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EXPERIMENTAL INVESTIGATION OF A STRUCTURAL ELEMENT MADE FROM HIGH-PERFORMANCE TEXTILE CONCRETE LOADED BY THE BENDING MOMENT

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Abstract

Investigation was carried out under laboratory conditions on thin elements made from ultra-high performance concrete reinforced by a textile glass mat. The concrete had a fine-grained matrix according to a recipe designed at the Klokner Institute. Thin-walled test specimens were subjected to a short-term load in the testing machine and also to a long-term permanent load. The 2D glass textile reinforcement was protected by an alkali-resistant treatment. The test specimens were loaded in four-point bending. The material properties of the matrix and of the glass reinforcements were determined by a number of accompanying tests. A comparison was made between the results of the experimental investigation and the results of a simulation based on a numerical model.

Keywords: Textile reinforcement, AR glass, fine-grained UHPC, computer simulation

1. Introduction

Textile concrete is a modern building material with characteristics that have been studied in laboratory conditions in the Czech Republic and abroad in the course of the last two decades with a view to its possible applications. A wide range of carbon, polyethylene, basalt, aramid, and glass textile mats have been studied. An advantage of this type of reinforcement over a conventional steel reinforcement is its higher corrosion resistance, which enables the covering layer of concrete to be reduced significantly. Textile concrete is a composite material that shows a higher level of heterogeneity than other composites. This paper presents the results of a study of a textile concrete matrix made from UHPC and reinforced by an AR glass mat. This concrete is characterized by great strength, high durability and resistance to aggressive components [1, 2, 3].

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Although this construction material is made using a very modern technology, its practical usability in real structures needs to be evaluated in the context of the production cost. The unit cost of a textile concrete is several times higher than the cost of a conventional concrete. This deficiency needs to be compensated by more light-weight construction, and also by significantly higher resistance to corrosive environments. Previous experience suggests that this concrete could be applied for thin-walled facade claddings of structures, for formwork, for structures in difficult conditions, and perhaps for shell structures.

2. Experimental program

In the framework of the research project, several series of thin specimens were produced, and were placed under water storage for 28 days. This paper presents the results for the test plates in four-point bending. The characteristic dimensions of the test specimens are shown in Table 1.

Tab. 1: Dimension of test specimens

Specimen	Cross section b/h	Length	Span	Spacing of forces	Cover layer	No. of fibers in cross section
	[mm]					
SP 1, 2, 3	121/21	1100	1000	200	3	6
LP 1, 2,3	250/32	2000	1900	650	4	13

The specimens SP 1, 2, 3 were loaded in the short-term procedure until failure in the testing machine, the specimens LP 1, 2, 3 were subjected to the constant force for a period of 225 days, and then by sequentially adding the load until failure. Specimens were stored and tested under laboratory conditions, i.e. t = 21 ± 2° C, RH = 45 ± 5 %.

2.1 Short-term loading

Three thin-walled elements - plates (tab. 1) made from fine-grained concrete - were subjected to a four-point bending test. The loading process was controlled by the processor, and the data were registered by data loggers. The testing load increased uniformly at a rate of 0.05 mm/s. The course of the load-displacement diagram is shown in

Fig. 1: Short-term loading test

Fig. 2: Long-term loading test

Fig. 5, which presents the results for all tested boards. In the initial stage of the loading process, no glass reinforcement of any kind is applied, and the first part of the graph shows a linear progression. After the first crack occurs, the loading force decreases, then the glass reinforcement is activated, and the load gradually increases until there is a further crack and the strength decreases again. In this way, the loading continues, more cracks gradually develop up to maximum deflection, at which point a collapse occurs. The results show that there is a difference between the tensile strength of the accompanying bodies and the tensile strength of the tested board. The results of this experiment were compared with a computer-simulated calculation. This shows that a numerical analysis only enables us to establish the initial course of the test up to the formation of the first crack, and also the final state up to the collapse. Values characterizing the course of the experiment are shown in tab. 2.

