Проведено за ступінчастими режимами теплову обробку гідроізольованих зразків із важкого бетону з використанням нагрітого повітря. Зазначено, що ці експерименти є складовою частиною досліджень способу теплової обробки бетонних і залізобетонних виробів з використанням повітря, нагрітого в колекторі сонячної енергії (вироби знаходяться в закритих формах). Наголошено, що в хмарні дні та в холодний період року використовується електричний повітронагрівач.

Підкреслено: в певних випадках порівняно нетривалою є періодична хмарність упродовж дня, і можна припустити, що в таких умовах незначним буде зменшення інтенсивності твердіння бетону внаслідок перерви в надходженні нагрітого повітря до камери.

Зазначено, що моделювання процесу нагрівання повітря в колекторі сонячної енергії здійснено за допомогою інфрачервоного нагрівача.

З'ясовано, що досліджувані ступінчасті режими теплової обробки нагрітим повітрям важкого бетону надають можливість у віці 1 доби в 1,59...1,76 разу збільшити міцність бетону на стиск порівняно з твердінням у повітряних умовах. Показано, що чим більшою є інтенсивність нагрівання бетону досліджуваного складу впродовж першої години теплової обробки (в межах від 4 до 8 °С), тим більшою є міцність на стиск бетону у віці 1 доби.

Рекомендовано з метою економії енергоресурсів в теплий період року при виникненні нетривалої періодичної хмарності не використовувати електричний повітронагрівач.

Установлено, що в досліджуваних випадках температура бетону після теплової обробки за ступінчастими режимами через 4 год 15 хв становила 30 °С, а температура бетону через 22 год твердіння в камері дорівнювала 26,3...27,2 °С. Зазначено: така температура бетону наприкінці терміну твердіння в камері свідчить про те, що відбувається порівняно інтенсивна гідратація цементу. Рекомендовано для аналогічних випадків аналізувати доцільність подовження періоду термосного твердіння бетону в камері

Ключові слова: бетон важкий, геліотермообробка, нагріте повітря, ступінчасті режими, міцність на стиск

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EFFECT OF STEP HEAT TREATMENT MODES ON THE PHYSICAL-MECHANICAL PROPERTIES OF CONCRETE

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1. Introduction

The effectiveness of concrete use is determined by the saving of material and energy resources while ensuring the appropriate quality and using environmentally friendly processes.

Heat treatment is the most energy-intensive process in the manufacture of concrete and reinforced concrete products, which is carried out in order to accelerate their hardening. The constant increase in the cost of energy resources forces manufacturers to exclude heat treatment from the production process. As a result, the binder consumption increases or cement of higher quality is used, special additives are used – hardening accelerators, the need to allocate large areas for the maturation of concrete and reinforced concrete products increases, and the reversibility of forms is reduced.

All this requires manufacturers to find new effective ways of heat treatment of these products. One of the ways to reduce the cost of concrete and reinforced concrete products (while maintaining operational properties) is the use of solar energy in combination with various types of chemical additives. But the overwhelming majority of methods of solar heat treatment of concrete and reinforced concrete products are intended for implementation in a hot climate.

It is necessary to create such methods of combined solar heat treatment of concrete and reinforced concrete products that can be introduced for a number of products under different climatic conditions.

The experiments reflected in this work are an integral part of research on the method of heat treatment of concrete and reinforced concrete products using air heated in a solar energy collector or in an electric air heater (the products are in closed forms). This method is intended for implementation not only in conditions of the hot climate. The experiments presented in this work are aimed at finding additional ways to save energy in the application of the investigated combined method of solar heat treatment of concrete and reinforced concrete products.

2. Literature review and problem statement

The articles [1–3] show the results of investigations of the optimal modes of solar heat treatment of products and structures of different types of concrete using an intermediate coolant in the climatic conditions of the Republic of Kazakhstan. In [1], it is noted that in the studied conditions during the day, concrete gains 50...60 % of the design strength, and on especially hot days concrete strength per day reaches 70...75 %. In this article, it is stressed that after demoulding the products are placed in a warehouse and covered with tarpaulin or polyethylene film. The article [4] proved the efficiency of combined year-round solar heat treatment of reinforced concrete products in the climatic conditions of Uzbekistan. The article [5] presents experimental studies on the use of solar energy to accelerate the hardening of concrete products. This method provides the application of steam as a coolant at the first stage. Solar energy is used after demoulding of the products. The article does not specify the need for waterproofing of the products during their storage after demoulding.

