Testing and mechanical properties of high strength concrete

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Abstract. The paper deals with mechanical properties of high-strength concrete, which are illustrated in various laboratory tests. The aim of the paper is to compare the possibilities of concrete compressive and tensile strength assessment and modulus of elasticity assessment. Results of nine type laboratory tests are presented in summary. Tested material properties are complemented with testing of small structural element, the beam without shear reinforcement. The behaviour of structural element is analysed also with a non-linear numerical model that respects the quasi-brittle properties of the concrete, where fracture-plastic model for concrete is used.

1. Introduction

The aim of current material research in the field of concrete structures is to develop concrete composition that is environmentally friendly using recycled materials or have improved performance properties [1], [2]. One of the most common improved mechanical property is compressive strength, whereby concrete with strengths above 50 MPa is referred as high strength concrete. In the case of improvements in other material properties such as durability, lifetime, workability, HPC concrete can be discussed. The HPC parameters for processing [3], mechanical properties [4], [5] or aspects of lifetime [6] cannot be used as for conventional concrete. Improved mechanical properties of concrete can also be utilised in sophisticated design methods of building construction, which, however, require detailed knowledge of mechanical parameters and quasi-brittle behaviour [7], [8]. Common testing of mechanical properties, where basic compressive strength tests and the modulus of elasticity tests are performed, are insufficient. There are also different values of results depending on the type of test. This knowledge about material properties is of limited value and insufficient for nonlinear computer simulations of structural stress-strain state. Essential mechanical properties for nonlinear analysis is especially tensile strength, softening functions are taken usually according to the recommendation [9]. Testing of mentioned material characteristics is technically difficult and there is a large dispersion of measured values. Fracture mechanics provides a detailed description of crack damage and propagation in quasi-brittle composites. The research is often focused on fracture mechanics area [10], [11]. The use of fracture mechanics high strength and high performance concrete is limited with the availability of suitable fracture mechanical characteristics of materials. Fracture mechanical parameters are influenced by number of factors, such as concrete recipe, manufacturing and testing method. Certain characteristics are available in databases and recommendations for common concrete, however often
has a number of limitations (scope of research, size or geometry of samples) and are insufficient for non-linear analysis of structural elements.

In current research great attention is paid to the testing of mechanical properties, where a number of recommendations and approaches can be found in the Model Code 2010 [12]. It is also important to note that concrete is often combined with fibres. In this case the determination of mechanical properties becomes a complex task. Mechanical properties should be determined using a comprehensive set of tests and inverse analysis is also used.

Shear failure can be considered as specific problem of concrete structures. The scope of the issue is very large [13], [14], [15], where the mechanism of collapse is affected by concrete, the shape of the cross-section, the position of the load and the reinforcement. The development and testing of the mechanical properties of new types of concrete is only one part of the innovative structural design and complex nonlinear task. The most important recommendations for advanced design include the Model Code 2010 [12], which outlines the basic principles of using advanced numerical models and nonlinear analysis. The material models respect real behaviour and the possibility of disruption in pressure and tension. Nonlinear numerical analysis is used especially in specific problems [16] and in design optimization [17], [18].

2. Experimental details and materials

The objective of the presented research is detailed description of mechanical properties of particular HPC. The composition of analysed HPC is listed in Table 1.

| CEM I 42,5 R (Mokrá) | 575 |
|----------------------|-----|
| Metakaoline (Metaver I) | 80  |
| PCE superplasticizer (ACE Glenium 300) | 20  |
| Water | 155 |
| Sand 0/4 (Lípa) | 680 |
| Crushed aggregates (4/8 Litice) | 200 |
| Crushed aggregates (8/16 Litice) | 810 |

Figure 1. HPC concrete structural element – RC beam without shear reinforcement.

The experimental program included testing of common laboratory samples and testing of a structural element. Structural element is shown in Figure 1. Laboratory tests includ a comprehensive set of experiments to determine compressive strength, tensile strength, and modulus of elasticity. Tests are carried out in a variant mode (cube/cylinder/beam). The tests are schematically shown in Figure 2 and Figure 3. Compressive strength was assessed in a variant for cubes, beams and cylinders. Both static and dynamic modulus of elasticity was tested. The tensile strength is then determined on the
basis of the split tensile test and three and four-point bending test. Testing was based on the Model Code 2010 recommendations.

