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Low-heat steaming treatment of concrete with polycarboxylate superplasticizers

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Abstract. Recommendations for quantity of polycarboxylate water-reducing admixtures, for the properties of Portland cement as well as the curing regimes is presented in order to reduce the Portland cement amount, to improve the transfer and design strength and durability of prefabricated structures. On the basis of experimental studies the parameters of low-heat steaming treatment of concrete with a polycarboxylate superplasticizer were stated: the duration of pre-exposure 2.5–3 hours, the rate of temperature rise 7°C/hour, the temperature of isothermal exposure 40–50 °C. The results obtained can be used in the production of precast prestressed sub-rail structures as well as other reinforced concrete structures with high performance characteristics at concrete plants with double or single mold turnover per day.

1. Introduction

In connection with the increase of requirements for sub-rail structures the issue of using high-strength and durable concretes in their production is relevant [1–4]. Sleepers, half-sleepers, prefabricated slabs of ballastless track of high-speed railway, etc. belong to the reinforced concrete sub-rail structures of factory production [5-7]. Increase of the durability of precast structures is possible through the use of polycarboxylate modifiers and reduction of the temperature of isothermal holding at heat-steaming treatment [4, 8].

At the same time, it is necessary to maintain high productivity of technological equipment for the production of sub-rail structures due to the double turnover of moulds per day. For lines with double turnover of moulds per day, the required transfer strength of concrete at the age of 10–12 hours should be more than 35MPa for B40 strength class and more than 44MPa for B50 strength class.

Water-reducing admixtures based on polycarboxylate esters are used to provide a high strength class of concrete [9–11], to increase concrete early strength [1], to obtain mixtures of high workability [12]. The reduction of water-to-cement ratio and the absence of forced high-heat treatment increase the durability of precast concrete structures [13]. The high temperature of isothermal holding at the heat-steaming treatment leads to the delayed ettringite formation in concrete structure [14–16]. This leads to the presence of high internal tensile stresses and, consequently, to the decrease of concrete strength [17].

According to De Bonte firm their sleepers produced without heat-steaming treatment have minimum service life of 40 years at speeds up to 350 km/h with the axial load of 225kN.

The required transfer strength of concrete for pre-stress release of reinforcement is achieved after 18–24 hours of hardening at normal conditions in a number of technologies of sub-rail structures production, for example, in the technology of large Italian manufacturer PLAN. However, the question of the use of water-reducing admixtures based on polycarboxylates for obtaining concrete with high transfer strength after low-heat steaming treatment of duration of 10–12 hours has not yet been studied. It is necessary to determine the conditions under which the use of method combining the modifier addition and thermal treatment provides the required transfer strength of concrete.

Polycarboxylate-based water-reducing admixtures are widely represented. The range of admixtures grows every year. However, the effect of admixtures on the technological properties of fresh concrete and on

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the rate of strength development of hardened concrete is different [12, 18, 19]. Some water-reducing admixtures can significantly slow the growth of concrete strength in the first hours of hardening [20–22]. According to this it is necessary to identify the criterion by which admixture can be selected in order to obtain high-strength concrete after heat-steaming treatment on the example of production of sub-rail structures with double turnover of forms per 24 hours. One can propose the comprehensive approach that considers the use of ordinary raw materials, effective water-reducing modifiers of concrete structure as well as optimal low-temperature modes of heat-steaming treatment.

The aim of the paper is to set the correlation among the concrete strength and the parameters of the mode of low-heat steaming treatment of concrete with admixture namely the duration of pre-exposure, the rate of temperature rise as well as the duration and temperature of isothermal holding. Recommendations on the amounts of water-reducing admixtures on polycarboxylate basis, Portland cement fineness as well as modes of low-heat steaming treatment must be given.

The obtained results can be used for increasing the durability of prefabricated prestressed reinforced sub-rail structures as well as other reinforced concrete structures in the production with double or single turnover of moulds per day.