Combined methods of solar heat treatment of products and structures, shown in [1–4], are intended for implementation under hot climates. The method of using solar energy to accelerate the hardening of concrete products, given in [5], can be implemented on the basis of arbitrary climatic conditions.

The publications [6–9] show developments regarding the combined method of solar heat treatment of concrete and reinforced concrete products (in closed forms) using air heated in a solar energy collector or in an electric air heater. The indicated method can be applied for the feasibility study in areas with different climates. The papers [7, 8] give experimentally grounded recommendations regarding the impossibility of introducing concrete pre-curing during the studied soft regimes of heat treatment. The article [9] shows the features of heat treatment of concrete pavement slabs with air, heated in a solar energy collector, in the conditions of the city of Poltava (Ukraine). It is experimentally found that heat treatment under soft conditions improves the structure of cement stone, promotes the formation of fine-dispersed, stronger tumors [6–10]. Investigation of this combined method of solar heat treatment was carried out with the continuous flow of heated air to the chamber during the chosen period (with subsequent concrete thermosetting).

The common advantage of a number of methods of solar heat treatment of concrete and reinforced concrete products in relation to the traditional methods of their heat or heat-moisture treatment is not only energy saving, but also soft regimes, which accelerate their hardening [1–4, 6–9].

During solar heat treatment, the presence of cement hydration heat acquires a special influence on the hardening temperature of products.

Investigation of cement heat generation during hydration has been carried out for several decades. Among such developments, there are the results reflected in [11–17]. The papers [11, 12] show the effect of various impurities: ash and others [11]; diatomaceous earth, molten bricks, and others on cement hydration heat [12]. The publication [13] analyzed the frequency of heat generation in the cement-water system during hydration and hardening. In [14], the correspondence of the heat release intensity of the cement paste and the strength kinetics is substantiated. The papers [15, 16] show the effect of plasticizers [15, 16], hardening accelerators, complex supplements [16] on cement hydration heat. The article [17] presents the results of the determination of cement hydration heat during solidification of a concrete mixture. Investigation of cement heat evolution during hydration contributed to the development of heat treatment of concrete and reinforced concrete products using only cement hydration heat. Such developments are reflected, for example, in [18].

The general problem related to any of the methods of solar heat treatment of concrete and reinforced concrete products is a different intensity of the arrival of solar energy to the heat transfer surface both during the year and during the day. The use of an additional (reserve) heat source can solve this problem [1–9].

The development of methods of solar heat treatment of concrete products should also be directed towards the use of efficient solar collectors, as reflected, for example, in [19, 20].

In conditions of intermittent clouds, it is expedient to search for the possibility of reducing the energy costs associated with the use of an additional source of heat.

This also applies to the investigated combined method of solar heat treatment of concrete and reinforced concrete products [6–9]. In order to save energy, it is suggested not to use an electric air heater in conditions of intermittent clouds.

There is a need to define a number of indicators of relatively non-intensive and relatively short-term heat treatment of concrete, which is due to the presence of intermittent clouds. Among these indicators:

– the temperature conditions of concrete hardening during heat treatment with heated air and during subsequent thermosetting (the intensity of heat emission during cement hydration, which is conditioned by a number of factors, some of which are reflected in [11–18] is important for creating temperature conditions of concrete hardening);

– concrete strength kinetics, etc.

But it is difficult to carry out relevant studies in natural conditions, since it is not always possible to predict weather conditions. Therefore, it is advisable to first conduct a series of experiments using a laboratory setup, which will provide an opportunity to simulate the step conditions of heat treatment with heated air.

It should be emphasized that it is expedient to use developments regarding step modes of heat treatment of concrete and reinforced concrete products using air heated in a solar collector for the analysis of additional energy saving in the arbitrary methods of solar heat treatment of these products.

3. The aim and objectives of the study

The aim of the work is to analyze the impact of the investigated step modes of heat treatment with heated air on the compressive strength of heavy concrete.

