Hybrid reinforced concrete with controlled volume deformations for hydrotechnical facilities

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Abstract: *The development of hydration processes in cement concrete is associated with the release of significant amounts of heat, which leads to a significant exothermic temperature increasing in the concrete body, especially valid for massive structures. This creates a temperature gradient from the inside of the array to the surface. The latter may be related to the development of unacceptable internal stresses, often leading to cracking, defects and reducing the durability of the facility. The report presents the individual stages of the search for an optimal technical solution for the construction of a specific hydro-technical facility - a massive hybrid reinforced trapezoidal wall of a water catchment gorge, in the area of Stara Zagora town. In the context of specified geometric dimensions of the facility, the specific features of the exothermic increase of the temperature in the concrete body as a function of the hydration processes are discussed. A reasonable choice of a specific type of cement is proposed in order to limit the amount of heat released - slag cement CEM III-A 42.5 N with a specific heat of hydration up to 280 J/g. A specific concrete mix design has been proposed, providing a balanced increase in temperature within acceptable limits, preventing cracking, in two possible scenarios - winter and summer outdoor temperature conditions. An additional advantage of the mix is the inclusion in the recipe of fiber-reinforcement and high-tech chemical admixtures - deep internal crystallization and shrinkage-compensating one. Specific calculation data for the kinetics of temperature increasing are presented, and the obtained values are critically evaluated in terms of guaranteed cracks eliminating in the structure.*

Keywords*: PORTLAND CEMENT CONCRETE, SLAG CEMENT HYDRATION PROCESSES, KINETICS OF EXOTHERMIC TEMPERATURE, CRACKING PREVENTION, CALCULATION TEMPERATURE INCREASING*

1. Introduction

The development of hydration processes in cement concrete is associated with the release of significant amounts of heat, which leads to an increase in temperature in the concrete body, especially valid for massive structures. This creates a temperature gradient from the inside of the array to the surface. The latter may be related to the development of unacceptable internal stresses, often leading to cracking, defects and reducing the durability and long-life of the facility.

According to **ACI 116R-00**, the term "massive concrete" means "any volume of concrete of sufficient size that requires measures to be taken with regard to the heat of hydration of the cement and the volume changes of the concrete, in order to prevent the cracks formation" [1]. It is known that the physical-chemical interaction (hydration) between Portland cement and water takes place with the release of a certain amount of heat, which depends on the mineral composition of Portland cement clinker, the fineness of cement grinding, the presence of mineral additive, etc.

The hydration heat release Q (J/g) of the main clinker minerals of cement is shown in Table 1:

Table 1 *Heat of hydration of the main clinker minerals of cement*

Reaction	Heat release at full hydration Q, J/g			
	Pure components		Clinker (measu-red)	Cement (calcu-lated)
	measu-red	calcu-lated		
$C_3S \rightarrow$ C-S-H + CH	380	520	570	490
$C_2S \rightarrow$ C-S-H + CH	170	260	260	225
$C_3A \rightarrow C_4AH_{13} + C_3AH_8$	1160	-	-	-
$\rightarrow C_3AH_6$	900	880	840	-
→ Etringite	1670	1670	-	-
→ Monosulfo-aluminate	1150	1140	-	1170
$\rightarrow C_4AF \rightarrow C_3(A,F)H_6$	420	420	335	-
Monosulfoaluminate	-	-	-	380
Etringite	730	-	-	-

It is seen that the presence in the composition of the cement of an increased amount of alite (3CaO.SiO2) and, in particular, of tricalcium aluminate ($3CaO.Al_2O_3$), leads to increased heat releasing, and in the initial periods of hardening. Such behavior is typical for rapid hardening cements - **Type III** according to **ASTM C 150-11** [2], cement or type "R" and to **BDS EN 197-1: 2011** [3].

Cements with increased content of belite (β-$2CaO.SiO_2$) and celite ($4CaO.Al_2O_3.Fe_2O_3$) emit less heat during hydration. The latter is typical for low thermal cements - Type IV according to ASTM C 150-11 or ordinary low thermal cements according to BDS EN 197-1: 2011.

In Bulgaria, the production of low-thermal cement CEM II/B-P 32.5 N LH from the plant "Vulkan", Dimitrovgrad, is currently suspended for the moment.