2. Methods and Materials of research

In transport construction the Portland cement of brand PC500D0-N (normalized composition without mineral additives where C_3A is up to 8 %, R_2O up to 0.6 %) according to Russian State Standard GOST R 55224-2012 "Cements for transport construction" is used for the preparation of concrete mixtures. The consumption of Portland cement in the manufacture of railway sleepers is between 450 and 500 kg/m^3 for concrete of B40 strength class and from 500 kg/m^3 for concrete of B50 strength class. The concrete of B50 strength class is manufactured with the use of superplasticizer.

The high amount of Portland cement is a disadvantage of the compositions since the compositions are designed on the basis of the condition of ensuring the required transfer strength of concrete after heat-steaming treatment at 80°C. The strength at the age of 28 days is provided due to the high consumption of Portland cement. Fresh concrete mixes with water-to-cement ratio up to 0.4 are used to ensure the early strength and durability of concrete according to Russian Application Standard OST 32.152-2000 "Sleepers for the Railways of the track of 1520 mm of the Russian Federation". Studies were performed on the composition of concrete for the production of sleepers with the weight ratio of 1:1.44:2.57 and with mixtures of the same workability. Granite coarse aggregate with the maximum size of 40mm and feldspar sand with the size modulus of 2.1 were used as aggregates.

Water-reducing admixtures must meet the requirements of Russian State Standard GOST 24211 "Admixtures for concrete and mortar." The polycarboxylate-based water-reducing admixtures Stachement 2280 and Stachement 2060 were chosen for the research.

The characteristics of the Portland cements chosen for the study are presented in Tables 1 and 2.

Table 1 Mineralogical composition of clinker.

Designation	Cement	C_3S	C_2S	C_3A	C_4AF
CEM-1	PC500D0-N "Maltsovsky Portland cement"	63.1	14.6	6.3	13.5
CEM-2	PC500D0-N "Volskcement"	63.9	13.0	4.1	16.0

Table 2 Physical and mechanical characteristics of cements.

Desig-nation	Fineness, the rest on sieve No.008, %	Normal consis-tence , %	Setting time of cement paste, hours-min.		Cement activity at normal conditions of hardening at 28 days, MPa	Cement activity after heat-steaming at 80°C *, MPa	Group of cement activity at heat-steaming treatment at 80°C *
			Begin	End			
Cem-1	3.3	27.6	2-30	4-20	51.3	34.1	II
Cem-2	2.3	27.0	2-10	4-20	52.5	40.8	I

*according to method [23]

Comparison of grains quantity of different fractions was made at the evaluation of particle size distribution of Portland cements in Table 3.

Table 3. Particle size distributions of Portland cements.

	The quantity of cement grains smaller than, %							
	2 µm	3 µm	5 µm	10 µm	16 µm	32 µm	50 µm	100 µm
Cem-1	6.3	8.6	14.1	23.7	48.8	68.9	80.2	95.2
Cem-2	11.6	16.6	23.7	38.6	49.2	75.2	90.1	98.7

3. Results and Discussion

3.1. Determination of the optimal amount of admixtures to increase the early strength of cement matrix

The problem of insufficient increase of fluidity of fresh concrete or insufficient reduction of water demand with the addition of superplasticizers due to the influence of chemical and mineralogical composition of Portland cement is known and studied by scientists [24–26]. This problem can rarely occur in the case of the use of Portland cement of brand 500D0-N that has the normalized composition according to standard Russian State Standard GOST R 55224-2012 "Cements for transport construction". However, it should be taken into account that water-reducing admixtures with the increase of their dosage can have a slowing effect on the hydration of cement systems at the early stage due to poor water permeability through the adsorption layers [27–29].

The results obtained in paper [30] at studying inhibitory effect of lignosulfonates lead to the conclusion about the adsorption of a large number of lignosulfonate molecules by the resulting ettringite. This leads to a slower crystallization of ettringite in calcium monosulfoaluminate that reduces the hydration of the C_3A. Hydration of alite also slows down if the concentration of lignosulfonate in the liquid phase remains high. As a result, the cement setting time is extended as well as the set of early strength of cement matrix slows down. The retarding effect of admixtures based on polycarboxylate esters on cement system hydration is also associated with their adsorption on ettringite [31] as well as with the effect of length of the main chain of their molecules [27].