To achieve this goal, the following objectives were set:

– to conduct heat treatment of waterproof samples of heavy concrete of the studied composition with heated air in accordance with conditioned step modes (with subsequent thermosetting) and determine the temperature of the concrete at the end of the break in the coolant flow into the chamber and at the end of thermosetting in the chamber;

– to determine: the compressive strength of heavy concrete at 1 and 28 days, hardening of which occurs with the use of heat treatment and without heat treatment; compressive strength of heavy concrete, solidification of which occurs in normal temperature-humidity conditions for 28 days;

– to find out the effect of the break in the coolant supply to the chamber after the first hour of heat treatment and the intensity of concrete heating during the first hour of heat treatment in accordance with the investigated step modes on the strength of heavy concrete of the studied composition at 1 and 28 days;

– to make recommendations as to the expediency of step modes of heat treatment of heavy concrete using air heated in a solar energy collector.

4. Materials and methods of research of heat treatment of heavy concrete with heated air

4. 1. Explored materials and equipment used in the experiment

In this work, Portland cement PC-I-500-N (DSTU B V.2.7-46: 2010), quartz sand with a fineness modulus $Mk=1$, crushed granite of fraction 5–10 mm, chemical admixture – hardening accelerator were used. Concrete composition: 1:1.55:2.65; $C=420.8$ kg/m^3; $S=652.3$ kg/m^3; $CR=$ $=1116.3$ kg/m^3; $W/C=0.44$.

Heat treatment of concrete on sunny days is carried out using air heated in a solar energy collector. On cloudy days and in the cold season of the year, an electric air heater should be used in the production conditions. Laboratory studies in such periods occur with the use of air heated in the energy collector using an infra-red heater (Fig. 1).

Fig. 1. Laboratory installation for studies of heat treatment of concrete using heated air [6–8]

The indicated laboratory installation was used during a series of studies of heat treatment of concrete samples and concrete paving slabs. Some of these experiments are reflected in [6–8].

4. 2. Methodology of research of heat treatment of heavy concrete with heated air

Heat treatment of heavy concrete occurred under the following conditions:

– samples of heavy concrete (10×10×10 cm) were used; polyethylene film is used for waterproofing of samples;

– pre-curing of concrete was not carried out (relevant recommendations [7, 8] were taken into account);

– the duration of the step modes of heat treatment of concrete with heated air was 4 hours 15 minutes; during this period, the concrete was heated to a temperature of 30 °C; a relatively short term of heat treatment of concrete with heated air was deliberately accepted in the work;

– total duration of concrete hardening in a laboratory chamber – 22 h;

– variations: concrete heating intensity during the first hour of heat treatment (in the range from 4 to 8 °C); the duration of the break in the coolant flow to the chamber (the break occurs after the first hour of heat treatment and ranges from 0.5 to 1.5 hours).

After hardening in the laboratory chamber, concrete samples were stored in air for 1 or 28 days, as well as in normal temperature-humidity conditions for 28 days.

In the conducted studies, simulation of heat treatment of concrete of air heated in a solar energy collector was carried out using an infrared heater. This makes it possible:

– to conduct experiments in any season;

– to regulate concrete heating intensity;

– to schedule the duration and frequency of breaks in the coolant supply to the chamber.

The choice of variation limits of concrete temperature during the first hour and the decision on concrete temperature at the end of heat treatment with heated air are taken considering previous experimental studies of heat treatment of concrete samples and concrete pavement slabs using air heated in the solar energy collector. Some of these studies are reflected in [6, 9].

Variation intervals of concrete temperature during the first hour (Δt_1, °C) and duration of the break in the coolant flow to the chamber after the first hour of heat treatment (τ_b, h) are shown in Table 1.

Table 1

Variation intervals of investigated factors

Code	Code value	Investigated factors	
		x_1 (Δt_1, °C)	x_2 (τ_p, hours)
Basic level	0	6	1.0
Variation interval	x_i	2	0.5
Upper level	+	8	1.5
Lower level	–	4	0.5

The research design matrix of step modes of heat treatment of concrete is shown in Table 2.

Table 2

Research planning matrix

Data point	Factor values			
	encoded look		natural look	
	x_1	x_2	x_1 (Δt_1, °C)	x_2 (τ_p, hours)
1	+1	+1	8	1.5
2	+1	–1	8	0.5
3	–1	+1	4	1.5
4	–1	–1	4	0.5
5	+1	0	8	1.0
6	–1	0	4	1.0
7	0	+1	6	1.5
8	0	–1	6	0.5
9	0	0	6	1.0
10	0	0	6	1.0
11	0	0	6	1.0

In experimental planning and mathematical and statistical processing, the recommendations used in the implementation of experimental studies, reflected in [6–8], were applied.