Tab. 2: Examination under short-term loading

Specimen	Deflection [mm]		Moment [10^6 N.mm]		Stress at crack initiation [MPa]
	at crack initiation	at failure	at crack initiation	at failure	
SP 1	2.1	72.8	0.0665	0.1692	6.78
SP 2	2.5	74.2	0.0698	0.1672	7.36
SP 3	2.7	71.4	0.0801	0.1710	8.39
FEM	2.0	71.1	0.0716	0.1720	8.88

2.2 Long-term loading

In the experiment, three thin plates were subjected to long-term loading under laboratory conditions. They were subjected to relatively high-level loading, around 75% of their capacity. The graph of the increase in deformation versus time is shown in Fig. 6. One of the loaded plates collapsed under testing after 105 days. This was due to the local lower strength of the UHPC matrix, and imprecise placement of the glass reinforcement in the plate. Thus, a problem that needs to be investigated in future is how to ensure that the glass reinforcement is positioned precisely along the cross section of the element.

Tab. 3: Examination under long-term loading

Specimen	Deflection [mm]		Moment [10^6 N.mm]		Stress at crack initiation [MPa]
	at crack initiation	at failure	at crack initiation	at failure	
LP 1	6.5	8.5	0.319	0.412	7.75
LP 2	6.6	*/	0.316	-	7.79
LP 3	6.7	8.6	0.315	0.406	7.76

3. Concrete matrix

An extensive experimental program was carried out in the laboratory of the Klokner Institute in order to optimize the UHPC mix. A program involving several dozen different mixtures was aimed at optimizing the composition of the fine-grained UHPC matrix and achieving higher tensile and compressive strength and better resistance to aggressive environments. The results of physical tests on this material are very sensitive to strict adherence to the amounts of ingredients, the production technology, and the storage and treatment of the resulting samples. Each of these influences was investigated. A recipe was chosen for the experiments; its contents per m^3 were:

- standard sand with a maximum fraction of 2 mm - 1267 kg
- CEM II 42,5R - 690 kg
- microsilica - 100 kg
- slag - 80 kg
- Glenium superplasticizer - 40 kg
- water - 160 l

The concrete mix was prepared with highly accurate sequential dosing of each component. Despite thorough measures to control the entire preparation process of the mixture, some variance in the physical characteristics occurs, especially in the strength characteristics. This variance is due to high sensitivity to relatively small deviations during preparation and storage. Because of the fine-grained character of the mix, the strength characteristics were verified on specimens with dimensions of 40/40/160 mm.

Approximate values of the material properties after 28 days:

- strength in tension - 12 - 16 MPa
- strength in compression 132 - 148 MPa
- modulus of elasticity – 41 - 43 GPa
- fracture energy Gf 130 - 150 N / m

There is currently no published regulation in the Czech Republic defining UHPC in dependence on tensile and compressive strength, or in dependence on durability. Generally speaking, UHPC is a fine-grained cement-composite material having tensile strength higher than 20 MPa and compressive strength greater than 150 MPa. Durability is not clearly defined, although it is one of the most important factors. The UHPC matrix mixed in the Klokner Institute varies slightly at lower compressive and tensile strength. As regards durability, a number of resistance tests [4] were carried out on the resistance of the cement concrete surface to water and defrosting chemicals, method C, resulting in maximum waste after 400 cycles of about 19 g / m^2 (+5 / -20 °C), and frost resistance tests in which there were no changes in the physical properties of the material after 400 cycles.

A problem that occurs when casting to a formwork is that a certain number of pores can appear. This is due to higher batch consistency, which is particularly important for processing and perfectly filling a thin formwork element. The problem can be reduced to some extent by vibrating the element. However, pores cannot be completely eliminated when the matrix structure of the UHPC is fine-grained.

Uneven distribution of the pores may result in local non-homogeneity of the material and in variable test results, particularly in the case of thin-walled elements. The difference between the test specimens and the resulting elements is determined by the way in which the UHPC is stored and the way in which the element is tested. One reason for the heterogeneity of the elements is the manufacturing method. A smaller mixing device was used in the initial test, and due to the sensitivity of the measurements the same matrix mix could produce different results. The Klokner Institute is currently working on reducing the variability of the results.

4. Textile reinforcement

The experimentally investigated structural elements were reinforced using AR glass, a textile 2D glass reinforcement (mesh 20 x 20 mm, Fig. 3) that was provided with protection against an alkaline environment. The mechanical parameters of the glass reinforcement, according to the available technical sheet, were not sufficient for use in the experiment numerical modelling. Several tests were performed to determine the strength and the modulus of elasticity of a single warp fiber [5, 6, 7]. The glass bar was adjusted using a two-component sealant for fixing in the test machine (Fig. 4), and a working diagram was determined by a data acquisition system on the basis of a 95 mm potentiometer sensor. The yield tensile strength value of the textile glass reinforcements was about 2200 MPa, and the elastic modulus was about 76 GPa for the so-called warp direction, i.e. the main bearing direction of the reinforcement. The manufacturer of the glass textile states that the fiber has a value of 2400 TEX [g/km].

