

# Studies of the Processes of Cement Hardening In the Course of Low-Pressure Steam Curing of Concrete

P. P. BUDNIKOV and E. YA. ERSCHLER, USSR

•THE PROBLEM of finding the optimum technological conditions for the rapid hardening of concrete is of primary importance for the production of reinforced-concrete units. In this respect the processes occurring in cement paste and concrete during low-pressure steam curing are of considerable interest.

In this paper we consider the results of our investigations on the low-pressure steam curing of concretes made with cements of various mineralogical compositions. As a result of these studies, the kinetics of the chemical reactions during the steam treatment, the influence of both the curing cycle and the humidity conditions at elevated temperatures, and the role of the mineralogical composition of the cement are established (1).

## STUDY OF THE HYDRATION OF PORTLAND CEMENTS DURING LOW-PRESSURE STEAM CURING

Low-pressure steam curing of concrete units based on portland cements considerably accelerates all the processes accompanying the hardening of the cement paste. Various workers have studied the hardening processes of the separate clinker minerals and cements at elevated temperatures (2-10). Some studies have been carried out by T. C. Powers (11, 12).

The studies reported here were made on eight cements of various mineralogical compositions and having specific surfaces near 3000 sq cm/gr. The mineralogical composition of the cements studied are shown in Table 1.

The samples of neat cement paste, at water-cement ratio 0.27, were cured at atmospheric pressure and a temperature of 80 C according to the cycle 0+3+7+0 hr (0-hr pretreatment, 3-hr heating, 7-hr isothermal steam curing, 0-hr cooling). The relative humidity of the steam-air environment was 100 percent. Every hour the cement samples were tested for compressive strength, amount of combined water, gypsum, and free  $\text{Ca(OH)}_2$  (expressed as CaO).

On the basis of their potential  $\text{C}_3\text{S}$  and  $\text{C}_3\text{A}$  contents the cements were divided into the following groups: 1, 2, 3, 4—cements high in potential  $\text{C}_3\text{A}$ ; 5, 6—cements of moderate potential  $\text{C}_3\text{A}$  content (i. e., containing moderate amounts of  $\text{C}_3\text{A}$ —8-10 percent); 7—cement high in potential  $\text{C}_3\text{S}$  and  $\text{C}_3\text{A}$ ; 8—cement high in potential  $\text{C}_3\text{S}$  and low in potential  $\text{C}_3\text{A}$ .

The studies showed that the most marked gain of strength occurs during the first six hours (Fig. 1). In order to reach maximum strength, the cements of various compositions require different times of steam treatment. The most rapid development of strength was found with cements having over 10 percent of  $\text{C}_3\text{A}$  and less than 45 percent of  $\text{C}_3\text{S}$  (cements 1, 2, 3 and 4). For these cements the optimum duration of steam treatment was 6-8 hours. In contrast with the high-alite cement (8), having 66.8 percent of tricalcium silicate and 1.2 percent of tricalcium aluminate, the development of strength was incomplete in this period of time. For this cement to reach maximum strength, 10 hours curing proved insufficient.

The amount of combined water increases with the gain of strength (Fig. 2). During a 10-hour steam treatment, the cements of various mineralogical compositions combined 10.3-13.3 percent of water by weight. The same cements on normal curing

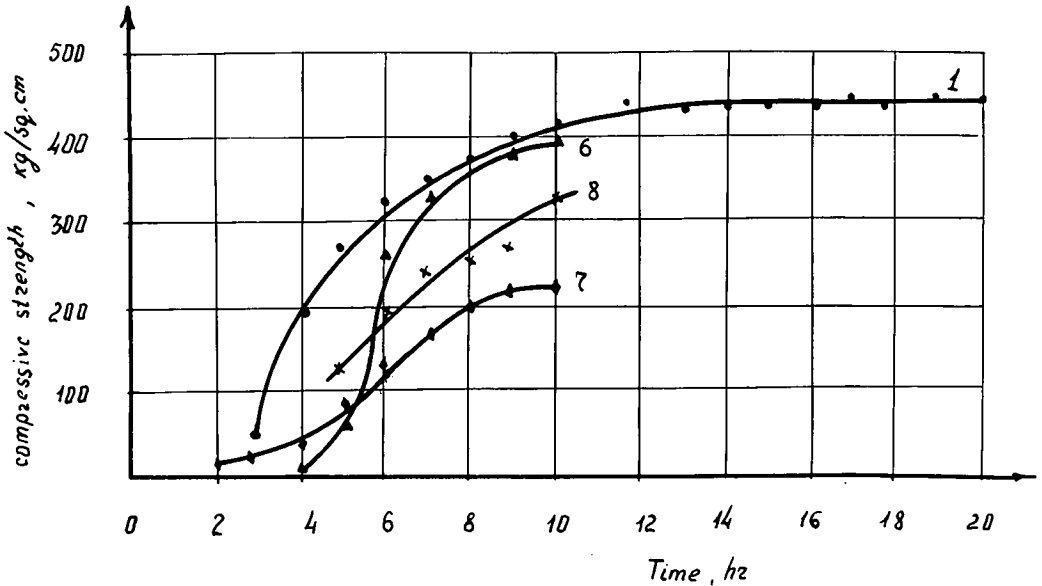


Figure 1. Development of strength of cement paste on steam treatment (cements 1, 6, 7 and 8).

TABLE 1  
MINERALOGICAL COMPOSITION OF  
CEMENTS STUDIED

Cement No.	Potential Phase Composition			
	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF
1	28.30	39.10	16.25	11.40
2	31.39	35.56	14.54	14.11
3	44.20	30.85	10.70	11.15
4	26.30	51.00	10.93	6.80
5	39.90	31.30	9.83	14.85
6	26.26	46.40	9.60	12.60
7	52.51	22.30	12.25	11.90
8	66.80	7.00	1.20	17.00

combined 11.8-15.9 percent at 28 days and 12.5-17.4 percent water at 90 days. After 10 hours of steam treatment the amount of combined water was 72-117 percent of the value obtained for the same cement after 28 days of hardening at normal temperatures. Some cements thus combined more water than at the age of 28 days at normal temperatures. Table 2 gives these results in more detail.

As already stated, the highest rate of strength development occurs during the first 5-6 hours. Figure 3 shows this in differential form. This is true even if the approach to maximum temperature is as slow as 20 degrees per hour. At longer curing times the strength gain slows down and then completely ceases.

If we take as a standard of efficiency the ratio of the strength of the steam-treated cement paste to that of the paste hardened under normal conditions for 28 days, this ratio being expressed as a percentage, it may be seen from Table 2 that the best cement for the steam treatment is No. 8—the high alite, low C<sub>3</sub>A cement. The cements high in C<sub>3</sub>A behave in different ways: cement 1 was much more effective for steam curing than cement 3, which is of the same type. Cement 5, of moderate potential C<sub>3</sub>A content, was highly effective. Thus the more C<sub>3</sub>A a cement contains, the quicker it hardens, both under normal conditions and on low-pressure steam treatment.

Let us consider the change of the hydration rate of cements of varying mineralogical composition in the course of time. For a standard unit of hydration rate we will take the increase in the amount of combined water during 1 hour.