Determination of the compressive strength of concrete samples and processing of experimental results were carried out in accordance with DSTU B V.2.7-214: 2009.

5. Results of studies of the effect of heat treatment with heated air on the strength of heavy concrete

In the experiments:

– the average initial temperature of the concrete mixture was 16.8 °C;

– concrete temperature at the end of heat treatment with heated air was 30 °C;

– the maximum decrease in concrete temperature at the end of the break in the coolant supply: 0.2 °C (data point 3);

– the minimum concrete temperature after 22 hours of solidification in the chamber was 26.3 °C (data point 3);

– the maximum concrete temperature after 22 hours of solidification in the chamber was 27.2 °C (data point 2).

The results of research on the concrete compressive strength at 1 day f_{st1} are shown in Table 3.

Table 3

Concrete compressive strength at 1 day

Data point	f_{st1}, MPa	Data point	f_{st1}, MPa	Data point	f_{st1}, MPa
1	23.185	5	23.739	9	23.168
2	24.131	6	22.595	10	23.163
3	21.680	7	22.427	11	23.161
4	23.337	8	23.732		

Mathematical and statistical processing of experimental data (concrete compressive strength at 1 day under conditions of hardening with the use of heat treatment) provided the opportunity to obtain the equation:

$$f_{st1}=23.173+0.5739x_1-0.6515x_2-0.0957x_2^2+0.1778x_1x_2.$$

Fischer criterion $F_p=9.7351<19.3$, hence the equation is suitable for use.

The compressive strength of concrete during hardening in air conditions is:

– after 1 day 13.677 MPa;

– after 28 days 39.351 MPa.

The concrete compressive strength at 28 days during hardening in normal temperature-humidity conditions is 39.702 MPa.

Concrete class B30.

The minimum value of the compressive strength of concrete, which was solidified using heat treatment, at 28 days is 42.746 MPa (design point 3), the maximum value of this indicator is 42.925 MPa (design point 2). The difference between these indicators is 0.4 %.

The concrete compressive strength at 28 days when solidified using heat treatment exceeds the compressive strength of concrete, hardening of which occurred:

– without heat treatment: 1.086 times (design point 3); 1.091 times (data point 2);

– in normal temperature-humidity conditions: 1.077 times (design point 3); 1.081 times (data point 2).

Table 4 and Fig. 2–9 show a quantitative analysis of the impact of the breaks in the coolant supply to the chamber and concrete heating intensity during the first hour in the investigated step modes of heat treatment on the compressive strength of concrete of the studied composition at 1 day.

Table 4

Relationship between the concrete compressive strength at 1 day

Data point	Δt_1, °C	τ_p, hours	f_{st1}, MPa	Relationship between f_{st1} values,%, if f_{st1} is taken as 100 %:	
				at the data point 2	at τ_b=0.5 h (separately for each Δt_1 value)
3	4	1.5	21.680	89.84	92.90
6		1.0	22.595	93.64	96.82
4		0.5	23.337	96.71	100
7	6	1.5	22.427	92.94	94.50
9–11		1.0	23.164	95.99	97.61
8		0.5	23.732	98.35	100
1	8	1.5	23.185	96.08	96.08
5		1.0	23.739	98.38	98.38
2		0.5	24.131	100	100

Heat treatment with heated air under step modes gives an opportunity to increase the hardening intensity of concrete at an early age compared with hardening in air conditions.

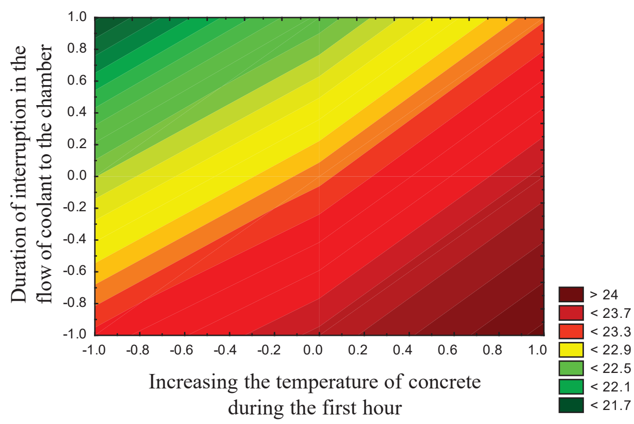

Fig. 2. Surface isolines of the response function the compressive strength of concrete, hardening of which occurred with the use of heat treatment, MPa, at 1 day

