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Heavy-weight concrete with increased early strength

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Abstract. Production process rate is the most important thing in industrial engineering of concrete and reinforced concrete products, which heavily depends on duration of concrete handling strength development. One of the methods of processes' intensification of concrete structure formation is steam treatment. However, destructive processes developing in concrete in some instances during its long steam treatment at the temperatures above 40°C necessitate reducing its duration. This is achieved through the use of methods of further intensification of concrete structure formation processes, one of which is hydromechanical activation of binder. Research results of joint effect of hydromechanical activation of cement binder and following steam treatment on kinetics of heavy-weight concrete strength development are presented in the paper; special aspects of hydration and structure formation of cement stone are studied. We found an increase in strength development rate of heavy-weight concrete during isothermal warming temperature increment. Technological parameters of steam treatment of concrete based on cement binder under hydromechanical activation are determined for preparing B30–B60 grade concretes using components for B25 heavy-weight concrete. Received results are of substantial interest to construction industry and can be used in prefabricated concrete and reinforced concrete technology, which gives the opportunity to reduce energy intensity of production and end product cost.

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1. Introduction

Improvement of the effectiveness of manufacturing processes of construction materials and products can be rated by how much the production duration is reduced and the costs are cut while maintaining or increasing the quality and marketability of the finished products in comparison with analogs. The research on rational combination of certain task components at hand is currently of great interest with respect to manufacturing process of concrete and reinforced concrete products [1]–[3].

Production process rate is the most important thing in production management, which heavily depends on duration of concrete handling strength development. The reason for this is that duration of concrete curing under normal conditions as per Russian State Standard GOST 10180-2012 until attainment of its handling strength far exceeds duration of all other manufacturing processes and necessitates increase of production area.

Processes' intensification of concrete structure formation is possible due to the use of technologic, chemical and thermal methods [4]–[9]. These methods provide different rate acceleration of processes of concrete structure formation and hardening, for which reason applicability of each of them is specified by conditions of production [10]–[15].

At the present time thermal methods of processes' intensification of concrete structure formation and hardening have widespread application in concrete and reinforced concrete production [16]. One of these methods is steam treatment (ST) that helps to get handling strength of products in a short time frame.

Moreover, ST mainstreaming into manufacturing process of concrete and reinforced concrete production makes it possible to largely increase form reuse.

However, it should be noted that apart from constructive processes that are conditioned by acceleration of structure formation and corresponding hardening of concrete structure under ST, destructive processes can also be initiated by volumetric changes of constituents of concrete, by internal deformations, by capillary pressure and moisture movement [17], [18]. Moreover, the effectiveness of ST is relatively not too high as a consequence of low performance coefficient of curing rooms that is within 45 %, which contributes to high cost of end products and lower market competitiveness.

Based on the aforesaid the question about ST duration reduction by the way of intensifying concrete structure formation processes is growing more urgent. One of the effective ways to increase concrete structure formation kinetics is mechanical activation of binder in water medium, or hydromechanical activation (HMA) [5], [10]. Intensification of concrete structure formation processes at early period of hardening during HMA of cement binder is conditioned by increase of mix contraction and also by accelerated primary phase ionic yield into mortar [19]–[23].

Another way to increase the rate of concrete strength development is introduction of plasticizing agents [24]–[26] into concrete composition that provide additional duration reduction of initial period of hydration that defines element formation of primary structure (crystalline hydrates and gel) [15], [27]–[29]. Besides, reduction of induction and crystallizing periods of concrete structure formation during HMA in the presence of chemical admixtures becomes agent for negative effect deficiency of binder hydration retardation by chemical admixtures. In this regard, HMA of cement binder in the presence of chemical admixtures provides a massive scale-up of ultimate bending and compression strength of concrete and reinforced concrete products in early period of hardening.

The question about combined influence of HMA processes of cement binder and following concrete ST on its structure formation kinetics is of great practical interest calling for substantial research.

