FRACTURE TOUGHNESS OF ULTRA HIGH PERFORMANCE CONCRETE SUBJECTED TO FLEXURE

Emanuela MANOLOVA

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK: 666.982:620.178.2
doi: 10.5937/grmk1601003M

1 INTRODUCTION

Ultra High Performance Concrete (UHPC) is a developing composite material with optimized structure, using industrial waste materials like silica fume, fly ashes, GGBFS and metakaolin, which generates economic benefits and at the same time creates structures, which are more strong, durable and sensitive to environment. Created at the beginning of 1990 in France and Canada, nowadays it is a worldwide material, successfully used in Germany, Denmark, Holland, Great Britain, Japan, Korea, Australia, etc. UHPC represents a new class of cement based materials with compressive strength over 200 MPa, achieved by high quantities of high class of cement, mineral admixture, quartz sand and flour, high class of super plasticizer and incorporation of fibre-reinforcement and thermal treatment. There is no coarse aggregate in the mix composition, because it is the weakest link in the concrete. Introduction of micro steel fibres enhanced deformability of UHPC and thus, flexural strength reaches 50 MPa [1]. At the same time steel fibres overcome the disadvantage of high brittleness and fracture toughness reaches 40 000 J/m^2 [2].

Fracture energy is defined as this energy, necessary for micro-crack formation and at the same time as energy, needed for macro-crack opening. It has an important meaning for UHPC behaviour, compared to other fibre-reinforced composites (FRC). In the literature there are many parameters defining the ductile behaviour of FRC [3; 4; 5]. It is represented by 'fracture toughness', 'fracture energy', 'energy absorption', 'characteristic length', 'ductile length' and 'crack- formation energy', but all these terms have a different physical meaning and dimension. No matter it has a great significance in structures and up to now this kind of research is limited in the world literature [6].

2 METHODOLOGY OF THE EXPERIMENT

2.1 Composition of UHPC

The matrix of UHPC is optimized by carrying out a Mathematically Planned Experiment, presented in details in a previous investigation [7]. The optimal mix is characterized by fine sand (Dmax=0,5 mm), high quantity of cement (more than 900 kg/m^3), high quantity of mineral additive (silica fume – 30% of the mass of cement) and very low water-cement ratio (0,22). A quartz powder is used to obtain a maximum density of the skeleton of granular materials. High quantity of polycarboxylate chemical admixture is used (3,5% of the mass of cement) to achieved a workable mix, with exact plasticity.

Two types of steel fibre-reinforcement are applied ("short" and "long") with different ratio (length L and diameter D) in three variations, totally used in 2% by volume – Table1.

Test samples are prisms with sizes 4x4x16cm. Demolded after 24 hours, they stay in mois t conditions until they are tested in flexure.

Emanuela Manolova, Department of Construction of buildings and facilities. Building materials and technology", European Polytechnical University, 23 "Sv. sv. Kiril i Metodiy" str., Pernik, 2300 Bulgaria
amymanolova@yahoo.com

Table 1. Different types of UHPC mixes, acc. to fibre-reinforcement

Signature	Matrix	Short Fibres	Long Fibres	Short And Long Fibres
L=6mm D=0.175mm	-	2.0%V	-	1.0%V
L=13mm D=0.2mm	-	-	2.0%V	1.0%V

2.2 Apparatus

There is no standard methodology for testing UHPC in flexure. Based on the detail literature, outlook are adapted using several standard methods for testing fibre-reinforcement concrete [4, 8, 9, 10].

Flexural behaviour of UHPC is made by simultaneously measuring the vertical deflection and longitudinal deformation in the tensile zone. Test loading is applied with constant speed of deformation, which is prescribed by the standards for fibre-reinforced cementitious composites in flexure. Due to these regulations, loading could be precisely applied, especially in the area of the diagram presenting the residual strength of the post-peak part, which eliminates the imperfections due to crack-formation and large displacements. Testing speed is an essential item – it should be adapted to the sample, in a way that stresses should be redistributed between different components and this effect is successfully noted on the working diagram. Static scheme, which is used for this test is a three-point bending, with one force concentrated in the middle of the span distance (10cm). Samples are directly tested without notching.

