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Experimental tests of the HPC in triaxial compression

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Abstract

In this paper we present an experimental study of the high performance concrete (HPC) in triaxial compression. The examined high performance concrete was developed at the Experimental Center, of the Faculty of Civil Engineering, CTU in Prague from the components locally available and, in addition, without using any special mixing technique or curing procedure. The uniaxial compressive strength was found out to be 130 MPa. We examined the behavior of HPC in triaxial compression in two different ways. The first way was triaxial chamber where cylinders were tested. The cylinders were 200 mm high and 100 mm in diameter. We tested cylinders in triaxial chamber under lateral stress equal to 10, 20 and 30 MPa. The second way of testing HPC in the triaxial compression was a triaxial loading machine where cubes were tested. The length of the cubes was 100 mm. We tested cubes under lateral stresses equal to 15, 30, 60 and 90 MPa. We provided two equations for both cylinders and cubes. Both equations described the strength development of HPC in dependence on different values of lateral stress. The difference between triaxial strength development of cubes and cylinders was slight. The results obtained in this study are in good correlation to the results gained from the literature. It was experimentally verified that the strength development of the HPC under different levels of the confinement pressure is not linear and tends to follow the power law function.

Introduction

Architects design very slender structures in modern architecture, such as thin columns or shells. The structural elements must be durable, resistant to environmental influences and must also have a great resistance to mechanical loading. These requirements keep high performance concrete. Compressive uniaxial strength is used for the design of reinforced concrete structures in most cases. However we can find multi-axial stress state in many structural elements. For this reason, it is necessary to examine high performance concrete in triaxial stress. This high performance concrete was developed at the department of the Experimental Center the Faculty of Civil Engineering of Czech Technical University in Prague. This high performance concrete can be made from only locally available materials and without using special procedures for mixing concrete or without special requirements for care at an early age of concrete [1]. The high performance concrete is with its composition very different from conventional concrete. In the HPC there is not at all coarse aggregate, just only fine-grained with fraction 03/08. Furthermore, in the HPC there is silica flour and silica fume. One of the other features of the HPC is the content of a large amount of cement and a small amount of water. Water ratio in this HPC is 0.22. A small amount of water is compensated by superplasticizer ingredients. This HPC requires very challenging conditions for production. Even small variations have a significant impact on the final properties of the concrete. Components already require increased dosage accuracy. We mixed HPC in the blender with a capacity of 10 liters and it has always been necessary to follow a uniform procedure dosage components and the length of their agitation. Subsequently, the concrete mixture was stored in a steel mold in which it was compacted by using a lower vibration. The day after the casting of samples we took out samples of the forms and stored them the other twenty-seven days in a water tank. After twenty-eight days from the concreting of samples we removed samples from the water tank and prepared them for testing. We examined samples in the triaxial pressure at about thirty days of age.

Experimental program – triaxial chamber

We used a triaxial chamber available at the Faculty of Civil Engineering CTU in Prague for testing cylindrical samples in multi-axial stress. We tested cylindrical samples with a height of 200 mm and diameter 100 mm in a triaxial chamber. We applied smoothing waterproofing layer on the cylinder in order to avoid a penetration of mineral oil to the concrete structure. The triaxial chamber creates principal stress (σ_1) in the vertical direction by creating the press and the horizontal stress ($\sigma_2 = \sigma_3$) created by mineral oil in the chamber (Fig. 1). This means that in a three-axis coordinate system, this can be understood, so that the two directions of the stress applied to a cylindrical sample for testing are constant ($\sigma_2 = \sigma_3$). In the third direction the stress creates a press (σ_1). The maximum value of the lateral stress in the triaxial chamber is 63 MPa and a maximum load power capacity of the press is 2500 kN. These limit values are very restrictive for testing the high performance concrete with a high compressive strength. Therefore, in my experimental program chamber stress could use only half of maximum value, i.e. 30 MPa. We created a total four series of cylindrical specimens which we tried on four levels of lateral stress - 0, 10, 20 and 30 MPa. The diagram (Fig 2) shows development of increasing stress applied to the concrete sample. The sample was prestressed by a steel cross member of the press (point 1) at first. The next step was filed the triaxial chamber with hydraulic fluid and pressurized chamber to the desired pressure (10, 20 or 30 MPa) (point 2). We started loading the cylindrical sample after pressurizing chamber, this means that the machine started to develop pressure. Thus began to increase the vertical stress applied to the sample (σ_1). Lateral stress ($\sigma_2 = \sigma_3$) already remained constant during the test. If the exam was fine, shear failure mode occurred at the cylindrical sample (point 3).

