# DAMAGE RESISTANCE AND MICROMECHANICAL ANALYSIS OF ULTRA HIGH PERFORMANCE CONCRETE.

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## ABSTRACT

A new generation of fibre reinforced Ultra High Performance concrete (UHPC) with an improved damage resistance is designed on a multi-scale reinforcement concept. Compositions with a better crack initiation control through improved matrix toughness Gc are developed from specific additives with chemical reactivity (modification of hydrates - CSH) and/or anisotropic geometry (toughening mechanisms) : Gc > 25 J/m$^2$. The fibre-matrix interface (adhesion, sliding) and the fibre characteristics (l/d ratio, fibre strength, effective volumic fraction) controls the crack propagation resistance : in case of metallic fibre, an increase of the interface shear strength $\tau_d$ (> 15 MPa) is proposed via surface treatment (reactivity, roughness). Reactive organic fibres (PVA) can be used in place of steel fibre.

The use of both a high toughness matrix and highly bonded short fibres leads to new concretes (DUCTAL®) with improved mechanical performances by controlled micro-cracking and fibre pull-out.

## INTRODUCTION

The development of ultra high performance cement based materials has been possible by the control of i) processing parameters and constituents that affect rheology and optimal particle packing, and ii) chemical reactivity of the constituents [1]. Very high compressive strength are reported with Densified Small Particles (DSP) concept [2], but these materials are difficult to use and quite expensive. The concept of high packing density has been recently reviewed, as a key for the processing of ultra high performance concrete [3]. Steel fibre reinforcement at different scale was proposed [4].

Reactive Powder Concretes (RPC) are recently developed Ultra High Performance Concrete (UHPC), which present an increased homogeneity by elimination of coarse aggregates (Dmax < 2 mm) and a packing arrangement that combined density of hardened state and rheology of the paste. [5]. The use of a relatively small amount (< 2 % vol.) of steel micro-fibres leads to an improvement of the ductility in tensile state : strain softening (pre-peak) and well controlled crack propagation (post-peak).

The microstructure of RPC is quite particular, with a very small porosity (typically below 2% after activation of the pozzolanic reaction : heating at 90°C), and a limited hydration reaction degree (large part of the clinker particles, typically 50%, unhydrated). RPC have very high compressive strength of about 200 MPa, and fracture energy of 15 kJ.m$^{-2}$ [6].

However, the extensive use of UHPC concretes, in engineering structures as in other applications, needs to reduce the dissymetry between tensile and compressive behaviour and to avoid thermal treatment. New concretes DUCTAL®are developed in this manner.

## FRACTURE BEHAVIOUR OF FIBRE REINFORCED UHPC : DAMAGE RESISTANCE ANALYSIS

Reinforcement in fibre reinforced composites, and especially in UHPC, occurs through strengthening, i.e. increase of the strength of the composite $\sigma_c$ over that of the matrix $\sigma_m$, or toughening, i.e. development of energy absorption mechanisms. Strengthening is developed through a stress transfer from matrix to fibres, which requires a fibre content Vf > Vc (critical volume) as well as a good fibre-matrix adhesion (interface shear stress : $\tau_i$). Toughening requires partial debonding and pull-out of the fibres bridging the cracks.

