Influence of presteaming period and curing temperature on the plasticized concrete strength

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Abstract. Heat-moisture treatment (HMT) is the main way to speed up the strength of reinforced concrete products. But this technology is the cause of high energy and resource costs. The use of traditional plasticizing additives in concrete is difficult in terms of early strength reduction. The modern industry of chemical additives allows regulating superplasticizers (SP) molecular structure. The use of such modifiers in concrete leads to early strength increase. The combination of HMT and SP using in concrete hardening makes the optimization of steaming parameters possible. HMT variable modes of concrete modified with polycarboxylate SP were investigated for early strength. The stripping concrete strength with an increase in SP dosage from 0.4 % to 2.0 % by cement mass decreases as follows: at the maximum curing temperature of 40 °C – on 32.8 %; at the temperature of 60 °C – on 27.2 %, at the temperature of 80 °C – on 23.8 %. The concrete compressive strength after HMT without the presteaming period is lower by only 5.4-14.3 % in comparison with concrete steamed with one for 1-2 hours. The research was carried out on concrete using sand with a low size modulus of 1.70. The authors show the superplasticizer effectiveness in terms of reducing the water-cement ratio and joint action with HMT. Mathematical models of the early concrete strength were obtained depending on curing temperature, presteaming period duration, and the SP dosage. The obtained results can be used in the reinforced concrete products production, subject to additional research.

1. Introduction

The modern construction industry strives to accelerate construction temps. Consumers are interested in getting high-strength and durable products in the shortest possible time. Manufacturer of reinforced concrete products strive for a higher formwork turnover, reducing energy and resource costs [1–4].

Concrete production with high early strength is possible using a special fast-hardening binder or using technical acceleration methods. Undoubtedly, the main way to achieve high strength of concrete on factory lines is heat-moisture treatment (HMT) [1,3,5]. In the total volume of precast concrete production, about 85 % of products are manufactured using the technology mentioned above.

However, since the mid-50s of the last century, the HMT has not undergone any significant changes requiring substantial energy resources or the use of high-grade cement with increased consumption. The duration of the HMT cycle for the most reinforced concrete products is 12-20 hours at high temperatures up to 80-90 °C which does not meet the requirements of concrete manufacturers and consumers [1,6].
HMT's first stage is the presteaming of products. This period can last from 2 to 6 hours, depending on the cement setting time, the thickness of the product produced, the steaming temperature, the concrete mix flowability, and some other factors [2,7]. Some studies have also considered longer (up to 1-7 days) periods of presteaming [8,9]. In the 50-80s of the XX century many scientists noted the negative impact of premature temperature rise on the strength and durability of cement concretes [4,10,11].

There are the following stages of HMT: temperature rise period, isothermal steam curing, and cooling of products. The temperature increase is the reason for the lack of concrete strength in comparison with a similar one, which hardens under normal conditions. Moreover, the higher is the maximum heating temperature, the lower are the strength and durability of manufactured concrete products. A decrease in the physical and mechanical properties of steamed concrete is associated with the presence of a temperature gradient in the hardening product mass, the occurrence of heat and mass transfer phenomena, and the directed capillary porosity development. Also, the contact zone of the cement system with the rebar is weakened during HMT, which can lead to a fault when transmitting the pre-stressing [1,7,11,12].

Currently, most concrete contains chemical additives that directly regulate the properties of produced concrete mixes and reinforced concrete products. The use of superplasticizers can significantly increase the workability of concrete mixes by reducing friction between cement particles and dispersing colloidal cement systems. Besides, the use of these additives has a positive effect on concrete strength and durability, mainly due to the water-cement ratio decrease [13–17]. However, the use of traditional plasticizers causes an increase in the HMT duration of concretes, since the setting time of cement systems slows down [18,19].

The latest chemical industry allows synthesizing superplasticizers with specified parameters, such as the length of the main and side chains, and the charge density. At the same time, it is possible to regulate the HMT modes, particularly in the direction of reducing the duration and steaming temperature [14,20–22]. It is noted that modern superplasticizers based on polycarboxylate esters (PCE) are initially adsorbed only locally on the aluminate and ferrite phases, and then on AFm and AFt phases, which reduces the destructive stresses in the hardening concrete [18,19,22,23]. At a later hydration stage, PCEs can also be linked with Ca^{2+} on C-S-H surfaces [24]. Several researchers obtained a transfer strength of plasticized concretes up to 70 % with a total HMT duration no more than 12 hours and heating temperature up to 60 °C. The attempts to regulate the presteaming time of concretes were also made [6,10,20,25,26]. The article [27] shows that in the manufacture of prestressed concrete railway sleepers, the pre-steaming time reduction from 5 hours to 2 hours and then to 0.5 hours did not have any noticeable effect on the 28-day’s strength properties of the hardened concrete. A slight deterioration in the physical and mechanical properties of concretes with a reduction of presteaming duration to 1 hour was noted in several studies [10,25,26].

