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Simulation of Curing Processes in Cast-in-place Thin-walled Structure under Different Climatic Conditions

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Abstract. The paper presents the study on the effect of heating wire pitch on the strength of concrete in cast-in-place thin-walled wall structure when heated with the use of heating wire in the mold made of 40 mm thick wood depending on the wind speed and outdoor air temperature using ELCUT software. The conclusions include recommendations on cold weather concreting of a cast-in-place reinforced concrete wall with the surface modulus $S_m = 10$.

1. Introduction

Concrete is an inherent element of modern construction. It is one of the most widespread materials which largely defined the level of development of our civilization. At the same time, concrete is a complex artificial composite material that may have completely unique properties. Strength is the key parameter that ensures quality of concrete structures and constructions. Development of strength occurs due to hydration, i.e. interaction between cement and water. Such chemical reaction requires conditions close to normal ones.

Considering the geography of Russia, especially location of oil and gas producing regions, specific methods shall be used for creating and keeping the required temperature in the concrete body for it to reach the ultimate strength, as freezing early age concrete has negative effect on its strength characteristics. At negative temperatures, water transits into solid state and hydration reaction stops. Internal pressure forces simultaneously occur in concrete due to water volume increase during solidification. At early stage, immature concrete structure is unable to withstand these forces. When thawing the hydration process resumes, however strength characteristics irreversibly decrease.

The science progresses and there are multiple methods (both heating and non-heating ones) of cold weather concrete production [1–4]. According to the standard regulations SP 70.13330.2012 “Load-bearing and separating constructions” the most economically viable curing method for cold weather concreting of cast-in-place structures is selected depending on the type of structure (surface modulus) and outdoor air temperature.

2. Experiment

The paper presents the study on the effect of heating wire pitch (HWP = 100, 150, and 200 mm) on the strength of concrete mixture in cast-in-place structure under various conditions: wind speed ($v = 0, 1, 5, 10$, and 15 m/s; convective heat transfer coefficient of the environment $\alpha_{o,c} = 3.78; 6.87; 18.14; 28.58$ and 37.29 W/(m²·K), respectively) and outdoor air temperature ($t_{o,a} = -5, -15, -25$, and -35 °C).

The structure under study was a wall sized $0.2 \times 3.0 \times 6.0$ m. Surface modulus $S_m = 10$, id est it is a thin-walled structure with minor exothermic processes that were neglected in this study.

Table 1 presents the mold type used in the calculations.



Table 1. Mold parameters.

Mold type	Material	Layer thickness, mm	Heat transfer resistance coefficient (W/ m ² ·°C)		
			Wind speed, m/s		
			0	5	15
II	Board	40	2.03	3.6	3.94

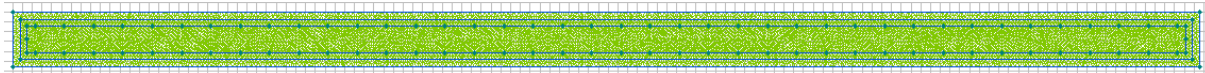
Three design models (DM) with finite element meshes (FEM) with different heating wire pitch (HWP = 100, 150, and 200 mm) were built within the research. The pitch was defined as a set of peaks at the depth of 30 mm with heat production capacity of $q = 35$ W/m. Heat losses occur through the mold side surfaces. B30 concrete with initial temperature of concrete mixture $t_{c,m} = 10$ °C was used.

The value $\alpha_{o,c}$ can be calculated with the help of Frank's equation (1):

$$\alpha_{o,c} = 6.31v^{0.656} + 3.78e^{-1.91v}, \quad (1)$$

where v is wind speed, m/s; $e = 2.718$ is the base of the natural logarithms.

The first term of equation (1) considers forced convection, and the second term refers to natural convection. Figure 1 presents DM No. 2 with FEM that has 3 blocks and 7,649 nodes.

**Figure 1.** DM No. 2 with FEM (mold type II, HWP 150 mm).

Thermophysical properties of the mold were taken from the software reference book.

Table 2. Thermophysical properties of materials.