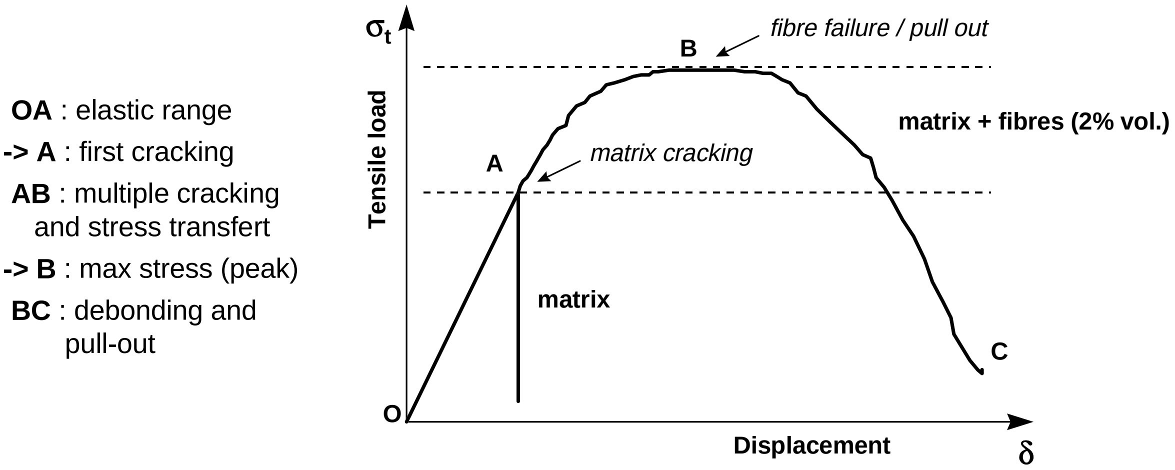

**Figure 1 :** Schematic stress-displacement curve for fibre reinforced UHPC

A schematic stress-displacement curve is shown in Figure 1. The overall mechanical behaviour can be described in terms of : i) elastic range up to the first damage (single crack) : crack initiation (OA);
ii) multiple cracking, stress transfer (matrix to fibres) and partial debonding with fibre pull out : crack propagation (AB + BC).

The crack initiation can be described by the Linear Elastic Fracture Mechanics, such as Kc or Gc. An energy balanced approach was proposed by AVESTON et al. (ACK model) [7]. In case of crack propagation, the analysis has to take into account the matrix and fibres (interface) characteristics. Several models have been developed [7, 8, 9].

Assuming a constant frictional bond strength, $\tau_f$, and a uniform distribution of the embedded length between 0 and l/2, the average resistance of a fibre to pull-out is : $\tau_f \pi dl/4$ (l : fibre length, d : fibre diameter). The number of aligned fibres per unit area is : $4V_f/\pi d^2$, and the composite ultimate strength $\sigma_c$ will therefore be proportional to $V_f \tau_f$ l/d :

$$\sigma_c = K V_f \tau_f l/d. \qquad (1)$$

The dissipated energy (Wf) is mainly due to fibre debonding and pull-out : interface must be not too cohesive, so as to assure sliding

A multi-scale reinforcement is proposed to design new high performance concretes :
- improvement of the matrix toughness Gc : micro-scale reinforcement;
- control of the fibre/matrix interface (adhesion /sliding) : macro-scale reinforcement.

## IMPROVEMENT OF HIGH PERFORMANCE CONCRETE THROUGH MATRIX TOUGHNESS

The mechanical behaviour of fibre reinforced concrete (FRC) can be well improved via the matrix itself [10].

If we consider the Linear Elastic Fracture Mechanics (Griffith criteria), the fracture stress is controlled by both the defect size (a) and the fracture toughness (Kc, Gc) of the material :

$$\sigma f = \frac{Kc}{Y\sqrt{a}} = \frac{1}{Y}\left(\frac{E.Gc}{a}\right)^{1/2} \qquad (2)$$

The mechanical behaviour of UHPC matrix (without fibres) is generally very brittle : tensile strength remains at a low level, because of its low fracture toughness.

Different toughening mechanisms can be developed in brittle materials so as to increase the critical energy release rate $G_C$ :

$$G_C = G^0{}_C + \Delta G. \qquad (3)$$

where $\Delta G$ corresponds to toughening mechanisms.
These mechanisms are operating in the vicinity of the critical defect (Griffith crack) by modifying the stress field ahead of the crack (crack shielding) or by developing specific interaction between cracks and some heterogeneities (crack interaction) [11]. For instance, in concrete, the additions of fillers (sand , aggregates) enhances the fracture toughness [12].

***Improvement of toughness matrix Gc.***
Both compressive and tensile strength of concrete can be improved -without metallic fibres- through a specific design using micro-scale reinforcement. These materials are characterized by a dense microstructure, due to the particle packing, combined with the presence of toughness promoting fillers.
Good results can be obtained with non isotropic filler, i.e. acicular or platelet morphology. In case of isotropic particles, interesting effect are developed in presence of some chemical reactivity : a control of hydrates morphology can be considered.

