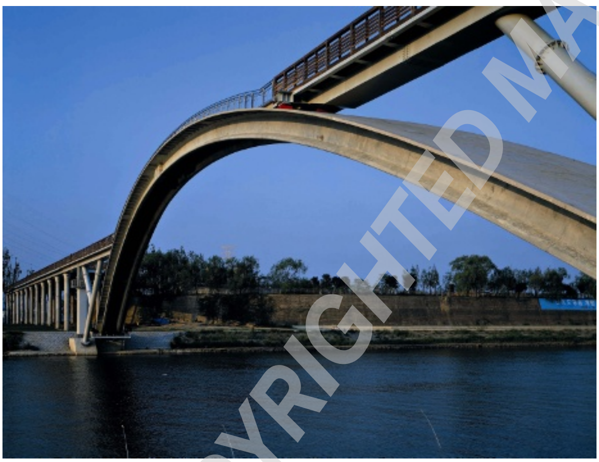
Part I

Genesis of a New Construction Material



Chapter 1

Introduction: What is a UHPFRC?

After recalling the definition of ultra high performance fiber-reinforced concretes (UHPFRC), this chapter details the basic elements of their composition. It presents the main products available on the market and provides a brief history of the development of these concretes. Then the chapter details the main features of UHPFRC, highlighting what distinguishes them from conventional concrete: heat treatment, delayed effects, compressive and tensile strength, performance in terms of sustainability and quality of the faces. The chapter analyzes the changes in design and implementation technology necessitated by UHPFRC development and ends with a presentation of the interest in these materials as part of sustainable development.

UHPFRC are materials with a cement matrix and a characteristic compressive strength between 150 MPa and 250 MPa. They contain steel fibers in order to achieve ductile behavior in tension and, if possible, overcome the use of passive reinforcement. UHPFRC differ from high performance and very high performance concretes in that:

– the systematic use of fibers ensures that the material is not brittle and can allow us to avoid any classical active or passive reinforcements;

– their compressive strength is generally greater than 150 MPa;

– their mix-design with a high binder content leads to the absence of any capillary porosity;

– the direct tensile strength of the matrix is systematically higher than 7 MPa.

Chapter written by Jacques RESPLENDINO.

The aim of UHPFRC development is to achieve high tensile strengths through participation of the fibers, which provide tensile strength after the cement matrix has cracked. When the tensile strength is sufficiently high, it may be possible, depending on the way the structure works and the way the loads to which it is subjected, dispense with conventional reinforcement. In general, we remove any traditional passive reinforcement cage in order to keep just the main passive or active reinforcement bars required when the resistance to major forces cannot be provided by the fibers.

1.1. The basis of UHPFRC mix-design

In ordinary concretes, the ratio of water to binder (W/B) is in the order of 0.4 to 0.6. To obtain a high performance concrete, the W/B ratio has to be decreased to below 0.4 (0.3 to 0.35). This reduction is possible thanks to the addition of an admixture (superplasticizer), which allows deflocculating binder, and cement with minimal amounts of water. In a high-performance concrete, if we wish, we can complement the W/B reduction with an extension of the granular spectrum through ultra-thin micrometer-sized additions (generally consisting of silica fume), 5 to 10 times smaller than the size of the cement particles. To obtain UHPFRC, we should further decrease the W/B ratio to below 0.25 (about 0.16 to 0.2). This decrease is generally obtained through a significant increase in the binder amount, and a quantity of water substantially the same as in conventional concrete. We should also add a large quantity of ultra-thin addition (typically silica fume) amounting about 20% of the cement mass. The UHPFRC aggregate size is also very small compared to ordinary concrete – the largest grain size is of the order of millimeters – and particular attention is given to the nature of the aggregates, which must present sufficient mechanical strength to avoid being the weak points of the mixture. The resulting material is extremely compact and has quite remarkable mechanical and durability performance.