The purpose of the present study is development of heavy-weight concrete with increased early strength by the way of HMA of cement binder including in the presence of chemical admixtures and further ST.

2. Materials and Methods

During experimental investigations we used the following raw components of concrete:

- Portland cement *CEM* II/A-P 32.5N produced by Ul'ianovskiy plant as per Russian State Standard GOST 31108-2016;
- fine aggregate: enriched sand of Kamsko-Ust'inskoe mineral assets with fineness modulus 2.7;
- coarse aggregate: granite macadam of Urals mineral assets 5–20 mm in size;
- water: plumbing potable water as per Russian State Standard GOST 23732.

For experimental research, we used B25 grade heavy-weight concrete with slump of concrete cone equal to 7–9 cm; the mixture ratio of cement : sand : granite macadam was 490 : 555 : 1315.

We chose “Relamix T-2” superplasticizer based on sodium salts of polymethylenenaphthalenesulfonic acids and formaldehyde with accelerating curing effect produced as per technical conditions 5870-002-14153664-04. Its content in concrete mix composition was 1 % by weight of cement.

HMA of cement binder was made in rotary-pulsed equipment (RPE) RPE-0.8-55A-2.2UZ produced as per technical conditions 5132-001-70447062.

For preparation of concrete mix at the first stage, we combined the required quantity of “Relamix T-2” additive and estimated quantity of gauged water. Then we mixed 50 % by total mass of cement and exposed the received mix to HMA in RPE for 2 minutes. After that we added the remaining portion (50 %) of cement, fine aggregate and coarse aggregate into the received suspended mixture and mixed in job mixer for 5 minutes. With the received concrete mixtures, we made test cube specimens with the dimensions of 10×10×10 cm.

To experimentally investigate the influence of isothermal warming temperature of concrete test cubes on their compression strength development kinetics during ST, we prepared four compositions:

- No.1 – reference specimen (unmodified composition without HMA of cement binder);
- No.2 – specimen based on cement binder under HMA in RPE;

- No.3 – specimen based on cement binder modified by “Relamix T-2” additive (without HMA of cement binder);
- No.4 – specimen based on cement binder under HMA in RPE in the presence of “Relamix T-2” additive.

Hereafter concrete specimens were exposed to ST as follows:

- curing of specimens for 2 hours at a temperature of 20 °C;
- temperature increase for 2 hours in curing room equipped with a microprocessor-based two-channel temperature controller, in accordance with set of rules SP 130.13330.2018;
- isothermal warming for 10 hours at different temperatures (30 °C, 40 °C, 80 °C) in according to SP 130.13330.2018 in curing room;
- temperature decrease for 2 hours.

Ultimate compressive strength of concrete specimens at 1, 3 and 28 days after ST was defined according to Russian State Standard GOST 10180-2012.

Special aspects of hydration and structure formation of cement stone were measured by the way of X-ray diffraction analysis (XRDA) and differential thermal analysis (DTA). During X-ray diffraction analysis diffractometer “D2 Phaser” produced by “BRUKER” company (Germany) was used. Powder mounts according to Bragg–Brentano geometry with the use of monochromated CuK-α radiation (λ = 1.54178 Å) in step SCAN mode were studied at the following measurement modes and factors record:

- tube tension – 30 kV;
- current – 30 mA;
- scan step – 0.02°;
- scan rate – 1°/min;
- angular range of scan according to Bragg–Brentano (BB) geometry – 3-60°.

Diffractograms received on the results of experimental investigations were compared with reference diffractograms. To do so, we accessed an international card-index database of powder diffractograms, PDF-2 ICDD.

