1. INTRODUCTION

Good knowledge of the material parameters, the material behaviour, and an accurate constitutive law for ultra-high performance fibre-reinforced concrete (UHPFRC) are necessary to model or design structures using this composite material. Therefore a large set of test specimens were produced without fibres and with 1 vol% and 2 vol% of fibres. The ultra-high performance concrete (UHPC) matrix was the same for the three mixtures with a maximum grain size of 0.4 mm. The water to cement ratio was 0.23, the water (including 70% of the superplasticizer) to binder ratio 0.21. For mixtures with fibres the same straight fibre type was used with the length of 15 mm and diameter of 0.2 mm. The tensile strength of the fibres was higher than 2000 N/mm². Size and shape of the specimens, production, storage, curing and testing of the specimens were according to ÖNORM EN 12390 [1] and ONR 23303 [2].

Digital Image Correlation (DIC) measurement system AN ADVANCED APPROACH TO DERIVE THE CONSTITUTIVE LAW OF UHPFRC

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Abstract

More than 200 specimens were tested in a comprehensive experimental campaign using ultra-high performance concrete with a mean compressive strength between 150 and 210 MPa and with different amounts of steel fibre reinforcement (0%, 1% and 2% by volume) from the first 2 days to 1.5 years after casting. From the large set of experimental tests related material parameters were derived. Based on compression tests with strain transducers and laser displacement transducers, the compression side of the constitutive law was derived, and based on the splitting tensile tests and flexural bending tests, the tensile side of the constitutive law was derived and the results are presented. For derivation of the tensile behaviour of ultra-high performance fibre-reinforced concrete an advanced approach was applied by using a photogrammetric camera system with digital image correlation (DIC).

Keywords: UHPC; Steel fibre reinforcement; Constitutive law; DIC measurement; Statistical analysis; Inverse analysis.
is an effective tool to measure and monitor structural deformations with high accuracy, and its usage is more and more common in research and engineering practice [3]. Comparison of the new, innovative measurement methods with the well-acknowledged, traditional ones provides the verification and validation of accuracy, reliability, and usability range of all these techniques [4, 5]. For derivation of the tensile behaviour of the used UHPFRC material, a DIC measurement system and traditional measurement techniques were used in parallel; and the evaluation of the results is presented in here.

2. DENSITY

Fig. 1 shows the average density of the concrete with different fibre contents 28 days after casting, based on measurements on more than 100 specimens of different size and geometry (cube and cylinders). The average density of concrete without fibres was 2339 kg/m³. Measured values varied between 2324 kg/m³ and 2353 kg/m³. Mean values measured on different types (size or geometry) of specimens were between 2338 kg/m³ and 2342 kg/m³. The average density measured on specimens with 1 vol% of steel fibres was 2403 kg/m³. Measured values varied between 2375 kg/m³ and 2440 kg/m³. Mean values measured on different types of specimens were between 2391 kg/m³ and 2407 kg/m³. The average density measured on specimens with 2 vol% of fibres was 2466 kg/m³. Measured values were between 2442 kg/m³ and 2485 kg/m³. Mean values measured on different types of specimens were between 2453 kg/m³ and 2472 kg/m³. According to these measurements addition of steel fibres increased the density by 62-64 kg/m³ per % by volume, which is larger than the 55 kg/m³ per % by volume calculated from the density and ratio of the concrete and steel.

Fig. 2 shows the development of the density in time between the age of the concrete of 7 days and 1.5 years. Values decreased from 2429 kg/m³ to 2412 kg/m³ by 0.7% in this time period. Since the specimens spent the first 7 days (between casting and testing) under water, the value related to 7 days age can be considered as fully saturated. Assuming that after 1.5 years the specimens reached the state of equilibrium under laboratory conditions, the average pore ratio of the specimens can be estimated as 1.7%.

