
STATE-OF-THE-ART REPORT ON ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

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ABSTRACT

Ultra - High Performance Concrete (UHPC) is a special material with compressive strength higher than 150 MPa and an increased durability, which is reflected in its name. It was discovered by Japanese researches in the mid eighties, but since then the study of this material has been expanded all over the world. Besides its high - strength it has an enhanced ductility, due to the presence of steel fibers in the concrete matrix. It can be used as structural material for buildings located in areas with high seismic risk and also in marine or industrial (where chemical attack is possible) environments. This type of concrete is still in the research-development stage, no design standard being available.

Keywords: ultra-high performance concrete; physical and mechanical properties; applications

REZUMAT

Betonul de ultra-înaltă performanță este un material special cu rezistență la compresiune mai mare de 150 MPa și durabilitate sporită, motiv pentru care poartă numele de beton performant. A fost descoperit de japonezi la mijlocul anilor 80, iar de atunci studiul acestui material s-a extins la nivel mondial. Pe lângă rezistența ridicată are o ductilitate sporită datorată prezenței fibrelor de oțel în matricea betonului. Poate fi utilizat în zone cu risc seismic ridicat la structuri zvelte și de asemenea în mediu marin sau cu atacuri chimice. Acest tip de beton este încă în faza de cercetare-dezvoltare, nefiind încă disponibile norme de proiectare structurală.

Cuvinte cheie: beton de ultra-înaltă performanță; proprietăți fizico-mecanice; aplicații

1. INTRODUCTION

Ultra - High Performance Concrete (UHPC) is a special concrete having an ultra - compact matrix and special physical and mechanical properties, such as: compressive strength greater than 150 MPa, tensile strength greater than 20 MPa, very low water and gas permeability and, by addition of steel fibers, an enhanced ductility [1]. The strength limits of this concrete depend on the matrix composition, thermal treatment type, quantity and type of dispersed fibers. As the lower strength limit is usually represented by 150MPa, is nowadays represented by 800MPa, when special treatments are applied [2]. A report was published in 2004 in Germany on state of the art on Ultra - High Performance Concrete at global level [3]; in USA another report was published in 2006 [4], about the physical and mechanical properties

of this type of concrete, the Ductal® term was used for the first time defining the UHPC.

In Japan, JSCE gave recommendations for mixing and transportation of UHPC reinforced with steel fibers [5].

Redaelli [6] recommended for optimization of UHPC mixtures some fundamental principles as: elimination of large-sized aggregates, use of reactive powders (silica and quartz powder), reducing water/cement ratio, using chemical additives, using of an optimized granulometric curve, heat treatment (with or without vibro-pressing) and addition of steel fibers.

Due to its good corrosion behavior this material needs no maintenance during service life.

2. UHPC APPLICATIONS

The use of UHPC allows construction of economic and sustainable buildings. Its increased resistance as well as its high

ductility makes UHPC the most advanced material in the high-rise building domain. It may also be used for bridge decks, manufacturing halls, thin membranes and slender columns.

Among the uses of UHPC there are large span slender girders for bridge [7] (Fig. 1).



Fig. 1. UHPC girders [7]

By comparing UHPC with usual reinforced concrete and high performance concrete cross sections for beams [7], an important reduction of material consumption is revealed. The cross section of UHPC for the same load bearing capacity is comparable to a steel one, as it can be seen in Fig. 2.



Fig. 2. Concrete and metal sections at equal load carrying capacity [7]

Other UHPC applications for bridges are:

- The Seonyu Pedestrian bridge from Korea [7], shown in Fig. 3, where both the arch and the deck were made out of this material;



Fig. 3. Seonyu Pedestrian Bridge (Korea, 2002) [7]

- The pedestrian bridge Sakata Mirai in Japan, where the supporting beam, shown in Fig. 4, was cast using UHPC;



Fig. 4. Pedestrian bridge Sakata Mirai (Japan, 2002) [7]

- The Washington bridge [7] in USA (Fig. 5), where π UHPC girders were used.