During differential thermal analysis derivatograph SDT Q600 produced by MOM company was used. Platinum lidded crucibles were used in a form of sample-holder, incinerated aluminium oxide – in a form of master sample. The analysis was carried out in helium that was pumped under quartz glass closing thermo-couple of sample and master sample. During the analysis we registered differential thermal curve. Samples’ mass was 150–250 mg, sensitivity of balance – 100–200 mg, sensitivity of DTA-channel – 250–500. Specimens were heated in the temperature range from 20 °C to 1000 °C, the heating rate was 25 °C/min.

For carrying out experimental investigations of special aspects of cement stone hydration and structure formation we prepared specimens of 4 compositions:

- No.1/S – reference specimen (unmodified composition without HMA of cement binder);
- No.2/S – specimen based on cement binder modified by “Relamix T-2” additive (without HMA);
- No.3/S – specimen based on cement binder under HMA in RPE in the presence of “Relamix T-2” additive.
- No.4/S – specimen based on cement binder under HMA in RPE in the presence of additive “Relamix T-2” with the following ST at isothermal warming temperature equal to 80°C.

3. Results and Discussion

Table 1 shows experimental results of the influence of isothermal warming temperature of concrete specimens No.1–4 during ST according to the mode received in Materials and Methods section on kinetics of concrete compressive strength development. There is ultimate compressive strength of heavy-weight concrete specimens in the numerator and increase of ultimate strength (%) relative to the specimens, hardening of which took place under normal conditions as per Russian State Standard GOST 10180-2012, in the denominator.

Table 1. Influence of isothermal warming temperature of concrete specimens during ST on kinetics of concrete compressive strength development.

No. of composition	Isothermal warming temperature, °C	Ultimate compressive strength, MPa		
		Day 1 of hardening	Day 3 of hardening	Day 28 of hardening
No.1	Standard curing	8.5	26	44.3
	30	10.2	27.3	46.07
		20	5	4
	40	11.5	30.2	50.1
		35	16	13
	80	14.7	33.1	50.5
		73	27	14
No.2	Standard curing	14.2	29.8	52.8
	30	18.6	31.7	54.4
		31	6	3
	40	19.6	33.6	57.3
		38	13	9
	80	28.5	39.4	60.7
		101	32	15
No.3	Standard curing	18.4	35.1	60.8
	30	22.08	39.8	63.2
		20	13	4
	40	27.1	40.4	65.0
		47	15	7
	80	44.5	50.0	66.9
		142	42	10
No.4	Standard curing	30.6	41.4	70.3
	30	36.1	46.7	72.4
		18	13	3
	40	41.0	51.2	73.2
		34	24	4
	80	50.5	59.6	74.5
		65	44	6

As we can see from Table 1, an increase of kinetics of concrete strength development during isothermal warming temperature increment can be observed for all compositions. The attained results analysis is illustrative of the largest increase (in relation to the specimens hardened under normal conditions) in ultimate compressive strength at day 1 for the specimens No.3 modified by "Relamix T-2" additive. The highest absolute values of ultimate compressive strength at days 1 and 28 can be observed in composition No.4 (compressive strength is increased by 13 % at day 1 and by 11 % at 28 days in comparison with No.3 specimens at isothermal warming temperature of 80°C). The attained results show the effectiveness of HMA of cement binder in the presence of superplasticizer in cooperation with the following ST upon criterion of increase of heave-weight concrete strength development.

The attained results helped to define dependences of curing time of heavy-weight concrete until its attainment of required strength grade on the concrete ST temperature of composition No.4 according to the mode received in part 2. The results of experimental investigations are shown in Table 2.

Table 2. Curing time of heavy-weight concrete until its attainment of required strength grade on the concrete ST temperature of composition No.4.

Concrete grade	Curing time for attainment of required concrete grade at isothermal warming temperature during ST (°C)			
	Standard curing	30 °C	40 °C	80 °C
B30	2 day	1.5 day	1 day	–
B40	7 day	4 day	2 day	1 day
B50	22 day	19 day	14 day	10 day
B60	–	–	–	28 day

As we can see from Table 2, curing time of heavy-weight concrete until its attainment of required strength grade can be drastically reduced by increasing isothermal warming temperature during ST. For example, the time of concrete strength grade attainment equal to B40 can be reduced by 6 days, strength grade attainment equal to B50 – by 12 days.