Some studies have shown that the highest rate of hydration of cements high in potential C<sub>3</sub>A occurs during the initial period but that in the course of time the rate drops and that by 10 hours it has fallen nearly to zero. The hydration rates of moderate

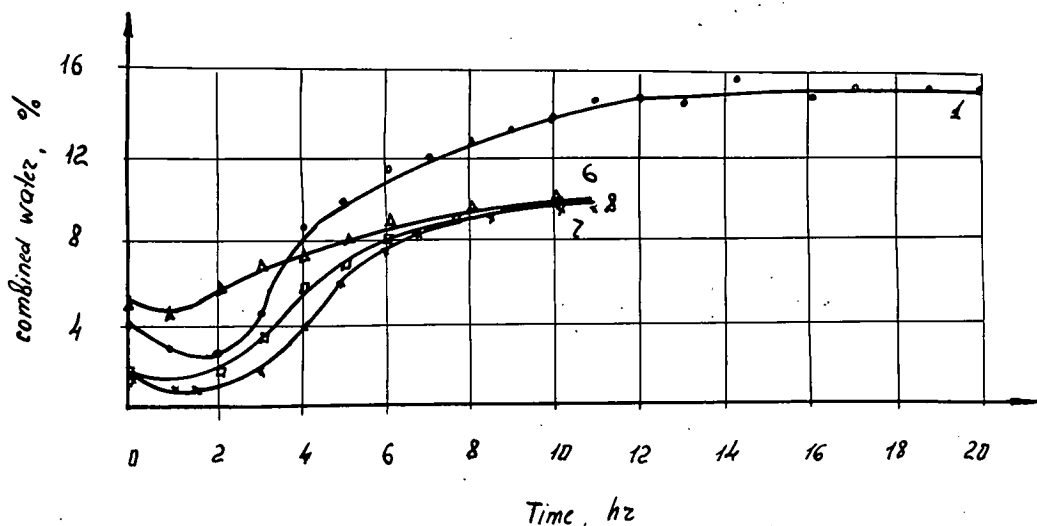


Figure 2. Water combined by cement on steam treatment (cements 1, 6, 7 and 8).

TABLE 2

HYDRATION OF CEMENT PASTES UNDER LOW-PRESSURE STEAM CURING AND NORMAL CONDITIONS

Cement No.	Compressive Strength (kg/sq cm)				Ratio*	Combined Water (percent)				Ratio*
	Steam Curing, 10 hr	Normal Hardening (days)				Steam Curing, 10 hr	Normal Hardening (days)			
		7	28	90			7	28	90	
1	420	380	570	580	74	13.3	3.6	11.4	12.5	117
2	306	280	620	790	50	12.5	1.2	14.3	17.4	87.5
3	240	475	590	605	41	12.3	1.2	15.0	15.1	82
4	230	340	465	475	49.5	13.2	0.5	15.9	16.3	83
5	220	280	390	480	56.5	12.4	1.6	11.5	16.9	107
6	390	405	555	760	70.5	11.4	0.8	14.0	15.4	81.5
7	230	390	520	645	44.4	10.3	4.9	14.4	15.8	72
8	340	345	350	400	97	10.9	1.3	11.8	13.5	93

\* Value for 10-hour steam treatment / Value for 28-day normal curing × 100.

C<sub>3</sub>A, high-alite, and high-alite-high-belite cements, as a rule, increase during the initial period of steam treatment. For different cements this period continues for 2-6 hours. Later on—as soon as the maximum value of the hydration rate is attained—it slows down and, after 10 hours, hydration nearly ceases.

The phenomenon of rapid combination of water in the course of steam treatment can be explained as follows. According to Kalousek (9), during the interaction of clinker minerals with water at high temperature and humidity, the higher the temperature of hardening, the lesser is the amount of gel phase (which he calls "X-phase"). Therefore, with increase of temperature up to 100 C, the ratio of crystalline to gelatinous products increases for any given curing time. But because the gain in strength of the cement paste lags behind the process of combination of water, the acceleration of the hydration process during the steam treatment is probably accompanied by an acceleration of crystal growth. Therefore the crystals would be somewhat coarser and would be surrounded by somewhat smaller amounts of gel in comparison with the product of normal curing. The nucleation of coarser hydrosilicate crystals during the hardening

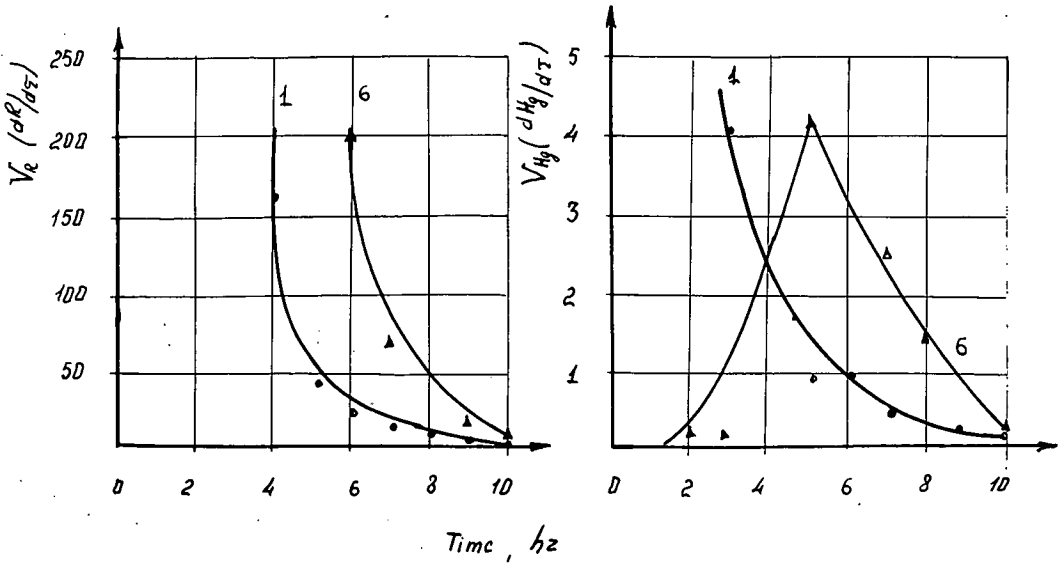


Figure 3. Rate of hydration,  $V_{H_2}$ , and strength gain,  $V_R$ , of cement paste on steam treatment (cements 1 and 6).