This experiment is made by compression testing machine type ShimadzuAG-50kNXplus (Figure 1-a). In standard ASTM C/1609 [10] testing speed is limited due to the size of the sample in accordance with the span distance. In our case test samples are even smaller than the smallest mention in the standard (350/100/100 mm); therefore, the minimum required testing speed - 50 μm/min was used. *TrapeziumX* Software of the compression testing machine simultaneously detects the loading F [N] and vertical deflection Δ [mm] of the machine. In fact, there is a difference between the detected displacement Δ [mm] and deflection of the sample δ [mm], due to the reaction of the machine i.e. due to the deformation of its components. In this case, its own deformation is around 0.15-0.25 mm and could be neglected, especially when samples are tested with similar stiffness. Therefore, it is assumed that diagram „F-Δ“ coincides with **„**F- δ**“.**

By measuring the longitudinal deformation „ε" in tensile zone the moment of cracking could be identified, and therefore the influence of fibre-reinforcement has been estimated. An electrical-resistant gauge *KYOWA* (KFG-5-120-C1-11L1MR) - fig.1-b was used during the experiment, wherein the electrical signal, caused by the change of the resistance of the gauge (following the deformation of the substrate), was converted into relative longitudinal deformation by the specific constant of the gauge.

2.3 Fracture toughness

For determination of the fracture toughness G_f, [*N.mm*] of UHPC an adapted methodology was used, based on the standards ASTM C 1609/C [10] and ASTM 1018-97 [8], using obtained working flexural diagrams „F-δ" and "F-ε". Fracture toughness G_f is calculated, according to the deflection δ, formed at the so called 'first crack' in the diagram 'load-deflection' („F-δ").

a) Compressive machine with constant speed of vertical deflection

b) Electrical-resistant gauge for measuring the deformation in the tensile zone

Figure 1. Apparatus

ASTM standards give a numerical method for determination of the deflection δ in FRC, but it cannot be applied in the case of UHPC, due to much bigger deformations (more than 10 times), compared to ordinary FRC. According to the standard ASTM 1609/C 1609M-10, first crack appears in the interval from 0 to L/600 (L is the span distance). In the case of UHPC - it means L/600=0,16666mm. Experimental results give a defection δ in the range of 0.40-0.50mm (Figure 2). Therefore, an analysis of the recorded diagrams „*F-δ*” and *”F-ε”* has been made for each sample due to estimate an exact moment of the first crack formation. A visible leap could be seen in both diagrams due to the formation of the first crack – in the diagram „*F-δ*” it is next to the long linear area, while in the diagram *”F-ε”* the inclination is changing visually.

Then, according to the prescriptions of ASTM C 1018-97, the so called ‘characteristic points’ of the deflection are calculated based on the diagram „*F-δ*”, as a function of the deflection *δ,* obtained by the first crack. These characteristic points correspond to deflection 3.*δ* and *5,5.δ* – Figure 3.

Fracture toughness *Gf*, expressed in N.mm, is calculated as the area under the diagram, up to each one of the characteristic points of the diagram, i.e. as the energy needed for the first crack (G_f=A(δ)), the energy up to deflection 3.δ ((G_f =A(3.δ)) and the energy of deflection equal to 5,5.δ ((G_f=A(5,5. δ)). These values of the fracture toughness (the areas) are used for determination of the toughness indexes (I_5 and I_{10}) and the residual strength factor $R_{5,10}$.