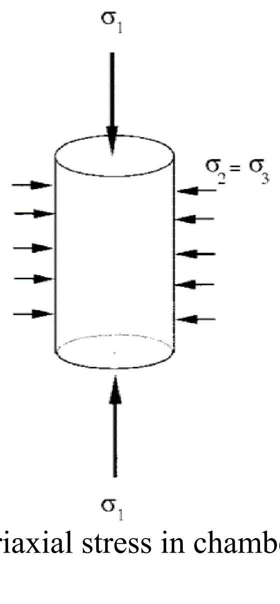

Fig. 1 – Triaxial stress in chamber

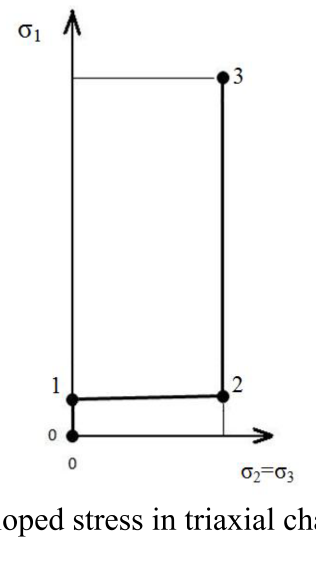

Fig. 2 – Developed stress in triaxial chamber

Experimental program – triaxial press

In this part of experimental program we used a triaxial press in the Technical University in Dresden, Germany. In triaxial press we tested concrete samples in form of a cube with an edge length of 100 mm. The principle of triaxial press work is very simple. On each sides of the cube is develop stress in the press (Fig. 3). Unlike in the triaxial chamber where stresses are equal, triaxial press can derive many combinations of stresses. In our experimental program we have used the triaxial press to achieve greater lateral pressure on the cube, similarly as in the previous section. This means that we only increased lateral stress that was achieved in the triaxial chamber. The procedure of testing concrete cubes in triaxial press was very simple. After inserting the test cubes to the press loading began. All stresses in all directions began to develop the stress on the cube at the same speed (0,005 mm/sec). At the moment of reaching the prescribed lateral pressure from two directions ($\sigma2 = \sigma3$) only stress in the third direction ($\sigma1$) was increasing further (Fig. 4) with same speed. Test was terminated, after the cube failed with shear failure mode.

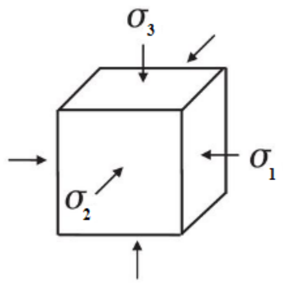

Fig. 3 – Triaxial stress in press

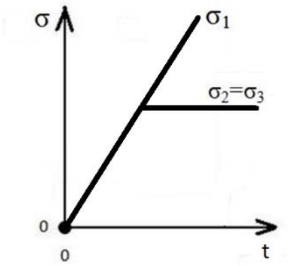

Fig. 4 – Developed stress in triaxial press

Evaluation of the results of the experimental program

The results obtained from the testing chamber are listed in the following table (Table 1). The table always brings average value for the whole group. The results are divided in the table into four groups according to the lateral pressure in the chamber (0 – uni-axial, 10, 20 and 30 MPa). The second column is the prescribed lateral stress and in the third column is the maximum stress of the sample at the time of failure. The next table (Table 2) shows the results of triaxial press in a similar way as in the previous table.

Table 1 - Results of testing in triaxial chamber

series	lateral stress fl [MPa]	stress at the time of failure fc [MPa]	fl/fc´ [-]	fc/fc´ [-]
0	0	122.5	0.00	1.00
10	10	178	0.08	1.45
20	20	208.5	0.16	1.70
30	30	230.5	0.24	1.88

The evaluation results, as in many other studies, capture and describe the trend of the maximum stress at the time of failure, depending on the lateral stress in the triaxial chamber. We used two ratios, the ratio of chamber stress (fl) to the average value of the unconfined compressive strength (fc'). The second used ratio is the ratio of the stress in the sample at the time of failure (fc) to the average value of the unconfined compressive strength (fc'). These two conditions are suitable for the evaluation of the results and universally used by many international studies on a similar topic.

