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MIXTURE DESIGN AND TESTING OF ULTRA HIGH PERFORMANCE FIBER REINFORCED CONCRETE

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Abstract: This paper describes the mixture formulation process of Ultra High Performance Fiber Reinforced Concrete (UHPFRC). The mixture was developed without using heat treatment, pressure or special mixer. Only ordinary materials available commercially in the Czech Republic were utilized throughout the process. In the first step of the process the cementitious matrix was optimized with respect to its compressive strength and workability. Several types of high-range water reducers (HRWR) and different mixture proportions were tested. In the second step of the optimization process short, high tensile strength steel fibers were added into the matrix that showed highest workability and strength. The compressive strength of the resulting UHPFRC mixtures exceeded 150 MPa after 28 days and the flexural strength in three point bending was in the range of 40 MPa. Such high strengths were achieved due to the utilization of the high strength fibers and low water-to-binder ratio. During the optimization process different amounts of fibers were tested. It was found that with respect to acceptable workability the optimal fiber content is between 2 and 3% by volume.

Keywords: *mechanical properties; fiber reinforced concrete; cementitious composite; optimization*

1.0 Introduction

Increasing requirements for durability, safety and security of concrete structures push its development still further. High rise buildings and other structures of strategic importance such as government buildings and television towers have become a symbol of developed cities worldwide. However, such structures are threatened by possible extreme-load events like earthquakes, gas explosions, car or plane impact and in recent years to terrorist attacks.

New hi-tech materials such as ultra-high performance fiber reinforced concrete (UHPFRC) are ideal for applications where high compressive and tensile strength, small thickness and high energy absorption capacity are required. For instance, the utilization of high strength concrete allowed construction of many skyscrapers around the world. In

addition, UHPFRC significantly improves blast resistance of cladding panels and walls while maintaining its standard thicknesses and appearance (Cauberg, Piérard et al. 2008).

Ultra high performance fiber reinforced concrete (UHPFRC) can be characterized as a composite containing large volume of steel fibers, low water-binder ratio, high microsilica content and absence of coarse aggregate i.e. larger than 4 mm (Wille, Naaman et al. 2011). It has outstanding material characteristics such as self-consolidating workability, very high mechanical properties and low permeability which results in excellent environmental resistance (Graybeal 2007). Typical strengths are 150 to 200 MPa in compression and 7 to 15 MPa in uniaxial tension. Moreover, these materials exhibit strain hardening under tension (Habel, Charron et al. 2008, Rossi, Arca et al. 2005) and high energy absorption capacity (Habel, Gauvreau 2008, Bindiganavile, Banthia et al. 2002). In addition, they show improved structural behavior when compared to conventional concrete and smaller spalling and scrabbing under impact loading.

2.0 Research Significance

To prevent collapse and injuries of people, high-rise structures from high strength materials must possess a much greater resistance to impact loading. It is well known that traditional fiber reinforced concrete (FRC) with normal strength matrix has large capacity to absorb energy (Wang, Mindess et al. 1996). However, several authors (Habel, Gauvreau 2008, Bindiganavile, Banthia et al. 2002, Farnam, Mohammadi et al. 2010, Maalej, Quek et al. 2005) suggest that UHPFRC has much greater capability to absorb energy both in quasistatic and dynamic loading.

This paper describes a formulation of UHPFRC mixture that will be used for preparation and testing of impact and shock loading effects. It describes the composition and mixing procedure of UHPFRC mixture and the measurement its mechanical properties, i.e. compressive strength, secant modulus of elasticity, uniaxial tensile strength on dog-bone specimens and flexural strength. In the first phase, several concrete mixtures were produced to find the best combination of constituents with respect to maximal compressive strength and workability. This was achieved by usage of fine materials and high volume of steel fibers (up to 3%). In the second phase mechanical properties of the final UHPFRC mixture were determined.

