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Article

Influence of Formwork Structure on Heat Treatment of Precast Concrete Elements by Solar Energy

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Abstract. The present paper aims to study the influence of the formwork structure on the efficiency of heat treatment (HT) of precast concrete elements (PCE) by solar energy in various climatic conditions. The objects of the study were different types of formworks composed of solar energy equipment for HT of PCE. In total, six types of formworks, made of steel sheet, laminated plywood and timber, with and without insulation were studied. Calculation and experimental study were carried out for humid continental, and subtropical climates. Experimental study was carried out in the laboratory and in the open air. According to the obtained results, the heat insulation material in the formwork structure contributes to increase the strength of concrete. Formwork with heat insulation layer of 40 mm gave the best results. However, the level of the contribution depends on climatic conditions. Heat insulation material in the formwork structure is necessary in humid continental climate. Even the thickness of the insulation layer of 20 mm gives good results and the difference between the concrete strength with thickness of 20 mm and 40 mm is insignificant. On the contrary, in humid subtropical climate, the heat insulation material in the formwork structure is favorable, but not compulsory, since the difference between the concrete strengths is not significant and the strength values, obtained in all six types of formwork, allow it to be removed after 24 hours of curing.

Keywords: Solar energy, precast concrete elements, heat treatment, formwork, solar energy equipment, strength of concrete, curing period.

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1. Introduction

Precast construction technology has certain advantages, such as time and cost reduction of the construction process due to the manufacturing of structural elements at plants and their erection in designed position at a construction site. Therefore, precast concrete and reinforced concrete structural elements are widely used for construction of civil and industrial buildings along with cast-in-situ around the world [1, 2].

Precast concrete industry manufactures a wide range of structural elements, and the main types are the following: foundation elements, wall panels, floor slabs, staircases, columns, beams, railway sleepers, airport pavement elements etc. [3-7]. Meanwhile, various types of reinforcement can be used in the manufacturing process, such as steel reinforcement and fiber reinforcement [8].

Heat treatment (HT) is used to speed up the curing process of precast concrete elements (PCE) and to get ready-made structures in a short time. Usually, precast concrete plants use steam or gas heating, electrical heating and other ways for HT [9, 10].

Introduction of green technologies in all fields of the world economy, especially in civil and industrial engineering, as well as the reduction of fossil fuels consumption, is a vital problem nowadays [11]. However, the transition to green technologies is connected with economical costs, which seem unjustified without taking into account its social and ecological points [12]. Meanwhile, it is necessary to take into account real cost of energy resources, reflecting real expenses for their production to compare correctly green technologies, using renewable resources, and the technologies, using fossil fuels [13].

On the one hand, fossil fuels are costly from the position of longstanding economic development. In future, the cost will increase inevitably, because of the distant fields of fossil fuels, involved in the production turnover. On the other hand, the technologies, using fossil fuels, pollute the environment. The world assessments of the direct social expenses, connected with the pollution impact, including diseases and human lifetime decline, harvest decline, the forests recovery and buildings renovation in the result of air, water and soil pollution, give us about 75% of the world prices for fuel and energy [14, 15].

Taking into account the above, the replacement of fossil fuels by renewable energy wherever it is possible can be considered as environmental saving activity and seems very important.

There are different ways to use solar energy (SE) as a renewable resource in the construction industry [16, 17]. One of the ways is the use of SE for HT during the manufacturing process of PCE, heating the concrete up to temperatures of 50-70 °C. It is less than usual temperature of HT, which is 80-95 °C, but it is enough to get within 24 hours of curing the 40-65% of the designed strength, which allows removing formwork and putting PCE in storage area [18]. Undoubtedly, the efficiency of SE for HT depends on climatic and weather conditions of the plant. However, the research results show that SE can be used for HT of PCE in cold countries, such as Russia, Finland, Sweden, Norway, Canada etc. For example, it is usable in Russia within 5 months for Moscow region (φ=56° N) and 7 months for South of Russia (φ=45° N). In this case, the manufacturing period does not exceed 24 hours during these months, and fossil fuels can be partly replaced by SE [19].

The research of the development of various types of solar energy equipment (SEE) is carried out in different countries [20, 21]. The most common types of SEE are solar collectors and solar panels nowadays [22, 23].

Podgornov N.I. proposed to equip formwork, which is used during the manufacturing process of PCE, by transparent cover and placed in the open air to heat the concrete by SE [18]. In this case, it is comparable with solar collector by thermo-physical processes, which occur in it, and can be considered as SEE. Therefore, the additional expenses to obtain SEE fall only on production of transparent covers for formworks (Fig. 1).

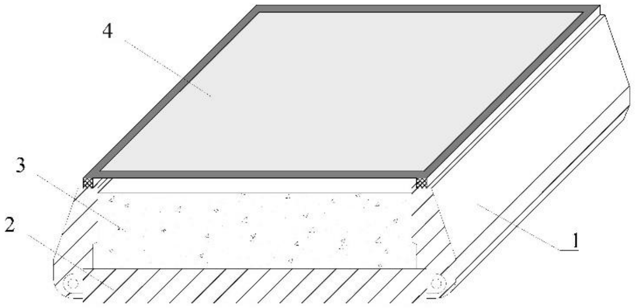

Fig. 1. Concept of formwork, equipped by transparent cover.
1 – walls of formwork, 2 – bottom of formwork;
3 – PCE, 4 – transparent cover.

In this case, the efficiency of SE for HT depends on design features of such SEE. One of them is the formwork structure. It can be produced from different materials, with or without heat insulation layer. Taking into account the above, the aim was to study the influence of the formwork structure on the efficiency of HT of PCE by SE in various climatic conditions.

There is no systematic study on the use of transparent cover formwork in other publications. The results available in [24] are more a statement of the very idea of using transparent cover formwork, and are insufficient to assess the effectiveness of such process engineering solution.

The objects of the study were various types of formworks as part of SEE for HT of PCE.

The subject of the study was the influence of the formwork structure on the efficiency of HT of PCE by SE in various climatic conditions.

The following tasks were defined to obtain the above aim:

- To select types of formworks for the study;
- To develop the calculation model of the curing process of PCE in SEE in various climatic conditions;

- To identify the efficiency characteristics of HT of PCE by SE;
- To compare the selected types of formworks, using these characteristics, and identify the best type of formwork structure depending on climatic conditions;
- To conduct an experimental study of verification of the calculation results.