The results of determining the optimal quantity of studied admixtures to produce concrete with high strength at an early age under normal hardening conditions are presented in Figures 1 and 2. The studies were carried out on a cement pastes with the normal consistency. Cubes of size 20×20×20 mm in precise plastic forms were made to determine the kinetics of the strength growth of cement matrix at different amounts of admixtures.

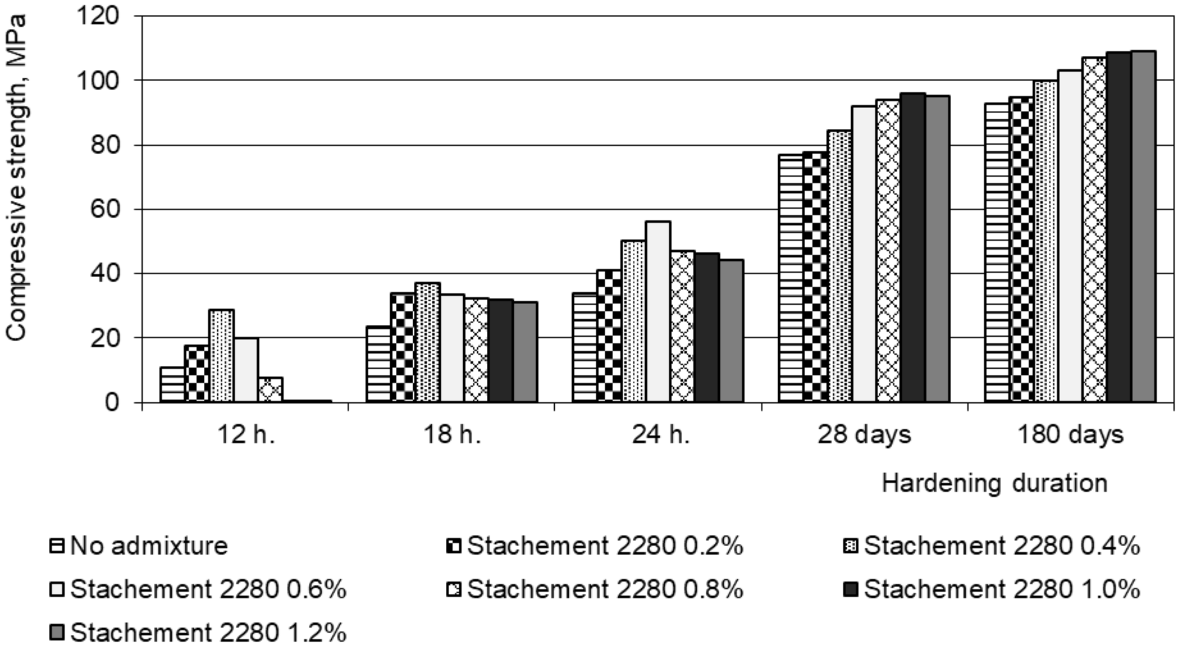

Figure 1. The strength growth of cement matrix at different amounts of Stachement 2280.

