# Ultra-High-Performance Concretes:
# First recommendations and examples of application

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## Summary

This paper draws a short review of the use of UHPC, since the first research from the first industrial applications at EDF nuclear power plants in 1997-1998 to the most recent engineering structures completed in 2003.

Then this paper draws a brief sketch of the main features of French recommendations for UHPCs, drafted by an AFGC-SETRA work group composed of all the private and public organizations working on these new types of material. The recommendations are intended to constitute a reference document serving as a basis for use of UHPC in civil engineering applications.

**Keywords**: ultra high performance concrete ; fibre ; reactive powder concrete ; recommendations ; durability ; design methods.

## 1. Introduction

UHPC refers to materials with a cement matrix and a characteristic compressive strength in excess of 150 MPa, possibly attaining 250 MPa. They are containing steel fibres in order to achieve ductile behaviour and, if possible, to dispense with the need for passive reinforcement.

The different UHPC currently marketed are :

- BSI "Béton Spécial Industriel" (special industrial concrete), which technology has evolved to come to Ceracem® concrete, developed by Eiffage in association with Sika.
- Different kinds of Ductal® concrete, including RPC (reactive powder concrete), resulting from joint research by Bouygues, Lafarge and Rhodia, and marketed by Lafarge and Bouygues,
- BCV® being developed by cement manufacturer Vicat and Vinci group.

Most cement manufacturers are developing products, and materials are being developed in the laboratories of EDF, LCPC (with CemTec Multiscale technology)…

## 2. Short review of UHPC applications

### 2.1 Sherbrooke footbridge

First research carried out on UHPCs were led by Bouygues from 1990 to 1995 on Reactive Powder Concretes [2] [3] [4]. The world's first engineering structure designed with this UHPC was the Sherbrooke footbridge in Sherbrooke, Quebec, built in 1997 [5]. Spanning 60 m, this precast, prestressed pedestrian bridge is a post-tensioned open-web space RPC truss (Fig. 1), with 4 access spans made of HPC. The main span is an assembly of six 10 m prefabricated match-cast segments.

*Fig. 1 : General view of Sherbrooke footbridge*

The cross section is made of a ribbed slab 30 mm thick, with a transverse prestressing made of greased-sheathed monostrands. The truss webs are made of RPC confined in stainless steel tubes.

The structure is longitudinally prestressed by an internal prestressing placed in each longitudinal flange and an external prestressing anchored at the upper part of the end diaphragms and deviated in blocks placed at the level of the lower flange.

### 2.2 First industrial applications : beams of Cattenom and Civaux power plants

During years 1997 and 1998, the utility EDF carried out two important precasting sites using beams of UHPC, made of BSI and Ductal® [6] [7].These building sites consisted in replacing cooling towers steel beams in Cattenom (with BSI and Ductal®) and Civaux power plants (with BSI).

The extremely aggressive environment of the cooling towers induces important corrosion of the steel structures. UHPC with its outstanding qualities in terms of durability allows to replace steel beams with light elements with very long lifetimes without maintenance or repair.

### 2.3 The World first road UHPC bridges : Bourg-lès-Valence bridges

During years 2000-2001, the French Government, represented by its Regional Department of Public Works for the Drôme district with the assistance of the Service d'Etudes Techniques des Routes et Autoroutes (SETRA) and the Centre d'Etudes Techniques de l'Equipement (CETE) of Lyon, realized the world first UHPC bridges, built by contractor Eiffage Construction with BSI on Valence bypass [10] [11] [12].

Each bridge has two isostatic spans of about 20 m. The road deck was made continuous by placing in situ UHPC between the two spans (Fig. 5).

Each deck supports a 9 m wide road pavement with 1 m and 2 m sidewalks. Transversally both decks are identical; they are made from an assembly of five pi-shaped precast beams made from BSI, jointed together longitudinally with in situ UHPC.

All the beams are prestressed by pre-tension. There is no transverse prestress, and no transverse passive reinforcement, except where π-shaped beams are transversally jointed together.