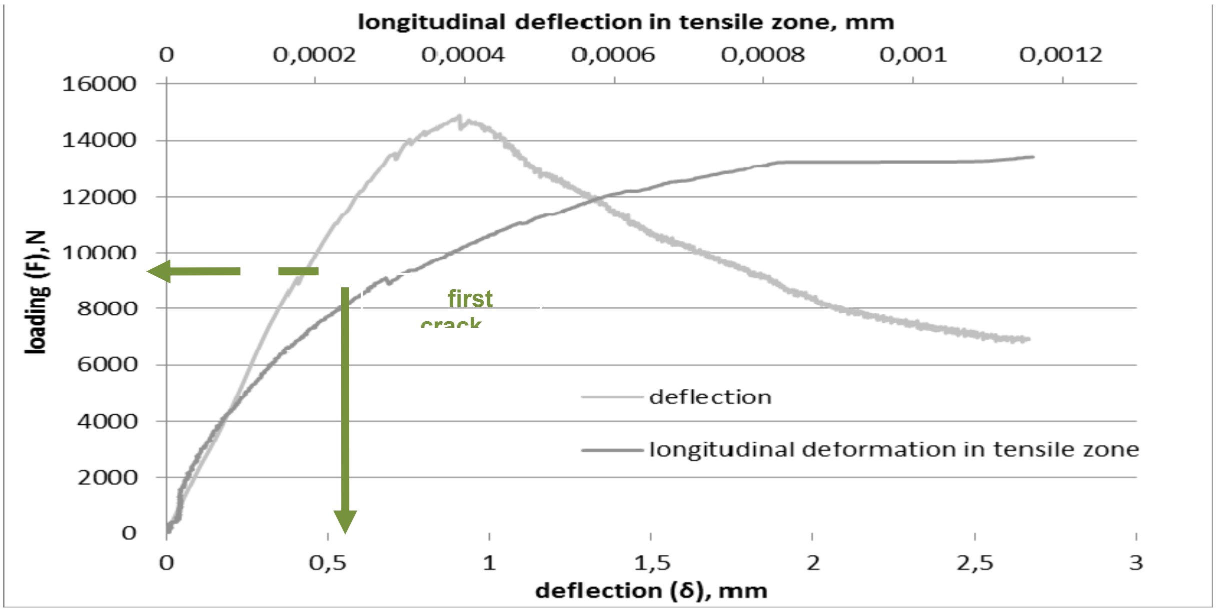

Figure 2. Working diagrams in flexure „F-δ” and ”F-ε”

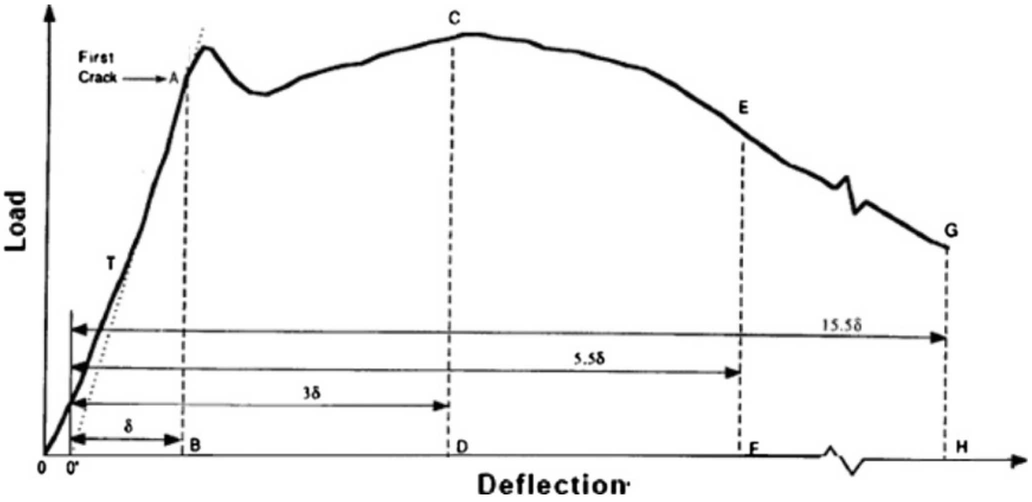

Figure 3. Important characteristics of the ‘Load-Deflection’ curve, according to ASTM C 1018-97 [8]

Using 1-2% of volume steel fibres in UHPC does not form a large area of residual strength. This effect is more visible by increasing quantity of fibres more than 10% [5]. In this case it is possible to obtain a material with elastic-plastic behaviour and both factors of the residual strength $R_{5,10}$ and $R_{10,20}$ will exceed 100. However, in UHPC, the most frequent amount of used fibres is 2%, which makes factor $R_{5,10}$ mostly reliable.