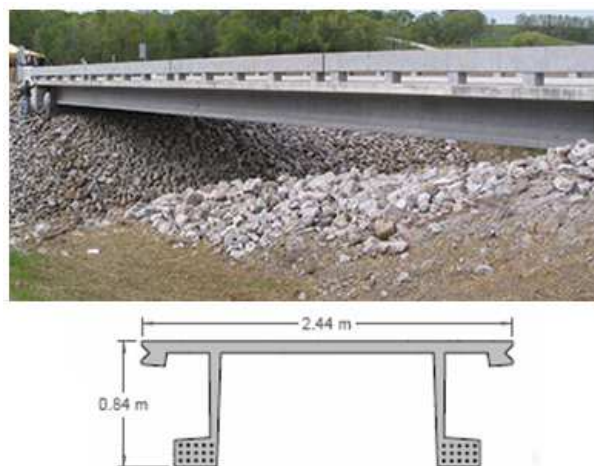


Fig. 5. Washington bridge (USA, 2004) [7]

Another application of the UHPC is for structures in aggressive environments where the durability performance is a demand.

As an example of industrial environment, in France, a cooling tower [7] exposed to chemical attack was made of UHPC (Fig. 6).

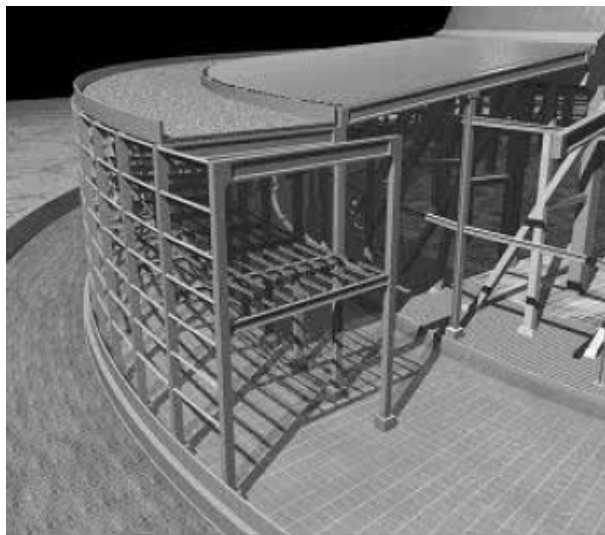


Fig. 6. Beams made of UHPC for a cooling tower (France, 1998) [7]

An example of marine environment use is the dock footing spatial concrete anchors exposed to chloride attack in Fig. 7 [7].

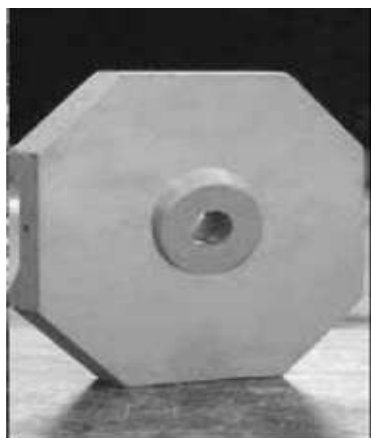


Fig. 7. Marine anchors in environments with chloride attack [7]

UHPC can also have architectural applications. In 2003 it was used to create the canopy of the Shawnessy station in Canada (Fig. 8) [7].

Another architectural application was to create decorative panels for a subway station in Monaco (Fig. 9) [7].



Fig. 8. Shawnessy station canopy (Canada, 2003) [7]



Fig. 9. Decorative panels for a subway station (Monaco, 1999) [7]

UHPC was used not only in construction or architectural domain. It found different applications which does not have connection with these fields. Due to its viscous composition it can take different shapes.

In France shower cabins were made, as presented in Fig. 10 [7], as well as flower supports shown in Fig. 11 [7], using UHPC.



Fig. 10. Shower cabins (France, 2000) [7]



Fig. 11. Flower supports (France, 2003) [7]

3. PHYSICAL AND MECHANICAL PROPERTIES

Physical and mechanical properties of UHPC are improved by using of steel fibers reinforcement. A fiber content of 2% seems to be the optimum amount to obtain superior properties [8]. The ultimate tensile strength is two times higher than the strength at the moment of first crack occurrence. In the case of UHPC, tensile strength 20-30 MPa can be up to ten times higher, compared to a usual concrete. Such increase of tensile strength can partly eliminate the constructive reinforcing bars or/and stirrups from the element. In Fig. 12, the crack pattern of a failed UHPC element subjected to bending is presented [9].