Cement exothermic is of great practical importance. At low outdoor temperatures, the heat released favors the hydration processes and vice versa, with massive facilities, especially in summer, can lead to a problematic increase in temperature in the concrete section to and above 50^0C. In the event of a subsequent decrease in the ambient temperature, there is a risk of a significant difference between the temperature of the concrete inside the structure and that on its surface. The occurrence of a temperature gradient generates tensile stresses, especially in the surface layer of solid concrete. At the same time, the concrete inside the array tends to expand and is under the action of compressive stresses. Under certain conditions, this leads to cracking in the surface layer of concrete, reducing the load-bearing capacity, increasing the permeability and reducing the durability of the structure at all.

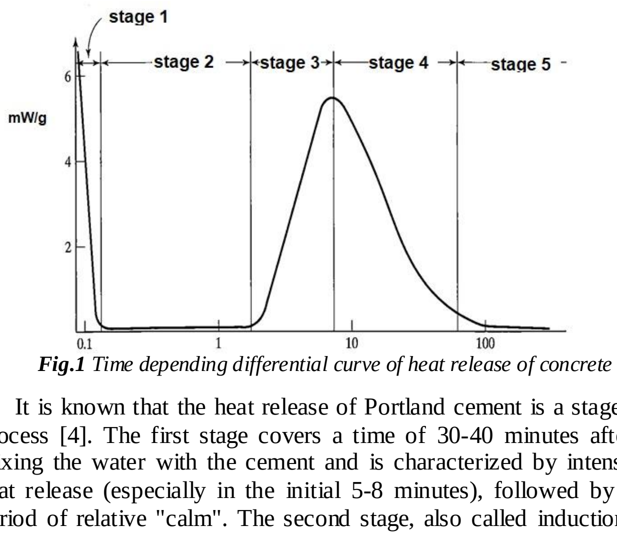

Fig.1 *Time depending differential curve of heat release of concrete*

It is known that the heat release of Portland cement is a staged process [4]. The first stage covers a time of 30-40 minutes after mixing the water with the cement and is characterized by intense heat release (especially in the initial 5-8 minutes), followed by a period of relative "calm". The second stage, also called induction, covers the time of 1-3 hours from the contact of the cement with the mixing water. Its duration depends mainly on the mineral composition of the cement, the fineness of grinding and the amount of gypsum (bonding regulator). The third stage, which is mainly due to the hydration of the alite, takes a time interval of 3-8 h from the homogenization of cement and water (initial setting of cement) and is characterized by increasing heat release within 5-10 h. Usually the maximum heat coincides with the end of setting time of cement. Then the intensity of the processes decreases (stage 4) and reaches a stable state (stage 5) - Figures 1 and 2.

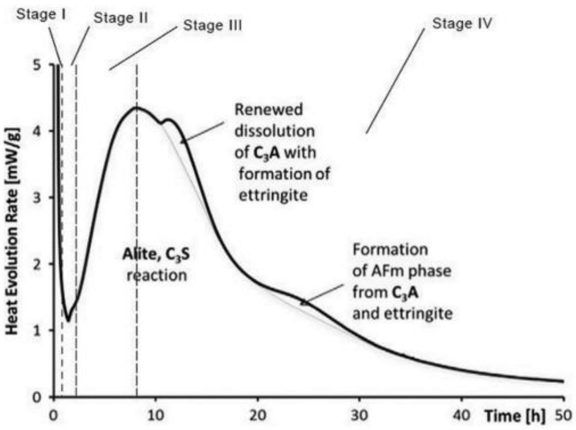

Fig. 2 *Typical calorimetry plot of ordinary Portland cement showing different stages in hydration process [4]*

It is well known that mineral admixtures, in proportion to the amount, used in the composition of cement, help to reduce the heat of hydration. As for chemical admixtures for concrete and mortars, they generally do not change the amount of heat released, but can significantly affect the intensity of heat release and its change in the initial setting time. A clear peak of heat release, respectively retarders cause the opposite effect - a smoother change in exotherm, delayed in time.

2. Concrete heat release stresses and deformations

In no standard document related to the concrete and reinforced concrete structures static calculation, even in the latest editions of **ACI 318-11** [5], **fib Bulletin 55 and 56** [6] and **EN 1992 Eurocode 2** [7], does not address the issue of thermal impact derived from the heat of hydration of cement.