3.0 Mixture Optimization

3.1 Matrix optimization

Before the fibers were added to the mixture a cementitious matrix was optimized to achieve both maximal compressive and flexural strength while maintaining good workability. High particle packing density is a key property of ultra-high compressive

strength of concrete. Therefore the mixture design was based on optimizing the particle packing density of sand (S), silica fume (SF), glass powder (GP) and cement (C). Improving particle packing was achieved mainly by changing the matrix composition and proportions and by selecting ranges of particles for sand.

In total 24 mixture designs were tested. Flexural strength was evaluated on 40×40×160 mm prisms and compressive strength on the halves of these prisms following CSN EN 1015-11. Workability was tested according to CSN EN 1015-3. Standard flow table test was used and the spread of the cementitious matrix was evaluated both before and after impacting the table.

The first mixture was designed following the proportions of C:SF:GP recommended by (Wille, Naaman et al. 2011) of 1:0.25:0.25 with a water binder (w/b) ratio[1] of 0.2. Subsequent changes in the most important parameters such as high-range water reducer (HRWR), water content (W), amount of aggregate (A), SF, and GP led to an optimized cementitious matrix in terms of compressive strength and workability. From the 24 tested mixtures, two best performing cementitious matrix compositions denoted as UHPC2 and UHPC3 are shown in Table 1 along with the first starting mixture (UHPC1). The comparison of mechanical properties of these mixtures is shown in Fig. 1. In Fig. 1, the parameters of UHPC1 were put equal to 1 for easy comparison between the mixtures. In the "spread" column a diameter of paste spread measured after filling and removing the standard cone and impacting the table 15 times is compared.

Table 1 : Design of Mixtures Without Fibers

Type	**UHPC1**	**UHPC2**	**UHPC3**
Proportions by weight			
Cement CEM I 52,5R	1	1	1
Silica fume	0.25	0.25	0.25
Glass powder	0.25	0.25	0.25
Water	0.25	0.22	0.22
HRWR: Sika SVC 20 Gold	0.031	-	0.031
HRWR: Sika ViscoCrete 20He	0.019	-	0.019
HRWR: Sika ViscoCrete 30He	-	0.025	-
HRWR: Sika ViscoCrete 1035	-	0.025	-
Fine sand 0.1/0.6 mm	0.42	0.42	0.42
Fine sand 0.3/0.8 mm	1	1	1
Water/binder ratio	0.2	0.176	0.1796
Average spread [mm]	140	150	150
Avg. compr. strength [MPa]	110.0	132.2	141.9
Avg. flexural. strength [MPa]	17.6	20.8	22.1

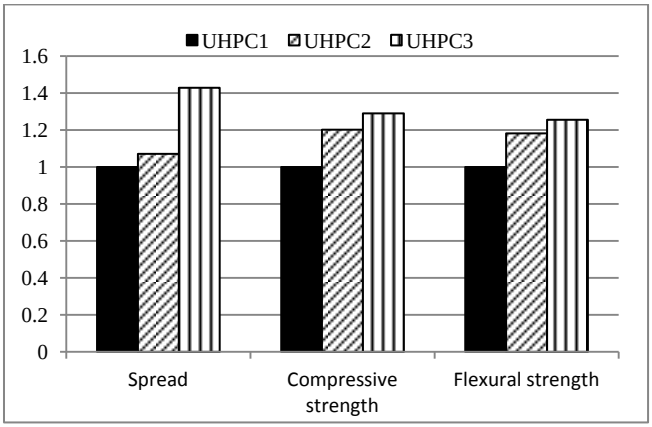

Figure 1 : Relative properties of best performing cementitous matrixes compared to UHPC1.

3.2 Mixing procedure and sample preparation

During the mixing of UHPC, it is very important to achieve good workability, particle distribution and packing density. In comparison to normal strength concrete UHPC contains more constituents and finer particles. Several researchers recommend (Wille, Naaman et al. 2011, Habel, Charron et al. 2008) to mix all fine dry particles first before adding water and HRWR. It is because small particles tend to agglomerate and it is easier to break these chunks when the particles are dry. For this reason, the mixing procedure described above was also adapted in this experimental work. It is also recommended to mix the coarsest particles with the finest, than the second coarsest particles with the second finest particles, etc. The specific mixing procedure was as follows:

- In the first step both types of aggregate (A) and SF were mixed for five minutes.
- In the second step C and GP were mixed for another five minutes.
- At the end of the procedure water and HRWR were added.