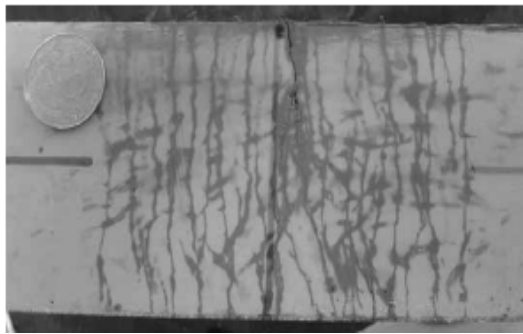


Fig. 12. Multiple cracking on a bent element made of UHPC [9]

3.1 Compressive strength

Uniaxial compressive strength is the main criterion in the definition and evaluation of the concrete performance. Any analysis of the complex state of efforts is based on compression strength. A normal concrete can resist under compression stress up to 60% of the strength without cracking. Up to this level micro-cracks are localized in isolated areas, and they appear at the interface between the matrix and the aggregates [9]. The compressive strength of UHPC is weakly influenced by the addition of fibers. For values of fiber amount above 2%, the compressive strength is not influenced at all. The specimen type can influence the compressive strength. Thus, some relationships between compressive strength and sample shape are given by the following equations [9]:

$$f_{cube,200} = 1.10 f_{cyl\phi150 \times 300} \quad (1)$$

$$f_{cube,100} = 1.15 f_{cyl\phi100 \times 200} \quad (2)$$

where: $f_{cube,200}$ is the compressive strength on 200mm cubes, $f_{cyl\phi150 \times 300}$ is the compressive strength on cylinders with diameter of 150 mm and height of 300 mm, $f_{cube,100}$ is the compressive strength on 100 mm cubes, $f_{cyl\phi100 \times 200}$ is the compressive strength on cylinders with diameter of 100 mm and height of 200 mm.

The thermal treatment has an important role in developing high levels of compressive strength and also in obtaining low shrinkage and high durability.

3.2 Tensile strength

The tensile behavior of steel fibers reinforced UHPC can be analyzed based on the stress-strain curve. In contrast with a concrete without fibers, the post-elastic bearing is more extended. The curve can be characterized by three zones, namely: elastic behavior, consolidation behavior and plastic deformation behavior, as shown in Fig. 13 [10]. The whole process is based on the bond between steel fibers and concrete matrix. When the bond is lost without fiber slipping, then the failure becomes brittle [11]. It is important to have a certain amount of fibers to allow slipping, creating a ductile behavior. The fiber stress should not exceed 80 - 90% of the ultimate resistance of fibers. This can be ensured when the following relationship is accomplished:

$$f_{s,f} * V_f > f_{ct,m} * V_m + \sigma * V_f \quad (3)$$

where: $f_{s,f}$ is the tensile strength of the fibers, V_f is the fiber volume, $f_{ct,m}$ is the tensile strength of concrete, V_m is the matrix volume and σ is the stress in the considered fiber.

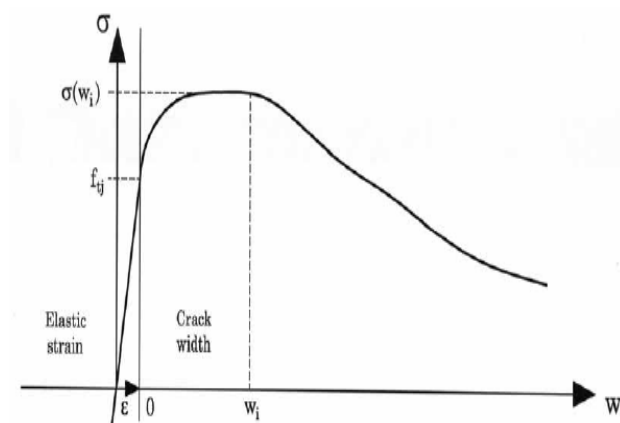


Fig. 13. Stress vs. crack width curve for UHPC [10]

The post-elastic behavior must be taken into account because it provides the ductility of the element. The post-elastic zone does not appear in the normal concrete diagram. Post-elastic behavior is influenced by the fiber orientation in the element. It is known that the micro-cracks appear after the tensile strength of the concrete is reached [11]. Based on this fact, a model was developed concerning the UHPC behavior under direct tensile stress (Fig. 14) [11], defined by four loading stages.