The concrete fracture toughness(without fibre) is measured from bending test on single edge notched beam (SENB) : a V notch is carefully machined with a diamond blade on 40x40x250 prisms, to a relative length a/w of about 0.4 (a : crack length, w : specimen size = 40 mm).

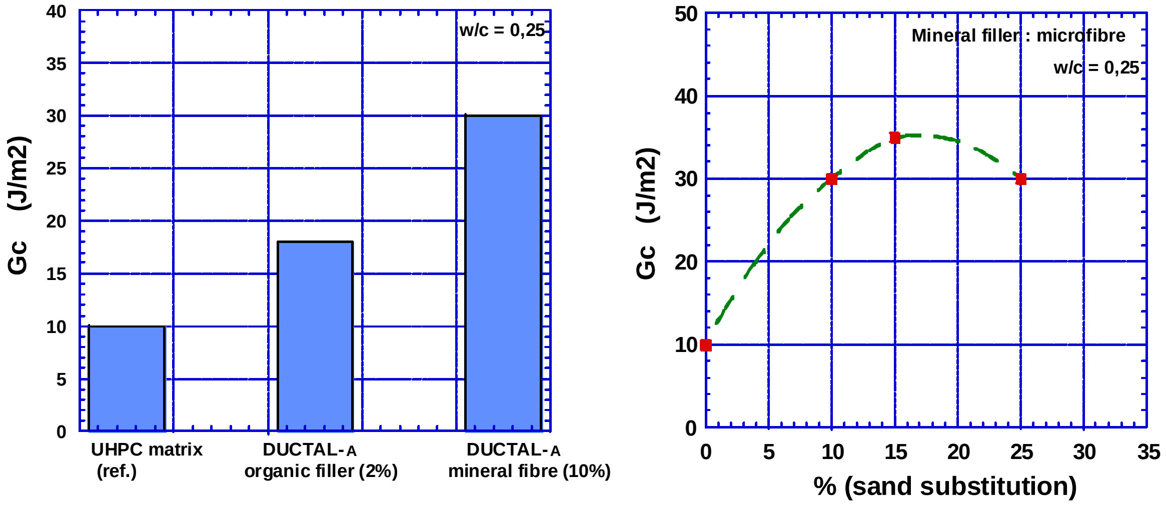

**Figure 2 :** Fracture toughness Gc of UHPC and DUCTAL® concrete matrix.

The critical stress intensity factor $K_C$ is obtained from the fracture load $F_C$ and the crack length $a_C$ at instability point (ASTM E399-83). $G_C$ is obtained from $K_C$ and E (plane strain conditions).

Natural inorganic micro-fibres for instance are very convenient for use in cement [13]. Mica flakes or wollastonite micro-fibres can be incorporated by partial substitution of the sand : the fracture toughness Gc is increased from 10 J/m$^2$ up to values higher than 30 J/m$^2$. Very high performances can be obtained with 10% of sand substituted by wollastonite, with a w/c ratio of 0.21 and a slump of about 200 mm. Similar results are obtained with mica, or hydrophilic (reactive) organic microfibres.

An optimum is obtained, which correspond to a compromise between toughness and rheology (figure 2). A dependance with the water content has been observed : the toughening effect decreases as the w/c ratio is higher than 0.27.

### *Fibre reinforced concrete : analysis of crack propagation (R-Curves)*

The resistance of materials toward propagation of a single crack in presence of fibre reinforcement cannot be taken into account by only the Gc criteria : it is necessary to use the R-Curve criteria, defined as fracture resistance R. R represents the fracture toughness and is a function of the crack extension [14].

Because of a non linear behaviour due to the fibre reinforcement, the fracture mechanics of these multi-scale toughened concretes have been experimentally analysed with the J-integral approach : J-Δa curve [15].

The fracture toughness (J-Δa curve) is measured from bending test on single edge notched beam (SENB), according to ASTM E813-89. It is not possible to experimentally determine the blunting line : the critical value Jc criteria is defined as the J value corresponding to a crack propagation of 0.2 mm (cf. ESIS protocole P1-92, on Polymers and Composites).

Micro and macro toughening mechanisms are operating in these materials, leading to enhanced damage resistance at both crack initiation and crack propagation stage.

