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TRIAXIAL COMPRESSIVE STRENGTH OF ULTRA HIGH PERFORMANCE CONCRETE

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Abstract. The aim of this work is to describe the strength of Ultra High Performance Concrete (UHPC) under triaxial compression. The main goal is to find a trend in the triaxial compressive strength development under various values of confinement pressure. The importance of triaxial tests lies in the spatial loading of the sample, which simulates the real loading of the material in the structure better than conventional uniaxial strength tests. In addition, the authors describe a formulation process for UHPC that has been developed without using heat treatment, pressure or a special mixer. Only ordinary materials available commercially in the Czech Republic were utilized throughout the material design process.

Keywords: UHPC; triaxial strength; material design.

1. Introduction

Ultra High Performance Concrete (UHPC) can be characterized as a composite material with a high cement and silica fume content, a low water-binder ratio and absence of coarse aggregate, i.e. aggregate larger than 4 mm [1, 2]. It has outstanding material characteristics such as self-consolidating workability, very high mechanical properties and low permeability, which results in excellent environmental resistance [3–5]. Typical strengths are 100 to 200 MPa in uniaxial compression and 6 to 15 MPa in uniaxial tension [6]. Moreover, these materials exhibit strain hardening under tension [7, 8] and high energy absorption capacity [6, 9–12].

Structural engineers have long recognized the importance of concrete behaviour under multiaxial stress states. Several researchers have studied the behaviour of Normal Strength Concrete (NSC) [13–15] or High Performance Concrete (HPC) [16–20] under triaxial compression. It has been widely established that the compressive strength increases when confinement pressure is applied to the sample. In addition, it has been specified for NSC that the strength increments are linearly adequate to the lateral stress increments [13]. For HPC, the gradient of the strength increments is not constant but tends to decrease as the confinement pressure increases. Using the least square method to cover this trend, polynomial regression is applied by some researchers [21]. However, power law regressions are mostly applied for HPC [13, 18].

This study focuses on an evaluation of the triaxial compressive strength of UHPC developed in the Czech Republic from local materials in order to verify its behaviour with respect to available literature sources. The results provided in this study can serve as valuable information for verifying material models, and also for design purposes.

2. Material

2.1. UHPC Design

In the first phase of the research, several concrete mixtures were produced to find the best combination of constituents with respect to maximal compressive strength and workability. The first mixture was designed following the proportions of cement : silica fume : glass powder recommended by Wille et al. [1] as 1 : 0.25 : 0.25, with a water-to-binder ratio of 0.2. Subsequent changes in the most important parameters, e.g. water content, silica fume and high-range water reducers, led to an optimized cementitious matrix in terms of compressive strength and workability. From the 24 tested mixtures [2], the best performing cementitious matrix composition denoted as UHPC is shown in Figure 1. Figure 1 also shows the basic material properties of the selected mixtures. In the “average spread” row, a diameter is shown of the paste spread measured after filling and removing the standard cone and impacting the table 15 times. The flexural strength was evaluated on $40 \times 40 \times 160$ mm prisms, and the compressive strength was evaluated on the halves of these prisms, following CSN EN 1015-11.

It is well established that the addition of short steel fibres increases the mechanical properties of plain UHPC mixtures [2, 6]. The shear action of the fibres helps to destroy any remaining agglomerates in the mixture, thus improving the workability and consequently the mechanical properties. However, UHPC without fibres was used for the triaxial compressive

Component	[kg/m^3]
Cement CEM I 52,5R	800
Silica fume	200
Glass powder	200
Water	176
HRWR: Sika SVC 20 Gold	24.2
HRWR: Sika ViscoCrete 20He	14.8
Fine sand 0.1/0.6 mm	336
Fine sand 0.3/0.8 mm	800
Water/binder ratio	0.176
Average spread	150 mm
Average compressive strength	141.9 MPa
Average flexural strength	22.1 MPa

Table 1. UHPC composition.

strength tests, as it has been found that fibres have no effect on triaxial compressive strength [19].