2. Materials and Methods of Research

The calculation model of concrete curing in SEE in various climate conditions was developed to study design features of formworks.

The efficiency of the formwork design was estimated by the following characteristics: heat loss through formwork, total heat loss from SEE, temperature of concrete, its maturity and strength.

Total heat loss from SEE consists of heat loss through transparent cover, walls and bottom of formwork during the day (1) [24] is

$$\Sigma Q_{loss} = F_c \int_{\tau_{24}}^{\tau_1} q_{loss(c)}(\tau) d\tau + F_w \int_{\tau_{24}}^{\tau_1} q_{loss(w)}(\tau) d\tau + F_b \int_{\tau_{24}}^{\tau_1} q_{loss(b)}(\tau) d\tau \qquad (1)$$

where F_c, F_w, F_b are areas of transparent cover, walls and bottom of formwork respectively, m²; $q_{loss(c)}$, $q_{loss(w)}$, $q_{loss(b)}$ are heat loss through 1 m² of area of transparent cover, walls and bottom of formwork, kJ/m²; τ_1 and τ_{24} are time intervals of concrete curing in SEE, from the first hour till the 24th hour, respectively.

Moreover, the intensity of heat loss depends on many parameters; the main of them is the environment temperature and the structures of transparent cover and formwork.

Single-layer transparent cover was used for this study based on the research results of its design [24].

The following materials were used to design six types of formworks: sheet steel with density 7850 kg/m³, laminated plywood with density 520 kg/m³, timber with density 520 kg/m³, mineral wool with density 150 kg/m³. Characteristics of formworks, used in the study, are illustrated in Table 1.

Table 1. Characteristics of formworks.

Type	Design and materials	Thickness [mm]	Heat transfer coefficient [W/(°C·m²)]
1	Steel	3	47
2	Plywood	12	0.15
3	Timber	40	0.15
4	Plywood Mineral wool Plywood	12 20 4	0.15 0.055 0.15
5	Steel Mineral wool Plywood	3 30 4	47 0.055 0.15
6	Plywood Mineral wool Plywood	12 40 4	0.15 0.055 0.15

The all types of formworks were placed on a heat-insulated base during the tests. Therefore, heat loss through the formwork bottom was not taken into account in the calculation.

Heat loss through 1 m² of area of the formwork walls is determined by Eq. (2) [24].

$$q_{loss(w)}(\tau) = U_{loss(w)}(t_c(\tau) - t_e(\tau)) \qquad (2)$$

where $U_{loss(w)}$ – heat transfer coefficient of the formwork walls, W/(°C·m²); t_c *and* t_e – temperature of concrete and environment respectively, °C; τ – time of concrete curing in SEE, hours.

The concrete strength after the estimated curing process is a key parameter, which characterizes the efficiency of the chosen formwork structure. Its calculation is based on the use of the strength dependency on the concrete time-temperature characteristics. In this case, it is the temperature, maturity and relative age of concrete (3) [25] is

$$R_c = f(x_i) \qquad (3)$$

where R_c is compressive strength of concrete, $\%R_{28}$; R_{28} is compressive strength of concrete after 28 days of curing in normal conditions; f is function of the strength dependency on the concrete time-temperature characteristic; x_i is value of the characteristic.

Table 2. Values of relative age of concrete (in days) depending on its average temperature and time between its measurements.

Average temperature of concrete	Time between measurements of concrete temperature [hours]					
	2	4	6	8	10	12
10	0.0	0.1	0.1	0.2	0.2	0.4
12	0.0	0.1	0.1	0.2	0.2	0.4
14	0.0	0.1	0.1	0.2	0.4	0.4
16	0.0	0.1	0.2	0.2	0.4	0.5
18	0.0	0.1	0.2	0.4	0.5	0.6
20	0.0	0.1	0.2	0.4	0.5	0.6
22	0.1	0.2	0.4	0.5	0.6	0.7
24	0.1	0.2	0.4	0.5	0.6	0.8
26	0.1	0.2	0.5	0.6	0.7	1.0
28	0.1	0.4	0.5	0.7	0.8	1.1
30	0.1	0.4	0.6	0.7	1.0	1.2
32	0.1	0.4	0.6	0.8	1.1	1.3
34	0.2	0.5	0.7	1.0	1.2	1.6
36	0.2	0.5	0.8	1.1	1.4	1.7
38	0.2	0.6	1.0	1.3	1.6	1.9
40	0.4	0.7	1.1	1.4	1.8	2.2
42	0.4	0.8	1.2	1.7	2.0	2.5
44	0.4	0.8	1.3	1.8	2.3	2.8
46	0.5	1.0	1.6	2.0	2.6	3.1
48	0.6	1.2	1.8	2.4	3.0	3.6
50	0.6	1.3	2.0	2.6	3.4	4.1
52	0.7	1.4	2.3	3.0	3.8	4.6
54	0.8	1.7	2.5	3.4	4.3	5.2
56	1.0	1.9	2.9	3.8	4.8	5.8
58	1.1	2.2	3.2	4.3	5.5	6.6
60	1.2	2.4	3.7	4.9	6.1	7.4

The following method was used to calculate the compressive strength of concrete after 24 hours of curing in various types of formworks, equipped by transparent cover. At the first stage, maturity of concrete, which is the sum of numerical values of concrete temperatures over the period of concrete curing (24 hours), was determined by Eq. (4) [25].

$$M_{concrete} = \sum_{i=1}^{n} t_c \Delta\tau_i \tag{4}$$

where $\Delta\tau_i$ is time between the measurements of the concrete temperature; t_c is temperature of concrete, °C. In the case of this study, $\Delta\tau_i$=1 hour and n=24 hours.

At the second stage, the relative age of concrete, depending on its average temperature and time between the measurements of the concrete temperature, was determined using experimental data from Table 2, obtained from the study of compressive strength of concrete under various methods of its HT [25].

At the third stage, the compressive strength of concrete was calculated using experimental data from Table 3 of the strength values depending on the concrete relative age [25]. The data from [25] in Tables 2 and 3 is shown only in volume, which was necessary for this study.

