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Ultra High Performance Concrete Reinforced with Short Steel and Carbon Fibers

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Abstract. **Fibers are usually used in High Performance Concrete with a purpose to increase bending strength and ductility. Important properties are the peak value of bearing stress (strength) and post-cracking behavior of bended element. In the framework of an experimental part, Ultra High Performance mix compositions were prepared using intensive mixer. Short steel fibers and carbon micro fibers in amount of 1% by volume, as well as its combination were used for cement matrix reinforcing. Results of compressive and bending tests proved an increase of strength value in the case of use both steel and carbon fibers. Carbon fibers were decreased the effect of explosive collapse of the UHPC cement matrix, at the same time still brittle bending behavior was take place. Steel fibers considerably improved bending ductility thanks to a pull-out mechanism of steel fibers. The best results were achieved in the case of combined application of both carbon and steel fibers.**

Keywords: **Steel fiber, carbon fiber, Ultra High Performance Concrete, bending behavior.**

I INTRODUCTION

Plain concrete is brittle material. Adding short fibers improves concrete ductility, bending strength and is minimizing crack formation risk [1]. The first fiber reinforced concrete (FRC) was patented in 1874 [2]. Researchers efforts during the last decades are focused on creating high strength fiber concrete having high bending strength and high ductility. The amount of steel fibers in modern FRC may reach up to 200 kg/m^3 and more. Steel fibers can be mentioned among the most effective, taking into account their mechanical properties and economical side of the problem. Simultaneously is observed high increase of non-metallic fibers use as a concrete disperse reinforcement during the last time. Advantages of the non-metallic fibers are high resistance against corrosion, chemical attack, light weight, high strength and easy mixing ability in fresh concrete statement. Tensile strength and tensile modulus (E-modulus) are the basic properties, which are determining fiber co-work with a cement matrix. The use of fibers having E-modulus lower then concrete E-modulus does not have any significant impact on bending strength (for example the polypropylene fibers). These types of fibers eliminate cracks formation on the early period of hydration and improve fire resistance of the hardened concrete [3][4]. Fibers, which have E-modulus higher than concrete one, are able to increase bending strength and to improve post-cracking behavior of the fiber concrete. Commonly used fibers and their basic mechanical properties are summarized in the Table 1.

TABLE I
PROPERTIES OF DIFFERENT FIBERS AND COMPARING WITH CONCRETE PROPERTIES

Material	Density, g/cm3	Elastic modulus, GPa	Tensile strength, MPa	Ultimate elongation, %
Steel	*7.80*	*200*	*400-1200*	*5-20*
Polypropilen	0.90	3.5-8.0	300-	10-25
Polyamid	0.90	1.9-2.0	720-750	24-25
Polyethilen	0.95	1.4-4.2	600-720	10-12
Acril	1.10	2.1	210-420	25-45
Neilone	1.10	4.2-2.5	770-840	16-20
Polyester	1.40	8.4-8.6	730-780	11-1
Carbon	*1,63-2.00*	*200-650*	*1200-4500*	*1-2.1*
Glass	2.60	70-80	1800-3850	1.5-3.5
Basalt	2.60-2.70	70-110	1600-3200	1.4-3.6
Typical concrete (C25/30)	*2.40*	*34*	*3-5*	*< 1*

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Carbon fiber is high performance non-metallic reinforcing material, basic mechanical properties of a carbon fiber exceeds properties of a steel (Tab 1). Originally carbon fibers began to be used in the second part of 20th century producing high performance composite materials for aerospace and military applications.

At present, carbon fibers increasingly are used in concrete constructions. The most popular application is strengthening reinforced concrete constructions by composite carbon strips as well as replacing traditional steel reinforcement by carbon composite bars [5]. The use of carbon mesh and carbon knitted fabric are becoming more and more popular for creating highly aesthetic thin constructions [6]. Short carbon fibers are very rarely used in practice as concrete disperse reinforcement and only few publications may be find in this concern . Large part of information deals with carbon fibers use in traditional concrete mixes in order to improve their mechanical properties [7]. Author Akihama et al [8] used short carbon fibers in amount of 0.2 % by volume in Portland Cement concrete having water cement ratio equal to 0.5 and compressive strength up to 35 MPa. Increase of flexural strength up to 85 % was achieved. Study [9] was focused on bond improvement between carbon fibers and cement matrix with an aid of special covering.