The addition of HRWR was gradual. The mixture became fully workable after another 5 minutes. In case of UHPFRC fibers were added gradually into the flowable mixture to avoid chunks formation during the last 5 minutes of mixing. The shear action of fibers helped to destroy any remaining agglomerates in the mixture, thus improving workability. The total mixing time was 15 minutes for UHPC mixtures and 20 minutes for UHPFRC. A food-type mixer with a capacity of 10 l was used to prepare the samples.

After each batch mixing a workability test using a cone and flow table was performed as described above. At the same time specimens were casted into the steel molds in two layers and shortly vibrated. After casting, each specimen was covered with plastic sheet

and stored at room temperature for 24 hours. After this, they were taken out of their molds and stored in a lime saturated water tank at 20 °C for an additional 27 days. All mechanical tests were performed after 28 days of casting.

3.3 Fibre addtion

In the second step of the optimization process straight steel fibers in different volume contents were added to the best performing mixtures UHPC2 and UHPC3 forming UHPFRC2 and UHPFRC3 mixtures. Straight fibers were used because it is known that they provide a good trade-off between tensile properties and workability of the composite. The fibers used in this research were 13 mm long with a diameter of 0.15 mm. Because of the high strength of the cementitous matrix, fibers with high tensile strength were chosen. In this case the tensile strength was 2800 MPa. The fibers were added up to 3% of volume in replacement of the equivalent volume of coarser sand. Mixture proportions can be found in Table 2. The second number after the type of matrix denotes the fiber content by volume. For instance UHPFRC 2-3 means mixture containing 3% of fibers which is based on the UHPC2 matrix design.

The mixtures containing fibers were evaluated in terms of spread, flexural strength (40 × 40 × 160 mm prisms) and compressive strength (halves of the prisms that were used for flexure). The results are shown in Fig. 2. The spread values are shown in Table 2. The three point bending (flexural) tests were deflection controlled with a loading speed of 1.5 mm/min. All specimens showed ductile post-peak behavior.

Table 2 : Tested Proportions of UHPFRC

Type of component	**UHPFRC 2-2**	**UHPFRC 2-3**	**UHPFRC 3-2**	**UHPFRC 3-3**
	Proportions by weight			
Cement CEM I 52,5R	1	1	1	1
Silica fume	0.25	0.25	0.25	0.25
Glass powder	0.25	0.25	0.25	0.25
Water	0.22	0.22	0.22	0.22
HRWR: Sika SVC 20 Gold	-	-	0.031	0.031
HRWR: Sika ViscoCrete 20He	-	-	0.019	0.019
HRWR: Sika ViscoCrete 30He	0.025	0.025	-	-
HRWR: Sika ViscoCrete 1035	0.025	0.025	-	-
Fine sand 0.1/0.6 mm	0.42	0.42	0.42	0.42
Fine sand 0.3/0.8 mm	0.8	0.7	0.8	0.7
Fibers	0.2	0.3	0.2	0.3
Spread [mm]	**153**	**140**	**240**	**160**

Table 3 : Final Mixtures Design

Type of component	**UHPFRC 3-1**	**UHPFRC 3-2**	**UHPFRC 3-3**
	Proportions by weight		
Cement CEM I 52,5R	1	1	1
Silica fume	0.25	0.25	0.25
Glass powder	0.25	0.25	0.25
Water	0.22	0.22	0.22
HRWR: Sika SVC 20 Gold	0.031	0.031	0.031
HRWR: Sika ViscoCrete 20He	0.019	0.019	0.019
Fine sand 0.1/0.6 mm	0.42	0.42	0.42
Fine sand 0.3/0.8 mm	0.9	0.8	0.7
Fibres	0.1	0.2	0.3

