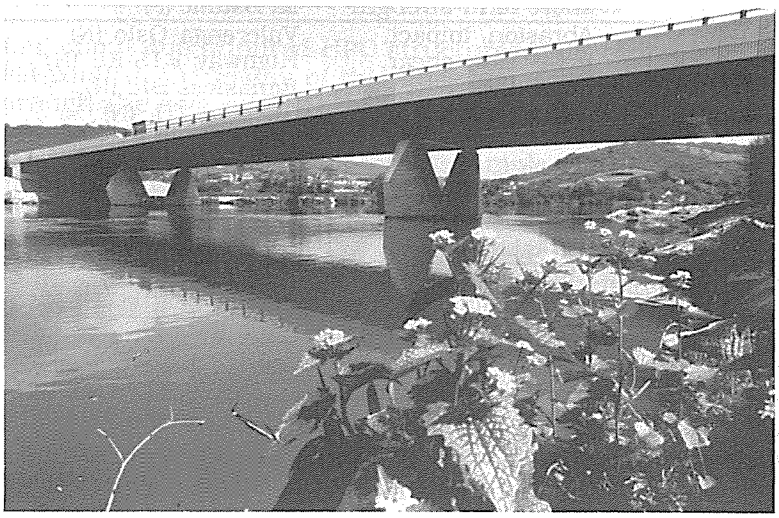
Table 2

TYPES OF STRUCTURE	PROPERTIES IMPROVED	PRACTICAL EXAMPLES
BRIDGES	Short term strength, workability, durability, deferred deformation, strength	Joigny(F), Rance (F) Perthuiset (F), Louhans (F) Champs du Comte (F) Sylans (F), Ré (F), Auzon (F)
OFFSHORE STRUCTURES	Durability, compression and shear, workability, abrasion and impact	Gullfaks B,C (N) Tere Neuve (CAN) Terre Adélie (F)
HIGH-RISE BUILDINGS	Compression and shear, workability, short term strength, constraint	Water T. PL Chicago (USA) Nova Scotia Toronto (CAN) 2 Union Sq. Seattle (USA) 1 Wacker Chicago (USA) 225 Wacker Chigaco (USA) 181 Wacker Chicago (USA) NW Hospital Chicago (USA) Arche Paris (F) Chibune R.S. Osaka (JAP.)
TUNNELS	Durability, compression, short term strength	Villejust (F) Manche (F and G.B.) La Baume (F)
HIGHWAYS	Abrasion, impact, frost-thaw, shear, durability, workability	Valerenga Oslo (N) Highway E18-E6 (N) Ranasfoss BR. (N) Shestad TU. (N) Highway 86 Paris (F) Paris Airport (F)
PRECASTING OF STRUCTURAL MEMBERS	Short term compression, shear, workability	Precast joists (F) Precast floor slabs (F)
STEEL-CONCRETE COMPOSITE CONST.	Shear, compression, workability, constraint	La Roize (F) 2U Sq. Seattle (USA)
DRAINAGE	Durability, abrasion, compression, workability	Paris (F)
SPECIAL FOUNDATIONS UNDERPINNING	Compression, workability, short term strength, deferred deformation	Hassan Mosque (MAR.)
NUCLEAR STRUCTURES	Durability, strength, water tightness	Civeaux (research) (F)

Photo 1 : Bridge of the "Ile de Ré" (F)
(Short term strength)

Photo 2 : Bridge of "Joigny" (F)
(workability, durability)



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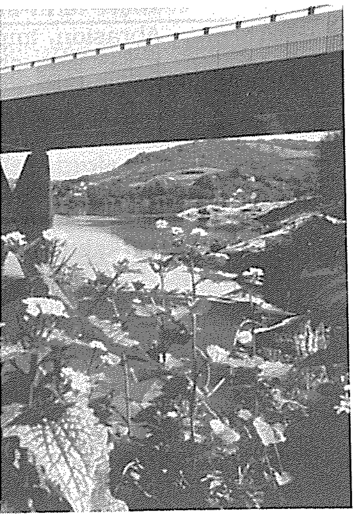

Photo 3 : Precast plankings (F)
(lightness)

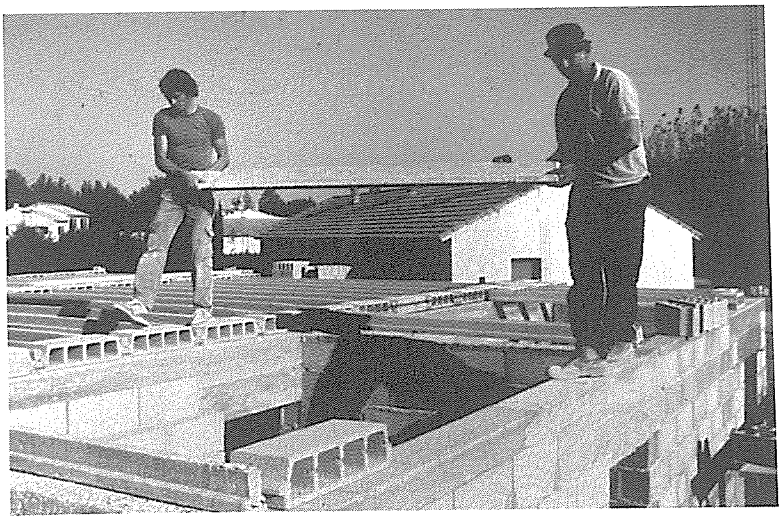

Photo 4 : "Grande Arche", Paris (F)
(workability, surface quality)