Table 3. Compressive strength of concrete (in $\%R_{28}$) under t_c=18 °C depending on its relative age.

Whole	Tenth of a day				
day	0.1	0.3	0.5	0.7	0.9
0	7.9	13.6	17.4	20.4	23
1	25.3	27.4	29.2	31	32.6
2	34.2	35.6	37	38.3	39.6
3	40.8	42	43.1	44.2	45.2
4	46.3	47.2	48.2	49.1	50
5	50.9	51.8	52.6	53.4	54.2
6	55	55.8	56.5	57.3	58
7	58.7	59.4	60.1	60.8	61.4
8	62.1	62.7	63.3	64	64.6
9	65.2	65.7	66.3	66.9	67.5
10	68	68.6	69.1	69.6	70.2

The experimental study was carried out in the construction materials laboratory of the RUDN University (Moscow, Russia) and in the open air to verify the above calculation model. Six types of formworks (Table 1) were made for concrete specimens with dimensions of 200x200x200 mm for the test.

The conditions of humid subtropical climate were simulated in the climatic chamber. The chamber was heat insulated. The electric reflector lamps were used to imitate solar radiation intensity. They were placed on a special panel on the roof of the chamber. The passage of the airflow above the lamps allowed keeping the necessary air temperature. The air temperature in the chamber was controlled by a digital thermometer with the help of thermocouples. The air humidity was controlled by a digital hygrometer.

The intensity of solar radiation in the chamber was changing according to parabolic law with the maximum value of 1300 W/m^2. The air temperature in the chamber was changing according to sine law in the range of 24-50 °C at the air humidity of 6-39%.

The conditions of humid continental climate were simulated in the open air of the RUDN University courtyard, Moscow, Russia in the end of June.

Temperature in the center of concrete specimens was measured by thermocouples and recorded on coordinate tapes by automatic recording device KSP-4A.

The study of the concrete strength was carried out in accordance with the Interstate Standard GOST 10180-2012 [26], taking into account the requirements of ACI 211.1-91 [27]. The strength was conducted after 24 hours of curing on a hydraulic press of 1500 kN at the compression test.

In accordance with the plan of experimental study, 70 specimens with dimensions of 200x200x200 mm were made. The specimens consisted of 2 series (for humid subtropical and humid continental climatic conditions), each series consists of 30 specimens (5 for each type of formwork). 10 specimens (5 for each series), as controlled specimens, were cured in air-humid condition in wet sawdust at the room temperature of 18-22 °C (normal conditions), which were tested after 28 days of curing.

Concrete C25 was chosen as the material of specimens. The following materials were used to make C25 specimens in proportion 1:2.1:3.4:0.6 (cement: sand: stones: water): Portland cement CEM I 42.5 N = 324 kg/m^3 as the binder; quartz sand with fineness modulus of 2.7 = 690 kg/m^3 as the fine aggregate; crushed stone = 1094 kg/m^3 as the coarse aggregate; tap water = 190 l/m^3 for mixing.

Portland cement CEM I 42.5 N was obtained from the Maltsovsky Cement Plant, Fokino District, Bryansk Region, Russia. Table 4 shows its chemical properties.

Table 4. Chemical properties of Portland cement.

Chemical Compositions	Percentage (%)
SiO_2	21.9
Al_2O_3	4.86
Fe_2O_3	3.3
K_2O	0.56
CaO	65.77
MgO	1.15
SO_3	2.1
Na_2O	0.36

Quartz sand and crushed stone, used in the present study, were obtained from the Quarry Plant "Tyutchevo", Naro-Fominsky District, Moscow Region, Russia. Table 5 shows their physical properties.

Table 5. Properties of quartz sand and crushed stone.

Physical Property	Quartz sand	Crushed stone
Grain size, [mm]	0.5-1	5-10
Bulk density (compacted), [kg/m^3]	1430	1320
Hardness (on the Mohs scale)	7	7
Abrasion	0.1	0.25
Humidity, [%]	1.7	1.8

The calculation of the curing process of PCE in various types of formworks, equipped by transparent cover, was carried out for conditions of humid continental climate, and humid subtropical climate to study the influence of the formwork structure on the efficiency of HT of PCE by SE.

As the humid continental climate's sample, the summertime period in the Moscow region of Russia (φ=56° N) was analyzed. For this case, the polyethylene membrane with the transparent coefficient of 0.8 was used as the cover. The height of air gap between PCE and the cover was 20 mm. Dimensions of the PCE model were 200x200x200 mm. Initial temperature of concrete mix was 21 °C. As the humid subtropical climate's sample, the summertime period in the summertime period in Krasnodar region, South of Russia (φ=45° N) was analyzed. For this case, the polyethylene-terephthalate membrane with the transparent coefficient of 0.86 was used as the cover. The height of air gap between PCE and the cover was 5 mm. Dimensions of the PCE model were 350x350x360 mm. Initial temperature of the concrete mix was 18 °C.

3. Results and Discussion

The results for humid continental climatic conditions, which satisfy the summertime period in Moscow region of Russia (φ=56° N), are presented in Tables 6-11 and Fig. 2.

The results for humid subtropical climatic conditions, which satisfy the summertime period in Krasnodar region, South of Russia (φ=45° N), are illustrated in Tables 12-17 and Fig. 3.

The tables demonstrate: temperature of concrete (in the center of the PCE) and environment, heat loss through the formworks walls (Q_{loss}) and total heat loss from SEE (ΣQ_{loss}) depending on time of the day.

Fig. 2 and Fig. 3 demonstrate: temperature of concrete (in the center of the PCE) in SEE with various types of formwork and the environment temperature. HT of PCE in SEE started at 10 a.m. and continued within 24 hours till 9 a.m. of next day.

The negative value of heat loss in Table 6 (from 5 a.m. until 9 a.m.) is explained by the fact that the concrete specimen in steel formwork (type 1) cooled off more intensively in the nighttime as compared with other formworks. In the result, its temperature in the morning time was less than the environment temperature, and it became heating up even through the formwork walls.