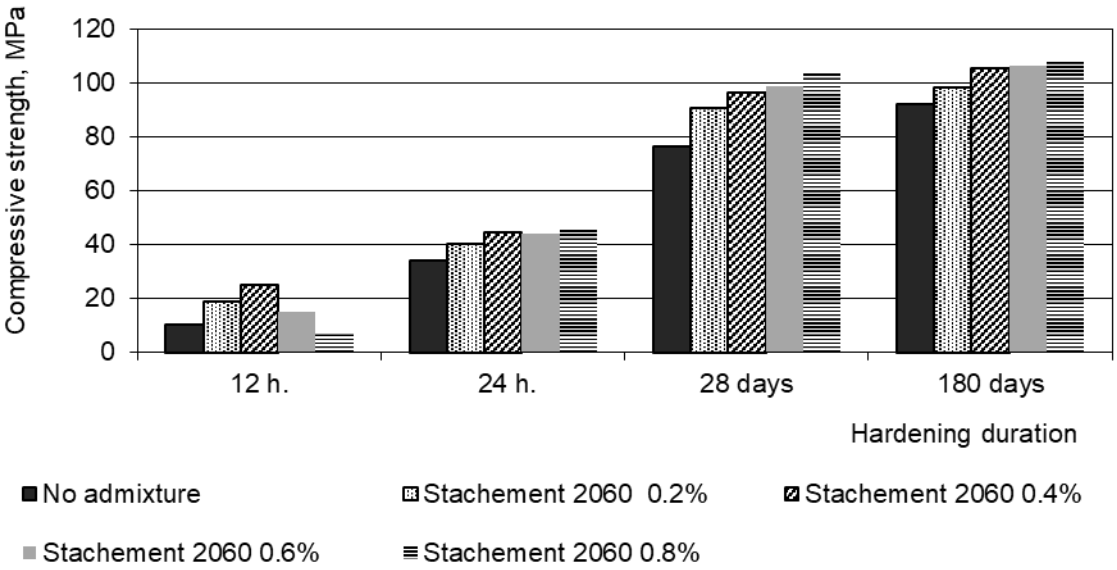

Figure 2. The strength growth of cement matrix at different amounts of Stachement 2060.

The analysis of Figures 1 and 2 has showed that clearly expressed maximum values of the compressive strength at the age of 12, 18 and 24 hours exist at the range of 0.4–0.6 % of Stachement 2280 admixture. The strength of cement matrix at the age of 12 and 18 hours decreases with increasing quantity of admixtures despite the increase of their water-reducing effect.

Thus, the optimal amount of polycarboxylate modifier exists to increase the strength of cement matrix in the early period of hardening, for example 12, 18 and 24 hours.

In the case of superplasticizer quantity less than the optimal one, no increase of early strength was observed due to insufficient water demand reduction. Conversely, the retarding effect of superplasticizer on cement hydration was manifested in the case of admixture quantity greater than the optimal one. The strength of cement matrix at the age of 28 days has increased with increasing quantity of admixtures in the studied range. It should be noted that the increase of strength was insignificant at the age of 180 days at the admixture quantity of more than 0.8 % of Portland cement mass.

3.2. Effective coefficients of strength of cement matrix

A scientifically based approach to determine the effective coefficients of strength of cement matrix taking into account the water-reducing effect of polycarboxylate admixture and the cement activity is proposed in paper [32] for the cement matrix of daily age.

Effective coefficients of strength growth of cement matrix at the age of 12 hours (K_e^{12}) taking into account the water-reducing effect of the admixture are calculated in this paper for the purpose of reasonable choice of admixtures for the studied technologies of production of sub-rail structures:

$$K_e^{12} = W_r \times K_c^{12}, \quad (1)$$

where

$$W_r = (W/C_n)/(W/C_{pl}), \quad (2)$$

Where W_r is water-reducing effect of admixture;

W/C_n is water-to-cement ratio of cement paste without admixture;

W/C_{pl} is water-to-cement ratio of cement paste with admixture.

$$K_c^{12} = R_{pl}^{12} / R_n^{12}, \quad (3)$$

where K_c^{12} is coefficient of relative activity of cement at the age of 12 hours in the presence of admixture;

R_n^{12} is cement matrix strength at the age of 12 hours without admixture;

R_{pl}^{12} is cement matrix strength at the age of 12 hours with admixture.

Similarly, the effective coefficients of cement matrix strength at the age of 18 and 24 hours were calculated in Table 4. It should be noted that the choice of plasticizing admixture and its amount depends on the requirements of precast concrete production technology.

Table 4 Effective coefficients of cement matrix strength.