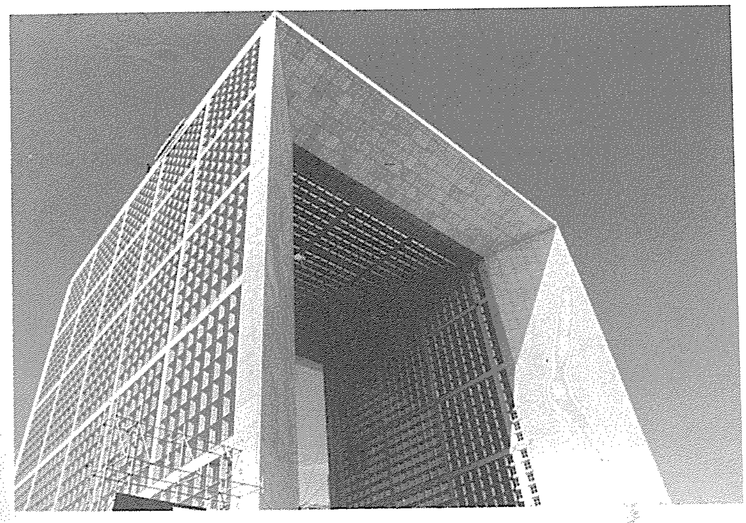

Photo 5 : Hassan Mosque, Casablanca (MAR)
(short term strength, diferred deformation, compression)

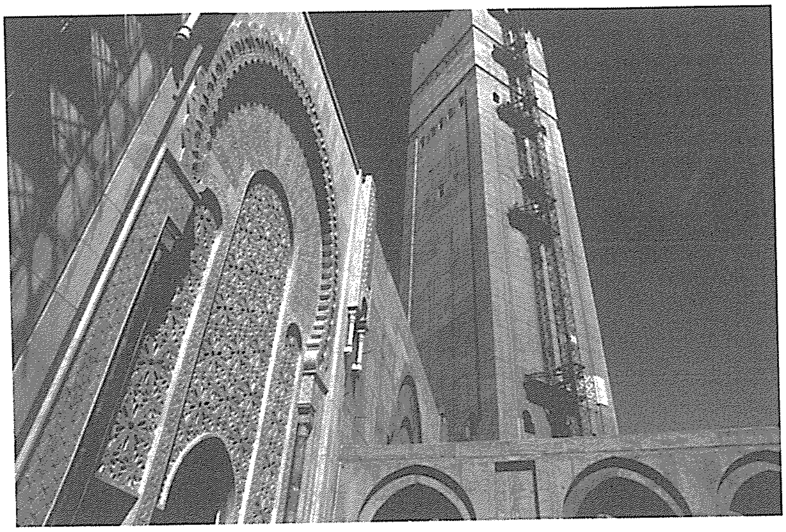

Photo 6 : Bridge of "Perthuiset" (F)
(durability, short term strength)

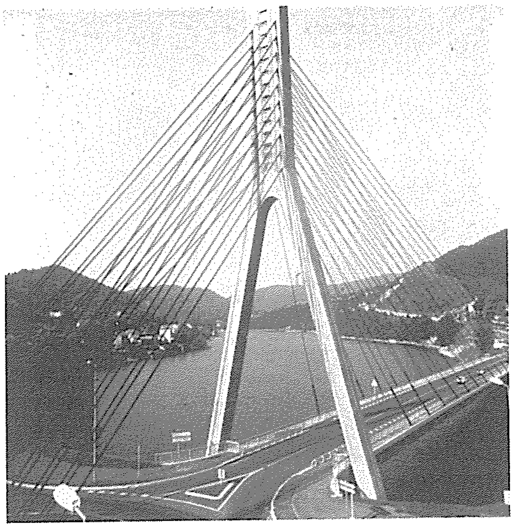

Photo 7 : Bridge of
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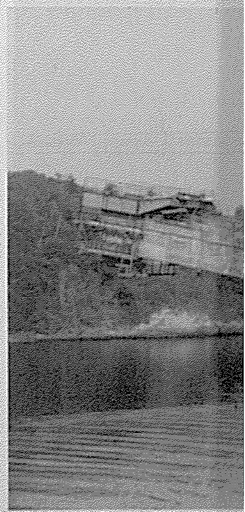

Photo 8 : Bridge of "
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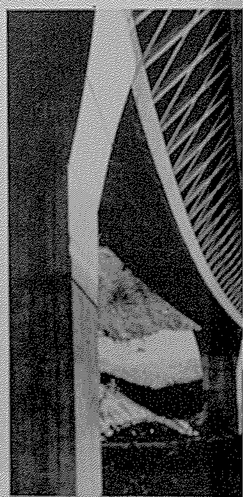