With such a formulation we relatively easily obtain compressive strength above 150 MPa, but the material becomes fragile: explosive in compression with complete disappearance of any plastic domain. To avoid this problem, it is necessary to add fiber in order to restore ductile behavior in compression. For structural uses (when mechanical performance of the material is needed to ensure the structural strength) we use the steel fiber and fiber rate needed to ensure a non-brittle behavior in bending (about 2 to 3% by volume, i.e. 160 to 240 kg of steel per cubic meter of concrete, up to 10% by volume in high-performance formulations in which we seek to ensure perfect hardening behavior in pure tension). To implement such proportions of fiber, they are generally straight and not serrated to prevent urchin formation and to ensure a proper rheology of the UHPFRC. The fibers are small needles made of very high resistance steel. Their size is matched to that of aggregates in order to limit shock embarrassment aggregate-fiber: a length from 12 to 20 mm and diameter from 0.1 to 0.3 mm. Some UHPFRC include several sizes of fibers that may have complementary behaviors (microfiber improving the anchoring of larger fibers, and sewing the first networks of microcracks). The high fiber content used in UHPFRC gives them quite interesting tensile and shear strength (about 8 to 11 MPa in direct tension and 25 to 40 MPa in bending) that allows traditional passive reinforcement frames to be dispensed with. The steel reinforcement is limited to acting principal forces on large sections. To enable the design of structures without any reinforcements, it was necessary to develop rules for specific calculations. This objective absolutely necessary to produce a work in public domain was one of the main motivations that led to the drafting of the AFGC (Association Français de Gènie Civil) recommendations on UHPFRC.

1.2. The main UHPFRC available on the market

UHPFRC currently available on the market in France are:

– the different DUCTAL® concretes, including RPC (Reactive Powder Concrete) from the research program between Bouygues, Lafarge and Rhodia in France and marketed by LAFARGE;

– BSI/CERACEM® developed by the group with EIFFAGE SIKA;

– BCV® developed by the cement and the Vicat group Vinci.

Other UHPFRC have been used for various applications:

– CEMTECmultiscale® developed by LCPC, applied to several works in Switzerland and Canada; and

– laboratory materials developed by EDF, the CERIB (Centre d'Études et de Recherches de l'Industrie du Béton).

Abroad, we can note CRC (Compact Reinforced Composite) technology developed by Aalborg Portland Cement (Densit) in Denmark. Some products are developed in Germany and Japan, knowing that it is mainly BSI/CERACEM® and Ductal® techology that are used in Western Europe, and Ductal® is the leading technology employed in Asia, Australia and North America (US and Canada).

1.3. Brief history of the development of UHPC

Early research into UHPFRC was carried out by Professor Bache in the 1970s in Denmark through the development of CRC technology. This technology is still very active and probably accounts for the biggest worldwide production by volume of

UHPFRC. However, this is a special technology in which a large percentage of metal fiber is added to a cement matrix to produce prefabricated building structures (balconies and staircases) that are reinforced by traditional means calculated without taking into account the mechanical participation of the fibers.

In France, initial research on UHPFRC was in the 1990s under the leadership of Pierre Richard (Bouygues Group) through Reactive Powder Concrete (RPC) technology. The design was then optimized in the Lagarge research center at l'Isle d'Abeau in partnership with Bouyghes and Rhodia to develop Ductal®, the first marketed UHPFRC, which was launched in the late 90s. This technology is distributed both in Western Europe [BEH 03, HAN 06], Asia [BEH 03], Australia [CAV 03] and in the United States. It is used in all kind of structural applications, such as bridges and building, and also in non-structural cladding like street furniture and/or decorative and design objects.

Under the leadership of EDF (the French power company), which has been a very influential contractor in the development of UHPC, technology BSI/CERACEM® was created by Eiffage in the late 90s and then developed with the assistance of the company SIKA. This technology gives rise to the realization of a growing number of applications, both in the field of new structures [DEM 08, ELG 08, HAJ 03, HAJ 04a, HAJ 04b, RES, THI 02] and in repairing or strengthening old structures [GEN 04], mainly in France and Western Europe. In the 2000s, the cement company Vicat with the support of the Vinci Group has developed the BCV, which is also the subject of significant structural achievements [RES 06]. With the experience and potential of these materials [RES 08], France was the first country to issue recommendations in 2002 [BET 02, HAJ 04c, RES 04] to formalize methods to characterize the performance of these materials and to give rules to design UHPFRC structure without any frame other fiber that constitutes the major innovation of this type of material.