Admixture	Amount, %	W/C	W_r, %	Compressive strength, MPa			K_c^{12}	K_e^{12}	K_c^{18}	K_e^{18}	K_c^{24}	K_e^{24}
				12 h	18 h	24 h						
No admixture	0	0.255	-	10.6	23.7	34	1.000	-	1.000	-	1.000	-
Stachement 2280	0.2	0.245	1.041	17.6	33.9	41.0	1.660	1.728	1.430	1.489	1.205	1.255
Stachement 2280	0.4	0.225	1.134	28.7	36.9	50.0	2.707	3.070	1.556	1.765	1.470	1.667
Stachement 2280	0.6	0.217	1.175	20.1	33.6	59.9	1.896	2.228	1.417	1.665	1.761	2.070
Stachement 2060	0.2	0.244	1.041	18.8	-	40.1	1.773	1.845	-	-	1.179	1.227
Stachement 2060	0.4	0.224	1.138	24.9	-	44.6	2.349	2.673	-	-	1.312	1.492
Stachement 2060	0.6	0.217	1.175	15.1	-	44.1	1.424	1.673	-	-	1.297	1.524

As one can see from Table 4 the optimal amount of admixture for precast concrete should be assigned not from the condition of its maximum water-reducing effect but from the condition of obtaining the maximum strength of concrete under normal conditions of hardening at the age when the requirements for transfer strength are imposed.

Studies have shown that the admixture amount for concrete with the necessary transfer strength after heat-steaming treatment of duration 10–12 hours should be assigned from the condition of the maximum value of the coefficient of relative activity of cement (K_c^{12}) at the age of 12 hours in the presence of admixtures. The coefficient K_e^{12} provides a more complete assessment of the effectiveness of admixtures since it also takes into account the water-reducing effect of the admixture.

Superplasticizers Stachement 2280 in the amount of 0.4% (K_c^{12} = 2.7; K_e^{12} = 3.07) and Stachement 2060 in the amount of 0.4% (K_c^{12} = 2.35; K_e^{12} = 2.67) were chosen according to the results of determination of the coefficients K_c^{12} and K_e^{12} for the selection of concrete composition to ensure the required transfer strength after heat-steaming treatment of duration up to12 hours.

Thus, the dependences of cement matrix strength on the type and amount of modifiers as well as the duration of hardening under normal conditions are stated. It is shown that the optimal amount of modifier in order to increase the strength at the age of 12, 18 and 24 hours exists for each type of superplasticizer.

The greatest increase of strength at the age of 12 hours was obtained with the addition of water-reducing admixture in the amount of 0.4% compared to the non-admixture composition. The studied admixtures at the amount of less than optimal one have not increase the early strength of concrete due to insufficient water reduction and at the amount higher than optimal one – their slowing effect on cement hydration has prevailed.

3.3. The modes of heat-curing of concrete with polycarboxylate-based admixture

Features of the production of precast reinforced concrete using superplasticizers and heat-curing were studied by many scientists [33–36]. However, obtaining the required strength of concrete after heat-curing was provided either by reducing the temperature of isothermal holding or the duration of heat-curing [37–41] or by reducing the cement quantity [42–46]. In this paper, the author sets the task to simultaneously reduce the Portland cement quantity and the temperature of isothermal holding. The optimal parameter values of low-heat steaming treatment for obtaining the high transfer and design strength as well as durability of precast concrete were stated.

It is shown that the duration of the pre-exposure of concrete before the low-heat steaming treatment is advisable to appoint considering the start of cement paste setting with a polycarboxylate modifier. Cracking was observed in samples with water-reducing admixtures at insufficient duration of pre-exposure or forced modes of heat-curing with the temperature rise rate of more than 10 °C/hour as shown in Figure 3. The width of the cracks was 0.5–1 mm which led to a sharp decrease of concrete strength. Thus, the pre-exposure must be 2.5–3 hours with the modifier of optimum quantity of 0.4 % by weight of Portland cement in contrast to the exposure of 1.5–2 hours used in the production of sub-rail structures (without water-reducing admixtures).