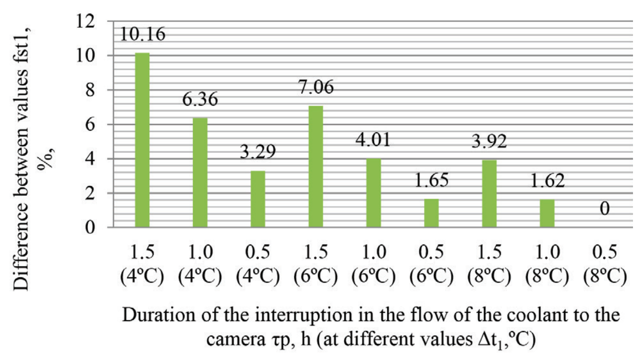

Fig. 3. Difference between the concrete compressive strength at 1 day at excellent values of τ_p and Δt_1, if f_{st1} is taken as 100 % with: τ_p=0.5 h; Δt_1=8 °C (data point 2)

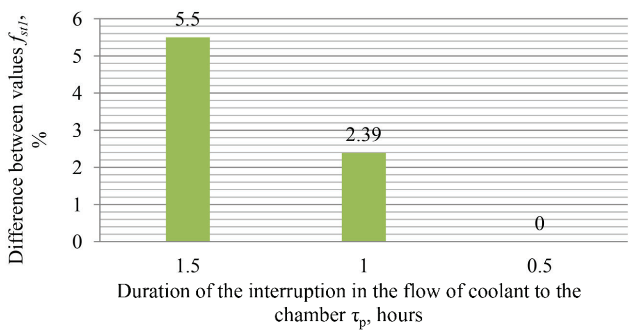

Fig. 4. Difference between the concrete compressive strength at 1 day at Δt_1=4 °C, if f_{st1} is taken as 100 % at τ_p=0.5 hours (data point 8)

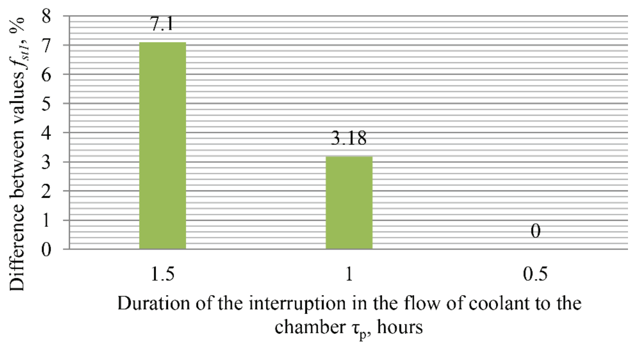

Fig. 5. Difference between the concrete compressive strength at 1 day at Δt_1=4 °C, if f_{st1} is taken as 100 % at τ_p=0.5 hours (data point 4)

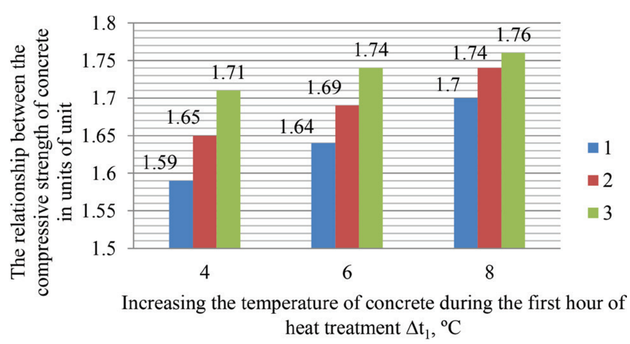

Fig. 6. Relationship between the compressive strength of concrete, which was hardened with the use of heat treatment and without heat treatment, at 1 day: 1 – for τ_p=1.5 h; 2 – for τ_p=1.0 h; 3 – for τ_p=0.5 h

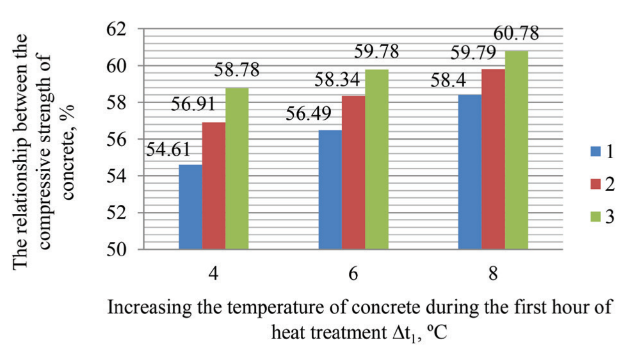

Fig. 7. Ratio between the concrete compressive strength at 1 day (concrete solidification was carried out using heat treatment) and at 28 days (concrete solidification occurred in normal temperature-humidity conditions): 1 – for τ_p=1.5 h; 2 – for τ_p=1.0 h; 3 – for τ_p=0.5 h