An approximate empirical methodology for calculating the increase in temperature in concrete ground slabs due to the heat release of cement is included in **ACI 207.4R-93** [8].

With such a focus are many scientific studies related to prediction of the thermal stress of massive concrete structures, as a result of which specific methods for on-site monitoring have already been developed [9,10]. The obtained experimental results for the development of the temperature in the concrete section, compared with those of the existing empirical dependences, allow to increase the reliability of the predictions. And this works in the direction of increasing the security, serviceability and durability of the facilities.

3. Concrete facility data

Two main cases of authoritative fragments of the facility are considered (Fig. 3), technologically performed separately from each other on different concreting strokes:

- reinforced concrete step with approximate dimensions length 10 m; width 3,0 m; height 1,0 m;
- trapezoidal reinforced concrete body approximately 9,5 m long; width 2,0 to 0,50 m; height 4,0 m.

4. Prescribed concrete mix design

From a design point of view, the design compressive strength class of concrete can vary from relatively low levels.

Relevant in this case are the achievement of the requirements to it, caused by the operating environment (environmental impact factors within the meaning of the requirements of **BDS EN 206: 2013 +2016 [10],** and **BDS EN 206: 2017 / NA National Annex** [11] - see **NA 5.3 and NA.F.1a** Limit values for concrete composition and properties.

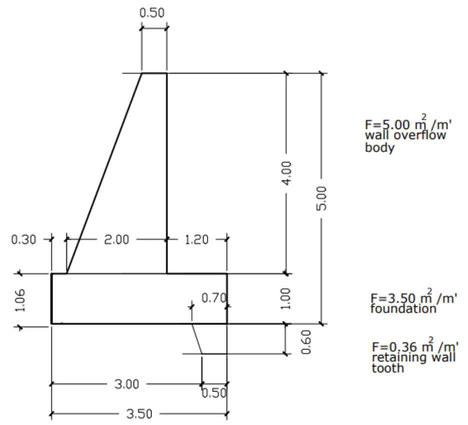

Fig. 3 *Facility cross section - geometric dimensions*

In this case, the limiting requirement is the resistance of the concrete to cyclic freeze-thaw without the presence of anti-icing agent (XF 3) and cyclic wetting and drying (XC 4) – in accordance of **Table 1 Impact classes** [11].

Simultaneous satisfaction of the above requirements imposes the following limits on the composition of concrete:

- minimum compressive strength class C30/37;
- cement content - min 320 kg/m^3;
- maximum water-cement ratio 0,50.

In order to limit the amount of heat released, slag cement CEM III-A 42.5 N (heat of hydration 280 J/g) was chosen for the production of concrete, which is produced in our country by the cement plants in Devnya. The other types of cements available on our market have a heat of hydration of about 400 and 440 J/g, which makes them unacceptable in this case.

Table 2 *Prescribed concrete mix design*

Components	**Quantity, kg/m^3**
Cement CEM III-A 42,5 N, LH	360
River sand, fraction 0-4 mm	840
Crashed stone – dolomitized limestone or similar, two fractions - 4/11,2 mm and 11,2/22,4 mm	990
Internal crystallization admixture with permanent action **KRYSTALINE Add1**	1,00
Shrinkage compensating admixture **KEPTONITE**	15,00
High range water reducing admixture (HRWRA) – Polycarboxylate Ether (PCE)	2,0
Mixing water	≈170

In this case, it is appropriate to apply an innovative approach to the composition of concrete with the inclusion of highly effective deep-crystallizing and shrinkage-compensating chemical admixtures of the latest generation. The latter provide a number of technical advantages - complete permanent impermeability of the concrete section, high physical and mechanical properties, increased frost resistance in cyclic freeze-thaw conditions, elimination of drying shrinkage of concrete and complete crack resistance.

Trying to ensure the best quality performance of the concrete mix design an innovation approach is proposed by additionally inclusion of a deep-crystallizing internal chemical admixture KRYSTALINE Add1 HD with permanent action in time, capable of compacting additionally formed concrete structure, ensuring the impermeability of the built protective section and shrinkage compensating admixture KEPTONITE [12, 13, 14].

It preliminary is assumed that the two parts of the wall will be casted separately, and the period between concreting will be more than one week, so as not to coincide with the peaks of heat release.