In the 2000s, several countries have engaged research on UHPFRC. The Japanese are very active. They published recommendations in 2004. They have made several outstanding designs [OKU 06] (footbridges, road and rail bridges) and currently have significant structural applications (components of high-rise buildings, airport structures in marine sites). In Australia, significant activity has developed based on the realization of structures [CAV 03] and the use of such materials in shields to protect against explosions. In 2005, the Germans started an ambitious program of research (€10,000,000) over six years involving a large number of universities under the guidance of the University of Kassel. They have little experience in the design and actual use of the material due to a lack of companies and building owners involved in the development of these technologies.

1.4. The main features of UHPC

This article does not purport to present all the mechanical characteristics of UHPFRC, but rather to highlight the specific performances that distinguish them from conventional concrete.

1.4.1. *Thermal treatment*

Some UHPFRC are subject to special treatment (called type 2 in the new recommendations) applied several hours after the concrete sets. This treatment consists of heating the element to a very high temperature (about 90ºC) and relative humidity close to saturation for approximately 48 hours. This treatment can significantly increase the durability and reduce delayed effects: no drying shrinkage and a very substantial reduction of creep. More traditional treatments, such as "steaming", applied in the early hours can possibly anticipate the beginning of the setting and accelerate the initial set of UHPFRC. These treatments are performed at a moderate temperature (about 40 to 50°C) and have a much smaller influence on delayed effects. Many UHPFRC are implemented without any heat treatment, which does not prevent them from very quickly developing resistance (greater than 70 MPa after a few hours). These mixtures often have a dormant phase before the setting phase, which is longer than conventional concrete. When setting starts, the increase in resistance is very fast.

1.4.2. *Shrinkage and creep*

Unlike ordinary concrete, the UHPFRC has a very low W/L ratio, which causes very high autogenous shrinkage (about 550 µm/m) and very small drying shrinkage (about 150 µm/m for UHPFRC without heat treatment, and no shrinkage after a type 2 heat treatment). The creep coefficient for UHPFRC without heat treatment is comparable to the coefficient obtained for HPC with silica fume (long-term creep coefficient between 0.8 and 1.0). After a type 2 heat treatment, the creep coefficient decreases dramatically (between 0.2 and 0.5). These characteristics have many implications on the performance and conditions of use of UHPFRC:

– the formwork of restrained pieces should be designed in order to allow free retraction and avoid important internal stresses or cracks;

– UHPFRC are ideally suited to precasting: after the end of the setting, subsequent delayed effects (shrinkage and creep) are very low compared to conventional concrete. This provides structural elements that do not "budge". This is especially true when the elements are subjected to a type 2 heat treatment;

– note that in the case of prestressing by pre-tensioning, a type 2 heat treatment has no influence towards limiting prestress losses: in fact, the heat treatment begins only several hours after the end of setting. It is made after the release of the cables and prestressing, so that the overall shrinkage causes prestress losses;

– on the other hand, in the case of post-tensioned prestressed concrete, applying a type 2 heat treatment to UHPFRC before prestressing tends to very significantly reduce the prestress losses due to a combination of lack of drying shrinkage and dramatic decrease in creep strains.

All these remarks are valid in the case of use of UHPFRC elements connected to a metal frame [TOU 05, TOU 08a, TOU 08b] or other material: the reduced delayed deformations of UHPFRC (shrinkage and creep) limit the internal forces due to the connection between the metal and the concrete.

1.4.3. *Compressive strength*

The UHPFRC behavior laws in compression are almost straight and have no real plastic range. The dispersions obtained on the compressive strengths are generally low due to the quality and homogeneity of the premix. Note that the very large compressive strengths (from 150 to 250 MPa) oblige us to reduce the size of the specimens compared to ordinary concretes (capacity presses are required) and special care is required in their creation. These requirements lead some firms to carry out checks using tests on cubes that are easier to make. This approach is accepted by the recommendations subject to having well-calibrated and justified correlation curves between strengths obtained on cubes and those obtained on cylinders in advance.

1.4.4. *Tensile strength*

The biggest challenge for UHPFRC, and what distinguishes them radically from the other concretes, is tensile strength. This concerns the strength of the material before cracking and the post-cracking resistance that involves mainly fiber strength. The tensile strength before cracking poses no real problem. Indeed, if control of the setting is correctly implemented (formulation, mixing time), it yields a low dispersion of the tensile strength of the cement matrix that governs the resistance before cracking. However, the fundamental issue of UHPC is to get control and ensure the strength after cracking in any structure knowing where this resistance depends on the orientation of the fibers, which depends on the conditions of implementation:

– any potential flow during casting tends to orient the fibers in the direction of flow;

– the fibers close to the walls tend to be oriented parallel to the formwork. This phenomenon only occurs for a depth less than or equal to the length of fiber. It has all the more influence on the tensile strength that the thickness of the structure is close to the fiber size;

– a preferred orientation of fibers in the direction of gravity can sometimes occur due to the natural behavior of fibers in the viscous liquid phase of the concrete before setting.