High strength concrete as well as High (HPC) and Ultra high performance concrete (UHPC) are rapidly improving materials during last few decades [10]. UHPC is characterized by very high compressive strength as well as high bending strength. Short steel fibers usually are used in such material as disperse reinforcement. Non-metallic fibers may have some benefits comparing to steel one, but their use in UHPC haven't investigated properly. To use a combination of different types of fibers (so called *fiber cocktail*) is an interesting idea in order to achieve the best result. The aim of this study is to investigate the effect of combined use of carbon and steel fibers in UHPC concrete mixtures.

II MATERIALS AND MIX DESIGN

In the experimental part typical UHPC basic mix composition was prepared. Main mix ingredients are the following: white Portland Cement CEM I 52.5 R (Aalborg), locally available quartz sand (combination of 2 fractions and quartz powder), pozzolanic admixture silica fume (Elkem, grade 920D), polycarboxilate based super plasticizer and water. Four mix compositions were produced: reference mix (REF), mix with carbon fibers (C), mix with steel fibers (S) and composite mix of carbon fibers together with steel fibers (C+S). Used TENAX® chopped carbon fibers are characterized by density 1.82 g/cm3, tensile strength 4275 MPa, tensile modulus 225 GPa and ultimate elongation 1.9%. Fiber length is 12 mm and diameter 7 μm, therefore, aspect ratio of selected fiber is very high: 12000/7 = 1714.

Used steel fibers are fibers with hooked ends, having length 30 mm and diameter 0.5 mm, therefore aspect ratio of selected fibers are: 30/0.5 = 60. Long steel fibers was used to provide quasi-plastic behavior and crack bridging effect during bending test. At the same time, "wall effect" is possible, where the moulds walls direct the fibers, which are too long compared to the mould size (40 mm). Volumetric concentration of carbon and steel fibers in experimental mixes was provided 1 % from the total volume of concrete. Proportions between mix components were calculated in order to provide optimum grading curve which determines dense micro-structural packing. Mix compositions of experimental mixes are presented in the Tab II.

TABLE II

UHPC MIX COMPOSITIONS, kg/m^3

	Dens., kg/cm^3	**REF**	**C**	**S**	**S+C**
Cements I 52.5 R	3.1	800	800	800	800
Sand Quartz 0.5/1 mm	2.65	800	800	800	800
Sand fine 0/0.3	2.65	300	300	300	300
Quartz powder	2.65	60	60	60	60
Silica Fume 920 D	2.2	140	140	140	140
Carbon micro fiber	1.82		**18**		**18**
Steel fiber 30 mm	7.8			**78**	**78**
Water	1	**200**	**200**	**200**	**200**
Superplasticizer	1.1	**13**	**13**	**13**	**13**
W/C		0.25	0.25	0.25	0.25
W/(C+SF)		0.21	0.21	0.21	0.21
Workability		flowable, plastic, good	flowable, plastic, good	plastic, too long fibers	plastic, too long fibers

III SAMPLES PREPARATION AND TESTING

Mix ingredients were dozen with accuracy $\pm$0.1% and mixed using the highly intensive laboratory mixer Eirich. Carbon fibers were added during mixing and additionally mixed one minute in order to distribute fibers uniformly. Steel fibers were added at the end of mixing without intensive mixing effect in order to prevent fiber deformation during intensive mixing process.

Prismatic samples 40x40x160 mm were produced in steel moulds, then were demoulded after 1 day and cured in water environment (+20^{o}C). Flexure and compressive test were performed after 1, 28 and 108 days of hydration. Force – deflection curves were obtained during three-point bending test using universal testing machine Zwick 150. The distance between supporting points 130 mm and rate of loading 5 mm/min was provided. Sample halves remaining after flexure test, were used to check compressive strength.

Compressive testing machine Controls Automax 5 was used, the rate of loading was 1.0 MPa/s.

SEM electronic microscope imaging was performed to investigate internal structure of produced material in details.