Table 2 - Results of testing in triaxial press

series	lateral stress fl [MPa]	stress at the time of failure fc [MPa]	fl/fc´ [-]	fc/fc´ [-]
0	0	148.4	0.00	1.00
15	15	231.3	0.10	1.56
30	30	279.8	0.20	1.89
60	60	361.5	0.40	2.44
90	90	431.6	0.61	2.91

The results obtained are plotted in the graph below (Fig. 5). In the graph is always on the vertical axis the ratio between the vertical stress applied to the sample at the time of failure and the average value of the stress at the moment of the uniaxial compression failure (fc / fc'). On the horizontal axis is the ratio between the value of the lateral stress in the triaxial chamber/press and the average strength at the moment of the uniaxial compression failure (fl / fc'). By stars are plotted in graphs results from each sample and by the large dot is given the average value of each of a series of samples. A growing trend can be observed along these points. Another challenge is to describe the growing trend. And to determine the equation that fits the best the dependence of the resulting maximum stress on the lateral stress. Trend results from the triaxial chamber describes the power law equation is an equation that has the form

$$\frac{fc}{fc'} = 1 + 2{,}0915\left(\frac{fl}{fc'}\right)^{0{,}6088} \qquad (1)$$

This equation applies to the results of the triaxial chamber. The results obtained from triaxial testing in the triaxial press in Dresden, was also approximated by the power-law trend that has the form

$$\frac{fc}{fc'} = 1 + 2{,}6766\left(\frac{fl}{fc'}\right)^{0{,}6868} \qquad (2)$$

In the graph (Fig. 5) are both equations shown. Solid line curve is plotted equations obtained from the results of triaxial press and the dashed line curve is plotted equations obtained from the results of triaxial chamber. It is apparent that the course is almost identical.

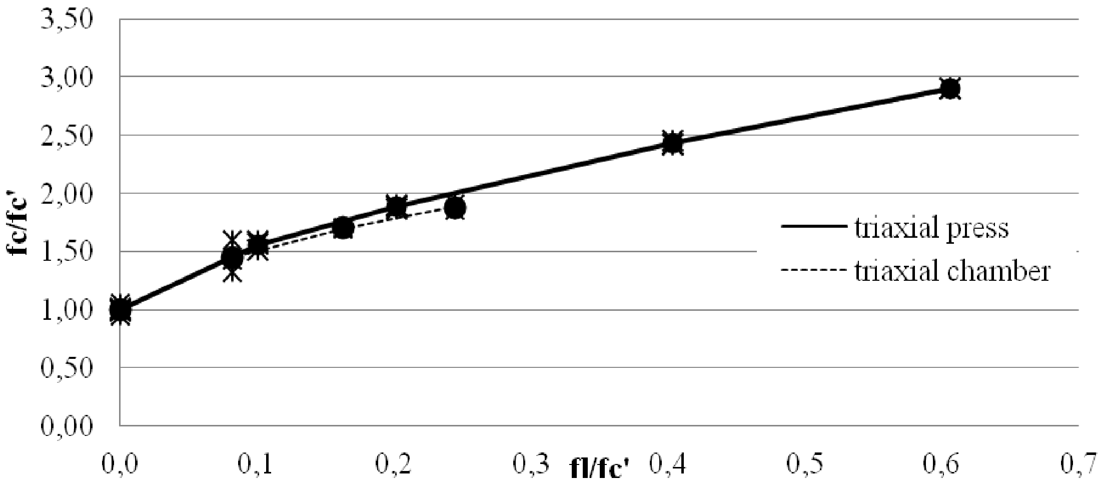

Fig. 5 – Results and curves in graph

Comparison of the results with foreign studies

In this section we compare our results with those results of similar studies on a similar topic. Below are the equations together with the description of the tested experimental samples and test the strength of concrete.

