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ANALYSIS OF THE EFFECT OF HYDRATION HEAT RESULTING IN THE FORMATION OF CRACKS ON THE EXPERIMENTAL BLOCK OF THE SPILLWAY AT ORLIK RESERVOIR

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Abstract. This article concentrates on the numerical analysis of hydration heat resulting in formation of cracks on the experimental block of the spillway at Orlik Reservoir and its verification with the experimental measurement. In order to eliminate the maximum of critical factors which could lead to appearance of early age cracking and faulty execution of the spillway, an experimental block was concreted. It served as a trial block for all steps of the execution process as well as a validating temperature measurement during cement hydration to confirm with the preliminary numerical analysis.

Keywords: Hydration heat, experimental measurements, numerical analysis, spillway.

1. Introduction

High hydration heat is a common complication while talking about massive concrete structures. Usually, we would try to avoid such complication by concreting in single layers of maximum thickness of 0.3 m, which nowadays might be seen as time consuming. Especially now when there is emphasis on fast production in every field, civil engineering meets the same requirements. Hence it is needed to study the behaviour of massive structures concreted in one go and to establish general rules to follow in order to avoid any kind of complications.

According to Czech standards and regulations below, the structure is considered to be massive:

- The ČSN 73 1208 (The design of waterworks concrete structures) [1] – any structure thicker than 2 m is considered massive.
- The ČSN EN 13670 (Execution of concrete structures) [2] – defines as massive any structure thicker than 1 m.
- Technical quality requirements defined by the Ministry of Transport, chapter 18, Concrete Constructions and Bridges (ŘSD TKP 18) [3] – a massive structure is any structure thicker than 0.6 m, which is also nonnegligible regarding hydration heat.

The main complication in massive structures is caused by uneven diffusion of hydration heat generated during cement hydration within the cross-section. The difference between the core temperature and temperature on the surface could be defined as an average thermal gradient. It is also recommended to limit the maximum core temperature of the structure because it could affect the final compressive strength of the concrete. Another complication due to the high temperature could be formation of secondary ettringite which may also cause cracking. That is why it is recommended to not overstep the maximum temperature 70 °C during hydration of cement [4].

Figure 1. Visualisation of the open part of the chute spillway (SO 03 on the left) [5].

2. The spillway of the Orlík dam

The experimental measurement and the numerical analysis were carried out at the Klokner Institute of Czech Technical University in Prague under the supervision of Povodí Vltavy, State Enterprise, which is the investor of the project "Orlík Dam – securing the Orlík dam against the impacts of extreme floods". The project documentation for the construction of the spillway and experimental block was prepared by the company Aquatis, Ltd. [5] and then executed by Metrostav, Ltd. [6].

The geometrical shape of the experimental block is based on one of the chute floor sections of SO 03 (Figure 1), with a maximum gradient of 40 % (Figure 2), plan dimensions of 7.5 m × 12.0 m and a variable construction thickness of 1.5 m – 1.8 m (Figure 3), all concreted at the same time [5].

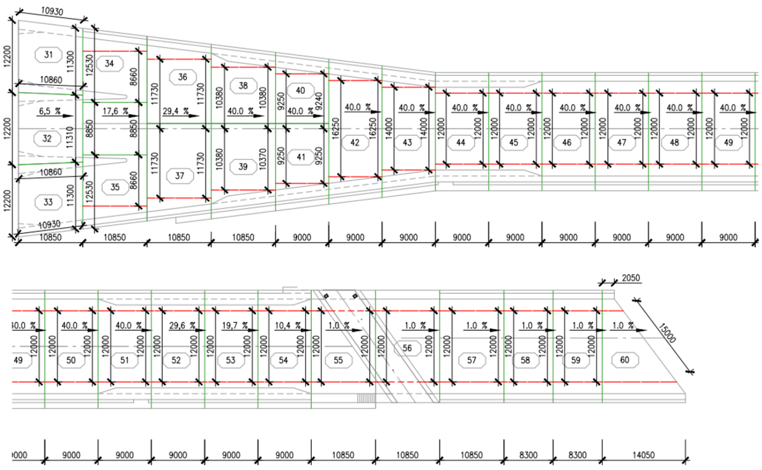

Figure 2. Floorplan of the chute with marked expansion (green lines) and work joints (red lines) [5].

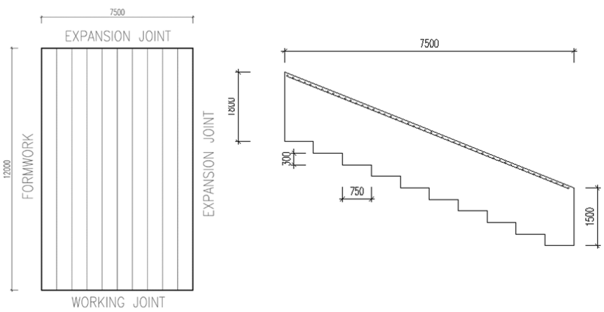

Figure 3. The geometry of the experimental block (dimensions in mm) [7].