A. Compressive strength

Testing results of compressive strength (Fig. 1) shows continuous increase of strength values during hardening time, this effect may be described by long-term pozzolanic reactions between silica fume and calcium oxide (product of cement hydration) [11]. In the age of 7 days compressive strength values are approximately 80% from 28 day strength, but 108 days results demonstrates strength gain up to 20%, comparing to 28 day results. Reference mix has the least strength values, but adding carbon and steel fibers has beneficial effect on compressive strength. Compressive strength gain is observed up to 9% in the age of 28 days, comparing to reference mix (see Fig. 1). The biggest gain of compressive strength is observed in the case of steel fiber and steel fiber combination with carbon fiber in the age of 108 days.

Reference mix composition REF (without fibers) is characterized by explosive collapse when maximum force is achieved. Composition with carbon fibers also is characterized by brittle behavior, at the same time collapse process is not so brittle and associated with crack formation. Destroying process of mixes with steel fibers is much more ductile and development of multiply crack system took place before maximum force is achieved.

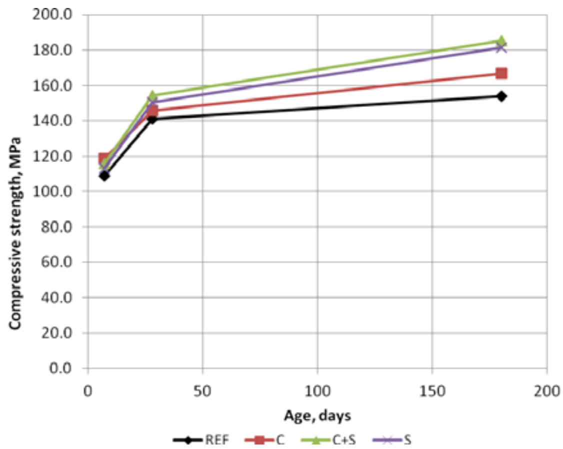

Fig. 1. Concrete compressive strength development.

B. Bending strength and ductility

Main task of adding fibers in concrete mix is increasing a bending strength and ductility. Analyzing peak values of bending strength (Fig. 2) in must be emphasized more positive influence of fibers on bending strength, comparing the effect on compressive strength. In the age of 28 days carbon fibers increases bending strength is up to 28% and for steel fibers up to 139%. The biggest improvement 186 % is achieved in the case of use carbon and steel fiber in combination (C+S).

Analyzing scattering of results, it must be stressed, that average squared deviation of compressive strength data in one series does not exceed 5% from the average result. The same deviation is found for bending strength of reference mix (REF) and composition with carbon fibers (C). Mix compositions with steel fibers (S and S+C) have the largest scattering of bending strength results (up to 15% from average result). High dispersion of bending strength results may be explained by non-homogeneous steel fiber distribution in the cross section of bended beam [12]. It must be stressed, that the length of used steel fibers (30 mm) is too big comparing to cross section dimension of sample (40 mm). In the future studies, shorter steel fibers (L<15 mm) should be used in order to prevent fiber unpredictable orientation and possible concentrations in local places.

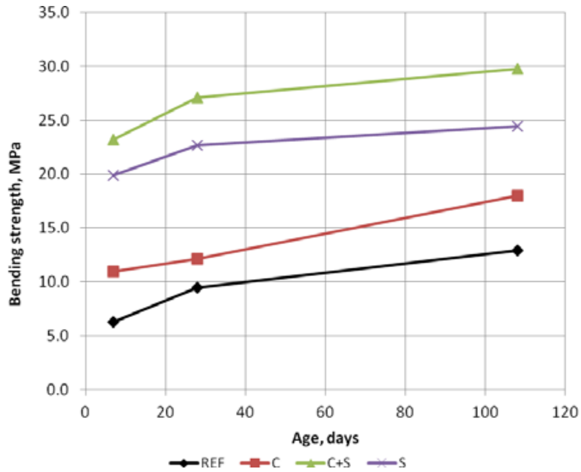

Fig. 2. Bending strength development.

Carrying out three-point bending test of mini beams, force – deflection curves were obtained. Curves give important information about bending behavior of material in the stage after crack formation as well as about ductility and bending energy. In order to compare bending curves, average curves for each mix composition were calculated, using experimental numerical data and Excel program. Curves related to 108 age samples are presented in the Fig. 3.