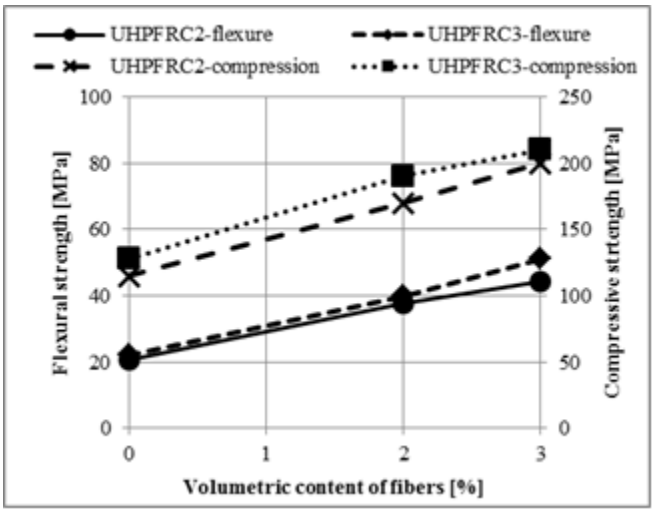

Figure 2 : Mechanical properties with respect to fibre content

3.4 Final mixture design

Based on the results presented in chapter III C mixture UHPFRC3 was chosen as the one with best workability and highest mechanical properties. For this reason a new set of samples with 0, 1, 2 and 3% of fibers by volume was prepared to describe mechanical behavior of this mixture in more detail. The exact composition is presented in Table 3. A different type of mixer (horizontal-pan rotating) with a volume of 30 l was used. The mixing procedure was the same as for previous samples. For each mixture (UHPC3, UPFRC3-1, UHPFRC3-2, UHPFRC3-3) six cylinders with a diameter of 100 mm and

height of 200 mm, three dog bone specimens and three 40×40×160 mm prisms were casted.

4.0 Mechanical Properties Measurement

4.1 Compressive Strength and Modulus of Elasticity

Compressive strength and secant modulus of elasticity were measured on cylinders with 100 mm diameter and height of 200 mm. Because the strength of the best available capping material (100 MPa) was significantly lower than the expected measured strengths, tops of the cylinders were cut off and grinded. Tests were performed using DSM 2500-100 testing apparatus. The apparatus consists of a stiff loading frame with loading capacity of 2500 kN. The elevation of loading platen is 100 mm. The loading frame is provided with a hydraulic servomechanism that allows both force increment and close-loop feedback deformation loading.

Compressive strength was measured on cylinders by monotonic increments of load with average speed of 36 MPa/min up to the level of 70% of the expected compressive strength. At this point loading was switched to deformation control with a speed of 0.5 mm/min for about 2 minutes in order to measure peak and post peak behavior. In the softening branch speed was increased to 1.2 mm/min.

Modulus of elasticity was measured using two strain gauges with a 150 mm base, attached to the sides of the cylinder specimen. A hydraulic loading machine DSM2500-100 was used and the loading procedure was stress controlled. The loading procedure for measuring modulus of elasticity of the specimens followed CSN ISO 6784 recommendations. In the first step the specimen was loaded to 1/3 of expected maximal compressive strength – in this case 50 MPa – for 60 seconds. Afterwards the specimen was unloaded to 5 MPa. This procedure was repeated three times. In the second step, the specimen was loaded until failure and compressive strength was determined. The secant modulus of elasticity was calculated following Eq. 1 from the third unloading branch.

$$E = \frac{\sigma_u - \sigma_l}{\varepsilon_u - \varepsilon_l} \tag{1}$$

where E is secant modulus of elasticity, σ_u is upper stress limit, σ_l is lower stress limit, ε_u is relative deformation at upper stress and ε_l is relative deformation at lower stress.

4.2 Direct Tensile Tests

Direct tensile tests were carried out on dog-bone shaped specimens without a notch as shown in Fig. 3. The length of the specimens was 330 mm. The specimens are categorized with respect to volumetric content of steel fibers as outlined in Table 3. Three specimens from each category were tested. All specimens were cast in layers which led to alignment of fibers in the direction of the applied load.