For the split-tensile test specimens of cube or cylinder shape can be used. With regard to laboratory testing capacity in the presented research split tensile strength was performed on cubes. All bending tests were performed on beams with cross-section 150x150 mm and length of 700 mm. The three-point bending test has a span of 600 mm. In the four-point bending test the distance between the supports and the load is 200 mm.

![Split tensile strength](image1)

![Compressive strength - cube](image2)

![Compressive strength - cylinder](image3)

![Modulus of elasticity](image4)

![Compressive strength - beam](image5)

![Modulus of elasticity](image6)

**Figure 2.** Laboratory set of tests – strength and modulus of elasticity.

![Four bending tensile strength](image7)

![Three bending tensile strength](image8)

**Figure 3.** Laboratory set of tests – bending tests.
3. Results and material properties of HPC

Laboratory test results are summarized in Table 2. The information in Table 2 is supplemented with graph in Figure 4. The resulting ratio of compressive strength for cube and cylinder specimen is 0.76. The compressive strength difference for cylinder and beam specimen is 15.1 MPa. The modulus of elasticity is similar to value given in Model Code 2010 for particular compressive strength. Dynamic modulus of elasticity is larger than static according to the assumption.

| Table 2. Mechanical properties of HPC. |
|----------------------------------------|
| Compressive strength - cube    | 102.0 MPa |
| Split tension strength          | 5.8 MPa   |
| Compressive strength - cylinder | 77.6 MPa  |
| Modulus of elasticity - static - cylinder | 42.1 GPa |
| Modulus of elasticity - dynamic - cylinder | 52.1 GPa |
| Compressive strength – beam      | 92.7 GPa  |
| Modulus of elasticity - static - beam | 39.5 GPa |
| Modulus of elasticity - dynamic - beam | 55.0 GPa |
| Bending tensile strength – 3-point | 7.25 MPa |
| Bending tensile strength – 4-point | 7.04 MPa |

Figure 4. Comparison of results of laboratory tests of modulus of elasticity and strength for cylinders/beams.

4. Non-Linear Analysis and Beam without Shear Reinforcement

The laboratory program also included testing of a small beam without shear reinforcement. The beam is designed to verify mechanical properties based on laboratory using non-linear analysis. The beam is of rectangular cross-section with dimensions 100 x 190 mm, where the span between supports is 900 mm. The three point bending test scheme is shown in Figure 5. The beam was reinforced with three B500B bars of 10 mm diameter on the bottom surface, the reinforcement cover was 20 mm. The collapse of the RC beam itself was caused by the formation of shear cracks. The maximum load capacity was 67 kN, the shear crack is shown in Figure 6. Photo of texture concrete shown in Figure 7.
For numerical analysis of the structural element 2D nonlinear model was used with concrete – fracture - plastic material model in ATENA \[19\]. The load was applied with deformation. Fracture energy was determined according to the ATENA and Model Code 2010 recommendations. The split tensile strength value for calculation fracture energy is used, which has been modified by however the coefficient 0.7. The calculation respects also further the recommendations \[18\] for nonlinear analysis. Comparison of calculation and experiment proved that the collapse mechanism is similar in both cases. The shear crack in the computational model is shown in Figure 8. The maximum load achieved in the calculation is 67 kN. The experiment maximum load capacity was also 67 kN, so the difference of results for the numerical model and experiment is to 1 %, only tenths of kN.

![Figure 5. RC beam without shear reinforcement – span 900 mm.](image)

![Figure 6. Shear crack of beam.](image)

![Figure 7. Photo of texture concrete.](image)

![Figure 8. 2D Computer model with crack.](image)
5. Conclusion
The paper deals with mechanical properties of particular HPC, which are assessed on a number of laboratory tests and verified on a small structural element. The results of compressive strength tests for cubes and cylinders have a 0.76 ratio. This is smaller ratio factor than the common concrete value. The modulus of elasticity is also sensitive area of mechanical properties. The resulting value is similar to a value given in Model Code 2010. The ratio of static/dynamic modulus of elasticity ratio is 0.8. The number of samples does not allow wider statistic assessment. Nonlinear analysis results with input data based on laboratory tests well captured the type of collapse and formation of shear crack and maximum load capacity in three point testing of small structural element. However, can be advisable to use for more complex beams and structures 3D model and special determination of fracture-mechanical parameters. The authors will focus on this area in further research.

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