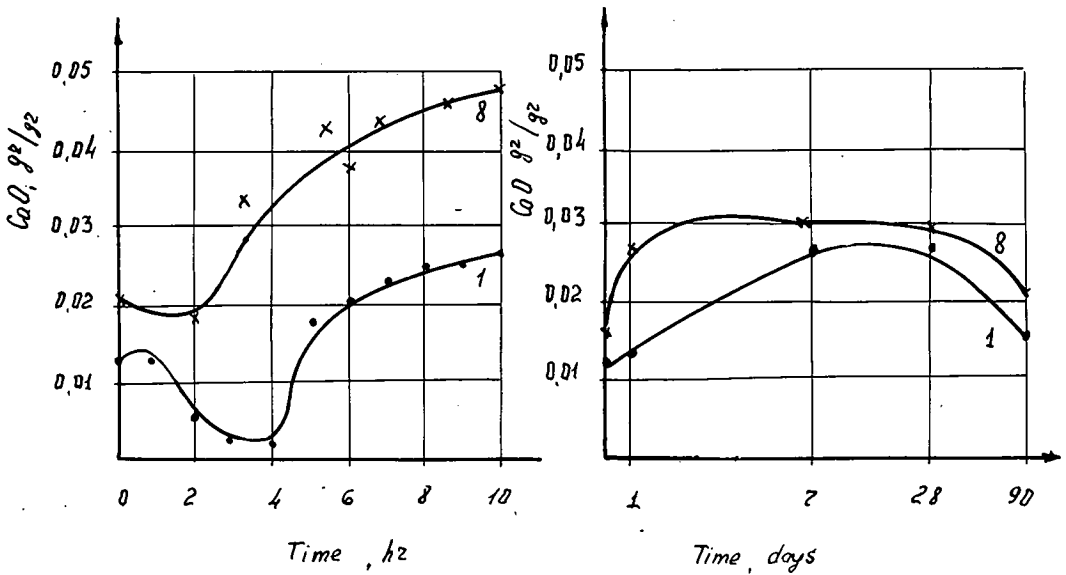


Figure 4. Changes of free CaO content in cement pastes in the process of steam hardening (cements 1 and 8). Left—steam treatment; right—normal hardening.

at elevated temperatures was observed in the course of some other studies (13). The larger size of the crystals and the smaller amount of gel between them contribute to the lower strength of the cement paste.

In cements of varying mineralogical composition the amount of free  $Ca(OH)_2$  in the cement paste during the steam treatment changes in different ways. For example, with

cements 1 and 2 the content of free  $\text{Ca}(\text{OH})_2$  falls during the first 2-3 hours of steam treatment (Fig. 4). The amount of free  $\text{Ca}(\text{OH})_2$  later increases and approaches a steady value by 6-8 hours. It is possible to suppose that at 60-70 C more basic hydration products form at first, which in the course of further heating transform into less basic modifications accompanied by release of  $\text{Ca}(\text{OH})_2$ .

Cements 5 and 7 show retarded release of  $\text{Ca}(\text{OH})_2$  during the first 2-4 hours; afterwards the curves pass through a maximum and later the free  $\text{Ca}(\text{OH})_2$  contents become steady. Toward the end of the steam treatment pronounced binding of free  $\text{Ca}(\text{OH})_2$  by new compounds (probably iron-containing) occurred. During the steam treatment cements 4 and 5 showed slow release of  $\text{Ca}(\text{OH})_2$ . In the high-alite cement 8, having 66.8 per cent  $\text{C}_3\text{S}$ , the release of  $\text{Ca}(\text{OH})_2$  sharply increased after 2 hours' steam treatment (Fig. 4). The slowing down of the process started within 4 hours but nevertheless the  $\text{Ca}(\text{OH})_2$  release continued up to the end of the steaming process. Hence it follows that the higher the content of  $\text{C}_3\text{S}$  in the cement (at low contents of  $\text{C}_3\text{A}$ ), the more free  $\text{Ca}(\text{OH})_2$  is formed in the hardened cement paste. But when cements contain small amounts of  $\text{C}_3\text{S}$  and considerable amounts of  $\text{C}_3\text{A}$ , this last phase retards the release of  $\text{Ca}(\text{OH})_2$ , as is seen in the case of cement 1. In the normal curing of cement, the greatest release of free  $\text{Ca}(\text{OH})_2$  in the cement paste was observed at the age of 28 days. Up to the age of 90 days in all cements the combining of free  $\text{Ca}(\text{OH})_2$  by new compounds took place, due to its sorption by the gel and to chemical interaction with the hydrated phases.

In the course of quantitative determination of free  $\text{SO}_3$  it was discovered that with all cements there first takes place rapid combination of calcium sulfate giving hydrosulfoaluminates, calcium ferrites, and formation of compounds of the trisulfate type. Above 60 C the amount of calcium sulfate in samples starts growing after 2 hours of steam treatment. According to studies by Kalousek (9) and Budnikov (11) this is accounted for by the transition of hydrosulfocompounds into the low sulfate forms; this is accompanied by release of free  $\text{CaSO}_4$  under the influence of high temperature and a liquid phase saturated with  $\text{Ca}(\text{OH})_2$ .

The most rapid strength gain of cement paste on steam treatment occurs during the first 6 hours of hardening. The temperature rise occurs during 3 hours of this time and during the rest of the time the conditions are isothermal. During this period the highest rate of combination of cement and water occurs.

After steam treatment of the cement paste, the strength reaches as much as 40-90 percent of that reached in 28 days hardening under normal conditions. The amount of combined water after steam treatment amounts to 71-117 percent compared with 28 days of normal hardening. Thus with steam treatment the hydration reactions of the cement proceed almost as far as on normal hardening though the strengths of the steam-treated samples are lower. The completeness of chemical processes in cement paste during steam treatment is quite considerable, but during the subsequent hardening, even under the most favorable conditions, the strength gains of steam-treated samples lag behind those of samples hardened at normal temperature. The reason for this lies both in the extent of the chemical processes occurring on steam treatment and in the formation of hydrates of quite different structure. Evaporation of moisture from the concrete is not a factor since the amount of moisture lost does not exceed 10 percent. Since the water contents of concretes are commonly considerably higher than the stoichiometric amounts of water, a 10 percent loss does not influence the hydration process.

Numerous studies have shown that hardening of cements rich in  $\text{C}_3\text{A}$  (over 10%) is a highly accelerated process, provided that the cements are also sufficiently high in  $\text{C}_3\text{S}$ .

It has been found empirically that the most suitable cements for steam treatment are either those of moderate  $\text{C}_3\text{A}$  content or those low in  $\text{C}_3\text{A}$  but high in  $\text{C}_3\text{S}$ . Figure 5 shows the relation between compressive strength of cement paste and water combined by cement in newly formed compounds during steam curing. As is seen, this dependence is linear. The present results show that such cements permit the shortest periods of steam treatment (as, for example, with cement 1).

The most effective steam treatment was obtained with cement 8. Here coincidence of relative strength values and free water contents are obtained (expressed as percentages of the 28-day values), these being 97 and 97.5, respectively. The paste made with this cement had a finer crystalline pattern than was obtained in pastes made with cements of other mineralogical compositions.

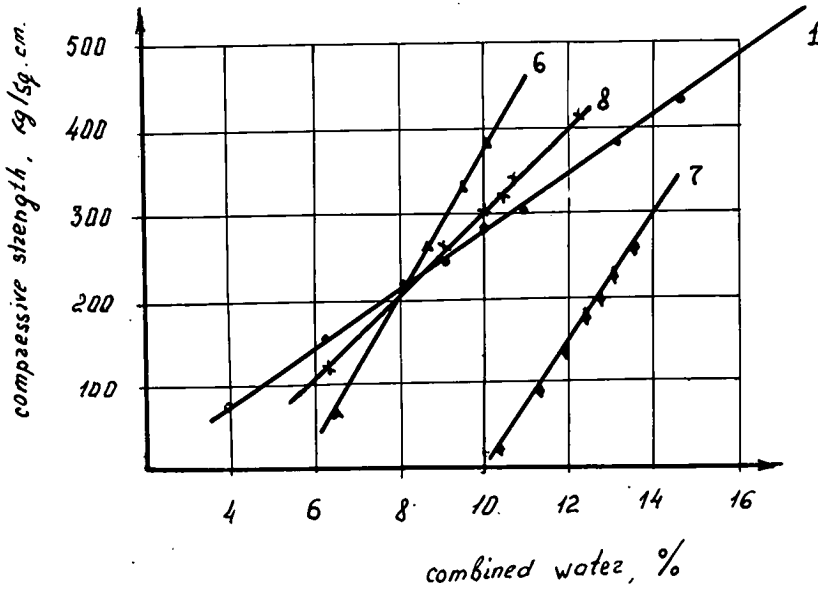


Figure 5. Relation between strength and amount of water combined by cement in the process of steam treatment (cements 1, 6, 7 and 8).