2.2. Mixing Procedure

During the mixing of UHPC, it is very important to achieve good workability, particle distribution and packing density. In comparison with NSC, UHPC contains more constituents and finer particles. Several researchers have recommended mixing all fine dry particles first before adding water and high-range water reducers. This is because the small particles tend to agglomerate, and it is easier to break these chunks when the particles are dry. The specific mixing procedure was as follows: In the first step, both types of aggregate and silica fume were mixed for five minutes. In the second step, cement and glass powder were mixed for another five minutes. At the end of the procedure, water and high-range water reducers were added. The water and the high-range water reducers were added gradually. The mixture became fully workable after another 5 more minutes.

3. Testing

3.1. Basic Mechanical Properties

The compressive strength and the secant modulus of elasticity were measured on cylinders 100 mm in diameter and 200 mm in height. Because the strength of the best available capping material (100 MPa) was significantly lower than the expected measured strengths, the tops of the cylinders were cut off and ground. The compressive strength was measured on the cylinders, and additionally on the cubes, by monotonic increments of the load with an average speed of 36 MPa/min up to a level of 70 % of the expected compressive strength. At this point, the loading was switched to deformation control with a speed of 0.48 mm/min in order to keep the test stable when failure occurs.

Uniaxial compressive strength	123/148 MPa
Secant modulus of elasticity	41.1 GPa
Poisson ratio	0.17
Modulus of rupture	9.9 MPa
Direct tensile strength	6.6 MPa

Table 2. Average mechanical properties of the UHPC.

The modulus of elasticity was measured using two extensometers with a 100 mm base, attached to the sides of the cylinder specimen. A DSM2500-100 hydraulic loading machine was used, and the loading procedure was stress controlled. In the first step, the specimens were loaded to 1/3 of the expected maximal compressive strength — in this case 40 MPa — for 60 seconds. Afterwards the specimens were unloaded to 4 MPa. This procedure was repeated three times. The secant modulus of elasticity was calculated from the third loading and unloading branch.

The Poisson ratio, representing the ratio of transverse to axial strain, was determined on the cylinders, using a pair of strain gauges glued to the perimeter of the cylinder in the middle of its height. The Poisson ratio was determined on the same samples using the same loading procedure as for the secant modulus of elasticity. Thus, the Poisson ratio was determined as an average value up to the stress level corresponding to 1/3 of the expected uniaxial compressive strength.

The modulus of rupture was determined on prisms 100 × 100 × 400 mm. The clear span was 300 mm. A three-point bending configuration was applied and the maximal force was measured. The loading was controlled by the deformation at all times. The loading speed was 0.2 mm/min.

Direct tensile tests were carried out on dog-bone shaped specimens without a notch. The specimens were 330 mm in length, and the cross-section of the narrowed part was 30 × 30 mm. The direct tensile tests were performed on an MTS loading machine. The specimens were mounted into specially developed grips. The loading speed was 0.1 mm/min.

3.2. Strength in Triaxial Compression

The triaxial compressive strength was determined simultaneously on the cylinder and cubes. The cylinders were 200 mm in height and 100 mm in diameter; the sides of the cube were 100 mm long. The cylinders were tested in a triaxial chamber, where the confinement pressure was provided by mineral oil. A waterproof coating was provided for all cylinders in order to avoid the ingress of mineral oil into the UHPC structure. It was verified experimentally that this kind of coating has no influence on the uniaxial compressive strength. At first, the cylinders were prestressed by