Material	Thermal conductivity (W/m·K)	Specific heat capacity (J/K·kg)	Density (kg/m ³)
Metal	58	470	7.850
Concrete	2.07	1.050	2.500
Pine	0.18	2.300	500

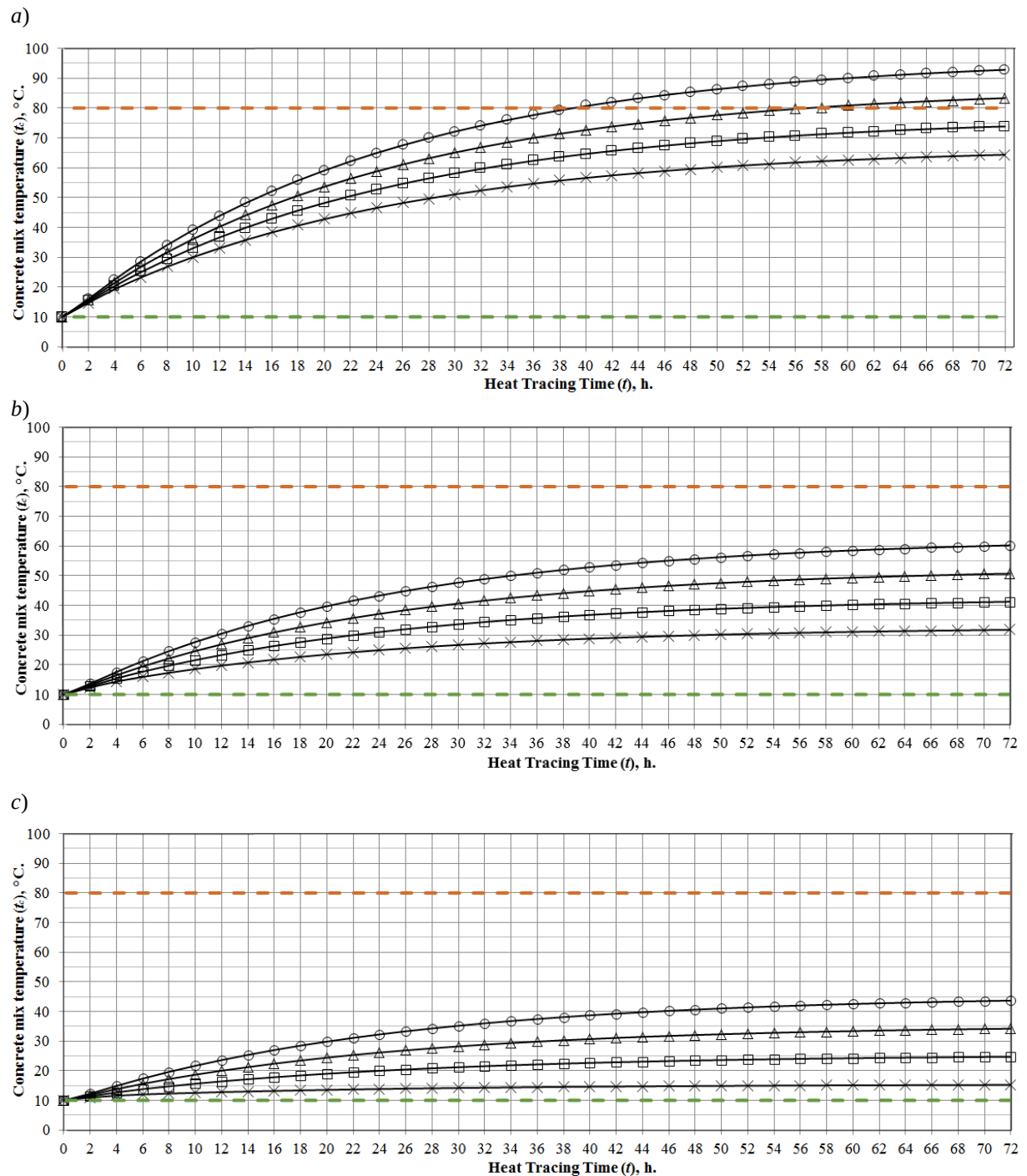
Heating parameters and time (3 days) were selected. Then follows task solving which can be called a “rapid calculation”. Such calculation is done using ELCUT software. The interval of solution is selected by the user. In this research the interval was set for 2 hours. The used software complex produces task solution with the account of heat capacity and thermal conductivity of all materials of the structure in the design scheme with regard to space and time. Convective heat exchange with the environment is also taken into account.