5. Calculation temperature increase in concrete

ACI 207.4R-05 presents a simplified method for calculating the maximum temperature rising of concrete in ground-based slabs. In this case, the software "Concrete works" V.2, developed by the University of Austin, Texas, USA, is used.

For the foundation slab respective initial conditions are specified:

- Air temperatures - during the day 22-25^{0}C; at night 14-16^{0}C;
- Temperature of the fresh concrete during casting - about 20^{0}C;
- Start of application - about 10 hours before noon.

Respective calculating results are presented in Figures 3-7**.**

It is visible that the maximal temperature difference within the foundation + 16^{0}C and maximal temperature of concrete + 36^{0}C.

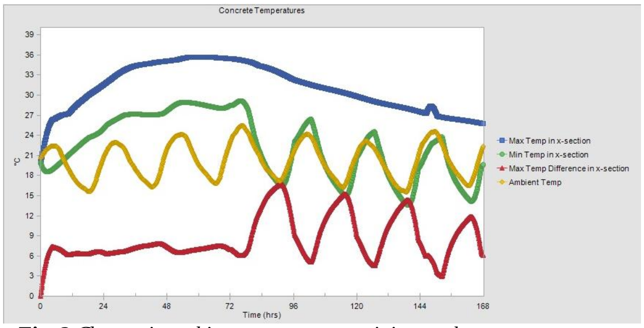

Fig. 3 *Change in ambient temperature, minimum element temperature, maximum temperature and temperature difference*

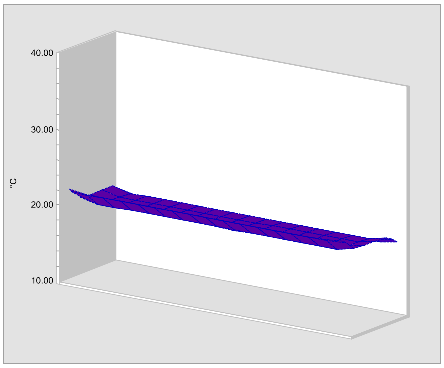

Fig. 4 *Temperature in the concrete massive at casting stage*

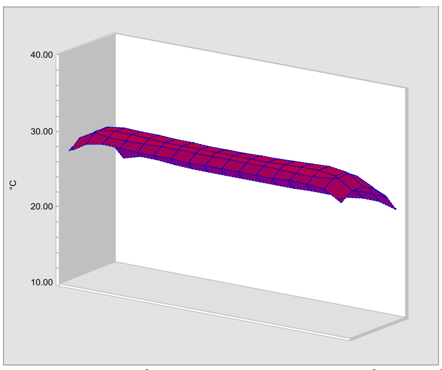

Fig. 5 *Temperature in the concrete massive at 24 hours after casting*

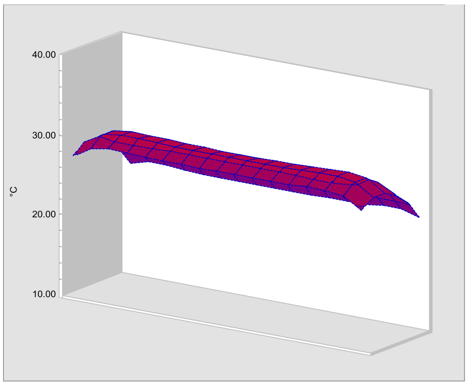

Fig. 6 Temperature in the concrete massive at 48 hours after casting

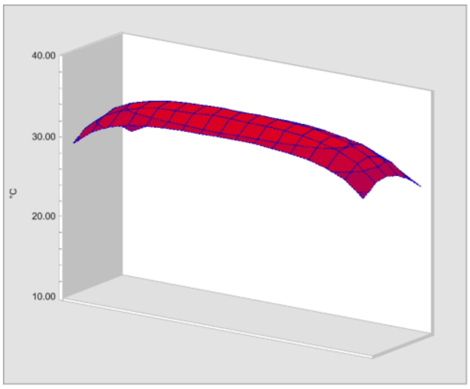

Fig. 7 *Temperature in the concrete massive at 72 hours after casting*

Concerning the wall body of the facility the same respective initial conditions are specified:

- Air temperatures - during the day 22-25^{0}C; at night 14-16^{0}C;
- Temperature of the fresh concrete during casting - about 20^{0}C;
- Start of application - about 10 hours before noon.