Each composition was tested by three samples (prisms 4/4/16cm). Diagrams are analysed by selection of the most representative for each composition – for example, in the case where one of the diagrams sharply differs from the other two, it is eliminated from the analysis. Also, the results are eliminated, due to random factors, such as defects in the matrix or other inhomogeneity.

3 ANALYSIS OF THE RESULTS

The results of the calculated fracture toughness, based on the method ASTMC1018-97, according to the vertical deflection, are shown in Figure 4.

Values of the fracture toughness (G_f) confirmed the assumption that short steel fibres contribute to a great extent (based on the large number per unit volume) for matrix unloading, so the first crack appears at higher level of loading, compared to composites with long steel fibres. Obtained values of (G_f) at first crack, i.e. G_f (δ) in composites with short steel reinforcement, are more than 50% higher than in the same composites with long steel reinforcement.

G_f (3δ) represents the behaviour of the strain-hardening zone, plasticizing and even in the case of partial loss of strength, i.e. G_f (3δ) is a general characteristic, which unites the differential effect of fibres (long and short) in different zones. For that reason, G_f (3δ) has approximately identical value in compositions with short and long steel fibres. According to ASTMC1018-97, obtained deformation of 3δ in ordinary fibre-reinforced composites, defines the zone of plasticity. In UHPC, even using long steel fibres, it is situated in the post-peak part of the curve – zone of the residual strength. Therefore it is not an appropriated characteristic for determination of UHPC behaviour with 2% of volume fibres.

In a greater extend G_f $(5,5\delta)$ represents the fibre contribution into prevention of sudden destruction and expectedly it has a 30% higher value in compositions with long steel fibres. Compositions with hybrid steel fibre-reinforcement (short and long) have much lower values of fracture toughness, but it also has a tendency to increase with large quantities of long steel fibres.

However, three calculated values of the fracture toughness indicate that the combination of short and long fibres has a synergetic effect – this combination needed more energy both for the occurrence of the first crack G_f (δ) and the strain-hardening and plasticizing of material G_f (3δ) as well as for its peak destruction.

The short fibre-reinforcement increases the matrix crack resistance – they bridge the micro-cracks only during strain localization, so fails to influence much the post-peak part of the load-deflection curve. First crack occurs in larger deformation, which reflects higher value of G_f (δ) – Figure 5. Subsequently, using long steel fibres expectedly have a greater contribution to strain-hardening behaviour and obtained hardening. Bearing capacity of the composite increases with large plastic deformation formations, compared to composites only with short steel fibres. The long steel fibres provide bridging stresses across the crack, which is a result of coalesce of micro-cracks. Thus, the fracture toughness defined to a certain deformation of G_f (3δ) covers mostly the residual strength of the post-peak part of the curve