3. Results

Figure 2 demonstrates dependency graphs of the impact of heating wire pitch on the concrete body temperature of the thin-walled wall structure (t_c) under various environmental conditions. Figure 2 also contains initial temperature of concrete mixture and the limits of heating temperature specified in the construction standard SP 70.13330.2012.

It is clear from Figure 2 that heating wire pitch is the key parameter having the most effect on the body temperature of the concrete structure. After studying one of the cases at constant wind speed $v = 5$ m/s and outdoor air temperature $t_{o,a} = -25$ °C it was found that the concrete body temperature decreases by 44.14 % as the heating wire pitch grows from 100 mm to 150 mm, and by 73.5 % with HWP increase from 100 mm to 200 mm.

While studying the case of HWP = 50 mm the concrete body temperatures exceeding those specified by SP 70.13330.2012 were observed.



With HWP = 100 mm, according to Figure 2 electric heating at wind speed $v = 5$ m/s is only admitted for the outdoor air temperature no lower than -15 °C. When the environment temperature goes down from -25 to -35 °C the concrete body temperature decreases by 12.9 %.

The most appropriate is HWP = 150 mm, as no overheating or low positive temperatures are observed during electric heating of the wall structure. In this case, when the outdoor air temperature drops from -5 to -35 °C the concrete body temperature decreases by 47.2 %.

With the increase of HWP up to 200 mm electric heating with the wind speed of $v = 5$ m/s is only recommended at outdoor air temperature higher than -25 °C. Otherwise, too low positive concrete temperature is observed, which requires huge amount of additional electric power and heating time for concrete to develop 70 % of R28 strength.

Table 3 gives the average concrete temperature ($t_{c.av.}$) values within the whole electric heating exposure period depending on the air velocity, outdoor air temperature and heating wire pitch.

Table 3. Average concrete temperature ($t_{c.av.}$) in the structure.

HWP (mm)	v (m/s)	$t_{o.a.}$ (°C)	$t_{c.av.}$ (°C)	HWP (mm)	v (m/s)	$t_{o.a.}$ (°C)	$t_{c.av.}$ (°C)	HWP (mm)	v (m/s)	$t_{o.a.}$ (°C)	$t_{c.av.}$ (°C)
100	0	- 5	E	150	0	- 5	E	200	0	- 5	47.30
		- 15	E			- 15	E			- 15	42.39
		- 25	E			- 25	52.68			- 25	37.20
		- 35	E			- 35	47.65			- 35	32.15
	1	- 5	E		1	- 5	54.35		1	- 5	40.68
		- 15	E			- 15	48.5			- 15	34.81
		- 25	E			- 25	42.66			- 25	28.96
		- 35	E			- 35	36.79			- 35	23.10
	5	- 5	E		5	- 5	45.7		5	- 5	33.88
		- 15	E			- 15	39.05			- 15	27.26
		- 25	55.62			- 25	32.44			- 25	20.63
		- 35	48.99			- 35	25.83			- 35	13.98
	10	- 5	E		10	- 5	43.41		10	- 5	32.09
		- 15	58.91			- 15	36.58			- 15	25.28
		- 25	51.95			- 25	29.76			- 25	18.46
		- 35	45.11			- 35	22.93			- 35	11.63
	15	- 5	E		15	- 5	42.42		15	- 5	31.33
		- 15	57.3			- 15	35.52			- 15	24.44
		- 25	50.4			- 25	28.63			- 25	17.54
		- 35	43.49			- 35	21.73			- 35	10.63

In Table 3, the letter “E” means that the concrete temperature t_c in the body of thin-walled cast-in-place wall exceeds $+80$ °C.