In most studies conducted, for example, in Europe and Asia, sand with a fineness modulus of 2.5 to 3.6 was used as a fine aggregate [1,7,10,24,25,27,28]. In this paper, the influence of the HMT modes on plasticized concrete is considered taking into account the use of quartz sand, which is characterized by a low fineness modulus. Fine-grained sand is the most common in Central Russia and the Volga region.

Thus, the study of the HMT influence on the plasticized concrete strength using fine-grained sands is especially important in our time, particularly in terms of reducing the presteaming duration and limiting the steaming temperature.

2. Methods
The main objective of this investigation is to study the influence of the HMT's presteaming time duration and heating temperature on the early strength of concretes modified with modern PCEs.

The development of plasticized concrete mixes was performed using local quartz sand with a low size modulus of 1.70. The granulometric composition of the sand is shown in table 1.
### Table 1. The granulometric composition of the sand used

| Residues, % | Residues on sieves with hole size, mm |
|-------------|--------------------------------------|
|             | 5.0  | 2.5  | 1.25 | 0.63 | 0.315 | 0.16 | <0.16 |
| Partial     |      |      |      |      |       | 3.07 | 2.63 |
| Complete    |      |      |      |      | 10.31 | 32.24 | 48.90 | 2.85 | 100.00 |

The Sika® ViscoCrete 24 HE PCE of the Swiss concern Sika was used to obtain workable concrete mixes and reduce the water-cement ratio.

As a coarse aggregate, crushed stone from deep-seated rocks with a size of 5-20 mm was used. According to the Russian State Standard (GOST) 8267-93, the material corresponds to the grade 1200 for crushing capacity. The grain composition of the crushed stone is shown in table 2.

### Table 2. The grain composition of the crushed stone used

| Residues, % | Residues on sieves with hole size, mm |
|-------------|--------------------------------------|
|             | >20 | 10 | 5 | <5 |
| Partial     | 2.43 | 64.50 | 32.05 | 1.02 |
| Complete    | 2.43 | 66.93 | 98.98 | 100.00 |

Portland cement CEM I 42.5 N produced by “Gornozavodskcement” was used as a binder. The Portland cement had the following mineralogical composition: C₃S=60.7 %, C₂S =13.4 %, C₃A =7.5%, C₄AF=12.8 %. The surface area of the cement is 3370 cm²/g.

The samples in the cubes form with an edge of 100 mm were made from concrete mixes with the mobility of P2 (a slump cone from 5 to 9 cm), which were subjected to the HMT under various modes. The samples were tested for compressive strength after the HMT.

The materials consumption per 1 m³ of concrete mix was: 350 kg of cement, 1200 kg of crushed stone, 780 kg of sand. The water-cement ratio depending on the PCE dosage, is shown in table 3.

### Table 3. Water consumption in concrete mix compositions depending on the SP dosage

| Water consumption, kg/m³ | PCE dosage, % by cement mass |
|--------------------------|-------------------------------|
| 172.7                    | -                             |
| 154.5                    | 0.4                           |
| 145.5                    | 1.2                           |
| 140.7                    | 2.0                           |

A three-factor experiment plan to optimize the concrete strength characteristics after HMT was implemented. Table. 4 shows the various levels of variable factors.

### Table 4. The various levels of variable factors

| №   | Variable factors name | The various levels of factors |
|-----|-----------------------|-------------------------------|
| 1   | X₁ – PCE dosage, % by cement mass | -1 | 0 | +1 |
| 2   | X₂ – heating temperature of the HMT, °C | 40 | 60 | 80 |
| 3   | X₃ – presteaming time duration, h | 0 | 1 | 2 |
During the experiment the following factors varied: presteaming time duration (0 h, 1 h, 2 h), the heating temperature (40 °C, 60 °C, 80 °C) and the PCE dosage (0.4 %; 1.2 %; 2.0% of the cement mass). Control samples without additives were also produced. The duration of isothermal heating was 6 hours, the cooling period lasted 2 hours. Thus, the duration of the HMT cycle was 6, 7, and 8 hours, depending on the presteaming time.