TABLE 3  
MINERALOGICAL COMPOSITION OF CEMENTS

Cement No.	Content of Clinker Minerals, %			
	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF
9	53.07	28.99	2.33	13.50
10	55.00	24.50	2.50	17.30
11	56.85	21.12	9.38	12.02
12	49.48	22.50	11.42	11.88
13	45.15	28.80	12.00	9.85
14	48.13	29.47	12.57	7.63

STUDY OF THE HEAT RELEASE OF PORTLAND CEMENTS DURING STEAM TREATMENT

Several studies have been devoted to the problem of temperature changes of concrete during steam treatment. Some authors point out a dependence between the heat release of portland cement and the hardening temperature (8, 18, 19). It is found that in the course of steam treatment, the exothermal hydration reactions cause a release of heat at early ages and thus raise the temperature of concrete relative to its environment.

In our studies we used some commercial cements with fineness 3000 sq cm/gr and of the mineralogical compositions given in Table 3.

Concrete (1:2:3, w/c = 0.45) and mortar (1:2, w/c = 0.3) samples having volumes of about 1 liter and made with cements of various mineralogical compositions were steam treated at 100 percent relative humidity. It was found that when the temperature of the environment was increased at the rate of 12 deg per hr the temperatures of the samples made with cements 4, 5 and 7 were higher after 2-2.5 hours than those of their environments. Under these conditions the heating rate at the center of a sample was, on the average, 15 deg per hr (Fig. 6a). When the temperature of the environment was increased at a rate of 20 deg per hr the heating rate of the concrete sample midpoint was 13-15 deg per hr, and that of the cement mortar sample 21-23 deg per hr. The sample was held at 80-85 C for 30-60 min; it showed a characteristic type of cracking which, as will be seen later, causes a decrease of strength. The temperature of the concrete rose until it was 7-15 deg higher than that of the environment; afterwards it dropped to the temperature of the environment. All this took place during the first 3-5 hours of isothermal heating. The cooling of the sample was slower than that of the environment, and the more massive the unit, the slower the cooling.

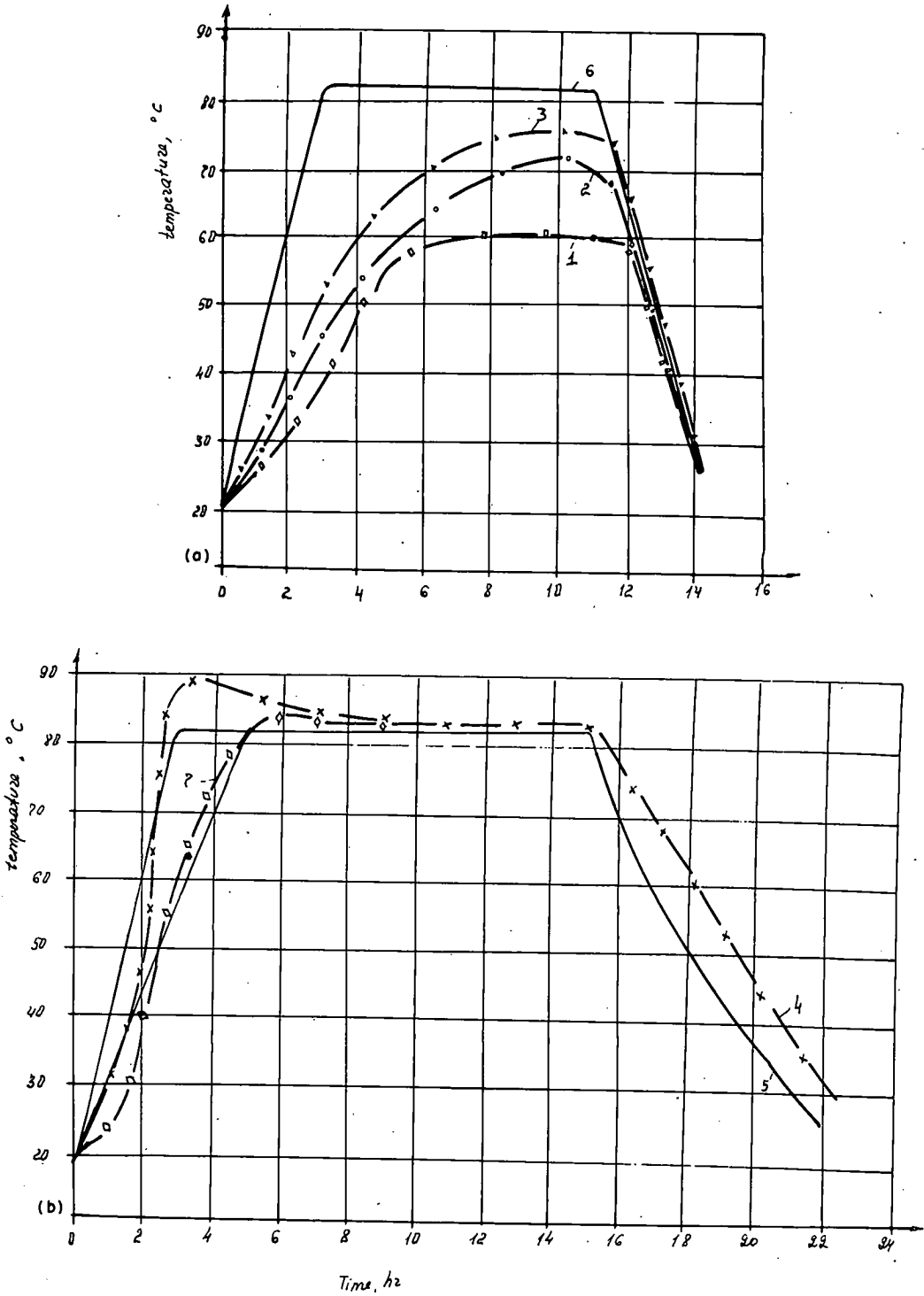


Figure 6. Change in temperature of concrete in the process of heat treatment: a—100 percent relative humidity; b—25-30 percent relative humidity; 1—temperature of the foreign body; 2,4—temperature of the concrete made with cement 10; 3—temperature of the concrete made with cement 12; 5,6—temperature of the environment.