Obtained results shows huge difference between sample without steel fibers (REF and C) and sample containing steel fibers (S and C+S), which are characterized by higher maximum force peak and wide range of post-cracking curve. This effect may be explained by crack bridging with steel fibers and its pull-out mechanism [13][14].

Sample fracture energy may be determined as an area below bending curve. Taking into account numerical data of bending experiments, bending energies U (N*mm, or mJ) were calculated for 4 intervals corresponding maximum force and deflections of 3, 4 and 5 mm correspondingly. The results are presented in the Fig. 4.

The first bars (corresponding maximum force) show that bending energy of mix containing carbon fibers is 70% higher than one of reference mix. At the same time, sample containing steel fiber has more than 10 times higher result. In the post-cracking stage bending energy determines pull-our work of mere long steel fibers.

The most interesting effect is considerable increase of energy (+15-20%) in the case of complex use both steel and carbon fibers. This difference (up to 5000 N*mm) is much more than the total bending energy of C mix, containing only carbon fibers. This phenomenon makes possible to draw hypothesis about steel and carbon fiber synergy effect. Obtained results goes in accordance with results of pull-out behavior of single steel fiber from cement matrix with and without carbon fibers [15] [13] (Krasnikovs, Khabaz).

SEM pictures of UHPC cement matrix containing carbon fibers (after bending test) are presented in Fig. 5 and 6. Cement matrix is characterized by high density and big pores and cavities (Fig. 5). Taking into account very high aspect ratio of carbon fibers (1714), pull-out effect of all fiber is not possible. At the same time, free ends of carbon fiber and empty channels (Fig. 6) indicates that fiber is breaking inside channel and possible pull-out effect. This is evidenced by increased ductility and fracture toughness of carbon fiber reinforced sample, comparing to reference mix. In the Fig 6 can be seen carbon fiber channel crossing micro crack in cement matrix. This picture helps to explain bridging effect of carbon fiber, as well as synergy effect of steel and carbon fiber (carbon fiber prevents formation and expansion of micro-cracks in cement matrix).

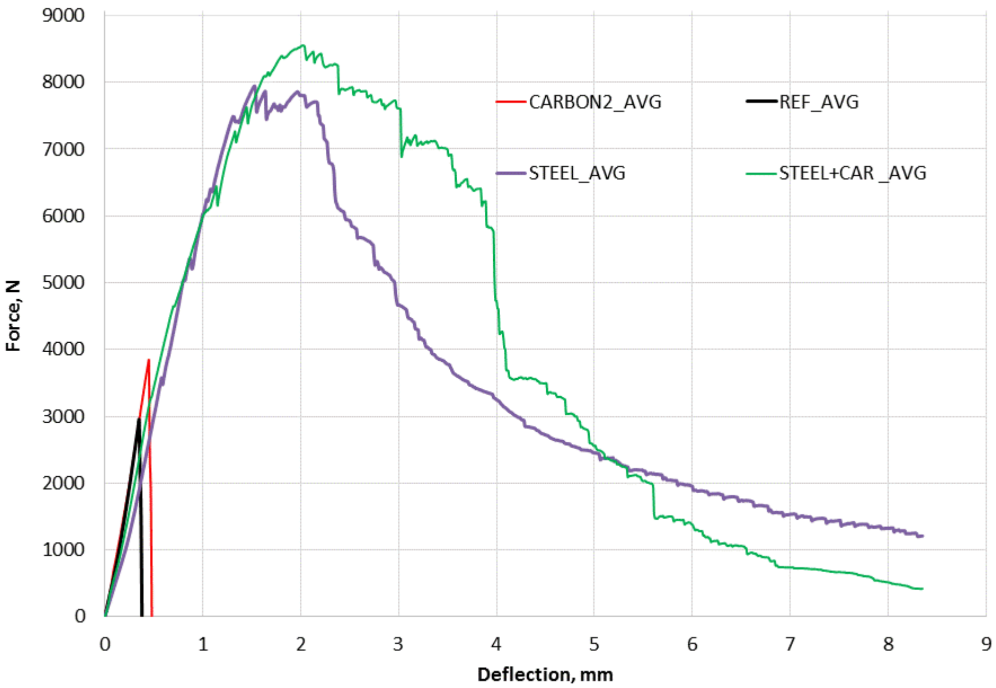

Fig. 3. Three-point bending force – deflection curves.