The set of equations set colleague:

- F. E. Richart [2]

  Cylindrical samples, compressive strength 20 – 50 MPa

$$\frac{fc}{fc'} = 4.1 * \frac{fl}{fc} + 1 \quad (3)$$

- Qingbin Li [3]

  Cylindrical samples, compressive strength 69 MPa

$$\frac{fc}{fc'} = 1 + 2.4305 * \left(\frac{fl}{fc}\right)^{0.6376} \quad (4)$$

- J. Xie [4]

  Cylindrical samples, compressive strength 60 – 120 MPa

$$\frac{fc}{fc'} = \left(1 + (21.2 - 0.05fc) * \frac{fl}{fc}\right)^{0.5} \quad (5)$$

- Oh Bohwan [5]

  Cylindrical samples, compressive strength 60 MPa

$$\frac{fc}{fc'} = -2.769 * \left(\frac{fl}{fc}\right)^{2} + 4.352 * \frac{fl}{fc} + 1 \quad (6)$$

- Fahrad Ansari [6]

  Cylindrical samples, compressive strength 40 - 103 MPa

$$\frac{fc}{fc'} = 1 + 2.45 * \left(\frac{fl}{fc}\right)^{0.708} \quad (7)$$

- Wang Chuan-zhi [7]

  Cubic samples, compressive strength 12 MPa

$$\frac{fc}{fc'} = 1 + 3.7 * \left(\frac{fl}{fc}\right)^{0.86} \quad (8)$$

In the graph (Fig. 6) are plotted curves containing all of the above equations and the equations set by our experimental program. Bold dashed line in the graph shows our equations. As can be seen from the chart, the individual curves are very similar, have similar outcomes. From this we conclude that our formulas proposed in this work are correct and have a comparable course to other equations from other studies.

Conclusion and further research

We studied the behavior of the high performance concrete in triaxial pressure in two ways in this work. The first way is to use a triaxial chamber. We tried in triaxial chamber four series of samples according to the value of lateral pressure. According to our available options 10, 20 and 30 MPa lateral stress was examined and one series in plain pressure. The second way is for testing concrete in triaxial pressure using triaxial press. We tested cube samples in four series (15, 30, 60 and 90 MPa lateral pressure) in the triaxial press. Finally, the result of this work is to determine the above equations that describe the behavior of high strength concrete in the triaxial pressure. This equation is only valid for our specific HPC research with unconfined compressive strength of about 130 MPa. These equations show the development of maximal stress depending on the value of lateral pressure.

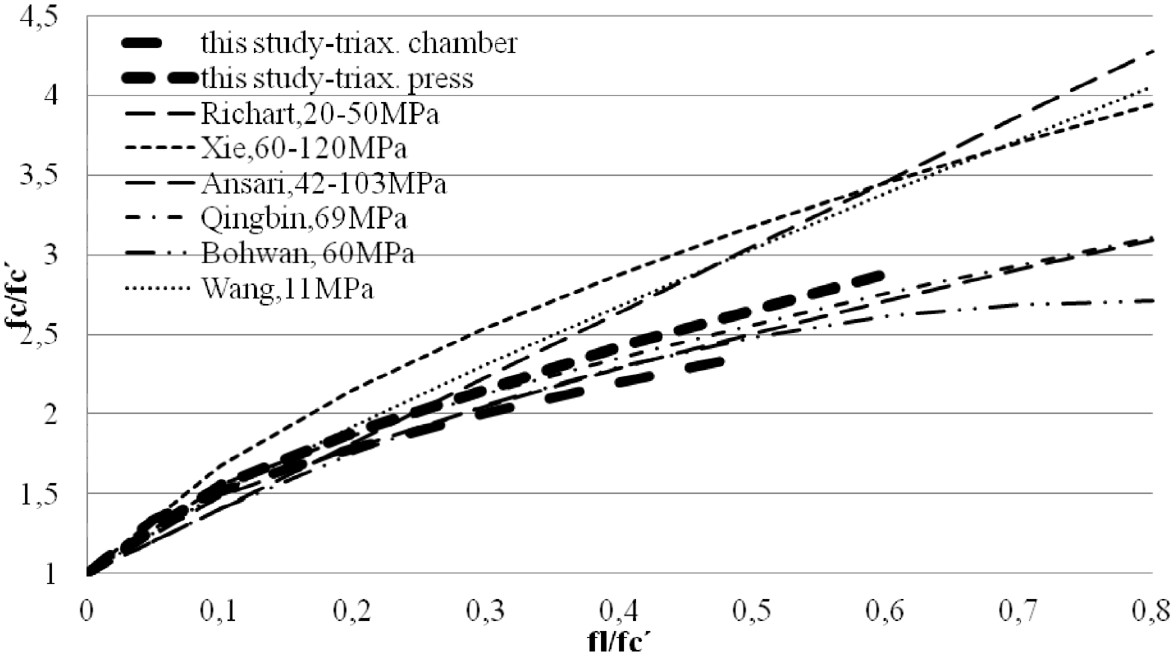

Fig. 6 – Comparison of equations

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