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THE APPLICATION OF UHPC ON THE MONOLITHIC PART OF THE ŠTVANICE FOOTBRIDGE

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Abstract. The use of UHPC with fibers is becoming an increasingly common topic in the world. This material is used for its superior mechanical and physical properties and long service life. However, the production cost is high, hence UHPC is used for special applications or for smaller prefabricated parts. This paper focuses on UHPC application for the construction of the Štvanice Footbridge, Prague, the Czech Republic. A monolithic part of the structure was made of UHPC from fresh transport concrete, which was produced by Skanska Transbeton. The special feature is that about 126 m^3 of fresh concrete was industrially prepared. This concrete achieved the properties of SCC and the final 28 day compressive strength was 120 MPa with tensile strength of 18.6 MPa. Due to high hydration heat release rate, an internal water cooling system was designed and sucessfully appled using water from Vltava River.

Keywords: Ultra High Performance Concrete, monolithic construction, production technologies, water cooling.

1. Introduction

Ultra High Performance Concrete with fibers (UHPC) is an advanced material based on the composition of conventional concrete, with the resulting properties reaching higher values. Haber, Zachary B. et al. [1] used a definition of this material as a cementitious composite material with water-to-cement ratio less than 0.25, with high percentage of discontinuous internal fiber reinforcement. The compressive strength was greater than 21.7 ksi (150 MPa) and sustained post-cracking tensile strength greater than 0.72 ksi (5 MPa). Farzad et al. [2] described UHPC as a cement-based material formed with a better gradation of grain components with a water-to-cement ratio less than 0.2, and a significant portion of internal fibers. Azmee et al. [3] defined UHPC as a fiber-reinforced, silica fume, cement mixture with the use of superplasticizers with low water-to-cement ratio. It contains very fine quartz sand with size of grain in range from 0.15 to 0.60 mm.

A combination of several approaches is used to achieve enhanced properties. A high proportion of cement is used in the composition of UHPC. The dosage per 1 m^3 is in the range of 800–1 100 kg, which is about three to four times more than that of conventional concrete. [4] Abokifa et al. [5] noted that the most of researches recommended CEM I or II due to a low content of tricalcium aluminate (C_3A) that can reduce the required amount of water.

In order to achieve low capillary porosity and high density of the cement matrix, the amount of added water is minimized and, as mentioned above, the water-to-cement ratio varies between 0.20 and 0.25. The reduced amount of water in the mixture also causes all the cement grains not to hydrate, which over time causes a self-healing effect of the concrete after cracking. [6]

To achieve the highest possible density of the structure, the goal is to create a "perfect" and continuous particle size distribution. Aggregate size is thus limited and very fine particles such as micro silica are used for this purpose. These very fine particles fill the voids between the cement and achieve a "filler effect". [7]

To improve the tensile properties of UHPC, a high dose of fine steel reinforcing fibers is normally used. The final dose and type depend on the final strength required. Abokifa et al. [8] již použito investigated the effect of dose and fibre type on the final properties of UHPC. The dosage of reinforcing fibers ranged from 0.5 % to 2.5 % by volume depending on the type used and the tensile strength increased with increasing fiber volume fraction.

All these improved properties describe concrete of high strength, long service life and improved final properties. Thanks to these properties, UHPC structures can be made one-third to one-half the size while maintaining the ability to carry the required loads. This saving has the advantage of producing slender structures and reducing overall costs. Reduction of steel reinforcing bars decreases labor costs and provides greater architectural freedom [9], which is why UHPC material was also used for the footbridge.

While UHPC production on the lab scale presents no substantial problem, large-scale structures with UHPC transport led to several challenges addressed in the article.

2. Experimental program

2.1. Description of footbridge and associated challenges

The footbridge was realized by Skanska company while the subsidiary company, Skanska Transbeton, was responsible for the monolithic part made from UHPC. The main part of the bridge deck is composed from prefabricated UHPC segments. A ramp slopes down on an island, creating a a complicated junction areare-lying on a monolithic design. A view of this section is shown in Figure 1.

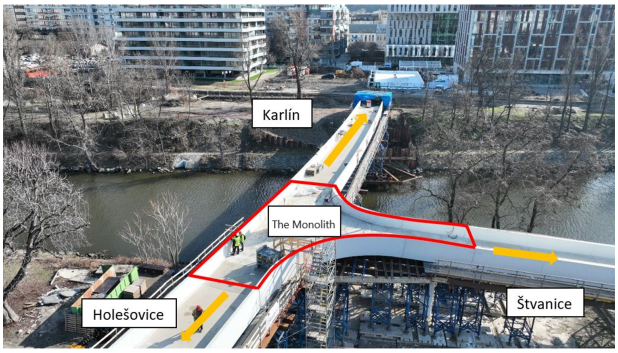

FIGURE 1. Complicated junction with a framed monolithic part.