3. Results and Discussion
As a result of the obtained data, adequate mathematical models, which meet the criteria of Cochran, Student, and Fischer, were constructed. The calculated strength value after checking the model's adequacy is shown in the last column of table 4.

The experience has shown a decrease in the water-cement ratio when using Sika Viscocrete 24 HE by 10.6 %, 15.7 %, and 18.9 % at dosages of 0.4 %, 1.2 %, and 2.0 % of the cement weight, respectively.

The dependence analysis of the PCE dosage on the concrete steaming temperature at the HMT without presteaming is shown in Fig. 1 (a). The early concrete strength with an increase in PCE dosage from 0.4 % to 2.0 % by cement mass decreases as follows: at the maximum heating temperature of 40 °C – on 32.8 %; at the temperature of 60 °C – on 27.2 %, at the temperature of 80 °C – on 23.8 %. Increasing the steaming temperature allows elevation of an early strength to 86.7-111.6 %, depending on the PCE dosage.

With a confidence probability of 95 %, the regression equation looks like:

$$Y = 15.89 - 2.48X_1 + 5.19X_2 - 0.37X_1X_2$$  \(1\)

As the presteaming time increases, the compressive strength indicators increase slightly. The mathematical models are shown in Fig. 1 (b) and Fig. 1 (c) for concrete with a presteaming time duration of 1 hour and 2 hours, respectively.

The regression model of stripping concrete strength (see Fig. 1, b) at the significance level \(\alpha=0.05\) has the form:

$$Y = 16.32 - 2.40X_1 + 5.62X_2$$  \(2\)

Polynomial model of the modified concrete compositions compressive strength (see Fig. 1, c) with a confidence probability of 0.95 has the form:

$$Y = 17.25 - 2.22X_1 + 5.72X_2$$  \(3\)

With a reduced PCE consumption, accelerated cement system hydration is observed, since this amount of additive is not enough to block the crystallization of \(\text{C}_3\text{A}\) and \(\text{C}_4\text{AF}\) cement minerals \[19,20\].
Figure 1. Diagrams of the concrete compressive strength (in MPa) after HMT depending on the PCE dosage ($X_1$ coordinate) and the steaming temperature ($X_2$ coordinate). There are different presteaming durations of concrete mixes: a – without presteaming; b – 1 hour; c – 2 hours.

For clarity, graphical models of the concrete strength after HMT depending on the PCE dosage and the presteaming duration at different maximum steaming temperatures are constructed (Fig. 2, a…c).

Figure 2. Diagrams of the concrete compressive strength (in MPa) after HMT depending on the PCE dosage ($X_1$ coordinate) and the presteaming duration ($X_2$ coordinate). There are different steaming temperatures of HMT: a – 40 °C; b – 60 °C; c – 80 °C.
There is slight excess of strength with an increase in the presteaming duration to 2 hours at the heating temperature of 40 °C. The increase in strength was only 7.8 %, 7.5 %, 8.1 % with the content of Sika Viscocrete 24 HE in the amount of 0.4 %, 1.2 % and 2.0 % by cement mass, respectively, in comparison with compositions without presteaming. At the heating temperature of 60 °C, the stripping concrete strength increased by 6.0-11.9 %; and at the temperature of 80 °C by 5.4-14.3 % with an increase in the presteaming time.

The experiments prove low efficiency of the presteaming period during HMT for the early concrete strength formation.

4. Conclusions
1. Experimental studies have confirmed the possibility of obtaining high-strength concrete products modified with modern polycarboxylate superplasticizers.
2. There is a possibility of reducing or eliminating the presteaming period of plasticized concrete mixes due to their insignificant impact on the early concrete strength.
3. Increasing the dosage of PCEs to 1.2-2.0 % by cement mass affects negatively the early concrete strength.
4. According to the data obtained, using PCEs effectiveness to reduce the HMT duration is somewhat lower in comparison with the tests conducted on fine aggregates with high grain size. This fact should be taken into account with the economic feasibility of superplasticizers used jointly with concretes that use small quartz sand.
5. The mathematical description of the early concrete compressive strength is obtained depending on the presteaming time duration, the PCE dosage, and the temperature of the HMT heating.
6. Reducing the heating temperature of concrete modified with modern PCEs relaxes the stress in the concrete structure and provides new opportunities in the HMT mode optimization.
7. The resulting compositions of plasticized concrete and the HMT mode can be recommended for introduction into the production of reinforced concrete products. In each case, additional laboratory tests should be carried out to study the effect of specific additives, HMT mode, aggregates, and binders on the concrete properties.

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