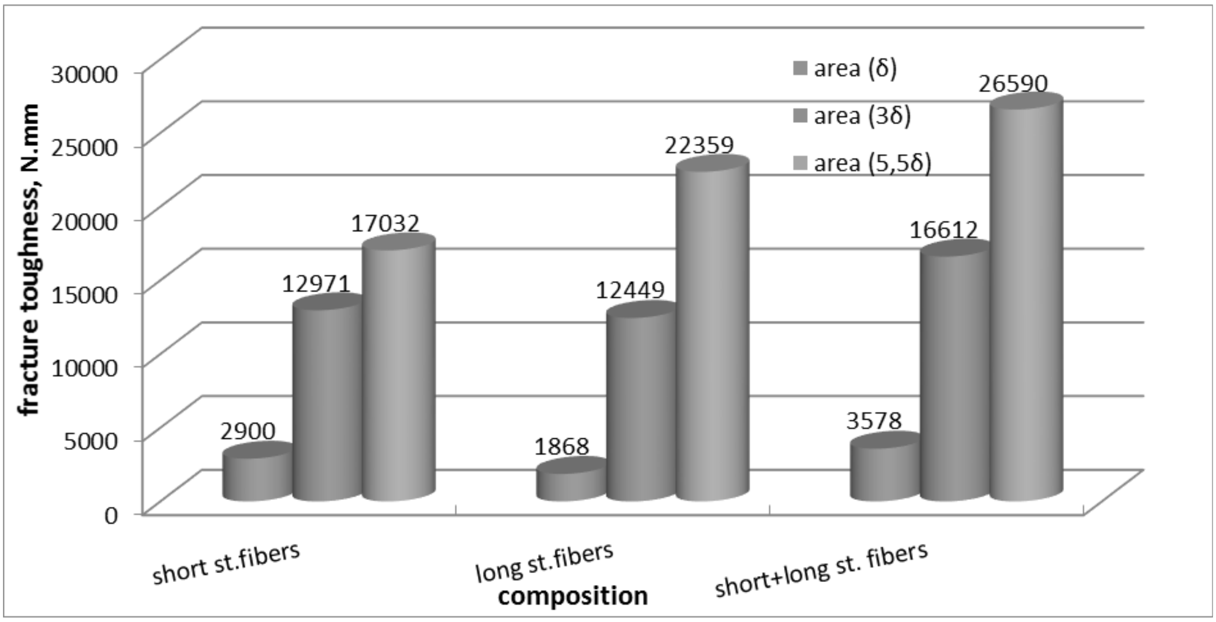

Figure 4. Influence of the type of fibre-reinforcement on fracture toughness of UHPC, according to ASTMC1018-97

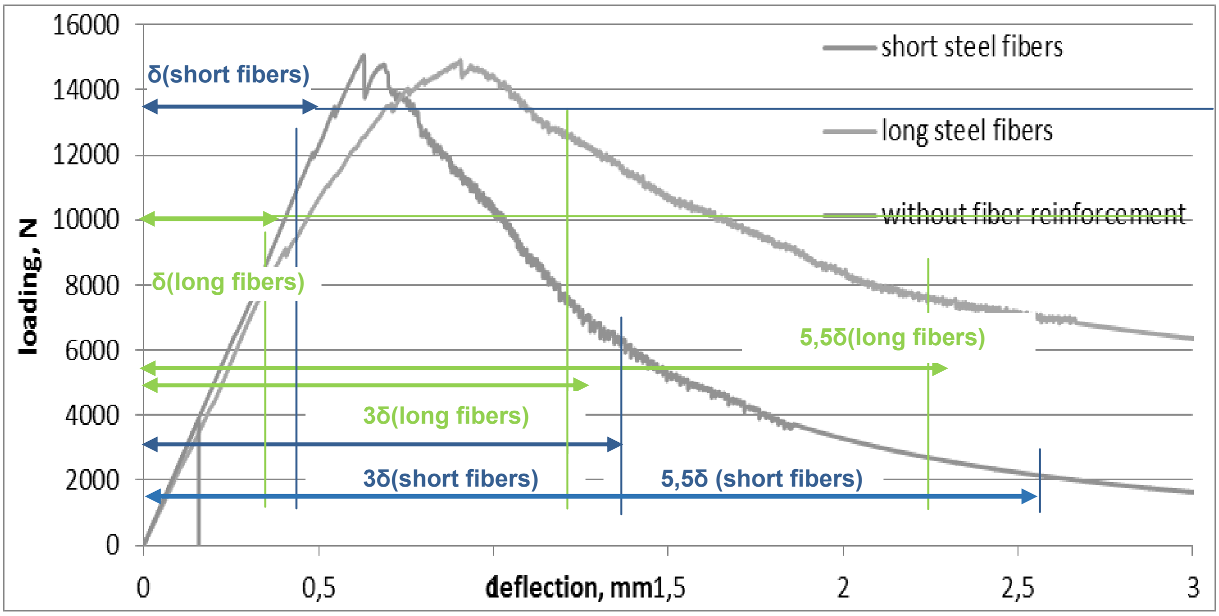

Figure 5. Main characteristics of the working diagram 'load-deflection' of UHPC with short and long steel fibres, according to ASTMC1018-97

Toughness indexes, according to ASTMC1018-97, represent the behaviour of FRC, mostly with elastic-plastic behaviour. Obtained results confirm the conclusions that long steel fibres have a significant contribution to ductile behaviour of UHPC.

Both indexes I_5 and I_{10} are substantially higher. However, the fact that I_5 exceeds 5 and I_{10} has a value over 10, for compositions with long steel fibres, indicates the strain-hardening zone of UHPC, which distinguishes their behaviour from ideal elastic-plastic materials, with defined maximum values of I_5=5 and I_{10} =10 (Figure 6).