The direct tensile tests were performed on MTS loading machine. The specimens were mounted into specially developed grips as shown in Fig. 4. The extension in the elastic region was measured with two foil strain gauges glued on both narrow sides. After the localization of a crack the extension was measured with two LVDTs mounted with a special frame on the dog-bone specimen as can be seen in Fig. 4. The loading speed was 0.1 mm/min for specimens without fibers. In case of specimens containing fibers the loading was performed in two steps. The loading speed in the first step was 0.3 mm/min and it lasted until significant opening of the macro-crack when the load decreased to approximately 70% of the maximal load. The loading speed in the second step was increased to 0.5 mm/min. This loading procedure was chosen in order to speed up the test as deformation after the crack opening was in order of magnitude larger than deformation measured until peak load.

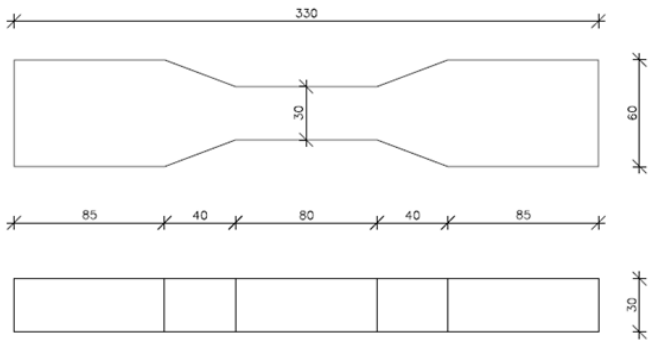

Figure 3 : Dimensions and geometry of the dog-bone shaped specimens for direct tensile stress tests in [mm].

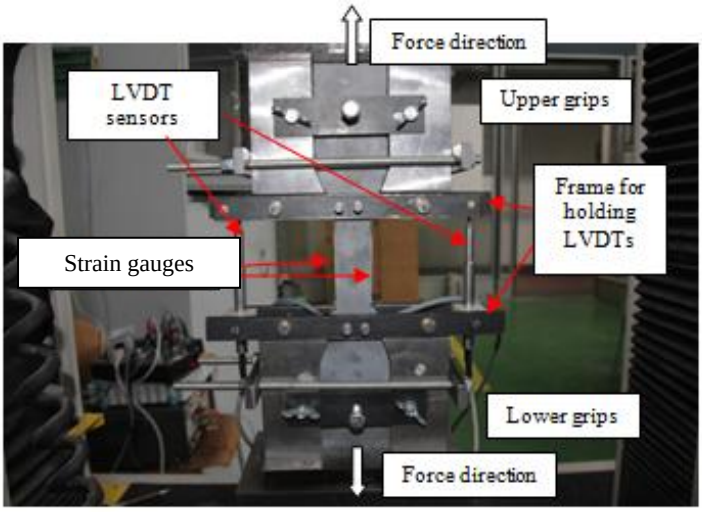

Figure 4 : Setup of the direct tensile stress test.

5.0 Results And Discussion

5.1 Compressive strength and modulus of elasticity

Fig. 5 shows measured compressive strength and secant modulus of elasticity of the developed mixtures with respect to fiber content. The values presented in the figure are averages from three samples both for compression and modulus of elasticity. It can be seen that the average highest compressive strength of 151.7 MPa was achieved for 2% volumetric content of fibers. In correspondence with that the highest average secant modulus of elasticity of 56.9 GPa was measured for 2% fiber volume. The researchers believe that the decrease in both compressive strength and modulus of elasticity for mixtures containing 3% of fibers is connected with decreased workability. The decreased workability causes thicker mixture that result in increase of air content in the sample. Unfortunately air content was not measured throughout the experimental process and will be measured in further investigation. However, it can be expected based on previous experience that the higher amount of air voids leads to overall decrease of the matrix strength and results in stress concentration in such voids.