Table 6. The calculation results for formwork of type 1 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	1.7	9.1	21
11:00	24.1	4.6	12.7	23.4
12:00	25.1	7.8	24.6	26
13:00	25.8	12	30.8	28.4
14:00	26	14.3	62.1	30.8
15:00	25.8	17	65.7	32
16:00	25.1	19.9	68.6	32.9
17:00	24.1	22.6	69.7	33.5
18:00	22.7	24.7	68.9	33.7
19:00	21.1	46.2	87	33.4
20:00	19.4	65.9	103.1	31.8
21:00	17.7	76.7	110.3	29.1
22:00	16.1	74	103.5	25.9
23:00	14.7	65	90.2	22.3
24:00	13.7	52.5	73.8	19.2
1:00	13	39.1	57.2	16.9
2:00	12.8	26	41.6	15.2
3:00	13	13.9	27.6	14.2
4:00	13.7	4.1	14.7	13.8
5:00	14.7	-3.8	4.8	13.9
6:00	16.1	-8.7	-0.8	14.5
7:00	17.7	-9.8	-2.4	15.4
8:00	19.4	-7.5	-0.6	16.6
9:00	21.1	-3.6	3.1	18.3
Maturity of concrete [°C-hours]				562.2

Table 7. The calculation results for formwork of type 2 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	1.4	8.9	21
11:00	24.1	3.8	12	23.5
12:00	25.1	6.4	23.8	26.2
13:00	25.8	9.9	29.2	28.7
14:00	26	11.8	60.7	31.3
15:00	25.8	14.1	64.1	32.6
16:00	25.1	16.5	66.7	33.6
17:00	24.1	18.7	67.5	34.3
18:00	22.7	20.6	66.6	34.6
19:00	21.1	30.6	73.5	34.4
20:00	19.4	38.7	79.1	33.4
21:00	17.7	43.6	82.3	31.7
22:00	16.1	43.8	80.7	29.7
23:00	14.7	41.9	76.3	27
24:00	13.7	38.4	69.9	24.5
1:00	13	33.6	62	22.3
2:00	12.8	27.8	52.9	20.3
3:00	13	21.4	43.1	18.8
4:00	13.7	14.8	33	17.7
5:00	14.7	8.5	23.6	17
6:00	16.1	3.2	15.2	16.7
7:00	17.7	0.1	8.6	16.9
8:00	19.4	-1	6.7	17.7
9:00	21.1	-0.4	6.9	19.1
Maturity of concrete [°C-hours]				613

Table 8. The calculation results for formwork of type 3 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	0.6	8	21
11:00	24.1	1.9	9.8	23.3
12:00	25.1	3.4	18.6	25.8
13:00	25.8	5.5	23.4	28.1
14:00	26	6.8	53.9	30.6
15:00	25.8	8.4	56.9	32
16:00	25.1	10.2	59.2	33.2
17:00	24.1	11.9	60	34.1
18:00	22.7	13.5	59.4	34.7
19:00	21.1	17.6	61	34.8
20:00	19.4	20.9	63	34.4
21:00	17.7	23.3	65.4	33.5
22:00	16.1	24	66.2	32.4
23:00	14.7	24	65.3	30.6
24:00	13.7	23.3	63.1	28.8
1:00	13	21.8	59.6	27.1
2:00	12.8	19.8	54.8	25.5
3:00	13	17.2	48.9	24.1
4:00	13.7	14.1	42.2	22.8
5:00	14.7	10.9	35	21.8
6:00	16.1	7.8	29.5	21.1
7:00	17.7	5.3	22	20.8
8:00	19.4	3.6	18.8	21.1
9:00	21.1	2.7	16.5	21.9
Maturity of concrete [°C-hours]				663.5

Table 9. The calculation results for formwork of type 4 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	0.6	8	21
11:00	24.1	1.7	9.8	23.4
12:00	25.1	2.9	19.9	26.1
13:00	25.8	4.5	23.6	28.7
14:00	26	5.6	54.5	31.4
15:00	25.8	6.8	57.4	32.9
16:00	25.1	8.2	59.4	34.2
17:00	24.1	9.5	60	35.2
18:00	22.7	10.6	59	35.8
19:00	21.1	13.1	59	36
20:00	19.4	15.1	59.8	35.6
21:00	17.7	16.4	61.2	34.8
22:00	16.1	16.7	61.7	33.8
23:00	14.7	16.7	60.9	32.1
24:00	13.7	16.2	59	30.3
1:00	13	15.3	56	28.6
2:00	12.8	14	52.1	27.1
3:00	13	12.3	47.2	25.6
4:00	13.7	10.4	41.5	24.4
5:00	14.7	8.4	35.4	23.3
6:00	16.1	6.3	30.9	22.5
7:00	17.7	4.5	29.1	22.1
8:00	19.4	3.5	20.3	22.1
9:00	21.1	2.9	19.1	23
Maturity of concrete [°C-hours]				690

Table 10. The calculation results for formwork of type 5 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	0.5	7.9	21
11:00	24.1	1.3	9.4	23.5
12:00	25.1	2.4	18.7	26.2
13:00	25.8	3.8	22.4	28.9
14:00	26	4.7	53	31.4
15:00	25.8	5.8	55.7	33
16:00	25.1	7	57.7	34.4
17:00	24.1	8.2	58.1	35.4
18:00	22.7	9.2	57.2	36.1
19:00	21.1	11.3	57	36.3
20:00	19.4	12.9	57.6	36
21:00	17.7	14.1	59.1	35.2
22:00	16.1	14.4	59.9	34.3
23:00	14.7	14.4	59.4	32.5
24:00	13.7	14.1	57.9	30.9
1:00	13	13.4	55.3	29.3
2:00	12.8	12.4	51.8	27.9
3:00	13	11.1	47.3	26.5
4:00	13.7	9.5	42.1	25.3
5:00	14.7	7.7	36.4	24.2
6:00	16.1	6	32.1	23.4
7:00	17.7	4.5	30.4	23
8:00	19.4	3.5	21.3	23
9:00	21.1	3	19.9	23.7
Maturity of concrete [°C-hours]				701.5