Index I_{10} usually matches the contribution of the zone of plastic deformations and its values are from 1 to 10: one is a fully brittle behaviour and 10 correspond to plastic behaviour. In compositions with long fibres this index is equal to 12, although it is mainly due to strain-hardening it means that larger plastic deformations are formed in total. Exceeding the upper limit of ideal elastic-plastic behaviour also occurs in literature [6].

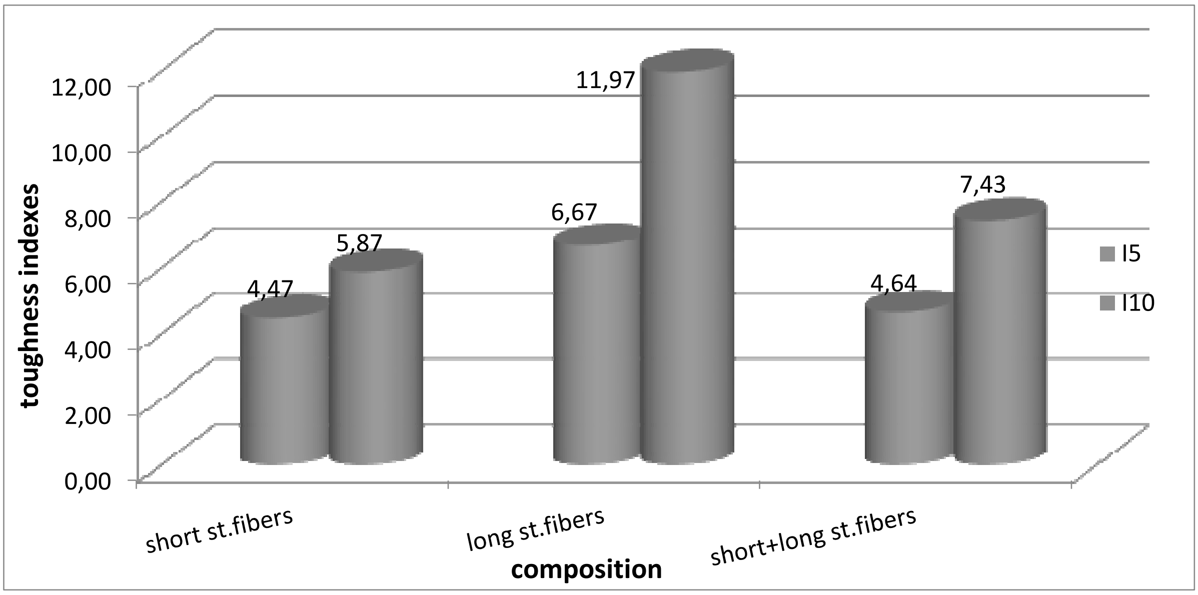

Figure 6. Influence of the type of fibre-reinforcement on toughness indexes of UHPC, according to ASTMC1018-97