Concrete strength in percentage of R28 was defined from the concrete body temperature during the whole period of exposure to electric heating (72 hours) on the basis of strength development graphs from MDS 12-48.2009 “Cold weather concreting with the use of heating wires”. For B30 (M400) concrete design compressive strength is 38.35 MPa according to the standard document GOST 26633-2015 “Heavy-weight and sand concretes. Specifications”.

The research outcomes are presented in Table 4 using which is convenient for defining strength depending on the heating wire pitch (HWP = 100, 150, and 200 mm), outdoor air temperature ($t_{o.a} = -5, 15, 25$, and 35 °C) and wind speed ($v = 0, 1, 5, 10$, and 15 m/s) after 3 days’ exposure to electric heating.

Strength for intermediate wind speed values can be obtained by using interpolation.

Table 4. Concrete strength in thin-walled wall structure depending on temperature, wind speed and heating wire pitch.

HWP (mm)	v (m/s)	$t_{o,a}$ (°C)	$t_{c,av}$ (°C)	HWP (mm)	v (m/s)	$t_{o,a}$ (°C)	$t_{c,av}$ (°C)	HWP (mm)	v (m/s)	$t_{o,a}$ (°C)	$t_{c,av}$ (°C)
100	0	- 5	E	150	0	- 5	E	200	0	- 5	68.4
		- 15	E			- 15	E			- 15	65.4
		- 25	E			- 25	72.2			- 25	62.0
		- 35	E			- 35	68.6			- 35	58.5
	1	- 5	E		1	- 5	73.5		1	- 5	64.4
		- 15	E			- 15	69.1			- 15	60.4
		- 25	E			- 25	65.6			- 25	56.3
		- 35	E			- 35	61.8			- 35	52.2
	5	- 5	E		5	- 5	67.4		5	- 5	59.7
		- 15	E			- 15	63.3			- 15	55.1
		- 25	74.5			- 25	58.7			- 25	50.4
		- 35	69.4			- 35	54.1			- 35	45.1
	10	- 5	E		10	- 5	66.1		10	- 5	58.5
		- 15	77.13			- 15	61.6			- 15	53.7
		- 25	71.6			- 25	56.8			- 25	48.8
		- 35	67.1			- 35	51.4			- 35	43.3
	15	- 5	E		15	- 5	65.5		15	- 5	57.9
		- 15	75.8			- 15	60.9			- 15	53.1
		- 25	70.3			- 25	56.0			- 25	48.0
		- 35	66.1			- 35	51.2			- 35	42.5

4. Conclusion

Mold of 40 mm thick wood is very susceptible to external effects of the environment, especially to wind speed. At constant outdoor air temperature $t_{o,a} = -25$ °C and HWP = 150 mm and with the increase of wind speed v from 0 to 15 m/s the concrete body temperature drops by 54.3 %.

In isolated cases 70 % of R28 strength is developed after 3 days of electric heating (Table 4), otherwise, additional time is required, which causes extra energy costs. Based on this one may conclude that this type of mold shows little efficiency.

Using the obtained research outcomes the following recommendations on concreting cast-in-place thin-walled wall structure in 40 mm thick wooden mold are developed:

- HWT = 50 mm are not recommended for use.
- HWT = 100 mm should be used in open and well ventilated plots or objects with wind speed higher than 1 m/s and outdoor air temperature lower than -15 °C.
- HWP = 150 mm is recommended to use for all the studied wind speed ($v = 0, 1, 5, 10$, and 15 m/s) and outdoor air temperature ($t_{o,a} = -5, -15, -25$, and -35 °C) values. However, it should be mentioned that 3 days of exposure to electric heating will not suffice for developing 70 % of R28 strength.
- With HWP = 200 mm electric heating shows lower efficiency. It is recommended for use in closed or poorly ventilated premises with wind speed less than 5 m/s and outdoor temperature higher than -25 °C. For other environment-related parameters low electric heating temperature is observed. In all cases, additional time of electric heating is required for concrete to develop 70 % of R28 strength.
- With HWP = 100, 150, and 200 mm development of ultimate concrete strength of 30% of R28 is provided in all cases.
- HWP = 250 mm is not recommended for use because of low electric heating temperature, and in cases of high wind speed and low temperature the concrete body temperature decreases to 0 °C and lower.

Acknowledgments

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