Table 11. The calculation results for formwork of type 6 in humid continental climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	22.7	0.4	7.8	21
11:00	24.1	1.1	9.1	23.6
12:00	25.1	1.9	18.5	26.4
13:00	25.8	3	21.8	29.1
14:00	26	3.7	52.4	31.5
15:00	25.8	4.6	55	33.2
16:00	25.1	5.5	56.8	34.7
17:00	24.1	6.4	57.1	35.5
18:00	22.7	7.3	56.1	36.4
19:00	21.1	8.6	55.2	36.8
20:00	19.4	9.7	55.4	36.5
21:00	17.7	10.5	56.7	35.8
22:00	16.1	10.7	57.6	34.9
23:00	14.7	10.7	57.2	33.5
24:00	13.7	10.5	56	31.9
1:00	13	10.1	53.8	30.4
2:00	12.8	9.3	50.6	28.8
3:00	13	8.4	46.6	27.6
4:00	13.7	7.3	41.9	26.4
5:00	14.7	6.1	36.7	25.3
6:00	16.1	4.9	32.9	24.5
7:00	17.7	3.7	31.6	23.9
8:00	19.4	2.8	33	23.9
9:00	21.1	2.5	20.1	24.4
Maturity of concrete [°C-hours]				716

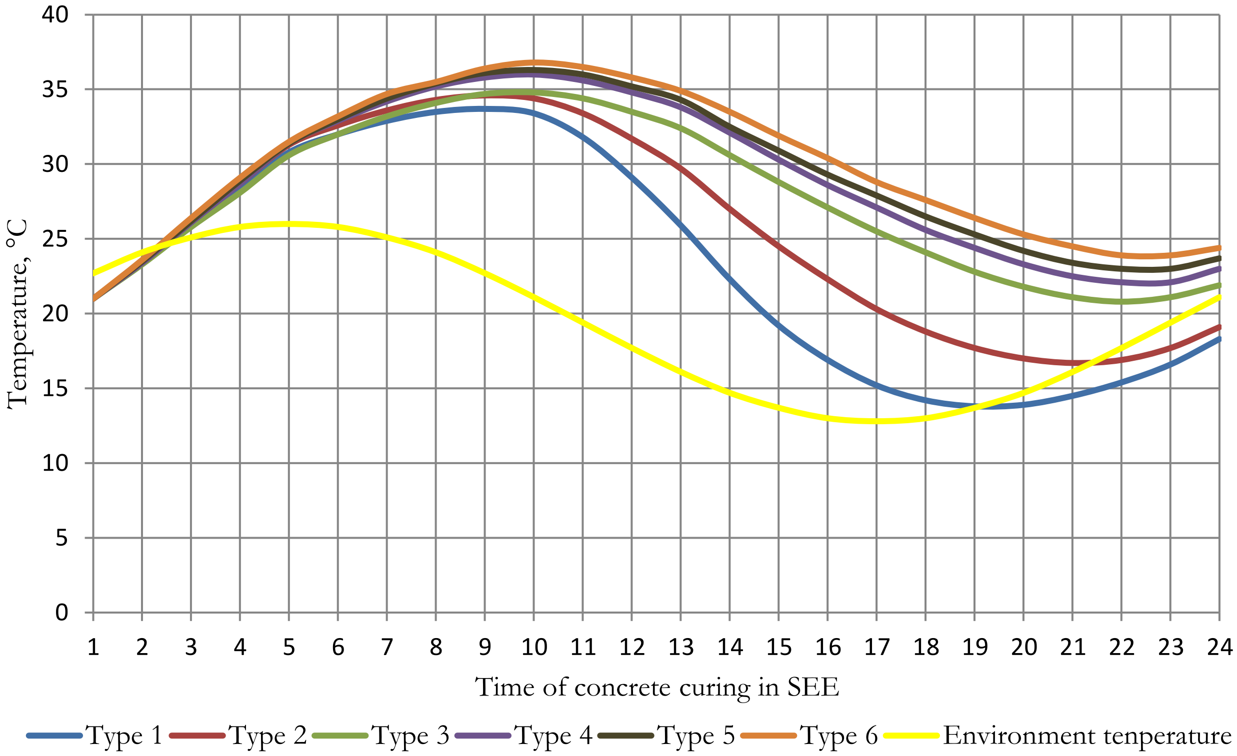

Fig. 2. Graphs of the concrete temperature (in the center of the PCE) in SEE with various types of formwork and the environment temperature during HT in humid continental climatic conditions.

Table 12. The calculation results for formwork of type 1 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-160.2	-205.3	18
11:00	42	-139	-180.1	22.3
12:00	43.6	-112	-146.2	26.8
13:00	44.6	-80.1	-104.5	31.2
14:00	45	-44.7	-56.5	35.4
15:00	44.6	-7.8	-5.4	39.3
16:00	43.6	27	150.5	42.7
17:00	42	61.1	176.9	45.3
18:00	39.9	92.1	207.8	47.5
19:00	37.4	116.6	215.1	49
20:00	34.7	137.8	254	49.8
21:00	32	155.1	286.2	50.3
22:00	29.6	161.7	301.7	50.5
23:00	27.4	164.2	307.8	49.6
24:00	25.8	162.5	306	48.6
1:00	24.8	153.8	292.3	47.6
2:00	24.4	142	271.3	46
3:00	24.8	127.3	245.1	44.7
4:00	25.8	109.6	213.3	43.5
5:00	27.4	90.1	178.1	42.5
6:00	29.6	71.6	181.8	41.7
7:00	32	53.1	171.8	41.5
8:00	34.7	36.9	163	41.8
9:00	37.4	24.1	156.9	42.1
Maturity of concrete [°C-hours]				997.2

Table 13. The calculation results for formwork of type 2 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-119.6	-164.6	18
11:00	42	-105	146.7	22.1
12:00	43.6	-86	-121.4	26.3
13:00	44.6	-63.2	-89.2	30.5
14:00	45	-37.4	-51.3	34.7
15:00	44.6	-10	-9.9	38.5
16:00	43.6	21	37.9	42
17:00	42	47.1	163.9	45.5
18:00	39.9	71.4	188.8	47.8
19:00	37.4	91.3	192.5	49.6
20:00	34.7	109.8	228.8	50.5
21:00	32	123.7	259.7	51.2
22:00	29.6	130.4	276.4	51.7
23:00	27.4	133.6	284.3	51
24:00	25.8	133.5	285	50.2
1:00	24.8	127.7	274.9	49.4
2:00	24.4	119.3	258.1	48
3:00	24.8	108.5	236.2	46.7
4:00	25.8	95.1	209.2	45.6
5:00	27.4	80.2	178.8	44.6
6:00	29.6	66.2	187.1	43.9
7:00	32	52	181.3	43.7
8:00	34.7	39.5	175.9	43.7
9:00	37.4	29.6	172	44.1
Maturity of concrete [°C-hours]				1019.3