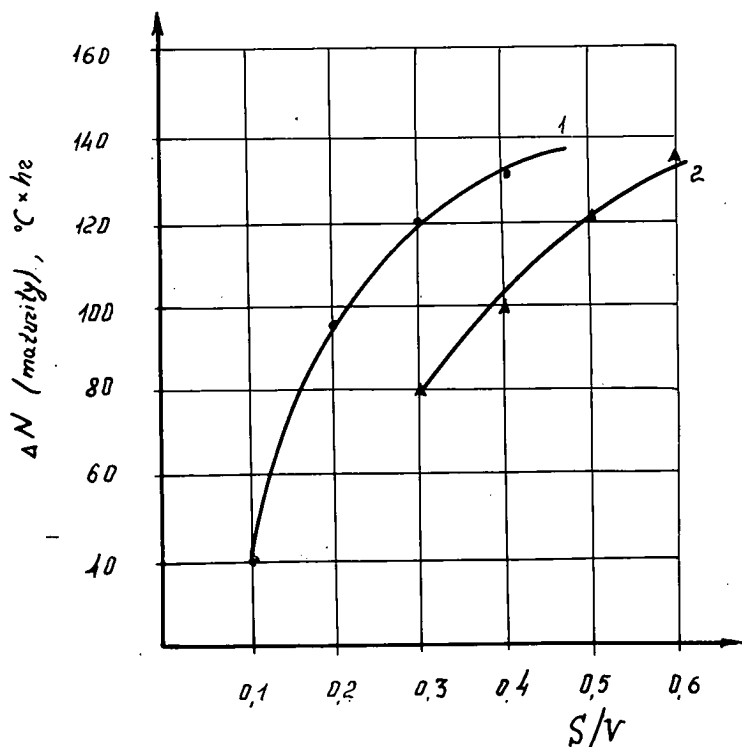


Figure 7. Dependence of heat release on modulus of surface: 1—in concrete; 2—in mortar.

TABLE 4  
HEAT RELEASE VS SIZE OF CONCRETE AND  
CEMENT MORTAR SAMPLES

Sample No.	Sample Composition	W/C	Sample Size (cm)	S/V	Heat Release (deg-hr)
1	1:2	0.40	10×10×10	0.6	136
2	1:2	0.40	15×15×15	0.4	116
3	1:2	0.40	20×20×20	0.3	81
4	1:2:3	0.45	15×15×15	0.4	132
5	1:2:3	0.45	20×20×20	0.3	124
6	1:2:3	0.45	40×40×40	0.14	40

"Heaving" took place only when thin units were steam treated. In the course of rapid steam heating, the heating up of massive concrete units was a slow process, the rate of which differed in various cross-sections of a unit. This is shown by the following result of our experiments.

Various concrete and cement mortar samples made using cement 10 of low  $C_3A$  content, and having sides 10, 15, 20 and 40 cm, were heated. It was found that the times needed to attain equal temperature of sample and environment were 2.5, 3.5, 4 and 6 hours, respectively. The maximum concrete temperature attainable does not depend on the specimen size, however. Insofar as increases of thickness of the sample reduce the rate of heating, the rate of their heat release due to the hydration reactions changes as well.



TABLE 5  
INFLUENCE OF MINERALOGICAL COMPOSITION  
OF CEMENT ON MAXIMUM TEMPERATURE  
REACHED DURING STEAM TREATMENT

Cement No.	Maximum Temperature of Concrete (deg C)
9	94
10	96
14	97
13	107

A measure of the heat released (in deg-hr) by the hydration of cement during the curing cycle can be obtained by integration of the area between the time-temperature curve for the concrete and the time-temperature curve for the environment. To obtain an accurate measure of heat release the integration must be made from the start of the curing cycle to the time that both the sample and environment have cooled to the initial temperature. Table 4 and

Figure 7. show the values of the heat release,  $\Delta N$ , so obtained for samples of different sizes in the course of steam treatment using the 3+12+5-hr curing cycle and a constant heating temperature of 80-85 C and subsequent cooling of samples at room temperature. The size of the specimen was measured by  $S/V$ , the modulus of sample surface.

With increase in thickness of a concrete (or mortar) sample the rate of temperature rise in the sample is decreased; consequently the rate of heat release from the hydration of cement will be decreased. Therefore, for equal durations of steam treatment and equal temperatures of isothermal heating, the thinner a unit is, the more rapid is its growth in strength. As may be seen from the data in Table 5, the mineralogical composition of the cement greatly influences the maximum temperature of a concrete (or cement mix) subjected to steam treatment.

$C_3S$  and  $C_2A$ , which are the clinker minerals with the most exothermic hydration reactions, have a particularly strong influence on the heat release of the cement in the course of steam treatment.

Along with temperature measurements of concrete and cement mortar samples submitted to steam treatment, the temperatures of the center of concrete samples of 1-liter volume were measured during heating in an environment with 25-30 percent relative humidity at temperature 80-85 C. The results of these measurements are contained in Figure 6. Two of the curves on this graph should be compared: No. 1, which is for a "reference foreign body" made from stone flour, sand and water and heated together with the concrete samples, and No. 2, which is for the concrete made by steam treatment at high humidity, using cement No. 10.

When heated in an environment of low humidity the temperature of the concrete always remained lower than that of the environment; this is explained by rapid evaporation of water from the sample throughout the process of heating, the loss of water being 20-30 percent by weight. This is the reason for the drop in strength of a heated concrete as compared with a steam-treated concrete. Heat release nevertheless plays an important role in the rise of concrete temperature for a relative humidity of 25-30 percent.

The temperature of the concrete for a more exothermic cement (No. 12) is higher than that of concrete made with cement 10, and both the curves run higher than the curve for the foreign body.

Temperature distribution in  $40 \times 40 \times 40$ -cm concrete samples of 1:2:3 composition at  $W/C = 0.45$  made with cement 10 were studied. The temperature was measured at 9 points within a sample (Fig. 8); it turned out that the point slowest to be heated was at the center of the sample, while the upper surface cooled most quickly. The part slowest to cool was the core of a sample. It follows that at various periods of steam treatment heat flows in different directions (Fig. 9). Studies showed that on heating a sample to the point where its temperature equals that of the environment, the heat stream is directed away from the environment to the core of the concrete body. During the period of isothermal heating, when the temperature of concrete due to the heat release is higher than that of the environment, the heat stream is directed from the core outwards. This is accompanied by heat transfer from the concrete to the environment. During the period of cooling the same phenomenon occurs, but the amounts of heat release,  $\Delta N$ , in various cross-sections of a sample are different. This leads to some differences in strength between separate parts of a sample.

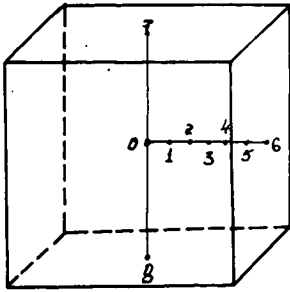


Figure 8. Location of thermocouples in a concrete sample of 40×40×40-cm size for study of heat flow during steam treatment of concrete units.

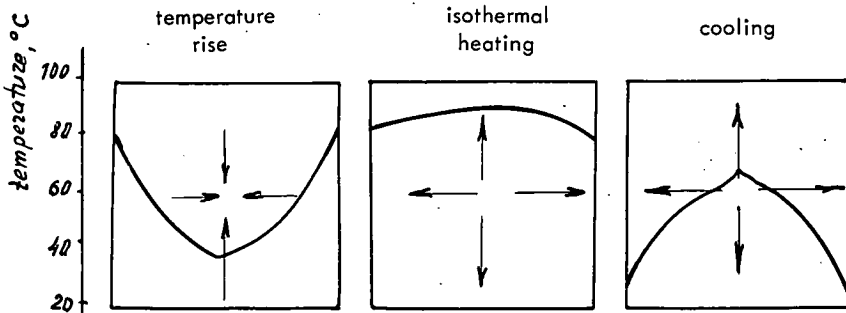


Figure 9. Directions of heat flow in a concrete sample of 40×40 cm cross-section in the course steam treatment.