Respective calculating results are presented in Figures 8-12**.**

It is visible that the maximal temperature difference within the foundation + 19^{0}C and maximal temperature of concrete + 39^{0}C.

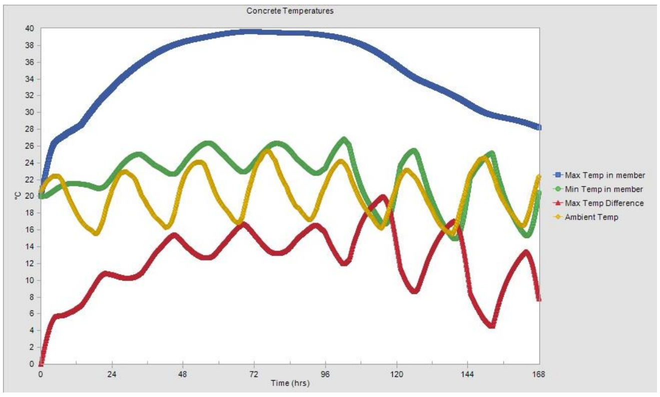

Fig. 8 *Change in ambient temperature, minimum element temperature, maximum temperature and temperature difference*

Acknowledgments

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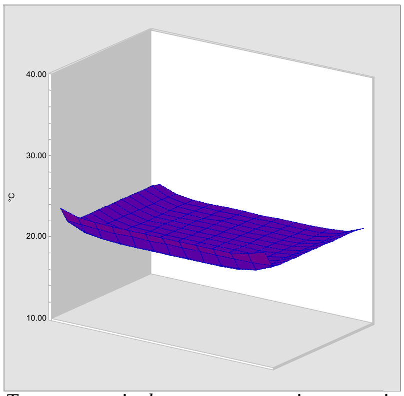

Fig. 9 *Temperature in the concrete massive at casting stage*

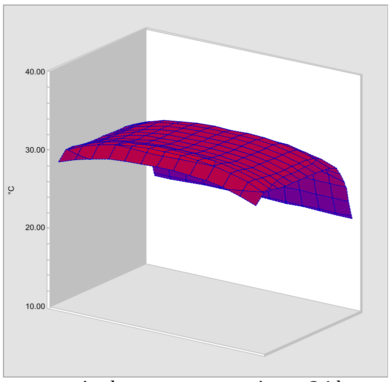

Fig. 10 *Temperature in the concrete massive at 24 hours after casting*

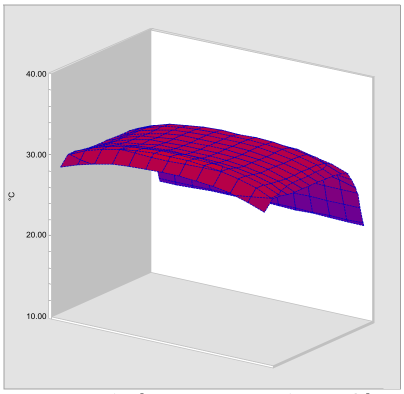

Fig. 11 *Temperature in the concrete massive at 48 hours casting*

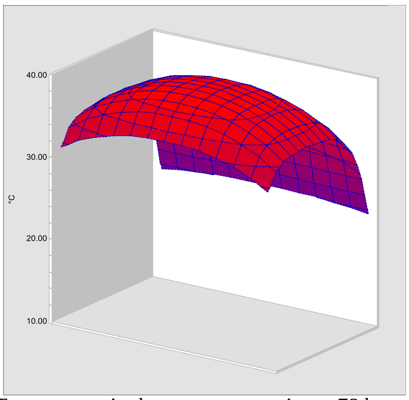

Fig. 12 *Temperature in the concrete massive at 72 hours after casting*

6. Conclusion

The analysis of the problem related to rising temperatures in the cross section of massive concrete and reinforced concrete structures due to active hydration processes in the cement shows opportunities for the development of additional stresses, often leading to unregulated cracking with potential to compromise durability of the facility under construction.

As a result of the proposed prescribed concrete mix design for the specific facility, the temperature difference in the concrete body is expected to be within acceptable limits - up to 20-25^{0}C, which does not pose a risk of compromising the facility during operation.

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