TABLE 1

Typical concrete composition (DUCTAL-A)

| Cement | Sand | Silica flour | Silica fume | Microfibre | Steel fibre | Super plasticizer | Water (w/c) |
|---|---|---|---|---|---|---|---|
| 1 | 1.25 | 0.1 | 0.15 | 0.2 | 0.22 | 0.016 | 0.21 |

The cement is a Portland cement with a high content of silica (HTS Lafarge). Sand and silica flour are quartz grade of 300 and 5 microns size. The silica fume is a low alkali and carbon content one. The superplasticizer is a PEG-based (OPTIMA 100, Chryso).

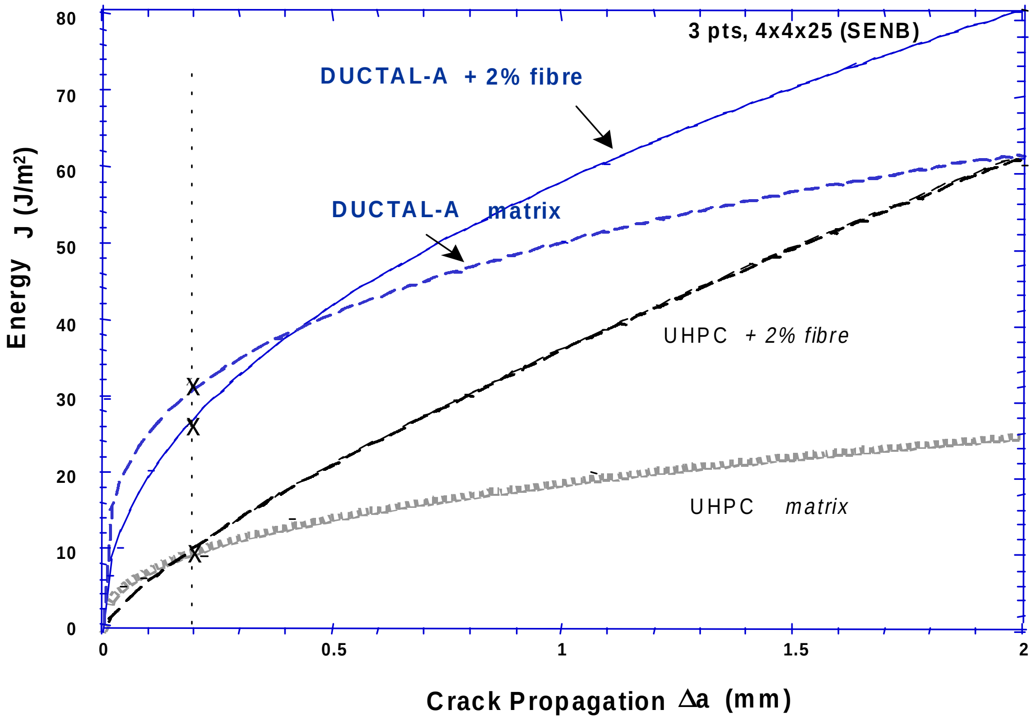

**Figure 3 :** Concrete damage resistance (J-Δa curve) : matrix and fibres contribution.

With micro-fibres, the Jc value (crack initiation critical energy) is: Jc = Gc = 30 J/m$^2$ (to compare with UHPC : Jc = Gc = 10 J/m$^2$). The dJ/d(Δa) crack propagation parameter is not affected by the presence of toughening filler (wollastonite), and increase with metallic fibre content (2%) as in figure 3.

***Mechanical performance : bending / tensile behaviour***

The mechanical behaviour of these new materials is well improved, as a consequence of the increase of matrix toughness.

Mechanical properties are measured on 40x40x250 mm specimen (3 pts bending - span : 200 mm), cured at room temperature (20°C, 28 days) : figure 4.