TABLE 6  
VALUES OF ΔN FOR DIFFERENT POINTS OF A SAMPLE AFTER 24 HOURS OF STEAM TREATMENT

Cycle	Points of Sample								
	0	1	2	3	4	5	6	7	8
0+0+12+0	195	193	246	—	156	234	230	167	96
0+3+12+5	56	92	110	116	126	62	73	—	—

TABLE 7  
HEAT EVOLUTION FOR CEMENTS ON STEAM TREATMENT

Cement No.	Heat Evolution, Cal/Gr	
	WC = 0.2	WC = 0.6
9	54.5	108.9
11	41.6	98.4
14	39.3	79.2

Heat release influences the values of ΔN inside the sample for over 16 hr from the start of steam treatment when the sample is cured by the 0+0+12+0 cycle, and for over 18 hr when the sample is cured by the 0+3+12+5 cycle. Starting from this time the value of ΔN in a sample becomes higher than in the environment. Table 6 gives values of ΔN for different points in the sample. These points are defined in Figure 8.

The greatest heat rise occurs at the points midway between center and surface.

This is explained by the fact that heating is more rapid than near the center, while the temperature increase due to the heat evolution is almost the same as in the center but

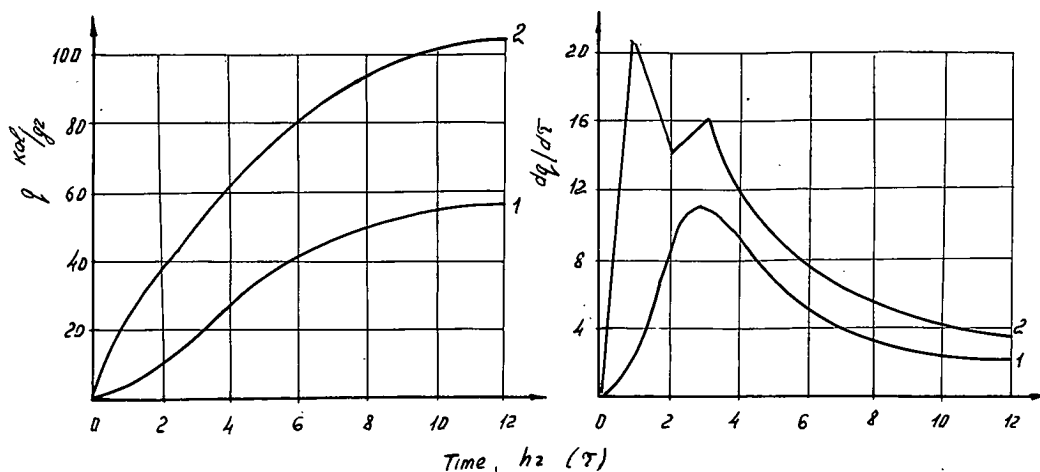


Figure 10. Heat evolution and rate of heat evolution for steam treatment of mortar samples of 1:2 composition made from cement 9: 1—W/C = 0.3; 2—W/C = 0.6.

higher than at the surface. On cooling, when the heat flow is directed from the core to the surface, these regions take up more heat than others.

Because of these considerations, when hardening massive concrete units it is possible to select curing cycles different from those used for thin-walled ones. For example, for massive units it is quite allowable, in our opinion, to have more rapid heating and cooling and a shorter isothermal heating period. To gain the same strength for thin-walled units, it is necessary to employ gradual heating and cooling and more prolonged isothermal heating.

Studies of heat evolution in mortars made with cements 9, 11 and 14 using steam treatment for 19 hours were conducted (Fig. 10). It was found that increase in W/C from 0.3 to 0.6 almost doubled the total amount of heat evolved (Table 7).

Increase in heat evolution depending on increase in the amount of water used and the fineness of the cement has been observed by a number of investigators. It can be explained by a more complete contact between the reactants in the paste at high water contents.

It follows from our study that the most rapid heat release takes place during the first 2-3 hr of the heating of the cement paste. Then the rate of heat evolution drops, this drop being particularly sharp between 4 and 8 hr; by 10 hr the heat evolution has practically ceased. With 2 and 4 hr or more prolonged curing of the cement mortar before steam treatment it was discovered that the lowest heat evolution was observed at 4 hr of preliminary curing at normal temperature. The reason for this is that on hardening a cement at normal temperature, the maximum evolution of heat occurs in the first 4-6 hr after the mortar is mixed. Since steam treatment in our studies started some time later, this heat remained unmeasured.

The cements studied had the following setting times: initial—not later than 1 hour; final—5 hours.

#### STUDY OF GAIN IN STRENGTH OF CONCRETE ON STEAM TREATMENT

These questions have been most completely elucidated in monographs by Mironov and others (20, 21, 22).

Studies of steam and "dry" treatments of concretes made with cements of various mineralogical compositions and of concrete mixes of low plasticity have proved that the rate of rise on steam treatment should not exceed 20 deg per hr; the strengths do not depend on the cooling rate. The duration of isothermal heating at 80-85 C for concretes made with cements low in potential  $C_3A$  is 6-8 hr. Prior to steam treatment it

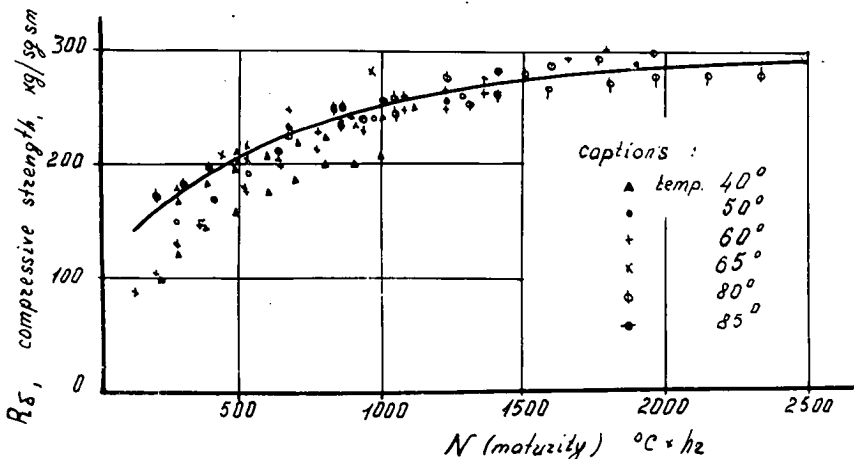


Figure 11. Relation between strength of a concrete made with cements of moderate C<sub>3</sub>A content and and the value of N in degree-hours (with 11.6 C correction).

is worthwhile to submit concretes to 4 hr of curing, as this increases the strength by 20 percent. Moreover, this preliminary curing may reduce the length of time needed during which the temperature of the environment must be raised.