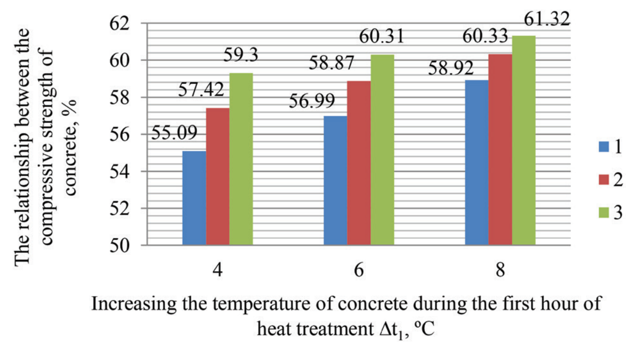

Fig. 8. Relationship between the concrete compressive strength at 1 day (concrete solidification was carried out using heat treatment) and at 28 days (concrete solidification occurred in air): 1 – for τ_p=1.5 h; 2 – for τ_p=1.0 h; 3 – for τ_p=0.5 h

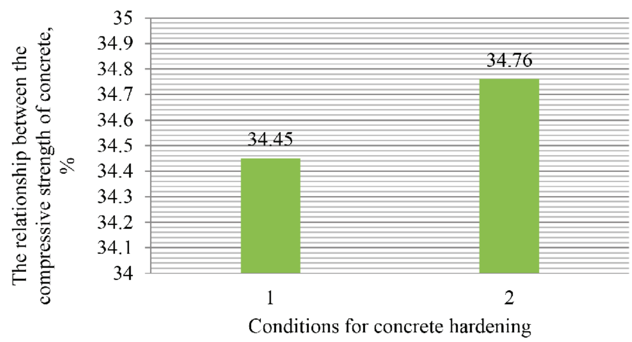

Fig. 9. Ratio between the concrete compressive strength at 1 day (hardening without the use of heat treatment) and concrete strength at 28 days, hardening of which occurred: 1 – in normal temperature-humidity conditions; 2 – in air conditions

6. Discussion of the results of studies of the strength of heavy concrete during heat treatment with heated air

1. In the studies, simulation of the processes of heat treatment of heavy concrete by the air heated in the solar energy collector, provided that there are intermittent clouds, is carried out. The infrared heater is used.

The advantage of research is that:

– the intensity of the increase in concrete temperature with the help of heated air specified in the work is taken considering the preliminary experimental data obtained with the use of a solar energy collector [6, 9];

– laboratory installation (Fig. 1) provides an opportunity to reproduce the intensity of heat treatment of concrete using heated air at a selected temperature in any period of the year.

But the following factors need to be taken into account:

– experiments are conducted in laboratory, and not in field conditions;

– when simulating the heat treatment of concrete products using concrete samples, it is impossible to reproduce the geometric similarity of the samples to the products.

Further, it is necessary to carry out appropriate research in the field conditions on the production and laboratory installation [9]. The advantage of such experiments with laboratory studies is obvious. But the disadvantage is also obvious: it is impossible to recreate the pre-planned step mode of heat treatment of concrete by air heated in a solar energy collector (caused by intermittent clouds).

In addition, in natural conditions, it is not always possible to avoid intermittent clouds when conducting the planned continuous heat treatment of concrete by air heated in a solar energy collector.

2. Heat treatment of concrete with the use of heated air even with a relatively insignificant temperature increase for a short time (up to 30 °C for 4 hours 15 minutes) and in the presence of a break in the coolant supply to the chamber (for 0.5–1.5 hours) provides the opportunity to accelerate the hardening of concrete at an early age (Table 3).

This factor is due to the fact that:

– when the coolant arrives, an increase in concrete temperature occurs, and the solidification processes are intensified, according to the Van't-Hoff rule [10];

– the presence of cement hydration heat affects the temperature regime of concrete during the break in the coolant supply to the chamber and during thermosetting [11–18].

