STUDYING THE DIFFUSION OF MOISTURE BY EXAMINING THE KINETICS OF HARDENING OF HIGH-STRENGTH CONCRETE FOR VARIOUS MEANS OF HEAT AND MOISTURE TREATMENT

L. Ya. Volosyan and V. P. Zhuravleva

UDC 532.72:536.248:666.97

We present results from an investigation into the diffusion of moisture in high-strength concrete during the hardening of the latter in processes of heat and moisture treatment in an electromagnetic field and in a vapor medium.

The processes of heat and mass transfer form the physical basis of the technology involved in the heat treatment of capillary-porous materials, in particular, of cement concrete. To calculate and control the transfer processes, we have to know the transfer coefficients and we have to determine the mechanism by means of which moisture and water-soluble substances are displaced in the kinetics of structural concrete formation. The transfer coefficients characterize the processes of internal heat and mass transfer in the phase and chemical conversions which take place in hardening concretes.

The transfer of mass in the hardening of concrete can be characterized by the coefficient a_m of moisture diffusion and the relative coefficient δ of the thermal diffusion of moisture. These coefficients have not been adequately studied for concrete that has hardened, and they have not been determined at all for the process of concrete hardening. In part, this can be explained by the difficulties which arise in the determination of stratified moisture contents. Existing methods of determining moisture content by a gravimetric method for such rheological media as a hardening concrete are not suitable, because of the variation in the porous structure which is in a process of formation, i.e., undergoing continuous change, as the specimens are mechanically separated into their separate layers. Moreover, with this approach of determining the moisture content, the specified regime of heat and moisture treatment is disrupted, since the test specimens – under the conditions of the experiment – must be removed repeatedly from the chamber so that they can be weighed.

To eliminate these experimental difficulties, we used a radiometric method of determining local moisture contents. The method and its technique are described in detail in [2]. The immediacy of this project is borne out by the fact that the Institute of Heat and Mass Transfer of the BSSR Academy of Sciences has spent many years in thoroughly investigating the quantitative relationships governing the transfer of heat and moisture in the processes of concrete heat treatment in an electromagnetic field [3-5].

It was assumed that we had to determine the moisture-diffusion coefficients for hardening concrete and cement solutions in the various methods of heat and moisture treatment. A special installation was developed for this purpose to permit heat and moisture treatment in an electromagnetic field and in a water-vapor medium [2].

We used reinforced specimens with dimensions of $150 \times 150 \times 60$ mm in the tests. The reinforced specimens were made up of two grids (with a cell spacing of 50×50 mm) of St. 3 steel, 6 mm in diameter. The compositions of the concrete and the solution are given in Table 1.

The specimens were subjected to heat and moisture treatment in metallic molds formed of five sides; the moisture was evaporated from the upper surface, i.e., we were dealing with a one-dimensional mass-transfer problem.

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 16, No. 3, pp. 448-455, March, 1969. Original article submitted September 23, 1968.

TABLE 1. Composition of the Concrete and Cement Solution

Material designation	Composition by weight, %			
	grade 500 cement	sand with size modulus 2.0	rubble fraction 5-10 mm	water
Ordinary heavy concrete	22,7	23,5	44,3	9,5
Cement solution	39,8	45,7	—	14,5