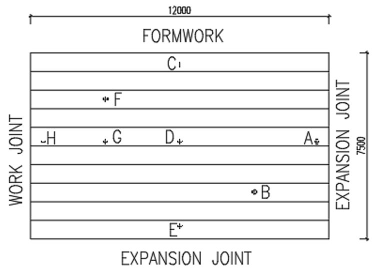

Figure 4. The location of strain gauges on the test block (dimensions in mm) [7].

Extensive temperature measurements were carried out at the construction site for a period of 28 days. ENCARDIO type EDS-20V-E string strain gauges with a sensitivity of 1 μ strain and a range of 3 000 μ strain and thermometers were used during the measurements (Figure 4).

Metrostav Ltd. secured and managed the concreting of the test block on 2nd November 2022 (Figure 5). Prior to the concreting of the block, the Klokner Institute, with the consent of the company Aquatis, Ltd., arranged the installation of a total of 26 strain gauges (Figure 6).

The observation run for 28 days, and the aim of the study was to control the maximum temperature in the core of the block and the temperature difference between the core and the surface in order to limit the cracking of the surface.

Figure 5. Finalisation of the surface.

3. Results and discussion

The results of experimental measurement were then compared with the results of the preliminary numerical analysis. The main requirement for maximum core temperature was to not exceed the limit value specified in the project documentation $T_{max} = 65\,°C$, while the average thermal gradient also should not exceed the limit value $\Delta T = 25\,°C\,m^{-1}$ [5].

The maximum core temperature predicted by ATENA simulation was 47.5 °C while the maximum core temperature measured on the experimental block was 49.6 °C. Based on these results and the graph below (Figure 7), the numerical model corresponds closely to the experimental measurement and could be used for further numerical analysis. E.g., the construction is subjected to different boundary conditions (ambient temperature) within its execution throughout the year, hence a parametric study with complementary experimental measurements was also carried out [8].

Figure 6. Installation of strain gauges at the construction site.

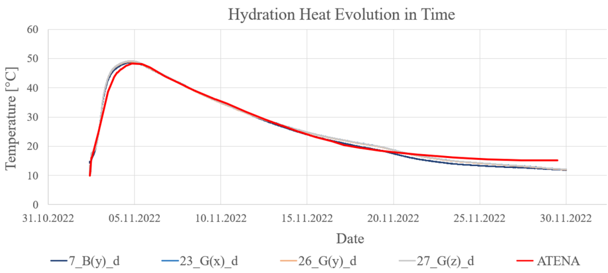

Figure 7. Comparison of the evolution of hydration heat during cement hydration – experiment and simulation (marked by red line) [7].

Distance between 2 sensors – 0.75 m Thermal gradient for distance of 1 m [°C m^{-1}]				
Position	**Strain gage [n°]**	**Temperature [°C]**	**Temperature difference [°C]**	**Average Gradien [°C m^{-1}]**
B	3 4	32.47 49.58	17.11	22.8
D (Core)	10 11	31.88 49.14	17.26	23.0
G (Core)	25 27	31.46 49.15	17.69	23.6

Table 1. Thermal gradient measured within the experiment – position marked "G" is placed in the core of the experimental block and compared to ATENA simulation [7].

The difference between the core temperature and the temperature on the surface, which could be defined as "average thermal gradient", causes uneven strains within the cross section, the emergence of compressive stresses in the core of the cross-section, due to the expansion of the concrete, and tension on the surface of the structure.

The experimental block was concreted in November 2022, whereas the day temperature was from 15 °C to 19 °C and the night temperature was around 10 °C during the first week after concreting the test block, when the core temperature peaked as well. As it is also visible from the Table 1, the weather conditions were very favourable and the maximum average gradient did not exceed the limit value $\Delta T = 25\,°C\,m^{-1}$. It should also be taken in consideration that the average gradient could be the limiting factor for concreting the

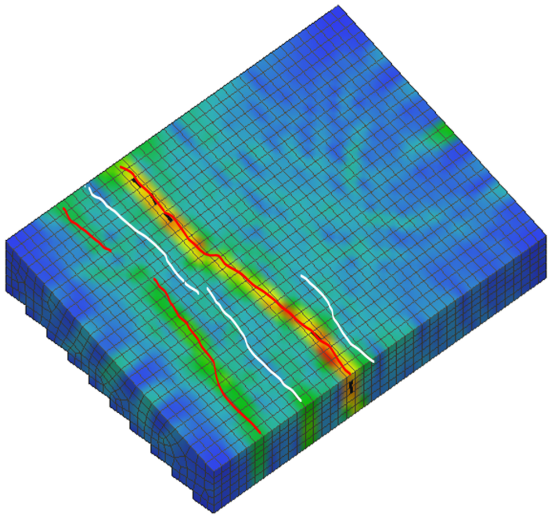

Figure 8. Comparison of the cracking observed on the test block (marked with white lines) and the numerical analysis (marked with red lines) [7], [8].