There is the maximum difference between the strength of concrete, hardening of which took place using heat treatment and without heat treatment, after the completion of the specified process (Fig. 6–8). The obtained results are consistent with the data presented in [6–9] when using continuous modes of heat treatment of heavy concretes of other compositions with heated air (with subsequent thermosetting).

The compressive strength of concrete of the studied composition, hardening of which occurred in air and in normal temperature-humidity conditions, at 28 days is slightly different. The compressive strength of concrete at 28 days when hardened using heat treatment exceeds these values 1.08...1.09 times. The given data make it possible to draw the following conclusion: hardening of products from heavy concrete after the heat treatment under investigation in the climatic conditions of the city of Poltava (Ukraine) does not require additional measures concerning the waterproofing of their surfaces (as opposed to the method of solar heat treatment and the climatic conditions reflected in [1]).

The compressive strength of concrete, hardening of which was carried out using heat treatment, is 54.61...60.78 % of this indicator for concrete, hardening of which occurred in normal temperature-humidity conditions (Fig. 7). The obtained data are consistent with the indicators (50...60 %) given in [1].

3. It was found that the higher the heating intensity of the concrete of the investigated composition during the first hour of heat treatment (in the range from 4 to 8 °C), and the smaller the break in the coolant supply to the chamber, the greater the concrete compressive strength at 1 day (Tables 3, 4, Fig. 2–8).

The obtained results are consistent with the data given in [6–9] with the application of continuous modes of heat treatment of heavy concretes of other compositions with heated air (with subsequent thermosetting).

4. The studies are aimed at reducing energy costs in the process of heat treatment of concrete and reinforced concrete products.

The application of cements with significant heat emission during hydration combined with the corresponding chemical admixtures provides the opportunity to regulate hardening of concrete products in conditions of intermittent clouds without the use of an electric air heater.

It is necessary to continue the processing of various types of step modes of heat treatment of concrete with heated air in order to determine additional ways to save energy in this technological process for a particular type and composition of concrete, for a specific period of the year, etc.

7. Conclusions

1. The research of heat treatment of waterproof concrete samples with heated air was carried out under the determined step modes: the duration of heat treatment of concrete with heated air was 4 hours 15 minutes; the concrete was heated to a temperature of 30 °C; general period of concrete hardening in the chamber – 22 h; concrete heating intensity during the first hour of heat treatment and duration of the break in the coolant flow to the chamber after the first hour of heat treatment varied.

It was found that in the investigated cases, the temperature of concrete after heating by air in step modes after 22 hours of hardening in the chamber was 26.3...27.2 °C. This concrete temperature at the end of solidification in the chamber indicates that there is a relatively intense hydration of cement. It is recommended for similar cases to analyze the expediency of extending the term of concrete thermosetting in the chamber.

2. The compressive strength of heavy concrete of the studied composition at the specified age was determined.

The compressive strength of concrete, hardening of which occurred with the use of heat treatment, is:

– at 1 day 21.680...24.131 MPa;

– at 28 days 42.746 MPa...42.925 MPa.

The compressive strength of concrete, hardening of which occurred in air conditions, is: after 1 day 13.677 MPa; after 28 days 39.351 MPa.

The compressive strength of concrete under hardening in normal air-humidity conditions at 28 days is 39.702 MPa.

3. It was found that the compressive strength of concrete with increasing breaks in the coolant flow to the chamber from 0.5 to 1.0 hours decreases by 1.62...3.18 %, and from 0.5 to 1.5 hours – by 3.90...7.10 %.

The relationship between the compressive strength of concrete, hardening of which took place with the use of heat treatment and without heat treatment, at 1 day:

– with τ_p=1.5 h is equal to 1.59...1.70;

– with τ_p=1.0 h equals 1.65...1.74;

– with τ_p=0.5 h is equal to 1.71...1.76.

It was found that the maximum values for each duration of the breaks in the coolant supply τ_b were obtained with the maximum values of concrete temperature rise during the first hour Δt_1=8 °C, and the minimum values – with Δt_1=4 °C.

4. It is recommended not to use an electric air heater in the warm period of the year during heat treatment of heavy concrete products using air heated in a solar energy collector or in an electric air heater, in the event of intermittent clouds. Instead, step regimes of heat treatment of these products should be introduced, which will provide an opportunity to save energy resources. It is recommended to collect data on the allowable duration of breaks in the supply of heated air and their number for the studied conditions.

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