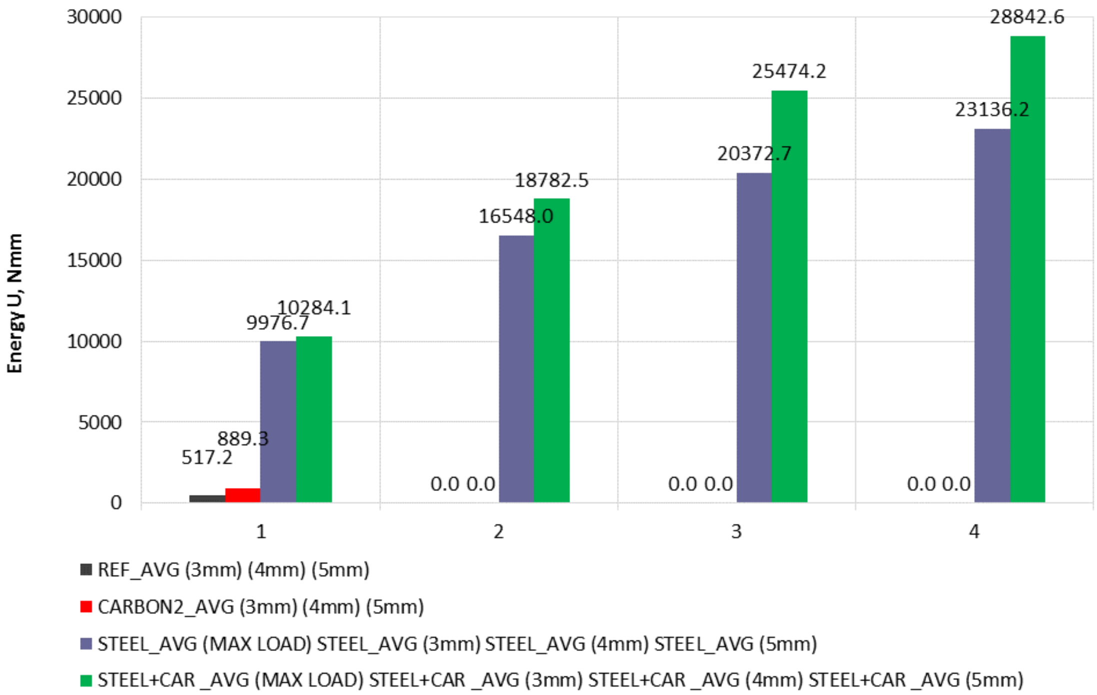

Fig. 4. Fracture energy – *1* Peak load; *2* crack opening 3mm; *3* crack opening 4mm; *4* crack opening 5mm.