3. COMPRRESSIVE STRENGTH

Specimens presented in this section did not undergo any compaction during casting or any after-treatment (heat or compression) later. The effect of compacting is discussed in section 6. The mean value of the 28 days compressive strength on cubes with 100 mm side length was 154.3 N/mm² without fibres, 167.8 N/mm² with 1% of fibres and 172.5 N/mm² with 2% of fibres (see Fig. 3 and Fig. 5). 1 vol% of fibres increased the compressive strength of the concrete by 13.5 N/mm² (8.7%), 2 vol% of fibres increased the compressive strength by 18.2 N/mm² (11.8%). The increase from 0 to 1% was around three times higher, than from 1% to 2% (4.7 N/mm², 2.8%). The mean compressive strength values after 28 days on 200 by 100 mm cylinders were 144.2 N/mm² for concrete without fibres, 161.5 N/mm² with 1% of fibres and 166.0 N/mm² with 2% of fibres (see Fig. 3). 1% of fibres increased the compressive strength of the concrete on cylinders by 17.3 N/mm² (12.0%), 2% of fibres increased the compressive strength by 21.8 N/mm² (15.1%). Compared to the strength values measured on cubes, the increase from 0 to 1% of fibres was significantly higher at cylinders, but the increase from 1 to 2% of fibres was around the same (at cylinders: 4.5 N/mm², 2.8%).
The ratio of the compressive strength measured on 200 by 100 mm cylinders to 100 mm cubes was slightly above 0.93 without fibres and was around 0.96 with 1% and with 2% of fibres. Taking into account all other series (number of batches over the years) with the same recipe and with 1% or 2% fibres, the ratios of cylinder to cube strength were between 0.91 and 0.97 with a mean value close to 0.94, and with a tendency that at higher fibre contents the ratio is closer to 1.0.

Fig. 5 also depicts the linear regression between compressive strength and density after 28 days with a regression coefficient of $183.8 \times 10^3$ Nm/kg.

Fig. 4 shows the development of the mean compressive strength during concrete aging from 2 days to 1.5 years. The increase of the compressive strength is especially fast in the first days (80 N/mm² after 2 days and 124 N/mm² after 7 days), but still there is a slight increase after 1 year.

4. MODULUS OF ELASTICITY

The measured modulus of elasticity values on 300 mm by 150 mm cylinders and on a 100 mm base length were 44.7 GPa without fibres, 46.9 GPa with 1% of fibres and 49.3 GPa with 2% of fibres. On 200 mm by 100 mm cylinders (with 100 mm base length) the measurements showed slightly (1–3 GPa) smaller values. Measurements were also performed on cubes with 100 mm side length on a base length of 50 mm, and they resulted in about 5 GPa higher modulus than the values measured on the 300 mm high cylinders, and in 6–8 GPa higher values than on the 200 mm high cylinders. Specimens tested at the age of 43 days showed 1.0–1.5 GPa higher values than at an age of 28 days. Fig. 6 shows the linear regression between the 28 days modulus of elasticity and density measured on 300 mm by 150 mm cylinders with a regression coefficient of $35.5 \times 10^6$ Nm/kg.

5. SPLITTING TENSILE STRENGTH

The mean value of the 28 days splitting tensile strength on 200 by 100 mm cylinders was 7.9 N/mm² without fibres, 14.1 N/mm² with 1% of fibres and 16.1 N/mm² with 2% of fibres (see Fig. 7). At specimens with 1% fibres, there was a clear sign of the first cracking at a splitting tensile stress of 8.1 N/mm².
Fig. 8 shows the linear regression between the 28 days splitting tensile strength and density with a regression coefficient of $63.1 \times 10^3$ Nm/kg.

6. EFFECT OF COMPACTING

While most of the specimens from self-compacting UHPC were produced without any compacting treatment during the mixing and casting process of the fresh concrete, some of them were prepared using a hand-compacting method. These specially handled specimens (cubes with 100 mm side length) showed a clear and significant advantage on the measured density and compressive strength (see dashed blue arrows in Fig. 9). According to the measurement, every 10 kg/m$^3$ density increase enhanced the compressive strength by 2.8 N/mm$^2$ on average with a range of 1.9–3.9 N/mm$^2$; or every 1% increase of density resulted in 3.8% average increase of compressive strength with a range of 2.8 to 4.9%. Fig. 9 also depicts the change of density and compressive strength between ages of 28 days and 1.5 years (continuous green arrows). The increase of the compressive strength was 26–29 N/mm$^2$ in this period, and reached the value of 213 N/mm$^2$ (compacted specimens with 2% of fibres). The decrease of the density was half (5 kg/m$^3$) for the compacted specimens in comparison to the non-compacted ones (10 kg/m$^3$).