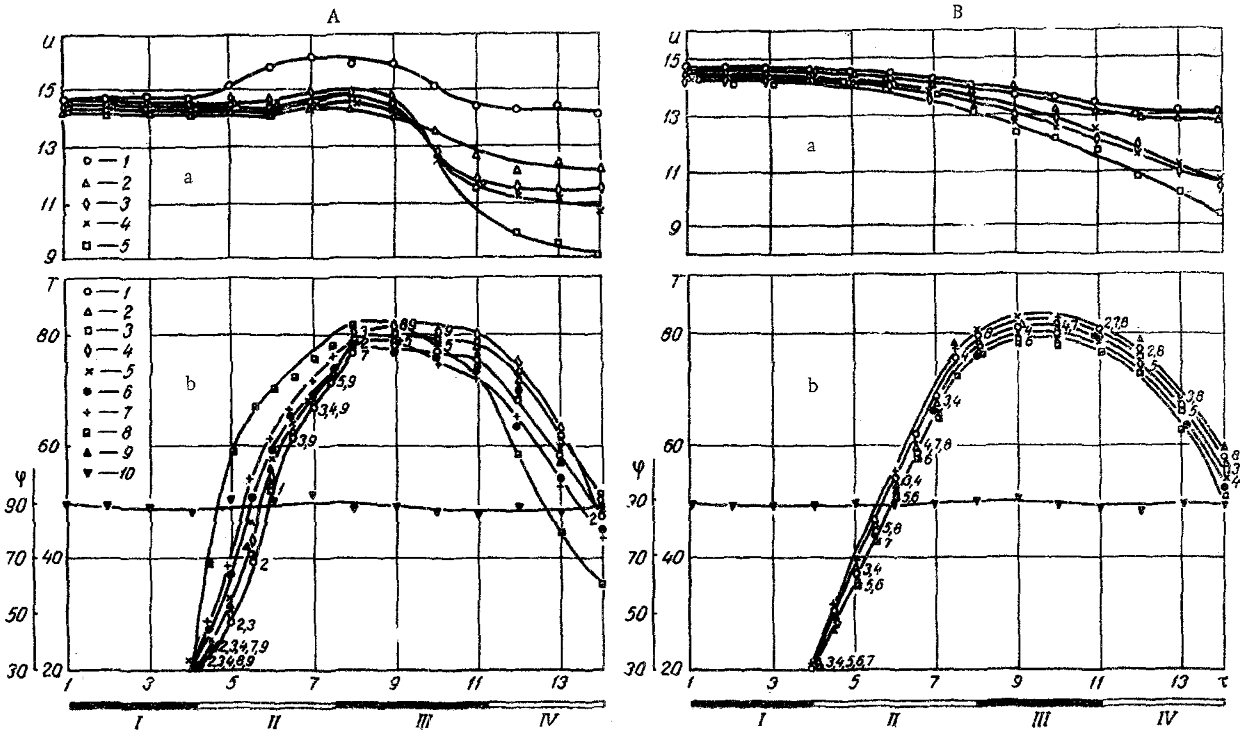

Fig. 1. Curves for the kinetics of the process of treating a cement solution (A – vapor-heat treatment; B – heat treatment in an electromagnetic field); a) distribution in time of local moisture contents: 1) 1st layer, the bottom; 2) 2; 3) 4; 4) 5; 5) 6 (the upper layer); b) time variation for the temperatures in the specimen and for the relative humidity of the medium in the chamber: 1) temperature of the 1st layer; 2) 2; 3) 3; 4) 4; 5) 5; 6) 6; 7) temperature of the bottom of the planking; 8) the temperature of the medium in the chamber; 9) the temperature of the reinforcing material; 10) the relative humidity of the medium in the chamber; I) dwell time prior to heat treatment; II) period of rising temperatures; III) period of isothermal treatment; IV) period of declining temperatures.

The local moisture contents were determined by illuminating the various layers of the specimens (Fig. 2II) by moving the specimens on a special platform, from top to bottom, with each layer placed on the axis of a collimated beam of gamma quanta, the accuracy having been fixed at ±0.3 mm. A thulium-170 isotope was used as the source.

From these experiments we obtained the curve for the kinetics of the process of heat and moisture treatment of concrete and the cement solution. Figure 1A shows the curves of the change in moisture content and temperature in specimens of the cement solution during the process of heat treatment in a water-vapor medium, while Fig. 1B shows the curves for heat treatment in an electromagnetic field whose intensity is 200 Oe, in a regime of 4 + 4 + 3 + 3 h. Similar kinetic curves have been derived for the concrete specimens [2].

It follows from Fig. 1 that the temperature difference across the thickness of the material during the period of the isothermal treatment is insignificant and amounts to 3-4°C.