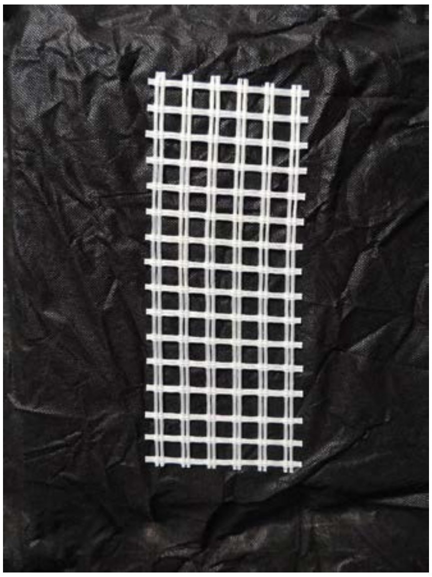

Fig. 3: AR glass reinforcement

Fig. 4: Testing of AR glass reinforcement

5. Computer analysis

To prepare the calculations, a computer model of the UHPC plates was created and calculated in a 3D environment using Atena 3D Engineering software [8]. The computer model of the specimen was modelled as a single macroelement. The reinforcement was modelled using line elements with assigned profiles of 0.6 mm according to the current 2D net. Steel plate elements were added for transferring the load to the model. The loading was realized by a displacement step equal to 0.1 mm. The displacement and the corresponding force were monitored. In addition to this monitoring, the volume of concrete was monitored to check the crack width. The model was meshed by hexahedral brick elements, whereby the height was divided into four elements approx. 5 mm in thickness and with plan dimensions of 40 x 40 mm. The material properties used in the numerical model were in correspondence with the accompanying material tests [9, 10].

6. Conclusions

Current experimental results show that fine-grained UHPC requires further development. There are relatively homogeneous results for the physical properties of most tests of the accompanying bodies, but the results for specimens with larger dimensions show tensile strength lower than for standard specimens. This can be explained by the different shape and dimensions of the specimens, by the different casting and treatment technology, and by possible deterioration mechanisms due to shrinkage, formation of micro-cracks, in the initial stage of concrete matrix hardening. The results of the numerical simulation of short-term loading conform relatively well with the experimental results, both in the initial stage of loading and in the final stage. Outputs of the simulation are shown in Fig. 7 (max crack width) and in Fig. 8 (max stress) after macro-cracks propagation.

In parallel with this experimental research, further tests on the concrete matrix are being performed, in order to assess the durability, the frost resistance and the permeability of the UHPC mixture.