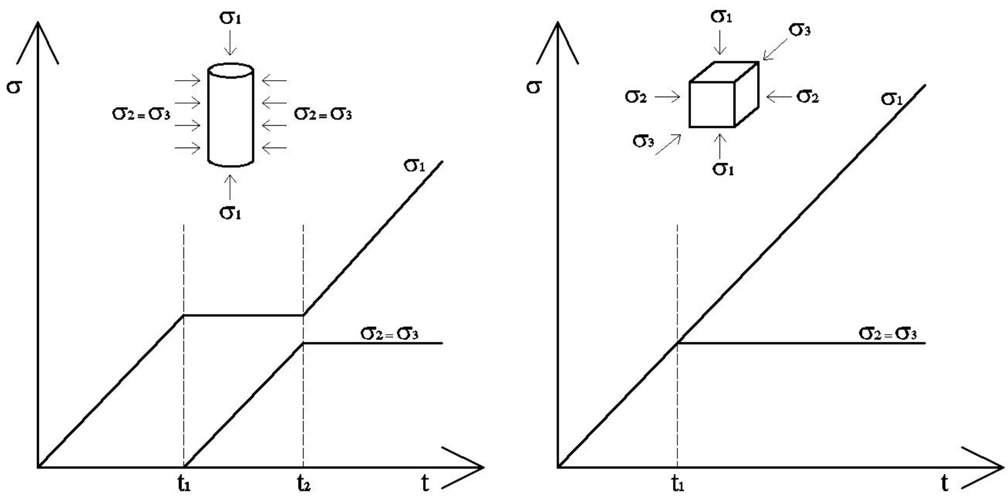

Figure 1. Testing procedure for UHPC cylinders and cubes.

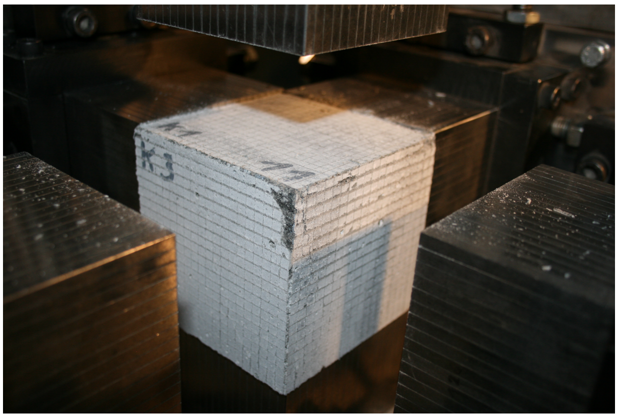

Figure 2. Triaxial hydraulic loading machine.

Confinement pressure [MPa]	Sample	
	Cylinder [MPa]	Cube [MPa]
0	123	148
10	178	–
15	–	231
20	209	–
30	231	280
60	–	362
90	–	432

Table 3. Triaxial compressive strength of the UHPC.

the crossbeam of the hydraulic loading machine. Afterwards, the chamber with the UHPC cylinder was flooded by the mineral oil, which was subsequently pressurised to the prescribed confinement pressure (Figure 1).

The cubes were tested in a triaxial hydraulic loading machine, in which each side of the cube was pushed by the loading plate with dimensions 95 × 95 mm (Figure 2). The cubes were placed in the hydraulic loading machine, where all the loading plates developed the compressive stress simultaneously until the prescribed confinement pressure. At this point, two directions were fixed to the prescribed stress, while the stress in the third direction continued on until failure of the UHPC cube (Figure 1). A further detailed description of the testing device and the testing procedure can be found in the work of Hampel et al. [22]. In both cases, i.e. cylinders and cubes, the loading was controlled by the increments of the deformation. The loading speed was 0.48 mm/min.

4. Results and Discussion

4.1. Basic Mechanical Properties

Table 2 shows the compressive strength, the secant modulus of elasticity, the Poisson ratio, the modulus of rupture, and the direct tensile strength of the UHPC mixture. The values presented in the table are averages from three samples.