The optimum temperature of isothermal heating for steam treatment of low-plasticity concretes made with cements of moderate C<sub>3</sub>A content is in the range of 60-70 C. Such concretes gain 55-78 percent of the 28-day strength as a result of such treatment.

Some workers consider the strength of concrete to be a function of the heat it takes up during hardening, this function being expressed in degree-hours. Various equations have been used to represent this function. We have conducted an experimental test of Plowman's formula (28). Figure 11 shows the strength of concretes made with cements of moderate C<sub>3</sub>A content as a function of N, the product of curing temperature and time in degree-hours. The fact that the temperature of the concrete is higher than that of the steam-air environment during some periods of the steam treatment is ignored.

As seen from Figure 11, most of the experimental points for strength of concrete plotted as a function of ΔN lie close to a median curve over the range from 500 to 1500 deg-hr. The points for concretes cured at 40 C and 60 C for 2-4 hours seem to follow a different relationship.

The most convenient way to express the strength, R<sub>s</sub>, of steam-treated concrete is as a percentage of its strength at 28 days on normal hardening. The equation of the curve in Figure 11 has the form

$$R = \alpha + \beta \log N \tag{1}$$

The equation for the relative strength as percentage of 28-day strength, R', is:

$$R' + A + B \log \frac{N}{1000} \tag{2}$$

where α, β, A and B are coefficients that depend on the composition of the cement and concrete, and N is maturity, expressed in degree-hours, counted from a base temperature of 11.6 C.

Figure 12 is drawn on the basis of the experimental data. One can see from the figure that the relative strength of the concrete is proportional to log N/1000 over the same range of values of degree-hours, the scatter of experimental points being the same as before.

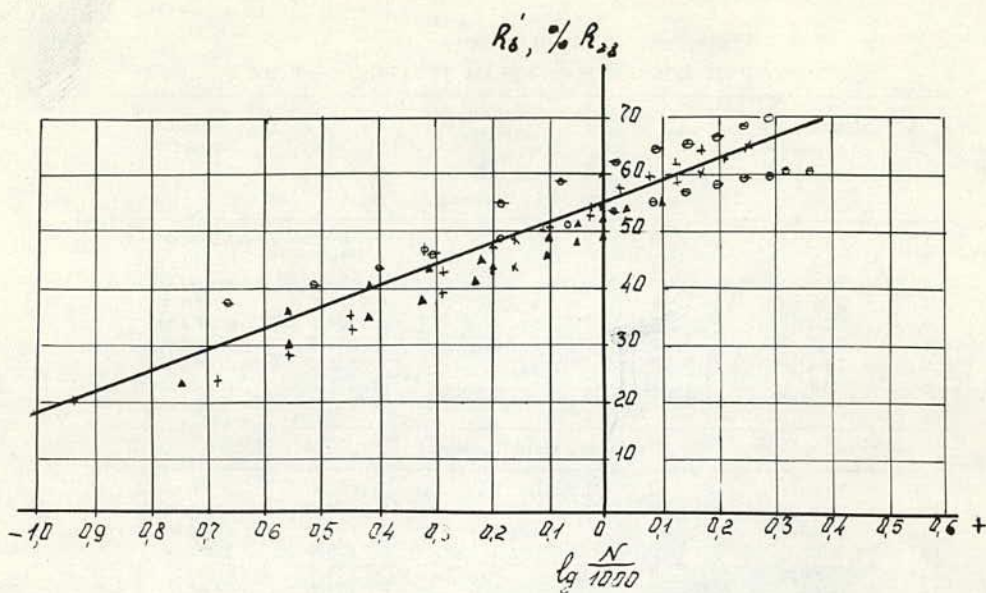


Figure 12. Relative strength of concrete ( $R'$ ) made with cements 16 and 17 expressed as a function of the number of degree-hours on a logarithmic scale.

TABLE 8  
CALCULATION FOR RELATIVE  
STRENGTH OF CONCRETE

N	$\log \frac{N}{1000}$	Values of $R'$	
		Calculated	Actual
600	-0.222	46.7	43.47
800	-0.098	51.0	45.51
1100	+0.042	53.0	54.57
1300	+0.124	58.9	58.61
1600	+0.240	63.0	59.65



Figure 13. Cracking in concrete due to rapid heating.

To define the coefficients  $A$  and  $B$  of Eq. 2, it is necessary to make some simple arithmetical solutions. The easiest way to define coefficient  $A$  is graphically. Its meaning corresponds to the length of a section cut by the straight line on the strength axis; thus  $A = 54.5$ .

To define coefficient  $B$  let us take some values of  $\log N/1000$  and find the corresponding values of  $R'$  with the help of Figure 10. Using these data we calculate the value of  $B$  to be 35.3. Eq. 2 then takes the form:

$$R' = 54.5 + 35.3 \log \frac{N}{1000} \quad (3)$$

To test the values of the coefficients  $A$  and  $B$ , the relative strength  $R'$  is calculated for a concrete in the range of 600-1600 deg-hr in Table 8. This range is the one of

TABLE 9  
STRENGTH OF CONCRETE ON STEAM TREATMENT AT 100 C

No.	Consistency of Concrete	Preliminary Curing (hr)	Isothermal Heating (hr)	R (kg/aq cm)	Sample Appearance
(a) Open Mold Hardening					
1	Plastic	0	2	57.2	All samples
2	Stiff	0	2	59.0	had heaved
3	Plastic	0	4	95.0	and were
4	Stiff	0	4	126.0	covered
5	Plastic	2	2	89.0	with a net
6	Stiff	2	2	145.0	of horizon-
7	Plastic	2	4	121.0	tal deep
8	Stiff	2	4	184.0	cracks, sur-
					face scaling.
(b) Sealed Mold Hardening					
9	Plastic	0	2	93.0	No heaving
10	Stiff	0	2	99.0	of samples,
11	Plastic	0	4	150.0	separate
12	Stiff	0	4	205.0	hairline
13	Plastic	2	2	124.0	cracks, no
14	Stiff	2	2	182.0	scaling.
15	Plastic	2	4	156.0	
16	Stiff	2	4	212.0	

TABLE 10  
DIFFERENCE IN STRENGTH  
OF CONCRETES

Steam Curing Cycle*	Plastic (%)	Stiff (%)
0+0+2+0	63	68
0+0+4+0	58	51
2+0+2+0	40	26
2+0+4+0	29	15

\*Pretreatment; heating, isothermal heating (steam curing), cooling.

greatest practical importance. The coefficients found make it possible to calculate values of the relative strength of concrete, in the form of mean values, which correspond to the mean curve in Figure 12. (These coefficients are valid for cements containing 8-10 percent  $C_3A$ .) Eq. 3 can be used to calculate either the curing time needed to produce a concrete, or its expected strength.

Various cycles of dry heating of concrete were studied along with the steam treatment. It was found that when heating concrete in an environment of low relative humidity (25-30 percent for isothermal

heating and 70-30 percent for heating and cooling), its strength depends on neither the heating nor the cooling rates; it is a function only of the general duration of heating.

The optimum duration of isothermal heating at 80-85 C is 8 hr for concretes made with cements high in  $C_3S$  and  $C_3A$ , or up to 12 hr for concretes made with cements high in  $C_3S$  and low in  $C_3A$ . The optimum duration of curing before heating is 10-12 hours.