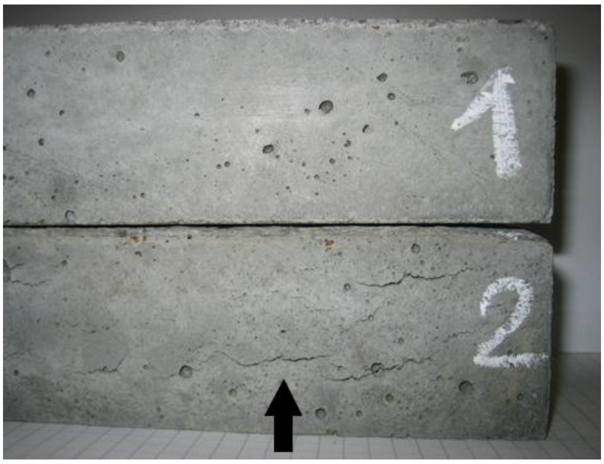

Figure 3. Samples of concrete after low-heat steaming treatment with different duration of preliminary exposure (sample 1 after treatment with mode of 3-3-5-1/40 °C, sample 2 after treatment with mode of 2-3-6-1/40 °C).

Modes with the temperature of isothermal holding of 40 °C and the total duration of 12 hours have differed in the rate of temperature rise as shown in Table 3. These modes were chosen to determine the effect of the rate of temperature rise on the strength of concrete with the optimal amount of admixture. The greatest increase of the concrete strength with admixture compared to the non-admixture concrete is obtained at the temperature of 40 °C as shown in Table 5. For comparison the Portland cements with different quantity of fine fractions were selected.

Table 5 Effect of the temperature rise rate on the concrete strength.

Cement	Admixture	Compressive strength after low-heat steaming treatment, MPa		
		3+1+7+1/40 ºC	3+2+6+1/40 ºC	3+3+5+1/40 ºC
Cem-1	Stachement 2280 0.4%	42.7	44.4	48.3
Cem-2	Stachement 2280 0.4%	44.7	50.6	49.7
Cem-1	Stachement 2060 0.4%	43.0	43.5	50.3
Cem-2	Stachement 2060 0.4%	45.5	51.1	48.4

Table 5 shows that the concrete reaches the greatest strength at the rate of temperature rise of 7–10 °C/hour. At the same time, the temperature rise can be 10 °C/hour for Portland cement with the grain quantity of less than 3 µm in the amount of 17 % (Cem-2).

The Portland cement activity with admixture at low-heat steaming treatment should be considered in addition to the activity of pure Portland cement at low-heat steaming treatment. Studies have shown that the optimal value of the isothermal holding temperature, corresponding to maximum strength, varies and depends on the type of modifier. Determination of the temperature of isothermal holding was performed at the temperature rise rate of 7–8 °C/h according to Table 6.

It is stated that the maximum absolute values of the concrete strength of samples with Stachement 2280 can be obtained at the isothermal holding temperature of 50 °C, with Stachement 2060 – at 40 °C. The maximum increase of strength of concrete with admixtures after low-heat steaming treatment compared with non-admixture concrete is achieved at 40 °C.

Table 6 Effect of the isothermal holding temperature on the concrete strength (Cem-2).

Admixture, %	W/C	Compressive strength after low-heat steaming treatment, MPa / in %			
		3+1+7+1/30ºC	3+3+5+1/40ºC	3+4+3+2/50ºC	3+5+2+2/60ºC
0	0.34	28.1/100	33.6/100	37.1/100	37.8/100
Stachement 2060 0.4%	0.30	39.1/138	49.2/145	48.8/130	48.7/128
Stachement 2280 0.4%	0.30	39.8/140	50.8/150	52.2/139	49.8/131

Accordingly, the Portland cement must have a high activity with water-reducing modifier at the optimum temperature of isothermal holding in order to significantly reduce the consumption of Portland cement.