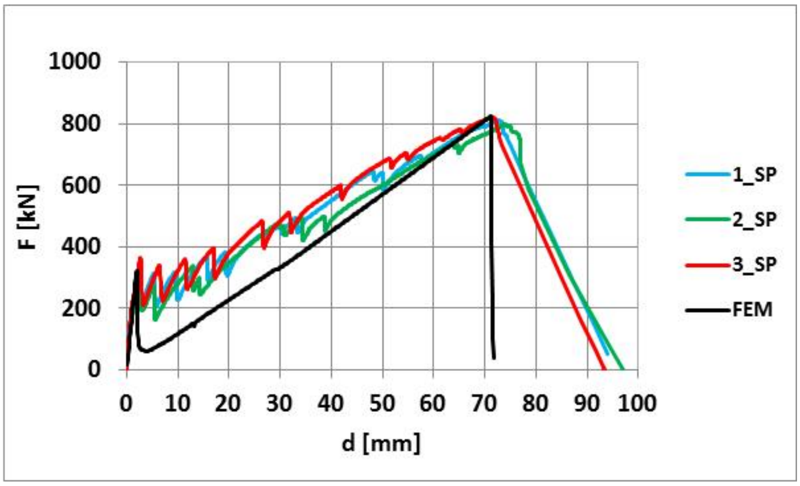

Fig. 5: F x d diagram for short-term loading

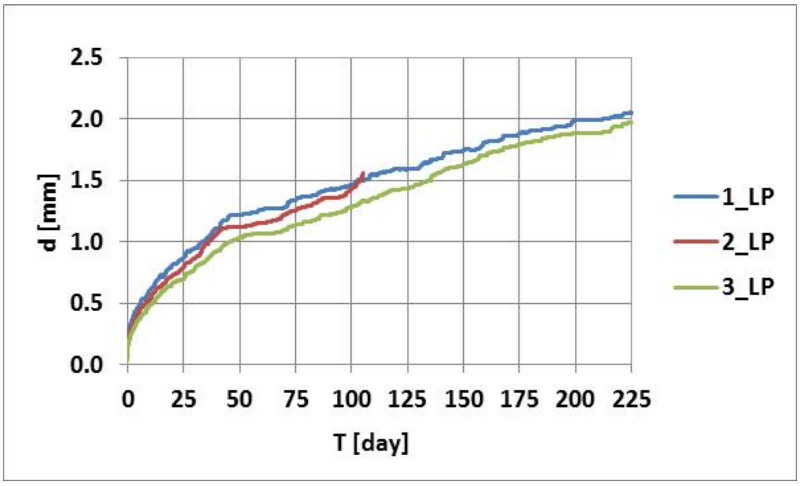

Fig. 6: Deformations of long-term loading

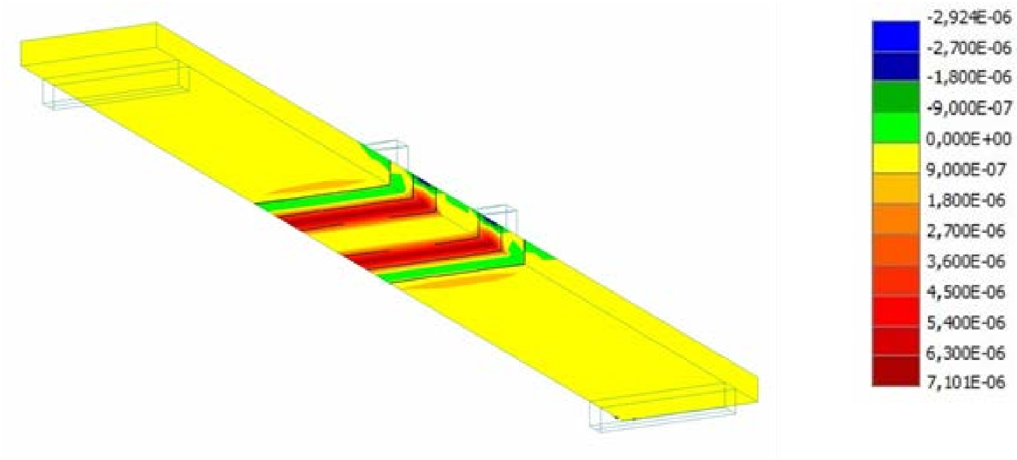

Fig. 7: Scheme of isosurfes after macro-cracks propagation, cracks width 0.0071 mm

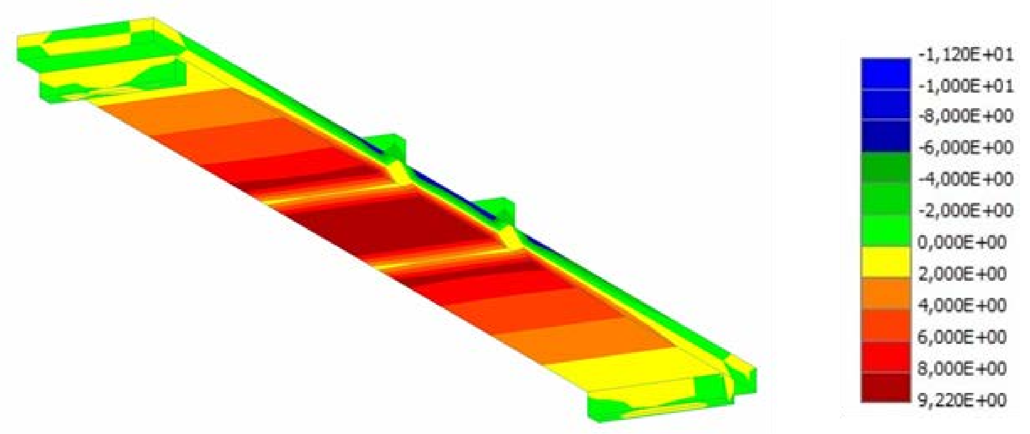

Fig. 8: Scheme of isosurfes after macro-cracks propagation, max value of stress 9.22 MPa

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