The strength of dry-heated concrete, as compared with the steam-treated product, is lower, on the average, by 25 percent. However, with dry heating, in contrast to steam heating, no drop of strength due to heaving is observed.

A characteristic type of cracking takes place as a result of the deterioration of structure of freshly molded concrete due to rapid heating. A great number of deep horizontal cracks form, especially at the surface (Fig. 13). The surface of the concrete in such a case is uneven and scaly. The cracking occurs because of the sharp swelling of the liquid phase, either in concrete or in mortar, on rapid heating at a time when the cement paste is of plastic consistency and has not yet acquired the necessary strength to withstand the tensile stresses which arise.

To test the above assertions, studies of plastic and low-plastic concretes were conducted, both being made with cements of moderate  $C_3A$  content. These concretes had the following compositions (by weight): plastic—1:2:3,  $W/C = 0.45$ ; stiff—1:1.25:3.7,  $W/C = 0.4$  (placing time according to technical viscosimeter data was 55 sec). The samples were steam treated at a constant heating temperature of 100 C. The cycles of hardening and the strength values obtained are given in Table 9. Half of the specimens were hardened in open molds while the second half were hardened in closed molds under a load. Steam treatment was performed with no rise and fall of temperature. The specimens were tested after an hour of steam treatment.

Table 9 shows that the drop of strength due to heaving is less in stiff mixes compared with plastic ones, thus proving the hypothesis mentioned earlier concerning the reasons for heaving. The difference in the strength values of concretes (in percent of the strength of concrete cured in the open mold) for the same curing cycle is given in Table 10.

The absence of both cracking and heaving when hardening in sealed molds can be explained by the pressure of an additional load (in the form of a sheet of rubber) which helps plastic cement paste to resist tensile stresses caused by a liquid phase expanding on rapid heating.

### CONCLUSIONS

The studies conducted make possible the following conclusions.

1. Portland cements containing near 45 percent  $C_3S$  and near 10 percent  $C_3A$  should be considered the most suitable for low-pressure steam treatment of concrete.

2. Steam treatment causes not only a more rapid gain in strength of the cement paste, but also speeds up the combination of water by cement into new compounds, the results being near to those of 28 days of normal curing.

3. In the course of steam treatment, formation of hydrosulfocompounds in cement paste takes place up to 60 C. At higher temperatures these are transformed into compounds of a lower sulfate content, and release of free calcium sulfate takes place.

4. The highest rate of all the hardening processes is observed during the first 3-4 hours for cements high in  $C_3A$ , and in the first 5-6 hours for cements high in alite and of moderate  $C_3A$  content. At 8 hours of treatment, deceleration of all the processes is observed and by 10 hours their rate drops to zero. The maximum rate of heat evolution is observed in the first 2-3 hours of steam treatment.

5. Steam treatment causes the formation in the paste of more coarsely crystalline hydrates compared with those produced on normal hardening.

6. In order to obtain the maximum possible strength of a concrete on steam treatment, the rate of heating should not exceed 20 C per hour. The rate of cooling does not influence the strength of the concrete. The duration of isothermal treatment should be 10-12 hours for concretes made with cements low in  $C_3A$  and 6-8 hours for those made with cements of moderate  $C_3A$  content. This assumes isothermal treatment at 80-85 C. The reasonable term of curing concretes prior to steam treatment is up to 4 hours; this provides for a 20 percent increase in their strength.

7. With massive concrete units it is possible to use more rapid heating rates, provided the period of isothermal heating is reduced, while for thin units it is advisable to have gradual heating and cooling and more prolonged isothermal heating.

8. For concretes of plastic mixes made with cements of moderate  $C_3A$  content, the most favorable temperature of isothermal heating on steam treatment is in the range of 60-70 C.

### REFERENCES

1. Budnikov, P. P., and Erschler, E. Ya. Doklady Akad. Nauk S. S. S. R., Vol. 155, No. 4, 1964.
2. Budnikov, P. P., Gorshkov, V. C., and Khmelevskaya, G. A. Stroitelnie Materialy, No. 5, 1960.
3. Butt, Yu. M., and Rashkovich, L. I. Tverdenie vyazhushchikh spri povishchennikh temperaturakh. Gosstroizdat, Moscow, 1961.

4. Berkovich, T. M. Doklady Akad. Nauk, S. R. S. R., Vol. 133, No. 5, 1960.
5. Kravchenko, I. V., and Vlasova, M. T. Trudy Instituta NIITsement, No. 8, 1960.
6. Strelkov, M. I. Trudy Soveshchaniya po Khimii Tsementov. Promstroizdat, Moscow, 1956.
7. Nurse, R. W. Building Research Congress, Vol. 86, No. 2, 1956.
8. Saul, A. J. A. Mag. of Concrete Research, No. 6, p. 127, 1951.
9. Kalousek, G. L., and Adams, M. Jour. ACI (Proc.), Vol. 25, No. 1, 1951.
10. Taylor, H. F. W. Fourth Internat. Symposium on Chem. of Cement, Washington, 1960. Proc.
11. Powers, T. C. Cement and Lime Manufacture, Vol. 29, No. 2, 1956.
12. Powers, T. C. Fourth Internat. Symposium on Chem. of Cement, Washington, 1960. Proc.
13. Budnikov, P. P., Royak, S. M., Malinin Yu. S., and Mayants, M. M. Doklady Akad. Nauk S. S. S. R., Vol. 148, No. 1, 1963.
14. Budnikov, P. P., and Gorshkov, V. C. Zhurnal Prikladnoi Khimii, Vol. 33, No. 1, 1960.
15. Rastrup, E. Mag. of Concrete Research, No. 7, 1954.
16. Handcock, M. G. Mag. of Concrete Research, Vol. 7, No. 20, 1955.
17. Zasedatelev, I. B. Povishenie Effektivnosti Teplovlazhnostnoi Obrabotki Sbornogo Zhelezobetona. TsBTI, Minstroya, 1957.
18. Malinovskii, R. Trudy Soveshchaniya po Khimii Tsementov. Promstroizdat, Moscow, 1956.
19. Poss, A. W. Proc. Inst. of Civil Engineers, Vol. 5; No. 6, Part 1, 1956.
20. Maryamov, N. B. Sbornik Trudov Instituta NIIzhelezobeton. Gosstroizdat, Moscow, 1959.
21. Mironov, S. A. Temperaturnii Faktov v Tverdenii Betonov. Gosstroizdat, Moscow, 1948.
22. Mironov, S. A., and Malinin, L. A. Uskorennoye Tverdenie Betona. Gosstroizdat, Moscow, 1961.
23. Graf, O. Betonstein-Zeitung, No. 4, 1957.
24. Shideler, J., and Chamberlin, W. Jour. ACI, Vol. 21, No. 4, 1949.
25. Reinsdorf, S. Silikattechnik, No. 11, 1959.
26. Skramtae, W. B. G., and Fal'kov, I. P. Sbornik Predvaritel'noye Napriyazhenie Zhelezobetonnikh Konstruktsii. Stroizdat, Moscow, 1947.
27. Vdov'eva, V. C. Byulleten Stroitelnoi Tekhniki, No. 11, 1950.
28. Plowman, J. M. Mag. of Concrete Research, Vol. 8; No. 22, 1956.