One can propose to simultaneously determine the efficiency coefficient of Portland cement with polycarboxylate modifier after low-heat steaming treatment (for example, at temperatures of 40, 50 and 60 °C) (4) and to choose the optimal temperature of isothermal holding as shown in Table 7:

$$K_{\partial t}=R_{\partial t}/R_c, \quad (4)$$

where $R_{\partial t}$ is activity of Portland cement with polycarboxylate modifier after low-heat steaming treatment at t = 40, 50 and 60 °C;

R_c is activity of Portland cement with polycarboxylate modifier at the age of 28 days.

Table 7 Efficiency coefficient of Portland cement with admixture after low-heating treatment.

Components	Efficiency coefficient of Portland cement at 40 °C*	$R_{\partial 40}$	$R_{\partial 50}$	$R_{\partial 60}$	R_c	$K_{\partial 40}$	$K_{\partial 50}$	$K_{\partial 60}$
Stachement 2060 0.4% Cem-1	0.60	43.2	45.7	42.0	57.5	0.74	0.79	0.72
Stachement 2280 0.4% Cem-2	0.71	46.7	46.8	45.0	56.8	0.81	0.81	0.78

* The efficiency coefficient of cement is determined by the formula 4 without the use of admixtures

The coefficient of efficiency of Portland cement with admixture after low-heating treatment allows setting the optimal temperature of isothermal exposure taking into account the properties of admixture and Portland cement.

Thus, the values of the parameters of curing of precast concrete with polycarboxylate-based admixture were stated: the duration of pre-exposure is 2.5–3 hours; the rate of temperature rise is 7–10 °C/h; the temperature of the isothermal holding is 40–50 °C.

Generalized mathematical dependence of the transfer strength of concrete after low-heat treatment from its duration and temperature of isothermal holding, quantity of Portland cement and water-reducing admixtures was derived (5). To do this, the multifactorial task of finding the dependence of concrete strength (Y) on the following factors is considered: R_d is admixture quantity (0.3; 0.4; 0.5%), R_c is cement quantity (400, 440, 480 kg), t is the duration of low-heat treatment (10, 12, 14 hours), T_{grad} is the temperature of isothermal holding (40 °C, 50 °C, 60 °C). The experimental results are presented in Table 8.

The equation of the regression function Y is represented as the polynomial of the 2nd degree of 4 variables with significant estimates of parameters and the coefficient of multiple determinations R^2 = 95.32 % as:

$$Y = -330.5+445.6\times R_d+1.2\times R_c-395.9\times R_d-0.4\times R_d\times R_c+3.9\times Rd\times t+0.2\times Rd\times Tgrad-0.001\times Rc^2 \quad (5)$$

Table 8. Multi-factor task of finding the dependence of compressive strength.

Matrix of the plan in values		Compressive strength of concrete after heat-steaming treatment with duration								
		at 40 °C			at 50 °C			at 60 °C		
		10 hrs, MPa	12 hrs, MPa	14 hrs, MPa	10 hrs, MPa	12 hrs, MPa	14 hrs, MPa	10 hrs, MPa	12 hrs, MPa	14 hrs, MPa
Admixture quantity, %	Cement, kg	Y_{10}^{40}	Y_{12}^{40}	Y_{14}^{40}	Y_{10}^{50}	Y_{12}^{50}	Y_{14}^{50}	Y_{10}^{60}	Y_{12}^{60}	Y_{14}^{60}
0.5	480	35.4	39.6	44.4	35.8	40.2	45.2	35.9	40.5	46.5
0.5	400	32.2	35.8	39.6	32.8	36.4	40.3	32.7	36.9	40.7
0.3	480	41.2	43.1	45.2	42.3	44.5	45.6	43.5	47.7	48.1
0,3	400	29.8	32.2	34.6	30.7	33.6	34.9	33.4	35.2	36.9
0.5	440	33.9	38.1	42.9	35.0	38.9	43.9	35.3	39.2	42.8
0.3	440	37.9	40.6	42.8	39.1	41.8	44.1	42.8	44.3	45.6
0.4	480	41.3	44.6	47.8	42.8	45.0	49.6	43.6	46.3	49.2
0.4	400	35.9	39.3	41.8	37.2	39.9	42.9	38.9	41.6	43.0
0.4	440	40.1	42.9	45.8	41.5	43.8	47.2	42.6	45.6	47.9

The graph of the regression function of concrete strength is shown in Figure 4.