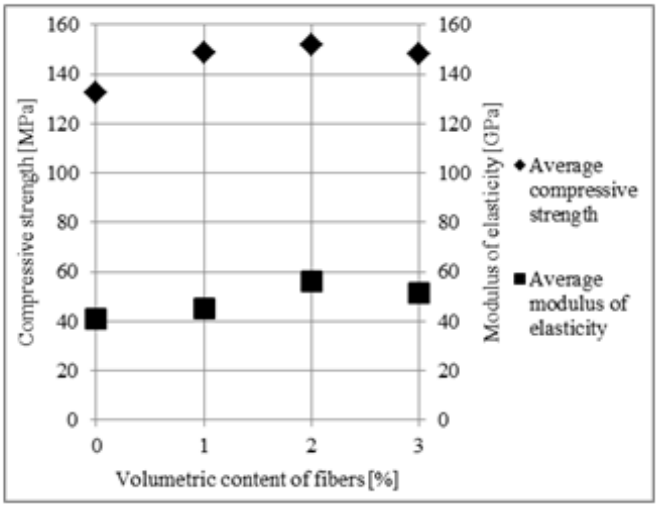

Figure 5 : Average compressive strength and modulus of elasticity of the UHPFRC mixtures.

5.2 Direct Tensile Stress

Measurement of direct tensile stress for concrete specimens is relatively complicated. For this reason the apparatus shown in Fig. 4 was utilized. It must be noted that this measurement is not ideal as cracks in all cases localized near the bottom grips. The research team believes that this is caused due to stress localization in this area. Therefore actual tensile stresses of the studied mixture can be higher than those presented in this paper. In addition, in the test setup there was only one joint at the top of the grips. A relatively rigid connection was provided between the bottom grips and MTS machine. Therefore, a slight eccentricity resulting in bending moment could be induced into the specimen.

Uniaxial tensile behavior of the matrix i.e. UHPC mixtures (without fibers) is shown in Fig. 6. The third number after the type of specimen is the number of specimen. For instance UHPC2-0-1 means first specimen made from UHPC2 mixture containing 0% of fibers. Due to the problems with the testing device, sample UHPC2-0-2 was destroyed prior to the test and is not presented in this figure. It can be seen that the average direct tensile stress of the specimens without fibers is 6.6 MPa. From the stress-strain diagram a linear-elastic behavior of the matrix can be seen.

The results of the uniaxial tensile tests of specimens containing 1, 2 and 3% of fibers respectively are presented in Fig. 7. The curves in Fig. 7 are average curves from three

samples to keep the chart as clear as possible. The figure is divided into two parts that are typical for UHPFRC behavior: a) linear-elastic and strain hardening part, which includes the linear-elastic stress rise and the strain hardening part of stress-strain diagram. It is possible to say, that energy dissipation is volumetric in this part; b) the softening part in which the energy is dissipated in a localized crack at the crack surface.

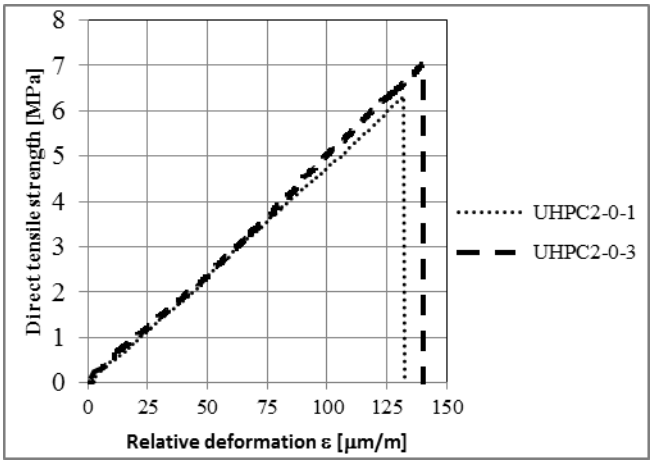

Figure 6 : Direct tensile behavior of specimens without fibers.

Fig. 7 a) shows the stress-strain relationship in the strain hardening part of the curve. The stress is calculated by dividing the measured force by the reduced cross-section of the dog bone specimen (30×30 mm). Strain values were determined from the average strain measured by two foil strain gauges, which were glued on the side of the specimen. Fig. 7 b) provides the relation between stress and total crack width during softening. The total crack width was measured as an average from two LVDTs which spanned over the entire reduced cross-section portion of the specimen.