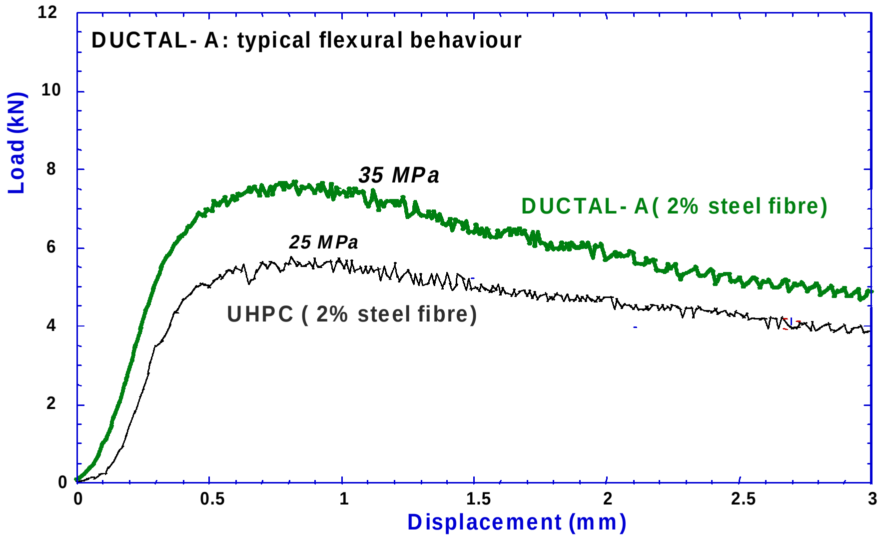

**Figure 4** : Mechanical behaviour of fibre reinforced concrete (3 pts bending test)

## IMPROVEMENT OF HIGH PERFORMANCE CONCRETE THROUGH FIBRE-MATRIX INTERFACE

The resistance to crack propagation depends on the mechanical properties of the matrix, fibres, and the fibre-matrix interface, as well as the fibre length, orientation, volume content, and spacing. Energy absorbing mechanisms include matrix cracking, fibre-matrix interfacial debonding, frictional sliding, fibre fracture, fibre elongation across the cracked surface; and fibre pull-out.

***Interface analysis : pull-out test.***

The load transmission between the matrix and fibres is done through interfacial bond, defined as the shearing stress at the interface between the fibre and the surrounding matrix. The bond parameters can be analysed from a stress approach, or from fracture mechanics.

The fibre-matrix interface is characterized by the critical shear stress corresponding to total debonding, for small values of slip displacement : $\tau_d$. An experimental pull-out jig, similar to that one developed by Shannag et al.[16], is used to characterize our materials : a single fibre is embedded in a 40x40x40 mm concrete specimen, so that both ends of the fibre are available. The real embedded length is controlled via a thin silicon rubber tube which is fitted around the fibre.

Test are performed on a Schenck-Trebel machine : the pull-out load and the displacement at both the top end and the bottom end of the fibre are used to determine the load $F_d$ at which complete debonding occurs and frictional pull-out starts.

Typical results on single fibre pull-out are presented in Figure 5-a). The 0.2 mm in diameter fibre is made of high strength steel, with a nominal strength of 2800 MPa. Concrete specimen correspond to the mix as described in Table 1.

The critical load is : $F_d$ = 62.5 N, and so the interfacial shear stress corresponding to total debonding : $\tau_d$ = 10 MPa. Different embedded length have been studied : 5 to 15 mm. There is no observation of variation of the critical shear stress : the debonding of the interface proceeds by controlled propagation of cracks, up to a critical length which corresponds to catastrophic failure. In this work, this critical length is lower than 5 mm.