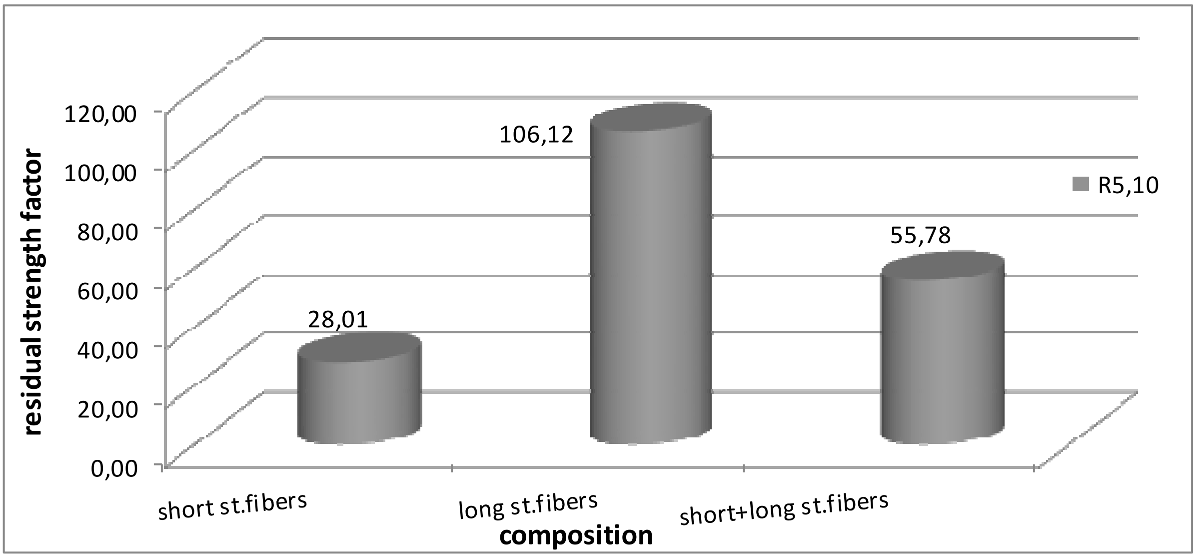

Figure 7. Influence of the type of fibre-reinforcement on residual strength factor of UHPC, according to ASTMC1018-97

Residual strength factor $R_{5,10}$ indicates how fast the strength could be lost, after the maximum force is reached – higher values indicate more ductile behaviour – gradually strength loss, accompanied by plastic deformation formations – in the case of UHPC with intensive micro-cracking, dissolving cracks and extraction of fibres – i.e. dissipation of energy.

It turns out that UHPC behaviour, reinforced with long steel fibres, is closer to ductile (Figure 7). $R_{5,10}$ exceeds 100, which indicates that the material is not ideal elastic-plastic, but it has a “reserve strength” due to the large strain-hardening zone.

Residual strength factor of the composition with short steel fibres is significantly lower ($R_{5,10}$ =28). It means that such kind of composition should not be used for elements, working in seismic areas. Composition with short and long fibres has an intermediate value of $R_{5,10}$ (55,78),i.e.no synergetic effect on residual strength is observed.

4 CONCLUSIONS

Fracture toughness and concrete strength are two primary mechanical characteristics that need to be carefully considered in structural design solutions. Toughness indexes are used to evaluate the capability of structural materials to bear loads with formation of cracks, absorb energy during deformation and carry large deformations with enough residual strength. Fracture toughness has become one of the most important parameters in UHPC, in a way that high strength is always related to high brittleness. Calculation fracture toughness, based on both diagrams in flexure („F-δ" and 'F-ε), could estimate the influence of different type of fibre reinforcement on various parameters of UHPC behaviour – using short steel fibres leads to increasing crack-resistance, but long steel fibres have bigger effect on strain-hardening and ductility of UHPC. Synergy effect is established by using combination of both types of fibres – more energy is necessary for first crack formation and strain-hardening and subsequently plasticizing, due to intensive cracking.

5 REFERENCES

[1] Collepardi S., Coppola L., Troli R., Collepardi M. : Mechanical properties of modified reactive powder concrete, Malhotra VM editor, Superplasticizers and other chemical admixtures in concrete, *American Concrete Institute Superplasticizers*, v.173, 1997, Pages: 1-21;

[2] T. Vande Voort, M. Suleiman, S. Sritharan, Design and Performance Verification of Ultra-High Performance Concrete Piles for Deep Foundations, Final Report, Nov 2008

[3] Lohaus L., Anders S.: Effects of polymer- and fibre modifications n the ductility, fracture properties and micro-crack development of ultra-high performance concrete, *Proceeding the First International Symposium on Ultra High Performance Concrete*, Kassel, Germany, March, 13-15, 2004, Pages: 625-636;

[4] Güvensoy G., Bayramov F., Ilki A., Sengül C., Tasdemir M., Kocatürk A.: Mechanical behavior of High Performance Steel Fiber Reinforced Cementitious Composites under Static Loading Conditions, *Proceeding the First International Symposium on Ultra High Performance Concrete*, Kassel, Germany, March, 13-15, 2004, Pages: 649-660;