In the first stage, micro-cracks appear in cement paste. In the second stage micro-cracks are developing. Then, in the third and fourth stages, micro-cracks become macro-cracks and the tensile effort is taken by the fibers.

The grip between fibers and concrete matrix, ensure a ductile failure of the element. This mean the displacements are increasing under constant loads.

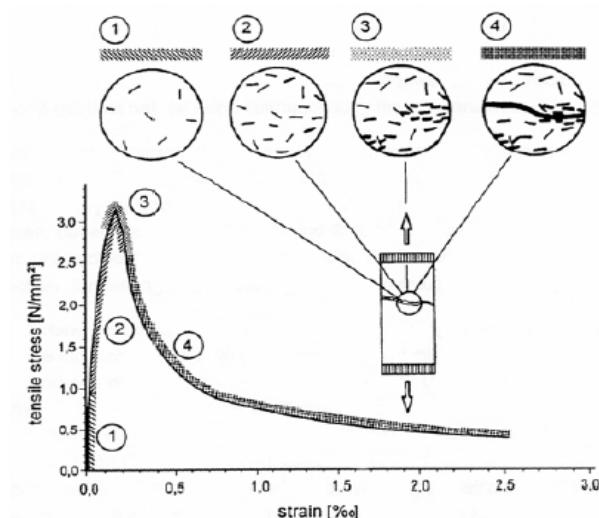


Fig. 14. Tensile behavior of UHPC [11]

The bending tensile strength [11] can be defined by the following relationships:

- Four-point bending:

$$f_{ct, fl} = \frac{Fl}{ah^2} \quad (4)$$

- Three-point bending:

$$f_{ct, fl} = \frac{3Fl}{2ah^2} \quad (5)$$

where F is the peak force, l is the span between supports and a and h are the cross-section dimensions.

3.3 Modulus of elasticity

The modulus of elasticity represents the relation between stress and strain, and it can be described according to the theory of elasticity as the ratio between the stress variation $d\sigma$ and the corresponding strain variation $d\varepsilon$ around a point on the characteristic curve. According to SR EN 1992-1-1:2004 [12], the elasticity modulus is expressed as static modulus or secant modulus and it is calculated with relation (6):

$$E_{cm} = 22000[(f_{cm})/10]^{0.3} \quad (6)$$

where E_{cm} is the secant modulus and f_{cm} is the average compressive strength.

This relationship is applicable only to concretes having strengths up to 90 MPa.

Other authors [11] proposed another relationship for concretes with compressive strengths between 90 MPa and 120 MPa:

$$E_{cm} = 21500 * \alpha_E * [(f_{cm})/10]^{0.3} \quad (7)$$

where α_E depends on aggregate nature and f_{cm} is the average compressive strength.

ACI Committee [13] proposed a relationship for the modulus calculation, for high - performance concrete with strength of 83 MPa:

$$E_c = 3320\sqrt{f_c} + 6900 \quad (8)$$

where E_c is the modulus of elasticity and f_c is the compressive strength of concrete.

3.4 Chemical attack

Steel fibers reinforced UHPC resists to chemical attack of acids better than normal concrete or high-strength concrete. In Spain, UHPC elements were tested at calcium sulfate, ammonium sulfate, acetic acid, nitrate and sea water attack [14]. The results were very good with no weight and strength loss for UHPC members. Also the concrete was tested to gas attack (CO_2 , CH_4 , S_2H) at 120 °C and in high pressures of 7 MPa environment. During these tests, a new phenomenon was seen, namely the „self-sealing” of concrete. This means that the cracks are closing due to the hydration of the cement that remained non-hydrated in the hardening process (Fig. 15) [14].

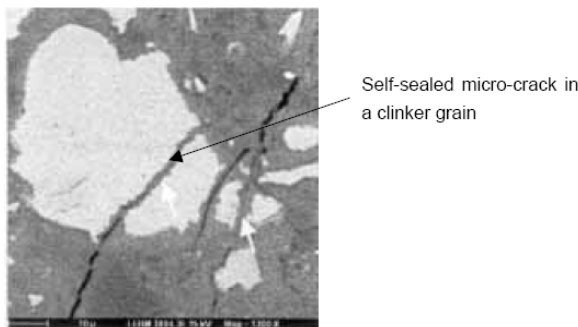


Fig. 15. Self-sealing phenomenon [14]

3.5 Creep and shrinkage

Creep is defined as time-dependent strain caused by a constant long-term load. Creep has two components, namely: basic creep and drying creep. Basic creep is a time-dependent strain that occurs in sealed samples, while drying creep occurs in elements exposed to the environment.