7. COMPRESSIVE STRESS VS. STRAIN CURVE

The compressive side of the constitutive law was derived from compression tests with deformation measurements. Deformation of the specimens was measured in parallel with strain transducers on the sides of the specimens and with laser (optical) displacement transducers between the two opposite surfaces of the hydraulic press. Strain transducers were used only until about 60% of the expected maximum load because of high risk of their damage during the failure process. Tests were performed on 100 mm cubes, on 200 by 100 mm cylinders and on 300 by 150 mm cylinders. Measured base length of the strain transducers was 50 mm in case of the cubes and 100 mm in case of the cylinders. The measuring length of the laser displacement transducers (base length for the strain calculation) was the same as the height of the specimens (100 mm, 200 mm and 300 mm).

Fig. 10 shows the mean curves for the different types of specimens. For this figure the curves from specimens without fibres and with 1% of fibres were evaluated together in the first, quasi-linear phase (higher number of measurements resulted in straighter and more trustable trend-like curves). As it is described in sections 3 and 4, curves measured on cubes were steeper and reached a higher strength, than curves measured on cylinders. Curves measured on 300 by 150 mm cylinders showed stiffer behaviour and would
have probably reached lower final compressive strength (not measured as the failure load exceeded the 3 MN capacity of the hydraulic press). Curves measured after 43 days were slightly steeper and reached slightly higher strength values than curves measured after 28 days. Fig. 10 shows the curves for specimens without fibres and with 1% of fibres separately from the point where their ratio of steepness started to change. This point was between 125 N/mm² and 140 N/mm², which is around 90% of the peak values of curves without fibres and around 80% of the peak values of the curves with 1% of fibres. Curves from specimens without fibres reach the peak value at 3.5‰ strain value on average (3.4–3.6‰), and with 1% of fibres a value of 3.9‰ on average (3.7–4.1‰). Specimens without fibres failed in an explosive way at the peak load, and the post-peak part of the curve could not be measured. Cylinders with 1% of fibres failed quickly, but they did not explode and the post-peak branch of the curve could be measured. Cubes with 1% of fibres failed slower and the load response dropped gradually. Specimens with 2% fibres failed slowly and they did not fall apart even at high degradation levels. Fig. 11 depicts the whole curves for specimens without fibres and with 1% of fibres.

8. TENSILE STRESS VS. STRAIN CURVE

The tensile side of the constitutive law was derived indirectly using flexural bending tests on prismatic specimens. The size of the specimens was 700x150x150 mm and specimens were tested in a four-point bending setup with a span of 600 mm according to the German guidelines [6],[7]. Specimens were measured in parallel using a traditional measurements system (displacement transducers, strain gauges and strain transducers) and a Digital Image Correlation (DIC) system, and the results from the two types of system were compared. The DIC technique is a useful tool to measure and monitor structural deformations. It is possible to directly measure the surface deformations or the crack opening values of every single crack. Based on the DIC measurements it is very easy to visualise the crack pattern of the measured surface. Fig. 12 shows a typical crack pattern at peak load with 1% of fibres and with 2% of fibres. Specimens with 1% of fibres have fewer cracks (4.2 on average) with sharper edges and with only a few branches. Specimens with 2% of fibres have more cracks (9.2 on average) with scratchy crack faces and more branching.
The basic results from flexural tensile tests are the load vs. deflection curves, and then the flexural tensile stress vs. deflection curves derived from them. The mean values of the maximum load and the flexural strength were 32.6 kN and 5.8 N/mm² for specimens with 1% of fibres, and 63.5 kN and 11.3 N/mm² with 2% of fibres (see Fig. 13). Deflection at the peak load was 1.2 mm on average for specimens with 1% of fibres and 0.9 mm with 2%. Beside the fibre content, other very important factors of the fibre-reinforced concrete are the fibre distribution and fibre orientation. A well-designed and performed mixing process should provide homogenous fibre distribution, but the casting process has a very big influence on the fibre orientation (and distribution of the fibre orientation inside the specimen). Therefore in this test series one of the specimens was cast differently: generally the fresh concrete was poured into the formwork at several discrete points (later referred to as “unfavourably oriented”), but at one specimen this happened without interruption in continuous longitudinal movement (later referred as “favourably oriented”). The difference was very pronounced: the specimen with favourably oriented fibres showed around double high values than specimens with unfavourably oriented fibres, and the peak value was similar to specimens with 2% of fibres (see Fig. 13).