As is well known, in the region near the initial moisture content of the concrete the relative coefficient δ of thermal moisture diffusion tends toward zero. During the period of isothermal treatment of the

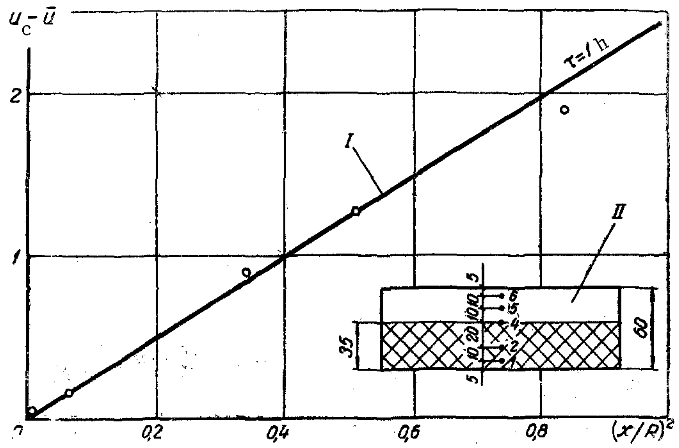

Fig. 2. Distribution curves for the moisture content $\bar{u}$ (I) through the cross section of the specimen (II): 1, 2, 4, 5, 6) number of the layers.

concrete, its moisture content is close to that at the beginning. The Posnov criterion $Pn = \delta\Delta T/\bar{u}_0$ can therefore be neglected. It must therefore be assumed that the potential of moisture transfer in this case is the moisture-content gradient. It is this circumstance that makes it possible to determine the coefficient a_m of moisture diffusion in the concrete during the process of its hardening (during the period of isothermal treatment), employing the method of calculating the coefficients of moisture transfer from the curves of the heat-treatment kinetics. The working formulas for the determination of the transfer coefficients have been derived from an approximate solution of the system of nonlinear differential equations of heat and mass transfer in capillary-porous materials for the case of one-dimensional flows of heat and moisture. Here an assumption was made as to the parabolic distribution of treatment and moisture content in the material [6]. This method is characterized by the fact that it makes it possible to calculate the transfer coefficients, regardless of the manner in which the heat is supplied.

As was pointed out above, the moisture content u was measured in five layers, through the thickness of the plate. It was difficult to determine $\bar{u}$ on the basis of these measurements (the mean integral moisture content of the entire plate) and also to determine $\bar{u}_1$ (the mean integral moisture content of the bottom layer of the plate); the thickness of the lower layer was assumed to be 35 mm. We can use the following calculation method for this purpose.

We will use the above-cited assumption as to a parabolic distribution of the moisture contents through the cross section of the material:

$$u = u_s - \frac{x^2}{R^2}(u_s - u_c). \tag{1}$$

This assumption is in good agreement with the experiment. Indeed, having plotted $u - u_c$ as a function of x^2/R^2 (Fig. 2I), we see that the points line up on the straight line passing through the coordinate origin.

It is demonstrated in the work of Luikov [1] that with a parabolic distribution of the moisture content the volume-averaged moisture content $\bar{u}$ is equal to

$$\bar{u} = u_s - \frac{N}{\psi}(u_s - u_c), \tag{2}$$

where N is a constant numerical coefficient which is equal to 1/3 for a plate; the coefficient ψ is calculated from the formula

$$\psi = \frac{\left(\frac{x_1}{R}\right)^2 + \left(\frac{x_2}{R}\right)^2 + \cdots + \left(\frac{x_5}{R}\right)^5}{5}. \tag{3}$$

We used formula (2) to calculate the values of $\bar{u}$ for a plate with a thickness of h = 60 mm and we used that formula to calculate $\bar{u}_1$ for the bottom layer of the plate, whose thickness was $\bar{h}_1$ = 35 mm, both for the cement solution and the concrete, treated by electromagnetic and convection method.