The average apparent strain at the end of strain hardening region of the quasi –static tests was 150 µm/m for samples with 1% of fibers, 608 µm/m for samples with 2% of fibers and 569 µm/m for samples containgin 3% of fibres. The average direct tensile strength was 7.8 MPa, 9.9 MPa and 10.9 MPa respectively.

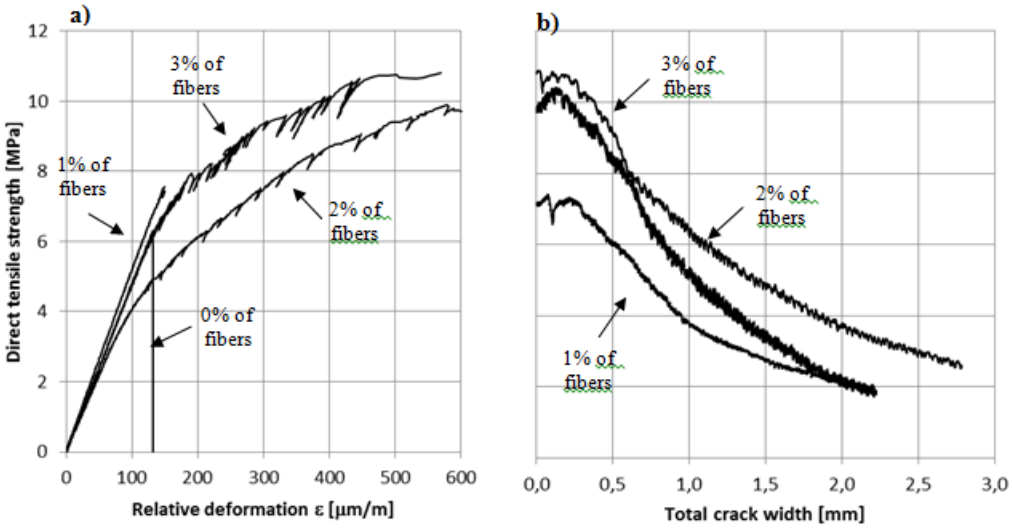

Figure 7 : Uniaxial tensile behavior of UHPFRC: a) lienar-elastic part and strain hardening and b) softening.

6.0 Conclusions

The research described herein has shown that it is possible and relatively simple to develop a UHPFRC without the need for special curing such as heat or pressure. It was also shown that it is possible to use standard laboratory equipment such as food-type and horizontal-pan mixers for mixing high performance cementitious composites. The initial strategy was to increase workability by optimizing the packing density of the mixture and using different types of HRWR. A spread of the paste measured during the simple flow-table test was found to provide good indication of workability. In addition, results from three-point bending (flexural) and compressive strength were utilized during the optimization process. All materials used in this research were commercially available in the Czech Republic.

The experimental work also showed the importance of strict mixing procedure. Especially mixing times must be strictly adhered to. In addition, it was also showed that mixtures containing more than 3% of fibers by volume have very bad workability and more optimization and usage of different HRWR and mixing techniques is needed in this area. The future research will focus on measurement of fracture energy of UHPFRC under different strain rates and on further optimization of the matrix composion.

The main findings of our research are as follows:

- An optimization of ultra-high performance cementitious composite was undertaken comprising laboratory tests on 24 mixtures with respect to its compressive strength, flexural strength and workability
- Based on the former parameters the final mixture was chosen for further expertise dealing with different amount of fiber content.
- Addition of fiber to the mixture increased the mechanical properties of the UHPFRC. However, more than 2% of fiber content tends to decrease the compressive strength and modulus of elasticity.
- Direct tensile strength of the UHPFRC seemed to increase gradually with increasing content of fibers up to the 3%.
- Based on the previous results it was found that the optimal amount of fiber content with respect to the mechanical properties and workability lies between 2% and 3% by volume.
- With an increase in target mechanical parameters, UHPC and UHPFRC become much more sensitive to quality of the components, the dispersion of the particles, mixing procedure, the specimen preparation and curing.

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