Substantial reduction of curing time of heavy-weight concrete until attainment of required strength grade is conditioned by increase of kinetics of concrete strength development and connected with special aspects of structure formation and hydrated formation of new growths. To detect such special aspects, XRDA and DTA of cement stone specimens were made. Fig. 1 shows diffractograms of cement stone specimens at day 1 (vertical axis – Bragg angles in degrees, horizontal axis – relative diffraction reflection of minerals in pulses per second).

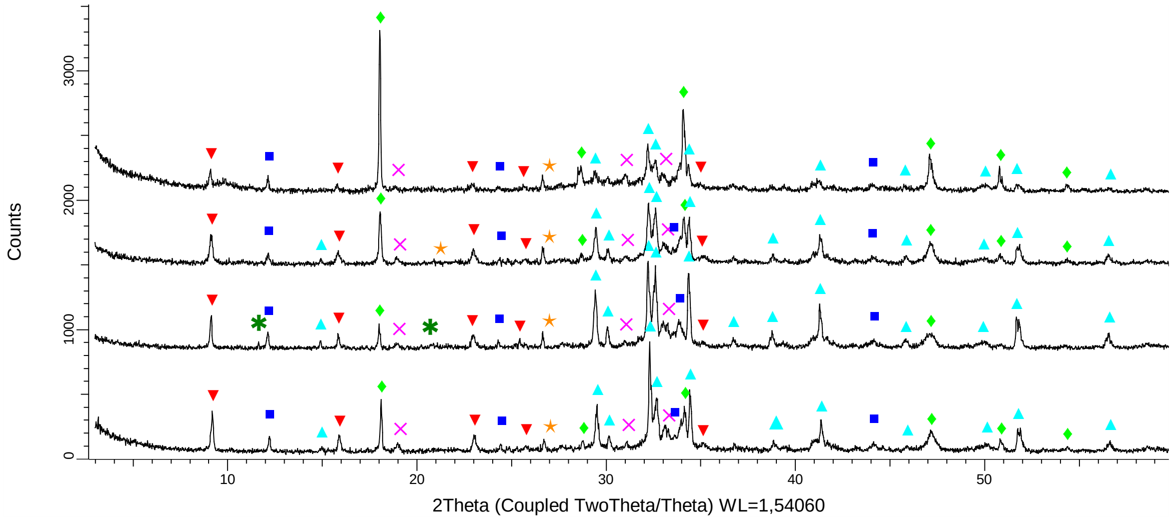

Figure 1. Diffractograms of cement stone specimens made of compositions No.1/S–4/S at day 1 (numeration bottom-up)

Symbol legend: – SiO_2; – $Ca_6Al_2(SO_4)_3(OH)_{12}$*$26H_2O$; – Ca_2SiO_4α-Ca_2SiO_4; – Ca_3SiO_5; – $Ca(OH)_2$; – $Ca_2(Al, Fe^{+3})_2O_5$; – Ca_2SO_4*$2H_2O$.

According to the findings most of ettringite is formed in specimen No.1/S, minimum – specimen No.4/S. Minimum of initial minerals of clinker Ca_2SiO_4α-Ca_2SiO_4 and Ca_3SiO_5 (alite and belite) and maximum of hydrated calcium silicates (CSH) can be observed in the cement stone specimen made of the composition No.4/S, which is illustrative of fuller binder hydration providing high concrete strength. In the compositions No.1/S and No.2/S equitable quantity of initial minerals of clinker can be observed, which is illustrative of negative effect deficiency of "Relamix T-2" admixture on cement hydration kinetics and on structure formation processes of cement stone.

In Table 3 quantitative mineral composition of the cement stone specimens No.3/S and No.4/S is shown.