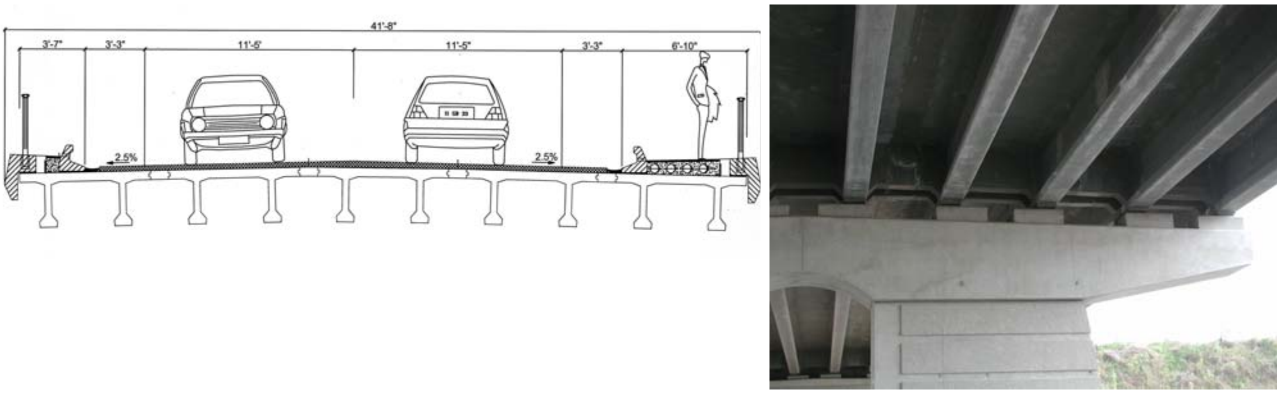

*Fig. 2 – Bourg-lès-Valence bridges - Typical cross-section and view at central pier*

The bridges were realized under an "Innovation Charter", and were designed and built in close collaboration with recommendations of a AFGC-SETRA working group on UHPCs.

This application also required to settle special calculation methods and design rules which are not currently covered by codes for the type of concrete employed. They were used to finalize some material characterization procedures and design calculation methods given by recommendations.

In 2001-2002, contractor Bouygues TP built a footbridge over the Han river running across Seoul in South Korea [13]. This foot bridge is made of an arch spanning 120 m, with two steel access spans (Fig. 3).

*Fig. 3 – General view of Seoul footbridge (left) and Sakata Miraï Footbridge (right)*

The arch has a π-shaped cross-section, 1.30 m deep. The upper flange is a ribbed slab 30 mm thick, with a transverse prestressing made of greased-sheathed monostrands. The arch is an assembly of six 20 m prefabricated segments, connected on site by means of temporary supports. The elements are jointed together by an internal longitudinal prestressing placed in haunches in the lower and the upper parts of the webs.

We can also mention the Sakata Miraï footbridge which is the first Ductal® footbridge built in Japan with a span of 50 m. The deck is a simple beam 2.4 m wide with circular web holes. The structure is longitudinally prestressed by an external prestressing and has no passive reinforcement. This footbridge was completed at the end of 2002 (Fig. 3).

The toll-gate of the Millau Viaduct, currently under construction, which will have an elegant roof based on a thin Ceracem shell, is the next step in the development of this new material.

This roof will look like an enormous twisted sheet of paper, 98 m long and 28 m wide, with a maximum thickness of 85 cm at centre (Fig. 4). Its alveolate structure will be like an aircraft wing and will be made of match-cast prefabricated segments, 2 m wide, connected together by an internal longitudinal prestressing. In all, 1000 m3 of Ceracem® will be used, weighing a total of about 2800 tons.