Table 14. The calculation results for formwork of type 3 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-76	-121.1	18
11:00	42	-68.9	-112.2	21.8
12:00	43.6	-59.1	-97.5	25.9
13:00	44.6	-46.7	-77.2	29.4
14:00	45	-32.1	-51.8	32.9
15:00	44.6	-16.2	-23.2	36.8
16:00	43.6	2.6	11.5	40.1
17:00	42	19.3	122.9	43.7
18:00	39.9	35.4	139.1	46.1
19:00	37.4	49.2	137.6	48.3
20:00	34.7	62	170.5	49.4
21:00	32	73.2	199.5	50.6
22:00	29.6	79.5	218	51.5
23:00	27.4	83.6	229	51.3
24:00	25.8	85.3	233.9	50.8
1:00	24.8	83.1	229.8	50.3
2:00	24.4	79	219.4	49.5
3:00	24.8	73.1	204.3	48.2
4:00	25.8	65.3	184.4	47.2
5:00	27.4	56.3	161.3	46.4
6:00	29.6	47.6	175.8	46
7:00	32	38.8	176	45.8
8:00	34.7	30.9	175.5	45.8
9:00	37.4	24.5	175	46.4
Maturity of concrete [°C-hours]				1022.2

Table 15. The calculation results for formwork of type 4 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-53.8	-98.8	18
11:00	42	-48.7	-91.9	21.5
12:00	43.6	-41.6	-80	25.1
13:00	44.6	-32.7	-63.1	28.9
14:00	45	-22.2	-41.6	32.6
15:00	44.6	-10.7	-17.2	36.2
16:00	43.6	3	12.7	39.6
17:00	42	15.1	121	43.1
18:00	39.9	27	133.8	45.7
19:00	37.4	37.3	129.5	47.8
20:00	34.7	46.9	160	49.2
21:00	32	55.4	187.1	50.6
22:00	29.6	60.3	204.9	51.8
23:00	27.4	63.6	215.7	51.5
24:00	25.8	65.2	220.9	51.3
1:00	24.8	63.8	218	50.8
2:00	24.4	61	209.2	49.9
3:00	24.8	56.8	196.1	49.2
4:00	25.8	51.2	178.7	48.4
5:00	27.4	44.8	158.3	47.7
6:00	29.6	38.6	175.4	47.2
7:00	32	32.2	178.2	47.1
8:00	34.7	26.6	180	47.2
9:00	37.4	22	181.5	47.6
Maturity of concrete [°C-hours]				1028

Table 16. The calculation results for formwork of type 5 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-47.1	-92.2	18
11:00	42	-43	-86.5	21.4
12:00	43.6	-37	-76.1	24.9
13:00	44.6	-29.5	-60.9	28.5
14:00	45	-20.7	-41.3	32.2
15:00	44.6	-10.8	19	35.8
16:00	43.6	1	8.8	39.2
17:00	42	11.5	114.5	42.8
18:00	39.9	21.9	125.1	45.7
19:00	37.4	31	119.5	47.6
20:00	34.7	39.6	149.1	48.8
21:00	32	47.2	175.5	50.1
22:00	29.6	51.7	193.3	51.3
23:00	27.4	54.8	204.3	52.4
24:00	25.8	56.4	210	52.4
1:00	24.8	55.4	207.9	52.1
2:00	24.4	53.1	200.2	51.5
3:00	24.8	49.6	188.1	50.5
4:00	25.8	44.8	171.9	49.5
5:00	27.4	39.3	152.7	48.7
6:00	29.6	33.9	170.9	48.7
7:00	32	28.4	174.8	48.1
8:00	34.7	23.5	177.4	48.1
9:00	37.4	19.5	179.4	48.5
Maturity of concrete [°C-hours]				1035.8

Table 17. The calculation results for formwork of type 6 in humid subtropical climate conditions.

Time of day	$t_{environment}$ [°C]	Q_{loss} [kJ]	ΣQ_{loss} [kJ]	$t_{concrete}$ [°C]
10:00	39.9	-35.6	-80.7	18
11:00	42	-32.5	-76.2	21.3
12:00	43.6	-28.1	-67.5	24.7
13:00	44.6	-22.5	-54.3	28.3
14:00	45	-15.9	-37	31.9
15:00	44.6	-8.5	-17.2	35.5
16:00	43.6	0.4	7.6	38.7
17:00	42	8.5	110.9	42.4
18:00	39.9	16.4	118.9	45.2
19:00	37.4	23.4	111.6	47.4
20:00	34.7	30.1	139.6	48.5
21:00	32	36	164.8	49.8
22:00	29.6	39.7	182.1	51.2
23:00	27.4	42.2	193.1	52.8
24:00	25.8	43.6	199	53.1
1:00	24.8	43	197.7	52.9
2:00	24.4	41.4	191	52.2
3:00	24.8	38.8	180.3	51.4
4:00	25.8	35.2	165.6	50.6
5:00	27.4	31	148	49.9
6:00	29.6	27	167.8	49.2
7:00	32	22.8	173.2	49.2
8:00	34.7	19.1	177.2	49.4
9:00	37.4	16.2	180.3	49.8
Maturity of concrete [°C-hours]				1043.6