The use of the DIC system allows for following the exact movement of any surface point, therefore it was interesting to compare with the traditional measurement techniques. Fig 14 shows the measured movements of one specimen: the way of the cylinder was measured by a built-in sensor of the testing machine; deflection was measured by a displacement transducer fixed on the specimen; and mid-point movement was measured using the DIC system. The deformation from the DIC system was derived as the subtraction of the mid-point movement and the movement of the fixing point (according to DAFStb, 2012) of the deflection transducers. This method provided the same results as recorded by the displacement transducer (see Fig. 14). Using the DIC system it is not required to fix any sensor on the specimen and it is possible to separate the elastic deformations from the support or rigid body movements.

The comparison of the crack opening measurements was another research topic. The cracking process was recorded by three strain transducers with 100 mm base length on the bottom surface of the flexural specimens as well as with virtual extensometers using the DIC system. Fig. 15 shows the crack measurements for one beam. While strain transducers usually measure more cracks together with elongation from the elastic deformation under their base length (300 mm all together), by using the DIC system each crack can be measured and it can separate the crack opening and the elastic deformation (base length of the virtual extensometers is 2–5 mm). To check the measurements, the crack opening values under the same strain transducers were summed up. Fig. 16 depicts the result for one beam: 2nd and 3rd crack was under the left strain transducer, 4th, 5th and 6th under the middle transducer and the 7th under the right transducer (1st crack was outside of the 300 mm range of the strain transducers); and the related curves are very similar (small differences came from the asymmetrical failure of the specimen). Other problems which can be avoided using optical measurements are: (a) strain transducers have a tendency to slip on the smooth, sometimes glossy surface of the UHPC; and (b) cracks that can be outside of their base length are excluded from the measurement.
The mean value of the largest crack opening at the peak load was 1.3 mm with 1% of fibres and 0.6 mm with 2% of fibres. Most of the cracks stayed smaller than 0.1 mm and only a few reached the range of 0.1 and 0.5 mm. Close to the peak load one of the largest cracks became the decisive one and from this point only the decisive crack increased and other cracks partly closed. The tensile stress vs. crack opening and the tensile stress vs. strain curves were derived from the measured load vs. crack opening curves according to the AFGC Guideline [8]. Fig. 17 and Fig. 18 show the derived curves from the three different types of flexural specimens.

9. CONCLUSIONS

A comprehensive experimental test series with a large number of specimens was performed in order to determine the material parameters, material behaviour and derive the constitutive law on the compressive and on the tensile side of a UHPC mixture without fibres and with a fibre content of 1% and 2% by volume, using a new measurement and calculation method:

- The mean density of UHPC after 28 days was 2339 kg/m³ and decreased by time due to concrete drying. The addition of steel fibres increased the density of the hardened concrete by 62–64 kg/m³ per % of fibres.
- The increase of the compressive strength by addition of the first % of fibres is significantly higher for cylinders (12.0%) than for cubes (8.7%), but around the same for the second % of fibres (2.8%).
• The ratios of cylinder to cube strength were between 0.91 and 0.97 with a mean value close to 0.94, and with a tendency that at higher fibre contents the ratio is closer to 1.0.

• The splitting tensile strength was 7.9 N/mm² without fibres, 14.1 N/mm² and 16.1 N/mm² with 1% and with 2% of fibres, respectively.

• The effect of compacting: 1% increase of density resulted in 3.8% increase of compressive strength on average, and decrease of the density by time was half for the compacted specimens in comparison to the non-compacted ones.

• The fibre orientation has a very strong effect on the tensile properties of the concrete: 1% of “favourably oriented” fibres have a similar effect like 2% of “unfavourably oriented”, and the tensile properties are about twice that high if the casting process takes care of the final fibre orientation.

• DIC technique allows a continuous optical measurement without interruption of the testing process, and the points of interest in the measured spatial and time range can be chosen later. Results from the traditional and the DIC systems were compared, and the advantageous applicability of the optical system was verified.

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