Such a construction required concrete with high compressive and flexural tensile strengths. For this reason, UHPC with fibers was chosen to meet the requirements of the structural design.

Several challenges arose with the production of UHPC. The high amount of fibre reinforcement had to be uniformly distributed in the concrete matrix. A high dose of cement combined with a high ambient temperature would have lead to overheating of the structure, so it was necessary to reduce the temperature of the concrete using a cooling system using water from the Vltava River. Finally, the demanding design required high flowability and long workability to guarantee perfect casting of the entire volume of the junction.

2.2. Technology of production

Technology of production The production technology of UHPC is different from that of conventional concrete. UHPC contains a high dose of cement exceeding 500 $\mathrm{kg\,m^{-3}}$, a high dose of admixtures, a low dose of water with a targeted low water-cement ratio of around 0.25. To achieve a high consistency, which guarantees consistent concrete properties even when realizing complex shapes, a very high dose of plasticizer is usually used, and retarders are often utilized to maintain the required workability.

The mix design was firstly developed in the laboratory and further tested in several steps. Skanska Transbeton faced several challenges in the development of the mix design.

The first major challenge was the effective mixing of the high dose steel fibers. The fibers used can be imagined as thicker needles that aglomerate and intertwine with each other. In the laboratory tests, the fibers were easy to dose and disperse because they were hand-dosed, and the clumps were broken before contact with the concrete mix. For efficient mixing in industrial production, a special mixing core, called a planetary mixer, had to be used, which rotates on its axis and the individual paddles rotate in different directions and speeds. A model of this mixer is shown in Figure 2.

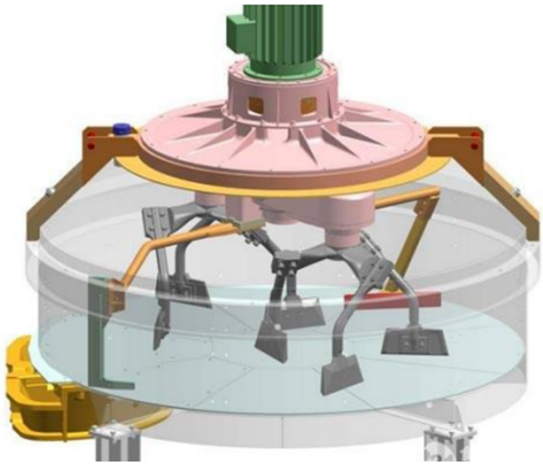

FIGURE 2. Planetary mixer core – figure available from `https://daswell.com/`.

Another challenge was the high dose of cement and expected casting in the hottest days of the summer. The combination of these factors would generate concrete core temperatures in excess of 100 °C, which is unacceptable. To limit the critical condition, experts from the CTU were involved from the beginning in the mix design.

3. Materials

In addition to the requirements for mechanical and physical properties, the specific shade of white was prescribed by the architect. For these reasons, special white cement from the most accessible transport location for the Czech Republic, CEM I 52.5 N Slovakia – Rohožník, was used.

To keep the white colour, aggregates up to 5 mm in size were used from the Provodín – CZ locality. This aggregate is used for glassmaking purposes and is characterized by its high quality and white colour. A special requirement for the sand producer was to dry the material and transport it on covered trucks, as the recipe was very sensitive to the water dosage and wet material could not be used (wet aggregate is normally used for ordinary concrete production). However, these materials did not meet the architect's requirements for the resulting white colour, and white pigment was also needed to add.

The actual composition of the mixture is subject to the company's know-how, therefore only an approximate composition is given in the Table 1 below.

Materials	Dosage
CEM I 52.5 N – white	Over 500 kg m^{-3}
Water-to-cement ratio	0.23
Super plasticizing admixture	3.8 % wt. to cement
White pigment	1.6 % wt. to cement
Sand fraction 0–5 mm	170 % wt. to cement
Reinforcing fibers	6 % wt. to total
Retardant additive	1.25 % wt. to cement

TABLE 1. Approximate composition of UHPC.

Due to the mechanical and physical requirements from the structure designers, the use of additional nano-materials and other fine particles was not necessary.