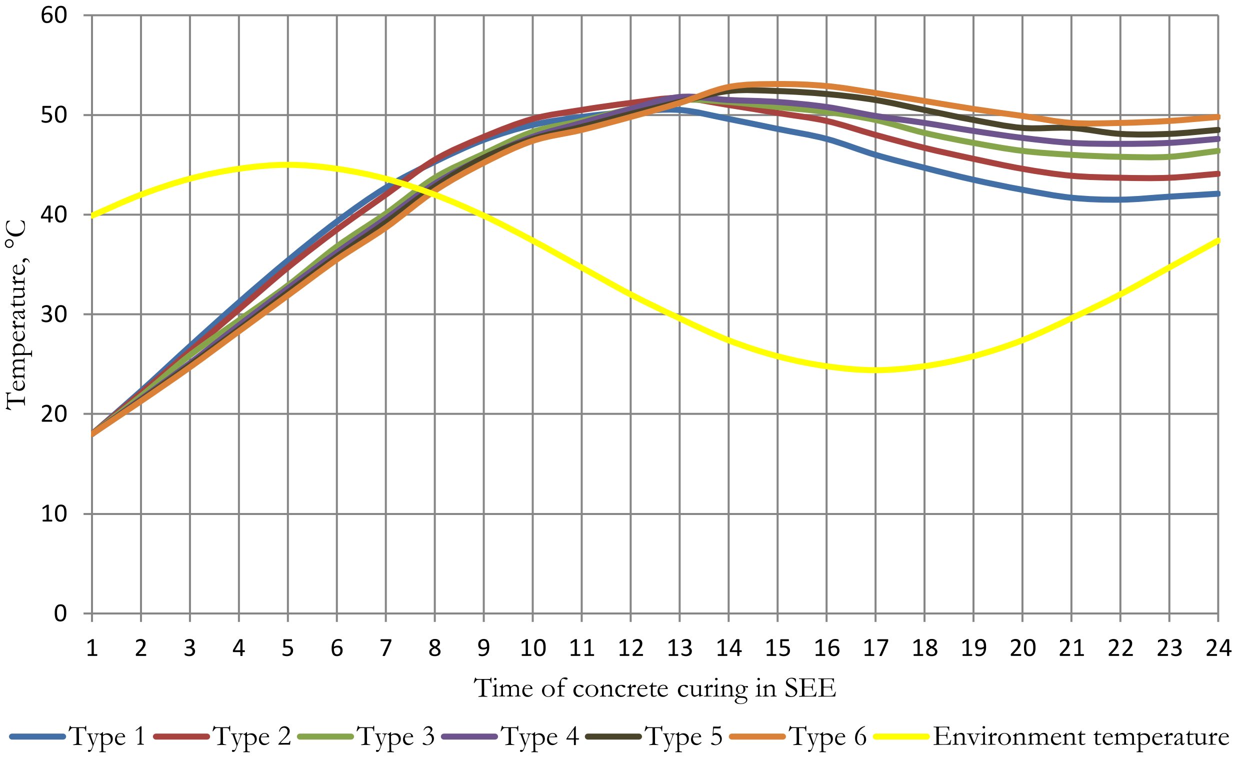

Fig. 3. Graphs of the concrete temperature (in the center of the PCE) in SEE with various types of formwork and the environment temperature during HT in humid subtropical climate conditions.

Tables 6-11 demonstrate that the presence of heat insulation layer in the formwork structure (types 4-6) contributes to retain heat in concrete during the nighttime and better maturity of concrete; and as a result, better concrete strength can be achieved. It allows making the conclusion that the heat insulation materials are necessary for the structure of the formwork, when we use it together with transparent cover as SEE for manufacturing of PCE by using SE under the average daily ambient temperatures in limits of 15-22 °C (summertime in Moscow region, Russia). Moreover, the analysis of Tables 9-11 shows that if we increase the thickness of heat insulation material from 20 mm (type 4) to 40 mm (type 6) the maturity of concrete will grow from 690 °C-hours to 716 °C-hours. However, we have to admit that this growth is insignificant (only 4%).

The negative value of heat loss in Tables 12-17 (from 10 a.m. until 3 p.m.) shows that the concrete specimens had the initial temperature less than the ambient temperature and it heated up through the formwork walls. The specimens in formworks without heat insulation materials (types 1-3) heated up more intensively in the first half of the curing period. However, in the nighttime heat insulation layers in the formwork structures (types 4-6) allow saving the heat in concrete and getting better results of the maturity of concrete. Analyzing data from Tables 12-17, we can conclude that steel formwork (type 1) is not suitable for manufacturing of PCE by using SE. Formworks from laminated plywood and timber (types 2-3) even without heat insulation layer can be used with transparent cover as SEE in humid subtropical climatic conditions as well as heat-insulated formworks, because they give only 2% reduction of the concrete maturity.

Fig. 4 presents the diagrams of environment temperature and concrete temperatures, curing in SEE (formworks of type 2 and type 4) in humid continental climatic conditions, based on the calculation and the test results. The similarity of the diagrams (Fig. 4) proves the adequacy of the chosen calculation model and the assessment of process, taking place during HT of PCE using SE.

Table 18 and Table 19 show the concrete strength, based on the calculation and test results for humid continental and subtropical climatic conditions.

Each value of compressive strength, obtained during the test, was determined as average value after testing of 5 specimens of each series. The standard deviation of the experimental data in Table 18 and Table 19 is also shown due to use of 5 specimens in each series.

The similarity of the strength values, obtained from the calculation and tests, as well as small values of errors between the results (1.6-3.1% in Table 18 and 3.8-5.6% in Table 19), testifies to adequacy of the chosen and the above-mentioned method of the strength calculation.