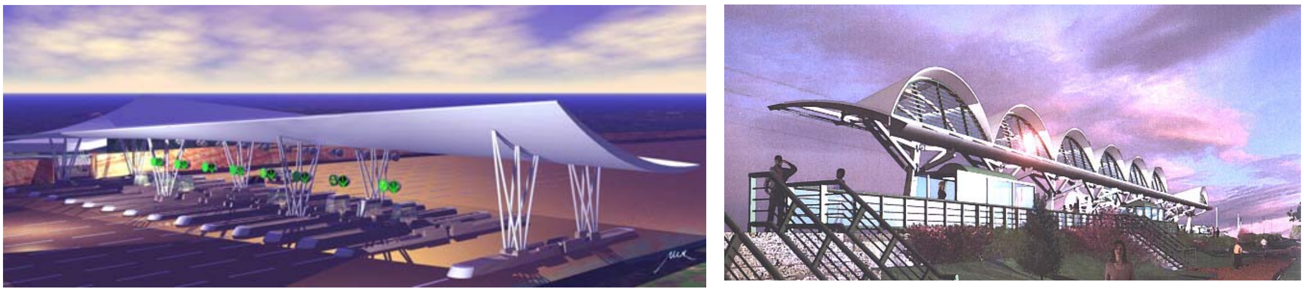

*Fig. 4 – General view of the roof of the Millau toll-gate and the Shawnessy tramway station.*

We can also mention the Shawnessy tramway station in Calgary, Canada, which is completely made of Ductal®. Its roof is composed of very thin precast shells realized by injection (Fig. 4).

At the end of 2003, began the construction of the Shepherds Gully Creek road Bridge in Croudace Bay, NSW, Australia, which has a deck made of precast prestressed I-girders beams connected to a traditional reinforced concrete slab.

Apart from these main civil engineering structures described above, some other applications have been realized with UHPC. Among these applications, we can make mention of these Ductal® ones:

- The construction of punched and thin accoustic sound panels for the underground Mocano railway station 1500 m2 of panels –30 m3 of concrete?
- The construction of architectural wall panels for Rhodia head office in Aubervilliers,
- The construction of 6300 anchor plates with polymer fibres and 200 plates with steel fibres for reinforced earth located on the sea-front on La Réunion island,
- a replica of the "Arbre Martel", a tree-shaped structure originally sculpted by brothers Martel,
- At the beginning of 2003, 30 m3 poured in steel tubes for making the pillars of the Keen Sofia Museum in Madrid (Span).

*Fig. 5 : General view of Lauterbrunnen footbridge*

BCV concrete developed by cement manufacturer Vicat and contractor Vinci has been used in some applications:

- Construction of stays for a treatment reservoir of rainwater in Les Houches, France,
- Injection of curved saddles for stay cables in the pylons of Sungai Muar bridge in Malaysia,
- Construction of foundations blocks for the roof of the Cluses toll-gate on A40 motorway,
- UHPC flooring of the Lauterbrunnen footbridge in Switzerland (Fig. 5).

## 3. The first recommendations on UHPC

The first French recommendations for Ultra-High Performance Fiber-Reinforced Concretes (UHPC) were published in 2002, in bilingual English-french version.

These recommendations are divided in three parts:

- A first part devoted to characterization of UHPC, giving specifications on the mechanical performance to be obtained and recommendations for characterizing UHPC,
- A second part deals with the design and analysis of UHPC structures,
- A third part deals with the durability of UHPC.

### 3.1 Behaviour and mechanical characteristics of UHPC

After reminding the principal effects of heat treatment [2] , the recommendations give a conventional compressive constitutive law for regulatory calculations, and also give values of Poisson’s ratio, thermal expansion coefficient, shrinkage strain and creep coefficient without or in case of heat treatment.

The recommendations also account for the knowledge on UHPC behaviour under dynamic loading [1].

#### 3.1.1 Tensile behaviour

An important part of the recommendations deals with the tensile behaviour and the post-cracking stage characterized by the tensile strength of the composite material reached after matrix cracking.

The post-cracking behaviour is very important because it may dispense with the conventional reinforcement in the design of some structures.

On the other hand, it is quite difficult to characterize this behaviour because it depends on the fibre orientation which depends very much on the placement process, and on the type of structure.

To integrate all the phenomena, the recommendations propose characterization tests depending on the type of structure (thin slabs, thick slabs, beams, shells), and which can be of two types of (direct tensile test or flexural tensile test).