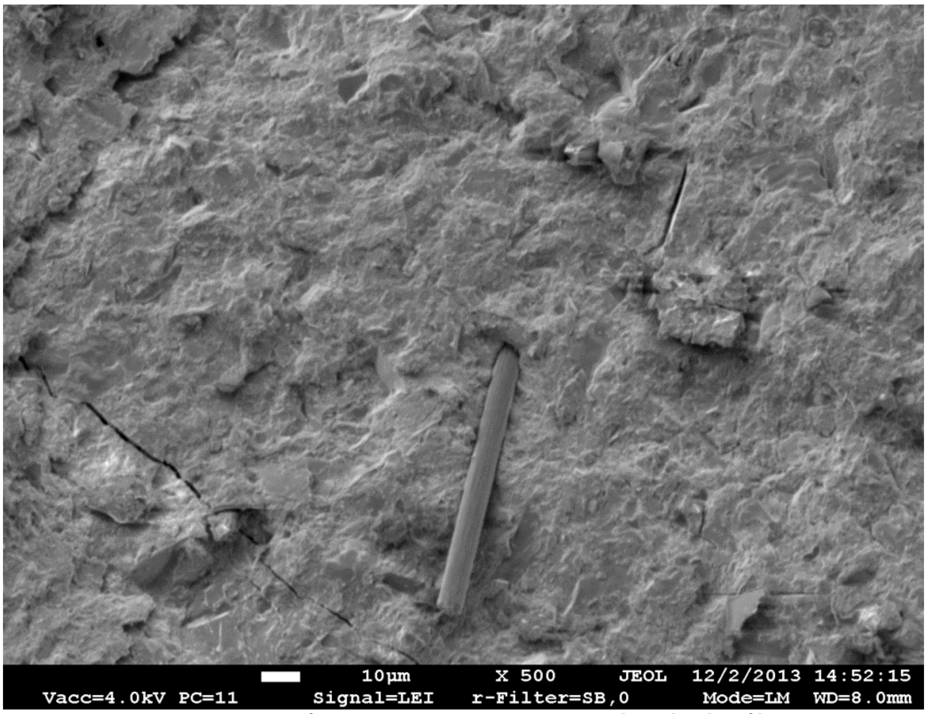

Fig. 5. SEM image of concrete microstructure, micro cracks and carbon fibers.

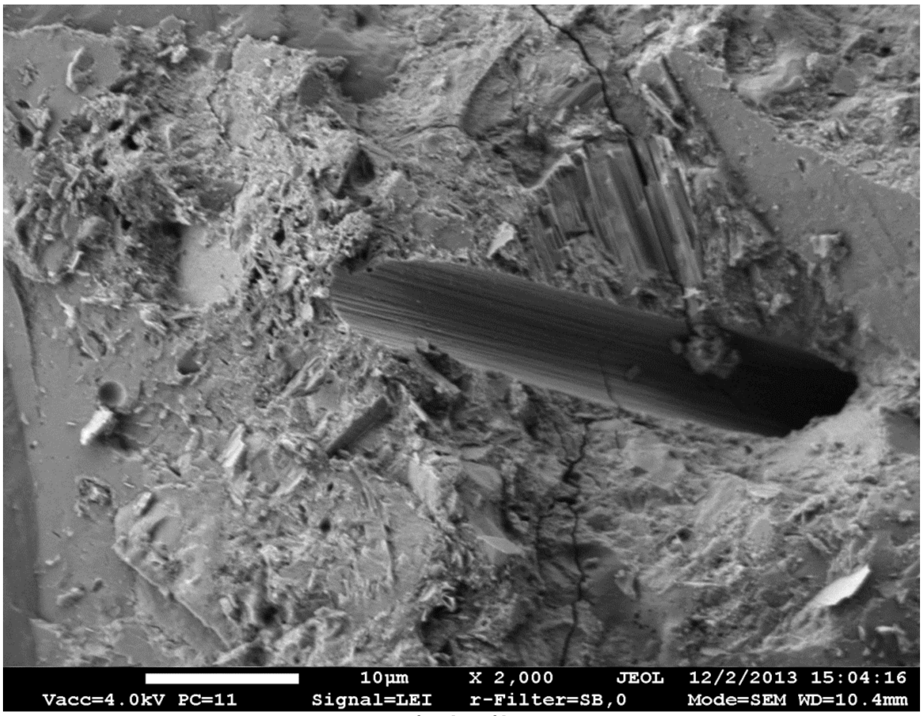

Fig. 6. SEM image of carbon fiber in concrete structure.

IV CONCLUSIONS

Use of intensive concrete mixer makes possible more uniformly distribute carbon fibers in the volume of the UHPC cement matrix. Introduction of carbon fibers in amount of 1% (by volume) improves bending strength of plain UHPC matrix up to 39% and compressive strength up to 9% and slightly compensates brittle behavior of collapse of ultra-high strength material.

Steel fibers are providing post-cracking bending behavior thanks to their pull-out hook mechanism. The best bending results was achieved in the case of combined use of both carbon and steel fibers. Considerable increase of the fracture energy in this case is explained by synergy work of two types of fibers. Carbon micro-sized fibers are reducing micro crack formation in the cement matrix and are improving steel fibers pull-out behavior. The task of future optimization UHPC mixes provides for finding optimum dosage of steel and carbon fibers, as well as its geometrical parameters in order to obtain the most economic mix composition, depending on used cement matrix.

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