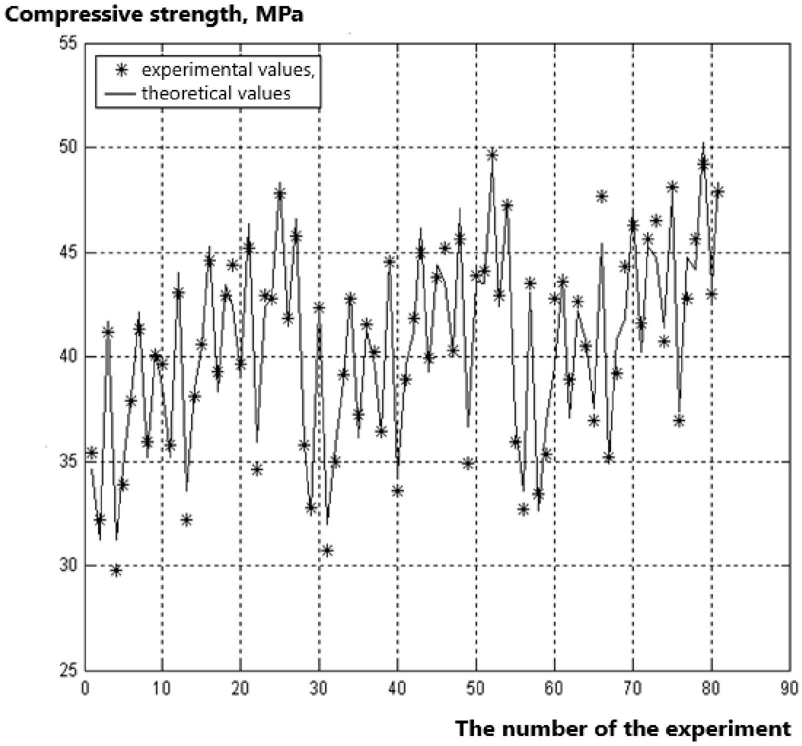

Figure 4. Experimental and, theoretical values of the regression function of concrete strength.

On the basis of the obtained model it was determined that the Portland cement quantity is 400 kg/m^3 in the conditions of application of Portland cement that meet the criteria for activity after low-heat treatment, chemical-mineralogical composition and fineness as well as water-reducing admixture in the optimal amount of 0.4 %. This consumption of Portland cement is 15 % less compared to the consumption in production of precast sleepers of B40 and B50 concrete strength class that are steamed at 80 °C to ensure the required transfer strength.

4. Conclusions

1. Recommendations on the amounts of water-reducing admixtures on polycarboxylate basis, Portland cement fineness as well as modes of low-heat steaming treatment were given in order to increase the strength and durability of prefabricated structures.

2. The optimal amount of polycarboxylate modifier exists to increase the strength of cement matrix in the early period of hardening, for example 12, 18 and 24 hours. In the case of superplasticizer quantity less than the optimal one, no increase of early strength was observed due to insufficient water demand reduction. Conversely, the retarding effect of superplasticizer on cement hydration was manifested in the case of admixture quantity greater than the optimal one. The strength of cement matrix at the age of 28 days has increased with increasing quantity of admixtures in the studied range.

3. Effective coefficients of strength growth of cement matrix at an early age were stated. These coefficients allow choosing the necessary type and quantity of admixture for precast concrete production.

4. The parameters of low-heat steaming treatment of concrete with a polycarboxylate superplasticizer were stated: the duration of pre-exposure 2.5–3 hours, the rate of temperature rise 7 °C/hour, the temperature of isothermal exposure 40–50 °C. The obtained results can be used in the production of precast prestressed reinforced sub-rail structures as well as other reinforced concrete structures with high durability at plants with double or single turnover of moulds per 24 hours.

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