4.2. Strength in Triaxial Compression

The triaxial compressive strength was described using various samples and loading procedures. The triaxial compressive strength was determined under confinement pressure of 10, 20, 30 MPa for the cylinders and 15, 30, 60, 90 MPa for the cubes (Figure 3). The triaxial compressive strength determined under elevated confinement pressure was standardised by the uniaxial compressive strength in order to obtain the first evaluating parameter. The ratio of the confinement pressure and the uniaxial compressive strength was used as a second parameter in order to describe the

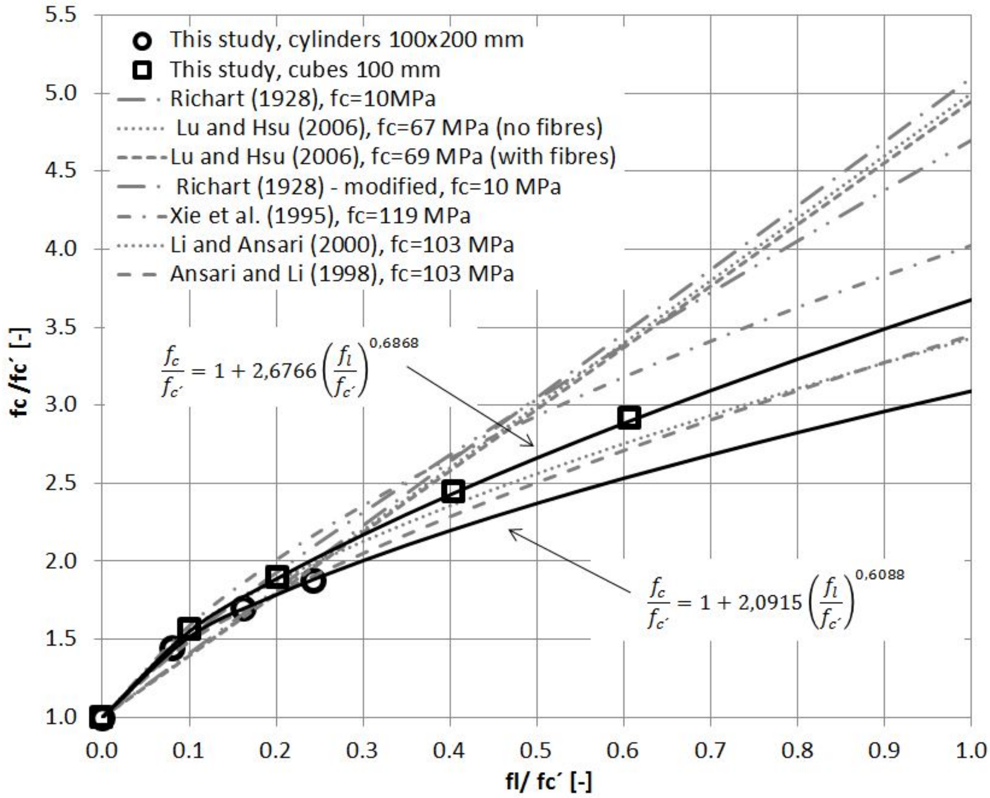

Figure 3. Development of triaxial compressive strength.

strength of the UHPC in triaxial compression. As the confinement pressure increased, the UHPC compressive strength also increased. NSC tends to follow a linear trend up to the level where the confinement pressure is equal to the uniaxial compressive strength. At this level, the triaxial compressive strength is roughly five times the uniaxial compressive strength. The best reliability, using the least square method, was achieved by fitting the development of UHPC triaxial strength by the power law function. The triaxial compressive strength derived from the power law regressions, established for the UHPC used in this study, were uniaxial compressive strength 3.1 for the cylinders and 3.7 for the cubes (Figure 3).

5. Conclusions

A UHPC mixture was developed in this study to find the best-performing combination of constituents with respect to workability and strength. As fibres play no role in triaxial compressive strength, a UHPC mixture without fibres was subjected to triaxial compression using both cylinders and cubes made of plain UHPC. It was verified experimentally that the development of the UHPC triaxial strength on confinement pressure can be fitted by the power form regression. Using established regression and confinement pressure equal to the uniaxial compressive strengths, it was determined that the triaxial compressive strength is 381 MPa for cylinders and 548 MPa for cubes. Therefore, the failure surface of UHPC falls below the failure surface of NSC, especially at higher confining pressures.

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