4. Cooling system

On the basis of preliminary calculations, a number of mock-up tests s were carried out, in order to test the proposed mix design and calibrate simulation model for the prediction of temperature field. As the strength requirements had to be met and it was impossible to change the cement dosage or type, water cooling was proposed as the most effective method, using the water available on site, i.e. water from the Vltava River. The cooling system was made of plastic hoses laid in three layers over a total length over 1 km. A view of the cooling system prepared for the UHPC casting is shown in Figure 3.

FIGURE 3. Cooling system before concrete casting.

The material of the cooling pipe was chosen with regard to the simplest implementation on site and economic feasability. Adek Tasri and Anita Susilawati [10] investigated in their work the effect of the cooling pipe materials on the resulting temperature in the concrete. They concluded that locations further than 100 m from the cooling water inlet showed no differences in the concrete temperatures regardless of steel, PEX or PVC pipes.

5. Result and discussions

5.1. Achieved properties

The declining ramp was designed with a longitudinal slope over 8 %, therefore the entire section was cast with a top cover, which limited the concrete placement area, and the entire volume was cast from a limited number of filling holes. These circumstances required a mixture of high flowability with self-compacting properties, which was achieved by a high dosage of plasticizing admixture.

Figure 4 (left) shows a view of the casting process in the morning, including the top surface covered (concrete is under the worker), Figure 4 (right) shows the filling hole during the casting.

FIGURE 4. Casting process over the morning hours (left), filling hole during the casting (right).

The total quantity of fresh concrete produced in the industrial environment of the batching plant was 126 m^3. The resulting consistency reached the requirements of the SCC mixture, which resulted in a perfect concreting of the junction. The final workability time of the fresh concrete was over 6 hours thanks to the retarder.

The average compressive strength tested on 100 × 200 mm cylinders was 120 MPa. The average flexural tensile strength was 18.6 MPa, and the residual strength after a 0.5mm crack opening was 18.3 MPa tested on 150 × 150 × 700 mm beams. These strengths were achieved without the use of special nanomaterials, and a larger aggregate size was used compared to the most of designs. Very good results were similarly achieved in the work of A. Arora et al. [11]. Their binders saved cement and achieved 90-day compressive strengths in the range of 145–165 MPa while they used three different sizes of coarse aggregates with the maximum sizes of 6.25 mm, 4.75 mm, and 2.36 mm.

The final date of the UHPC casting was postponed and the actual production of concrete took place during October 2022, which was more than desirable from the point of view of temperatures. In order to minimize the temperature during production and deposition, the production was started at night, therefore the air temperature was around 15 °C. The maximum measured temperature of the concrete was 81 °C at

14 hours with internal water cooling. After the maximum temperature of the bridge core was reached, the temperature decrease due to water cooling was monitored. When the temperature of the concrete dropped to approximately 40 °C, the cooling was turned off to avoid overstressing the material due to the temperature difference. The efficiency of the cooling system is also supported by the increase in cooling water temperature by about 20 °C. The resulting temperature history is shown in Figure 5.

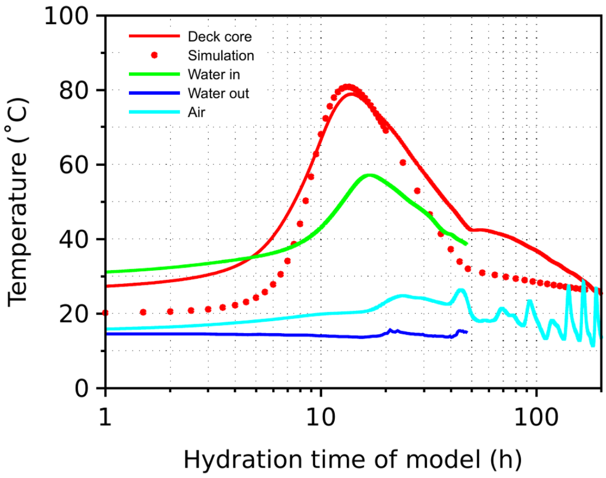

Figure 5. Temperature evolution and validation of UHPC with internal water cooling.

6. Conclusion

The production of transport UHPC brings several challenges and risks. By appropriate formulation of the mix design, desired requirements were met. The composition of the concrete is based on a high proportion of cement without the need for additional special nano and fine additives. By limiting the number of input materials, production on an industrial scale is guaranteed and quality production of UHPC in larger quantities was achieved. The proposed formulation met the requirements given by design engineer – in terms of high mechanical and physical properties, as well as the requirements for the required white color given by the architect.

Acknowledgements

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