Table 3. Quantitative mineral composition of the cement stone specimens

No. of specimen	Quantitative mineral composition, %								Sum, %
	SiO_2	$Ca_6Al_2(SO_4)_3$ $(OH)_{12}$ *$26H_2O$	Ca_2SiO_4 α-Ca_2SiO_4	$Ca_2(Al, Fe^{+3})_2O_5$	$Ca(OH)_2$	Ca_3SiO_5	$CaCO_3$	Ca_2SO_4*$2H_2O$	
3/S	4.91	10.12	16.85	13.78	9,52	44.82	–	–	100
4/S	5.83	8.18	10.08	21.11	24.97	29.83	–	–	100

Data analysis shown in Table 3 provides evidence of intensification of binder hydration processes in the cement stone specimen No.4/S under curing in comparison with the specimen No.3/S, which agrees with research results [30], [31]. For instance, quantity of alite reduction by up to 1.5 times can be observed along with quantity increase of calcium hydroxide by a factor of 2.6.

Thermograms of the cement stone specimens of compositions No.3/S and No.4/S are shown in Fig. 2.

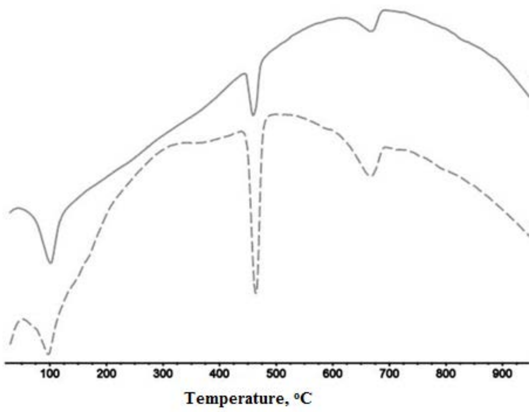

Figure 2. Thermograms of the cement stone specimens of compositions No.3/S and No.4/S at day 1 (numbering scheme from up to down).

Substantial increase of endothermic effect in the interval of temperatures 440–480 °C that describes removal of chemically combined water from compounds of calcium hydroxide according to the formula: $Ca(OH)_2 \rightarrow CaO + H_2O$, provides evidence of its significant content in the cement stone specimen No.4/S. This confirms the results received during XRDA and agrees with research results [30].

4. Conclusion

1. The authors revealed an increase in kinetics of strength development in heavy-weight concrete test specimens during isothermal warming temperature increment. The findings are comparable with the results of fundamental investigations about the influence of curing temperature on kinetics of concrete strength development. The highest absolute values of ultimate compressive strength at days 1 and 28 can be observed in the concrete specimen received with previous HMA of cement in RPE together with “Relamix T-2” additive.

2. The synergistic effect of HMA of cement binder in the presence of “Relamix T-2” additive with the following ST was established, which makes it possible to significantly increase the early strength of concrete. As the result, at 80°C of isothermal heating on the first day of hardening, the concrete specimens obtained corresponded to B40 grade, which is justified by the lowest content of ettringite and initial clinker minerals (Ca_2SiO_4α-Ca_2SiO_4 and Ca_3SiO_5), as well as the largest amount of calcium hydrosilicates (CSH) and hydroxides calcium ($Ca(OH)_2$). This indicates a more complete hydration of the binder causing an increased strength of heavy concrete.

3. The required isothermal warming temperature during ST of concrete based on cement binder under HMA in RPE in the presence of “Relamix T-2” additive was found, and duration of this cement binder hardening for concrete with B30 to B60 grades was also found while using components suitable for B25 grade heavy-weight concrete production.

4. As the result, positive influence of HMA of cement binder in the presence of superplasticizer followed by ST of the specimens based on it on processes of structure formation and on kinetics of heavy-weight concrete strength development was determined, which is of increased practical interest for the building materials industry.

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