Graybeal B. and Davis M [15] proposed a diagram which defines the creep phenomenon of UHPC (Fig. 16) [15]. The diagram was obtained from tests on cylindrical samples ($\varnothing 150 \times 300 \text{ mm}$) subjected to compression and rectangular samples ($60 \times 30 \times 300 \text{ mm}$) subjected to tension. The tests shown the compression creep is equal to tension creep.

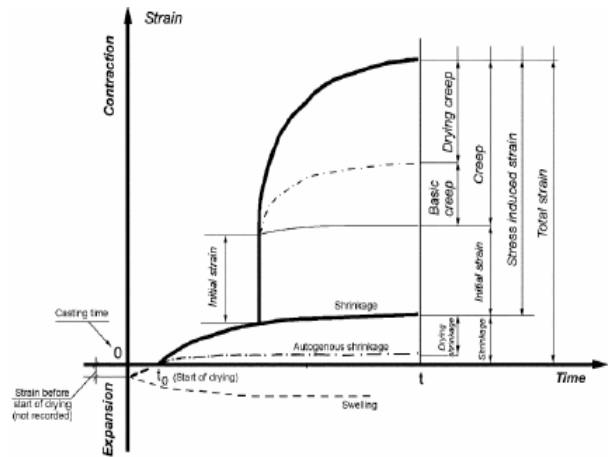


Fig. 16. Creep phenomenon of UHPC [15]

UHPC creep occurs following the steps: viscous creep of gels resulted after the cement hydration; infiltration of water from the gels in capillary spaces and possibly evaporation into the environment; water evaporation through micro-cracks.

The CEB-FIP Model Code 2010 [16] defines creep of high-performance concrete using the following relationship:

$$\varepsilon_{cc}(t) = \varepsilon_c(t) - \varepsilon_{cs}(t) - \varepsilon_{ci}(t_0) - \varepsilon_{cT}(t) \quad (9)$$

where: $\varepsilon_{cc}(t)$ is the total creep strain; $\varepsilon_c(t)$ is the total concrete creep strain at a certain age; $\varepsilon_{cs}(t)$ is the concrete creep strain at the same age; $\varepsilon_{ci}(t_0)$ is the instant creep strain given by loading and $\varepsilon_{cT}(t)$ is the heat treatment strain of concrete.

The total creep strain of UHPC (including elastic strain) having a water/cement ratio (w/c) of 0.17 [17] can be expressed as:

$$\varepsilon_l(t_0) = \frac{\sigma}{E_i} [1 + \varphi_f f(t - t_0)] \quad (10)$$

where σ is the loading stress, E_i is the elasticity modulus, φ_f is the creep ratio and $f(t - t_0)$ is a coefficient depending on the heat treatment.

Shrinkage is defined as the decrease of concrete volume with time. According to [17] the decrease is due to water volume changing

in the concrete and to physical and chemical changes that occur in the absence of an external load. Shrinkage types are: drying shrinkage; autogenous shrinkage and carbonation shrinkage. The relationship for estimating the shrinkage of an UHPC is:

$$(\varepsilon_{sh})_t = \frac{t^a}{f + t^a} * (\varepsilon_{sh})_u \quad (11)$$

where f is the concrete age in days, $(\varepsilon_{sh})_u$ is the strain from shrinkage, t is the time after heat treatment and a is the specimen shape coefficient.

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4. CONCLUSIONS

UHPC is a relatively new material with high strength and increased durability that has various applications in structural and architectural design.

The main features of UHPC are: compressive strength higher than 150 MPa; tensile strength greater then 20 MPa when steel fiber reinforcement is used; a good behavior in aggressive environments and, in contrast to the normal concrete have practically no shrinkage and creep.

Another specific phenomenon in case of fiber reinforced UHPC is cracks self-sealing after force release and in wet conditions.