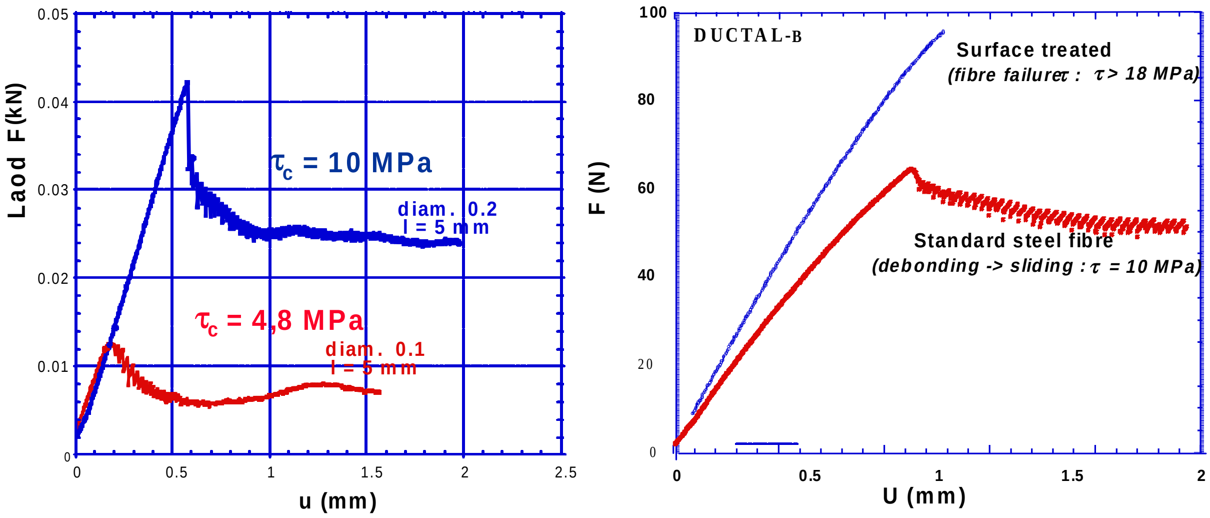

**Figure 5 :** Pull-out behaviour : a) effect of fibre diameter and embedded length
b) effect of surface treatment (steel fibre)

The fibre-matrix adhesion mechanism is mainly due to the compressive hydrostatic pressure developed around the fibre by the shrinkage of the concrete matrix. As a consequence the critical shear stress is a function of the fibre size (diameter). This dependence with the fibre geometry has been experimentally observed.

TABLE 2
Interfacial shear stress for different fibre diameter

| | 0.4 mm | 0.2 mm | 0.1 mm |
|---|---|---|---|
| $\tau_d$ (MPa) | 12 | 10 | 4.75 |

With such a critical shear stress of : $\tau_d$ = 10 MPa, only half of the strength of the fibre is used in the fibre reinforced concrete.

***Increase of adhesion fibre/matrix***

Matrix or fibre modifications can be developed as a way of improving the bond-slip fibre characteristics in a cementitious matrix.[17].

Different additives can be used, as sub-micronic reactive filler (precipitated silica, calcium phosphate) as well as polymers (polyvinylic alcool, latex); defoamers are very useful to provide higher quality interfaces. Most impressive results on the fibre-matrix bond are obtained by modifying the surface fibre : reactivity by surface coatings, roughness or variable section. With steel fibre, chemical modification as Zn-phosphatation seems very convenient[18].

With such surface treatment, adhesion to the matrix is well increased and no sliding is observed during pull-out test : the stress applied to the fibre corresponds to the fibre tensile fracture strength, i.e. $\sigma = 2800$ MPa, with fracture of embedded fibre.

The equivalent shear stress $\tau$ is about 18 MPa : that means the critical shear stress $\tau_d$ is considerably improved : $\tau_d > 18$ MPa.

The significant improvement in the fibre matrix bond strength can be due to both effect : surface chemistry, and surface roughness.

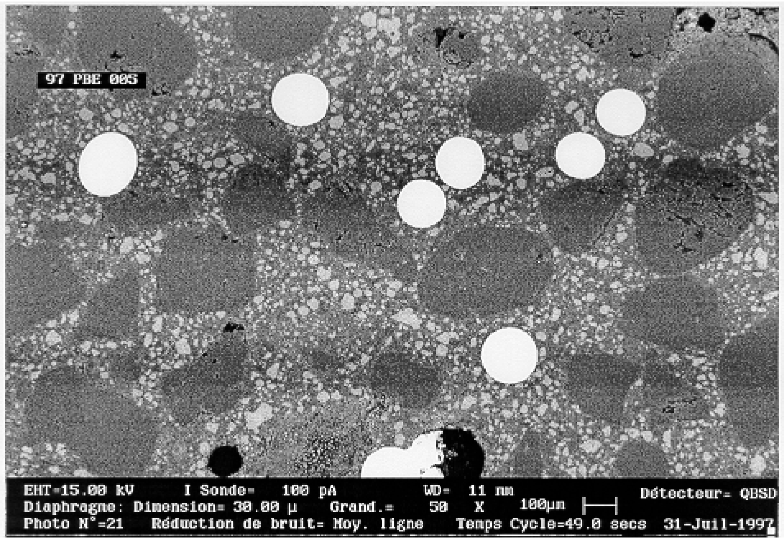

**Figure 6 :** Microstructure of DUCTAL® concrete : fibre and sand grains dispersed in a very dense cementitious paste.

Organic fibres can also be used, despite their low modulus : good results are obtained with polyvinyl alcohol fibres. This is due to a good adhesion between fibre and concrete matrix : the interface is made of a polymer-cement hydrates hybrid, on a few microns zone.