(MAR)
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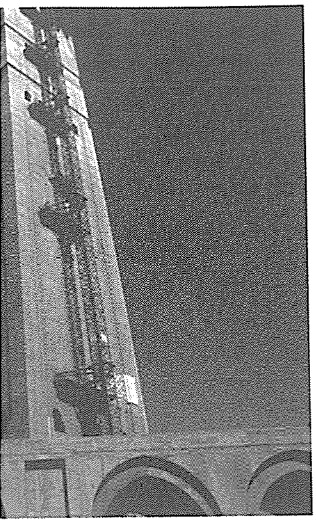

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Photo 7 : Bridge of the "Rance" (F)
(compression, short term strength , workability)

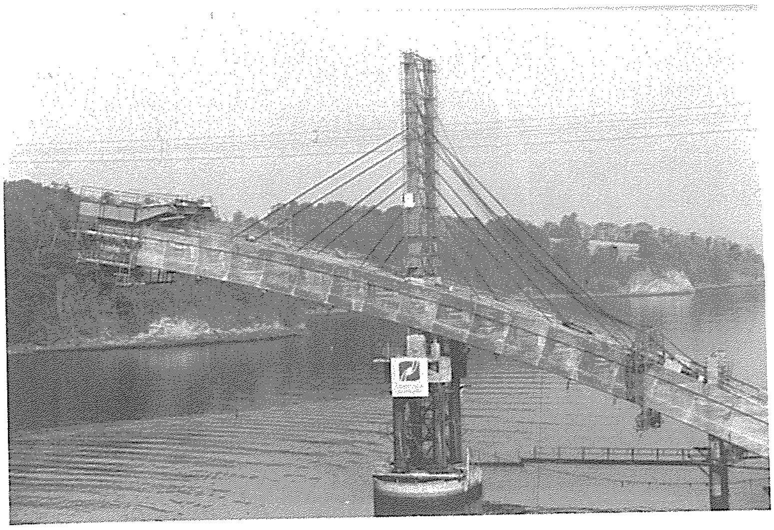

Photo 8 : Bridge of "Sylans" (F)
(high strength, short term strength, diferred deformation, workability)

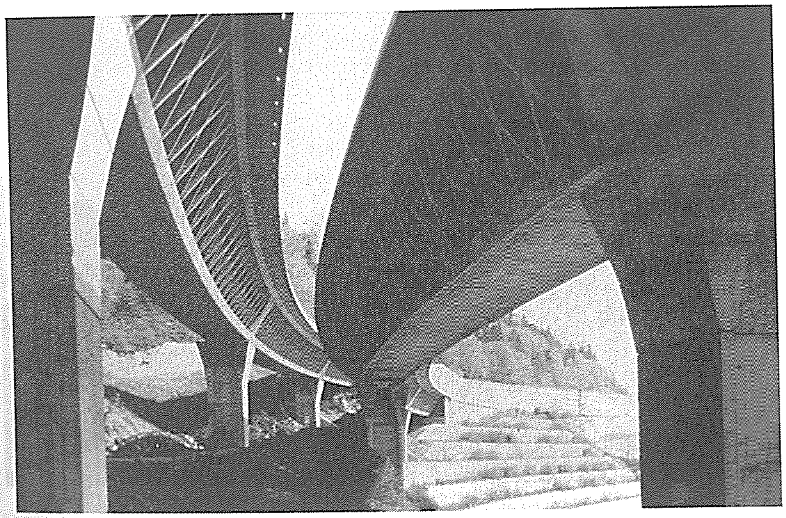

Photo 9 : Roof of the "Grande Arche", Paris (F)
(lightness, high strength, workability)

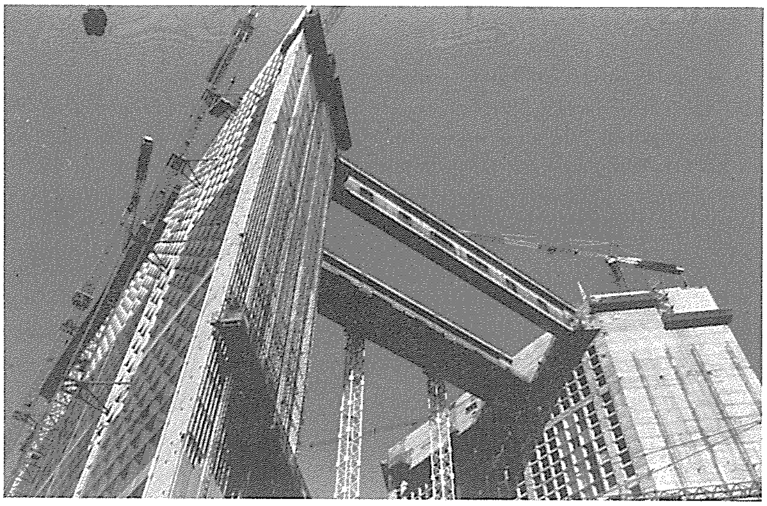

Photo 10 : Bridge of "Champs du Comte" (F)
(durability, abrasion, frost-thaw)