To better control the orientation of fibers during implementation, the general principle is to create the pieces by putting UHPFRC directly to its final position, to avoid flows. If we cannot remove flows, we try to compensate for and/or direct the flow in the direction of the main forces. In any event, to validate the process of implementation, we systematically perform a suitability test upstream of the actual structure. This suitability test consists of creating a specimen representative of the real structure, made of the same material and realized using the same procedures as those proposed for the execution of the actual structure. In that element we cut out several prisms in the direction of the main forces and perform bending tests in order to determine the actual tensile behavior law in the structure and correct the outcome of the theoretical law of laboratory specimens (the concept of the corrective coefficient K).

For structures of substantial thickness for which the wall effect is limited, the size of specimens for tensile bending test must be relatively large compared to fiber size. Indeed, if the size of the prism is too small, the wall effect tends to comb the fibers in the direction of the prism (they are parallel to the edges) and it overestimates the actual strength of the laboratory material. Conversely, if the size of the specimens collected in the structure is too small, we obtain a very important dispersion on sawn samples that tends to underestimate the actual strength of the structure, or even render the statistical analysis of these samples impossible.

Conversely, for thin elements in which the wall effect is fundamental (thickness of the element minus three times the fiber length, tending to favor a 2D orientation of the fibers), we directly test elements of the same thickness as the actual structure, both for prior laboratory tests and suitability tests.

1.4.5. *UHPFRC durability*

UHPFRC materials are by definition extremely close and compact. They have a special porous structure characterized by an absence of porosity and capillary porosity in very small non-interconnected scale (see Figure 1.1). This feature gives them quite exceptional performance in term of durability: water porosity, air permeability and chloride-ion diffusion factors are greatly reduced compared to ordinary or high-performance concrete. These performances make them suitable for all structures subjected to aggressive external environments [BEH 07]. Furthermore, their resistance to abrasion (Compagnie Nationale du Rhône – CNR test) and resistance to dynamic effects [SER 98, TOU 99] make it particularly relevant to applications for the protection of hydraulic works or structures subjected to shocks or explosions. Note that in shocks, the presence of small fibers limits the flying chips, which can sometimes pose safety risks for people.

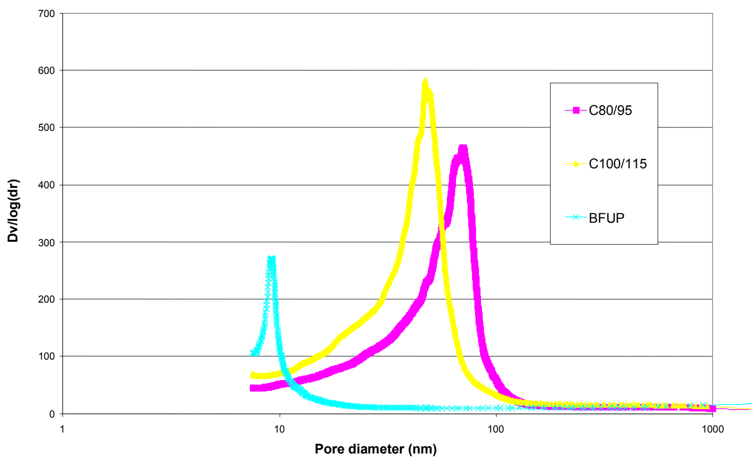


Figure 1.1. *Distribution of pore sizes for different concretes (courtesy of CERIB data)*