## MULTI-SCALE REIFORCEMENT (DUCTAL®)

A multi-scale toughened reinforcement concept, mainly a high matrix toughness with properly bonded fibres (low content : 2% vol.), is designed to improve performances.

Materials with a matrix incorporating toughening particles and surface treated steel fibres have been prepared.

Raw materials are the same as in previous Table.

Mechanical properties are measured on 40x40x250 mm (3 pts bending, span = 200 mm).

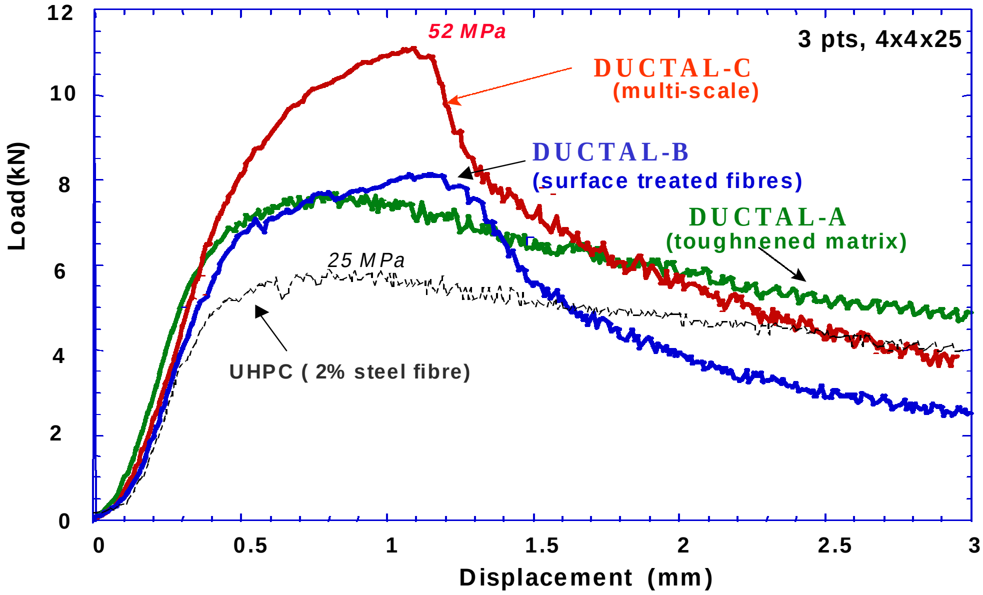

**Figure 7 :** New DUCTAL® materials : mechanical behaviour of concretes (3 pts bending)

An increase of the matrix toughness enhances the first crack stress level in the fibre reinforced concrete : experimentally, an increase of about 35% to 50% has been observed. With properly tailored interface bond, both the first crack stress value and the maximum stress are increased.

A synergy effect (multi-scale reinforcement) can be observed (Figure 7). The peak stress (max.) is about : $\sigma$ = 52 MPa (between 50 and 55 MPa, on 3 pts 40x40x250mm prisms), that is two times the typical value quoted for UHPC.
Typical compressive values are about 225 MPa, and elastic modulus of 58 GPa.

In presence of the multi-scale reinforcement, the damage resistance process is modified, with the development of large multi-cracking process.

## CONCLUSION

Based on the damage resistance analysis and experimental data on fibre reinforced UHPC, the following conclusion ca be stated :
1. New concrete materials with ultra high mechanical properties and durability as well as workability (DUCTAL®), can be developed from high toughness matrix or highly bonded fibre.
2. Processing conditions are easy to use : good rheology, no thermal treatment.
3 The multi-scale reinforcement, with some synergetic effect, seems to be a promising way of improving tensile strength of fibre reinforced high performance concretes.

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