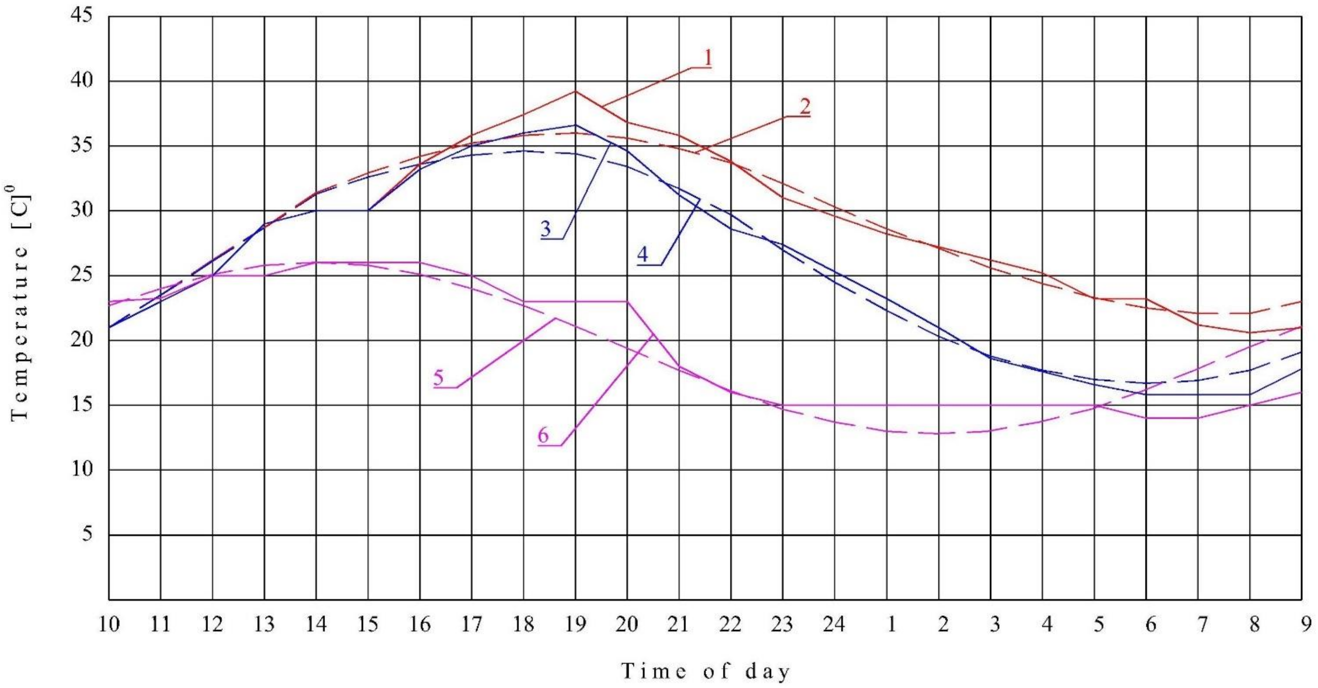

Fig. 4. Graphs of concrete and environment temperatures during the curing process in SEE (formworks of type 2 and type 4) in humid continental climatic conditions.
1 – temperature of concrete in formwork of type 2 (the test results – Moscow region, Russia, June); 2 – temperature of concrete in formwork of type 2 (the calculation results); 3 – temperature of concrete in formwork of type 4 (the test results – Moscow region, Russia, June); 4 – temperature of concrete in formwork of type 4 (the calculation results); 5 – environment temperature, modelled in the calculation; 6 – real environment temperature in the test.

Table 18. Strength of concrete in various types of formwork in humid continental climatic conditions.

Type of formwork	**Calculation results of compressive strength of concrete, MPa (%R$_{28}$)**	**Test results of compressive strength of concrete**		**Error between the calculation and test results**
		The average value, MPa (%R$_{28}$)	**Standard deviation σ of the test data**	
1	10.6 (33.1 %R$_{28}$)	11.4 (35.4 %R$_{28}$)	0.59	2.5%
2	10.9 (34 %R$_{28}$)	11.7 (36.6 %R$_{28}$)	0.47	2.5%
3	11.6 (36.3 %R$_{28}$)	12.6 (39.2 %R$_{28}$)	0.63	3.1%
4	12.8 (39.8 %R$_{28}$)	13.3 (41.5 %R$_{28}$)	0.43	1.6%
5	13 (40.4 %R$_{28}$)	13.6 (42.5 %R$_{28}$)	0.39	1.9%
6	13.1 (40.8 %R$_{28}$)	13.7 (42.6 %R$_{28}$)	0.52	1.9%
Compressive strength of concrete after 28 days of curing in normal conditions is 32.1 MPa				

Table 19. Strength of concrete in various types of formwork in humid subtropical climatic conditions.

Type of formwork	**Calculation results of compressive strength of concrete, MPa (%R$_{28}$)**	**Test results of compressive strength of concrete**		**Error between the calculation and test results**
		The average value, MPa (%R$_{28}$)	**Standard deviation σ of the test data**	
1	17.9 (55.9 %R$_{28}$)	19.1 (59.6 %R$_{28}$)	0.66	3.8%
2	18.3 (57 %R$_{28}$)	19.9 (62.1 %R$_{28}$)	0.71	5%
3	18.4 (57.3 %R$_{28}$)	20.1 (62.8 %R$_{28}$)	0.59	5.3%
4	18.7 (58.4 %R$_{28}$)	20.4 (63.8 %R$_{28}$)	0.48	5.3%
5	19 (59.1 %R$_{28}$)	20.8 (64.8 %R$_{28}$)	0.57	5.6%
6	19.2 (59.8 %R$_{28}$)	21 (65.4 %R$_{28}$)	0.62	5.6%
Compressive strength of concrete after 28 days of curing in normal conditions is 32.1 MPa				

However, the error between the calculated and test results can be explained by the fact that the experimental data from Table 3, used to calculate the strength values depending on its relative age, was obtained during the experimental study of concrete [25], cured in normal conditions (temperature of concrete t_c=18 °C), but the strength gains faster with the increase of concrete temperature. It understates the calculation results of the concrete strength as compared with the test results due to the real average temperature of concrete in the tests, which was more than 18 °C.

Moreover, the error between the calculated and test results grows from 1.6-3.1% in Table 18 to 3.8-5.6% in Table 19 due to the increase of the average temperatures of the concrete specimens during HT in SEE under humid subtropical climatic conditions as compared with humid continental climatic conditions.

4. Conclusion

The evidence from the research work points towards the idea that solar energy can be successfully used as a renewable energy resource to speed up the curing process during manufacturing of precast concrete elements, partly or fully replacing fossil fuels and keeping the working schedule of the plant. Despite difficulties, connected with the introduction of this new technology at precast concrete plants, it should be done, taking into account its environmental saving features.

Returning to the aim, posed at the beginning of this study, it is possible to state that the formwork structure influences on the efficiency of heat treatment of precast concrete elements by solar energy.

In general, heat insulation material in the formwork structure contributes to better strength of concrete. Therefore, formwork with the heat insulation layer of 40 mm gives the best results.

However, it depends on climatic conditions. For humid continental climatic conditions, heat insulation material in the formwork structure is necessary. Even thickness of 20 mm of heat insolation layer gives better results, and the difference between the concrete strength under 20 mm and 40 mm of the layer thickness is insignificant. On the contrary, in a humid subtropical climate, the heat insulation material in the formwork structure is favourable, but not compulsory, since the difference between the concrete strengths is not significant, and the strength values obtained in all six types of formwork allow it to be removed after 24 hours of curing.

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