[5] Brameshuber W., Brockmann T., Banholzer B.: Textile reinforced ultra high performance concrete, *Proceeding the First International Symposium on Ultra High Performance Concrete*, Kassel, Germany, March, 13-15, 2004, Pages: 511-522;

[6] Graybeal B. Characterization of the behaviour of Ultra-high performance concrete, *dissertation*, University of Maryland, 2005;

[7] Manolova E., Zaharieva R., Petrov B., Nazurski D. Application of the Mathematical Method of Planned Experiment in Ultra High Performance concrete Mix Design, 12th International Scientific Conference, University of Structural Engineering and Architecture, Sofia, Bulgaria, 2012, v.2, pages: V-49-55.

[8] ASTM C 1018-97: Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading).

[9] Empelmann M., Teutsch M., Steven G.: Improvement of the Post Fracture Behavior of UHPC by Fibers, Proceeding the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, March, 05-07, 2008, Pages 177-184.

[10] ASTM C 1609/C 1609M-10: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading).

SUMMARY

FRACTURE TOUGHNESS OF ULTRA HIGH PERFORMANCE CONCRETE BY FLEXURAL PERFORMANCE

Emanuela MANOLOVA

This paper describes the fracture toughness of the innovative structural material – Ultra High Performance Concrete (UHPC), evaluated by flexural performance. For determination the material behaviour by static loading are used adapted standard test methods for flexural performance of fiber-reinforced concrete (ASTM C 1609 and ASTM C 1018). Fracture toughness is estimated by various deformation parameters derived from the load-deflection curve, obtained by testing simple supported beam under third-point loading, using servo-controlled testing system. This method is used to be estimated the contribution of the embedded fiber-reinforcement into improvement of the fractural behaviour of UHPC by changing the crack-resistant capacity, fracture toughness and energy absorption capacity with various mechanisms. The position of the first crack has been formulated based on *P-δ* (load-deflection) response and *P*-ε (load – longitudinal deformation in the tensile zone) response, which are used for calculation of the two toughness indices I_5 and I_{10}. The combination of steel fibres with different dimensions leads to a composite, having at the same time increased crack resistance, first crack formation, ductility and post-peak residual strength.

Key words: Ultra High Performance Concrete, Fracture Toughness, Flexural Behaviour, Impact test, Energy absorption

REZIME

ŽILAVOST PRI LOMU BETONA SA ULTRA-VISOKIM PERFORMANSAMA SA ASPEKTAPONAŠANJA PRI SAVIJANJU

Emanuela MANOLOVA

U okviru rada analizirana je žilavost pri lomu inovativnog konstrukcijskog materijala-betona sa ultra-visokim performansama (UHPC), procenjena s aspekta njegovog ponašanja pri savijanju. Za određivanje ponašanja materijala pod statičkim opterećenjem, upotrebljene su prilagođene standardne metode za ispitivanje ponašanja pri savijanju betona armiranog vlaknima (ASTM C 1609 i ASTM C 1018). Žilavost pri lomu je procenjena na osnovu vrednosti deformacija preuzetih sa dijagrama opterećenje-ugibdobijenog pri ispitivanju slobodno oslonjene grede pod dejstvom opterećenja u sredini raspona, upotrebom servo-kontrolisanog mehanizma. Ova metoda se koristi u cilju procene doprinosa ugrađenih vlakana ponašanju pri lomu UHPC, promenom kapaciteta otpornosti na pojavu prve pukotinem žilavosti pri lomu i sposobnosti absorpcije energije. Položaj prve pukotine je formulisan na osnovu odgovora P-δ (opterećenje-ugib)i P-ε (opterećenje-podužna deformacija u zateznoj zoni), koji su upotrebljeni pri proračunu dva indeksa žilavosti - I_5i I_{10}. Kombinovanje čeličnih vlakana različitih dimenzija daje kompozit koji istovremeno poseduje povećanu otpornost na pojavu pukotine i razvoj prve pukotine, duktilnost i zaostale čvrstoće nakon dostizanja maksimalne čvrstoće.

Ključne reči: beton sa ultra-visokim performansama, žilavost pri lomu, ispitivanje otpornosti na udar, ponašanje pri savijanju, absorpcija energije