1.4.6. *Formed surfaces and esthetic aspects of UHPFRC*

The very compact characteristics of UHPFRC and the fineness of the material allow us to obtain surfaces of very high architectural quality, with the possibility of using a very fine matrix for the formwork. Yet esthetic problems may appear on unformed surfaces and due to trace oxidation related to the presence fibers at the surface of the walls in clear tint concrete, observable at short distances. Regarding unformed surface treatment, great care must be taken to curing. Several techniques can be used for leveling and/or smoothing unformed surfaces to avoid fibers that go beyond the surface. These treatments include the application of plastic or rubber spike rolls to fit the fibers and set the surface, avoiding adhesion problems related to the viscosity of the material. Techniques using slippery sheets can obtain similar results, while providing interesting solutions. For limiting the quantity of fibers appearing on the formed surfaces, efforts must be made on mix-proportioning and on the nature of the formwork to avoid any apparent fiber at the surface; such efforts thereby eliminate the risk of rust spots later. The joints between form panels should be completely sealed. If a significant number of fibers appear at the surface, special surface treatments can be implemented to prevent further corrosion of the fibers. Note that in architectural applications made with a white premix, CRC technology provides the implementation of stainless steel fibers. This technology is not common and has never been tested for a structural UHPFRC without passive reinforcement (CRC Danish technology combines UHPFRC with traditional passive reinforcement). Similarly, for certain precast applications we can make sandwich panels from steel fiber UHPFRC bordered by a surface layer made of an organic UHPC fiber. One of the main UHPFRC uses, for esthetic and architectural purposes, is that any shape can be created knowing that there are no longer geometrical constraints due to traditional reinforcement cages.

1.5. UHPFRC: a material that needs to revolutionize the technologies of design and implementation

The design and implementation of structures made of UHPFRC require removal of the reflexes that exist in traditional reinforced or prestressed concrete. The volumes of structures are further modified with widths that can bevery thin, which can be alarming to the uninitiated but which are often perfectly appropriate. The reduction in thickness promotes the fiber orientation and increases the resistance of the material. The absence of reinforcement makes the notion of minimum thickness required for steel reinforcement coating redundant. The ability to make very slender parts requires vigilance with regards to deformation and verification efforts, especially during transitional phases like handling or assembly. In addition, the more slender the elements are, the more reduced the dimensional tolerances have to be. Manufacturing processes and controls must be adjusted accordingly. The shape of the formwork must be completely reviewed. Traditional structures include angles allowing an easy shaping of the reinforcement frames. With UHPFRC rounded surfaces are better as they facilitate the implementation of the material and avoid discontinuities of flow.

The lack of reinforcement allows us to design all forms of structures as long as the geometry is coherent and provides a good resistance to the effort. The formwork technologies should evolve through solutions made in plastic or polystyrene automatically cut to create any 3D shapes. The development of prefabrication should go hand-in-hand with research on connections between elements to achieve the most efficient transmission of forces, tightness and durability of the assembly. UHPFRC as an almost inert material should be developed in the design of composite structures and/or as a connection solution between a steel frame and a traditional part in reinforced concrete. A major hindrance to the development of the material is probably related to the methods of calculations, which are not traditional for engineers. Strength calculations of fiber-reinforced concrete are poorly understood. It is the same for methods of tensile strength testing in bending, which are little known by laboratories and require specific digital tools (inverse method).

1.6. UHPFRC and sustainable development issues

A UHPFRC contains about twice the cement volume as conventional concrete, and thus produces twice as much CO_2 and consumes twice as much energy in production. Yet experience using UHPFRC shows that if used appropriately, the quantities of material used in a structure can be divided by two or three. A UHPFRC structure therefore provides a slight gain in terms of initial CO_2 footprint and energy compared to a conventional solution. It also offers a significant gain in terms of durability, lightness and global economy of material. It is therefore important to incorporate an anticipation of sustainability earnings enabled by UHPFRC solutions; this is particularly relevant when searching for long-life or evolutive structures and when taking into account economic cost, image, operating constraints and the environmental costs of all operations of maintenance required by traditional solutions.

1.7. Conclusion and outlook

The design and construction of UHPFRC structures require us to dispose of the reflexes attached to traditional reinforced or prestressed concrete. UHPFRC are not revolutionary materials, in the sense that their cost of production and implementation is still high and requires optimization to ensure a significant financial gain. Niches exist and powerful applications tend to increasingly grow as far as durability, esthetics, timeliness for erection, scalability, possible layouts and material gain are concerned. These uses are growing and UHPFRC can bring real innovative responses. Researches and important projects currently under way will further strengthen their medium-term development and contribute to further demonstrate their structural and architectural potential.

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