To take into account the effect of the placement methods, the recommendations impose suitability tests conducted on representative models of the actual structure, and give the way to determine the safety coefficient to be applied to the tensile strength curve.

### 3.2 Structural design methods

The design methods proposed in the recommendations are based on semi-probabilistic limit states verifications.

#### 3.2.1 Normal stress verifications

For normal stress verification, the recommendations use the AFREM method [8] which concerns fibre concrete, and use a stress – crack width constitutive law $\sigma = f(w)$.

In order to simplify calculation, the recommendations give the way to go from a stress – crack width law $(\sigma, w)$ to a more traditional stress - strain law $(\sigma, \varepsilon)$.

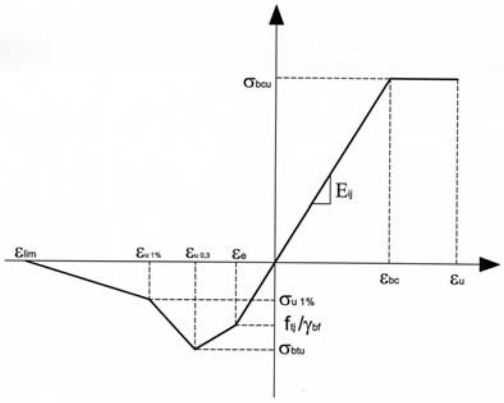


*Fig. 6 : ULS strain hardening law*

To guarantee sufficient ductility (in tension and compression), the recommendations consider a minimum fibre content and a non-brittleness check.

At the Serviceability Limit States, checks for traditional reinforced or prestressed concretes are completed when there is no passive or active reinforcement by prescriptions concerning crack width.

For ultimate resistance calculation, recommendations propose concrete behaviour laws (Fig. 6).

#### 3.2.2 Shear stress verifications

The recommendations introduce fibre shear strength, which complete resistance of the concrete and the potential active or passive reinforcements.

#### 3.2.3 Checks of zones submitted to concentrated forces

The recommendations complete actual regular prescriptions dealing with verifications of beam end blocks (equilibrium of bottom wedge, equilibrium of the compression strut), and verifications of the distribution of the prestressed concentrated forces. They account for complementary resistance brought by fibres.

## 4. Durability of UHPC

The recommendations provide the main UHPC durability indicators proposed by the AFGC working group “durability indicators”.

The following table shows that the values obtained for UHPC indicate a clear improvement in durability, compared to any other types of concrete [22]:

| | OC | HPC | VHPC | UHPC |
|---|---|---|---|---|
| Water porosity (%) | 14 - 20 | 10 - 13 | 6 – 9 | 1.5 – 5 |
| Oxygen permeability ($m^2$) | $10^{-16}$ | $10^{-17}$ | $10^{-18}$ | $<10^{-19}$ |
| Chloride-ion diffusion factor ($m^2/s$) | $2.10^{-11}$ | $2.10^{-12}$ | $10^{-13}$ | $2.10^{-14}$ |
| Portlandite content ($kg/m^3$) | 76 | 86 | 66 | 0 |

*Table 1 Durability indicators for UHPC, traditional concrete and HPC*

Moreover, the recommendations deal with specific indicators to UHPC (stability of the admixtures, possible rehydration, corrosion of steel fibres, chemical aggression of polymer fibres).

So far all the available research and published results show that there is no real problem with any of these phenomena.

## 5. Conclusion

The "Interim recommendations on Ultra High Performance Fibre-Reinforced Concretes (UHPC)" constitute the first reference document serving as a sure basis for use of this new material in civil engineering applications.

The different applications built with this kind of material have demonstrated UHPC's great qualities, making particularly durable parts with outstanding mechanical performance.

Several projects in progress should make the technique going forward and contribute to the development of the material.

The publication of the AFGC-SETRA recommendations reinforced interest of foreign countries, and a UHPC Bridge has been built in United States on behalf of FHWA.

Within the framework of National Project MIKTI led by IREX, a feasibility study of UHPC slabs for composite bridges should demonstrate the interest of this material which presents little delayed shrinkage and creep effects.

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