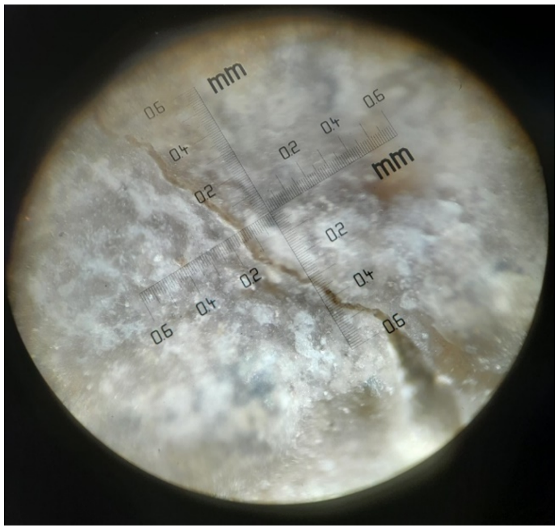

Figure 9. Microscopic picture of a crack of 0.02 mm width [7].

blocks during summer or winter and corresponding curing of the concrete surface should be designed.

According to the picture above, the cracking calculated within the nonlinear analysis corresponds closely to the cracking observed on the test block after 28 days (see Figure 8). The size and the location of the cracks is also alike and the normative serviceability limit state requirements for maximal width of crack which cannot be greater then 0.2 mm was also not overstepped (see Figure 9) [9].

4. Conclusion

The numerical analysis of the impact of hydration heat evolution and thermal gradient was carried out as a part of the project "Orlík Dam – Securing of the Orlík Dam Against the Impacts of Extreme Floods" [7]. The accuracy of the numerical model was confirmed by experimental measurements which were carried out in co-operation of Klokner Institute of CTU with the company Metrostav, Ltd. Verified numerical model is further used for a parametric study where the impact of different factors is analysed [8]. The experimental measurement is also going to be repeated throughout the year to be able to monitor the influence of ambient temperature on maturing concrete block and to verify corresponding numerical models.

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References

[1] Navrhování betonových konstrukcí vodohospodářských objektů [The design of waterworks concrete structures]. Standard, Czech Standard Institute, Prague, 2010.

[2] Provádění betonových konstrukcí [Provádění betonových konstrukcí]. Standard, Czech Standard Institute, Prague, 2010.

[3] Betonové konstrukce a mosty [Concrete constructions and bridges]. Technical quality requirements of structures, Ministerstvo dopravy České Republiky, 2016.

[4] Beton pro konstrukce [Concrete for constructions]. Technical quality requirements of structures, Správa železnic, 2022.

[5] Aquatis, Ltd. Construction documentation: Orlík Dam – Securing of the Orlík Dam against the impacts of extreme floods, 2023.

[6] Metrostav Ltd. Execution documentation: Orlík Dam – Orlík Dam – Securing of the Orlík Dam against the impacts of extreme floods, 2023.

[7] Klokner Institute CTU in Prague. VD Orlík – SO 03 open Chute Spillway – Partial report on the experimental measurement and numerical analysis of the impact of hydration heat on the formation of cracks on the experimental block ZB4 at Orlík reservoir, 2022.

[8] Klokner Institute CTU in Prague. VD Orlík – SO 03 open Chute Spillway – Analysis of the impact of hydration heat on the formation of cracks – Parametric study, 2023.

[9] Červenka, V. et al. ATENA program documentation, part 1 – theory, 2018.

[10] Navrhování betonových konstrukcí – Část 1-1: Obecná pravidla a pravidla pro pozemní stavby [Design of concrete structures – Part 1–1: General rules and rules for buildings]. Standard, Czech Standard Institute, Prague, 2004.

[11] Beton – specifikace, vlastnosti, výroba a shoda [Concrete – Specification, performance, production and conformity]. Standard, Czech Standard Institute, Prague, 2021.

[12] Cement – Část 1: Složení, specifikace a kritéria shody cementů pro obecné použití [Cement – Part 1: Composition, specifications and conformity criteria for common cements]. Standard, Czech Standard Institute, Prague, 2012.

[13] Metody zkoušení cementu – Část 9: Stanovení hydratačního tepla – semiadiabatická metoda [Methods of testing cement – Part 9: Heat of hydration – Semi–adiabatic method]. Standard, Czech Standard Institute, Prague, 2010.