TABLE 2. The Kirpichev Number Ki_m as a Function of the Mean Integral Moisture Content $\bar{u}$

Material	Method of speeding up hardening	$\bar{u}$	$\bar{u}_1$	Ki_m
Ordinary heavy concrete	electionagnetic heat treatment	0,072	0,0770	0,120
		0,076	0,0808	0,115
		0,080	0,0846	0,110
		0,084	0,0882	0,100
		0,088	0,0920	0,096
		0,092	0,0958	0,091
		0,094	0,0974	0,081
	Vapor–heat treatment	0,089	0,0910	0,0473
		0,091	0,0926	0,038
		0,093	0,0944	0,033
		0,095	0,0963	0,031
		0,097	0,0982	0,028
		0,099	0,1001	0,026
		0,101	0,1020	0,024
Cement solution	electionagnetic heat treatment	0,130	0,1349	0,0526
		0,132	0,1367	0,0505
		0,134	0,1382	0,0450
		0,136	0,1397	0,0400
		0,138	0,1408	0,0300
		0,140	0,1422	0,0237
	Vapor–heat treatment	0,124	0,1276	0,0423
		0,126	0,1295	0,0412
		0,128	0,1314	0,0400
		0,130	0,1332	0,0376
		0,132	0,1350	0,0353
		0,134	0,1366	0,0306
		0,136	0,1384	0,0282
		0,138	0,1400	0,0235

On the basis of the data calculated in this manner we constructed the graphical functions $\bar{u}(\tau)$ and $\bar{u}_1(\tau)$. The values of $\bar{u}$, taken from these graphs, have been compiled in Table 2. With the use of the formula

$$a_m = -\frac{d\bar{u}}{d\tau}\frac{(R^2 - R_1^2)}{6(\bar{u}_1 - \bar{u})} \tag{4}$$

from these data we have calculated the coefficient of moisture diffusion. The derivative $d\bar{u}/d\tau$ was found for the period of a constant rate of moisture-content loss to be the slope of the tangent to the curve $\bar{u} = f(\tau)$ with the axis of abscissas. The difference between the moisture content of the bottom layer of the specimen and that of the entire specimen, i.e., $\bar{u}_1 - \bar{u}$, was found graphically for a specified instant of time from the magnitude of the ordinate segment enclosed between the curves $\bar{u} = f(\tau)$ and $\bar{u}_1 = f(\tau)$. The quantity $R^2 - R_1^2$ was found to be the difference between the squares of the thickness for the entire specimen and that of the lowest layer of the specimen.

The values of the moisture-diffusion coefficient for the concrete and the cement solution, as functions of the variations in moisture content during the hardening process, are given in Fig. 3a, b.

The figure shows that both for the cement solution and for the concrete hardening during the process of vapor-heat treatment, the $a_m(\bar{u})$ curve is located above the corresponding curve, obtained in the electromagnetic heat treatment. This is yet another confirmation of the fact that a more disperse and denser material structure is formed in the electromagnetic method of heat treating the concrete and the solution than is the case for concrete and for the cement solution that are produced by vapor-heat treatment. It also follows from Fig. 3 that the $a_m(\bar{u})$ curves for concrete treated in various ways lie in somewhat different moisture-content regions. This indicates that when the concrete is subjected to heat and moisture treatment in an electromagnetic field it loses some of its moisture content, beginning with the period of a rise in temperature, whereas in the case of a vapor-heat treatment the moisture content increases during this period. This last circumstance is explained by the difference in the mass and heat transfer mechanism of the processes of heat treating the concrete in various ways. In analyzing the kinetic curves and in examining the mechanism of mass and heat transfer it should be noted that the basic disruptions of the forming structure during periods II and III (Fig. 1A) occur as a result of the appearance of excess pressures within the pores of the material, as a consequence of moisture migrations. During this stage of hardening the diffusion of the moisture in the concrete – which is in a plastic-viscous state, gradually changing into the elastic-brittle state of a moist capillary-porous material – proceeds in the direction of the heat flux.

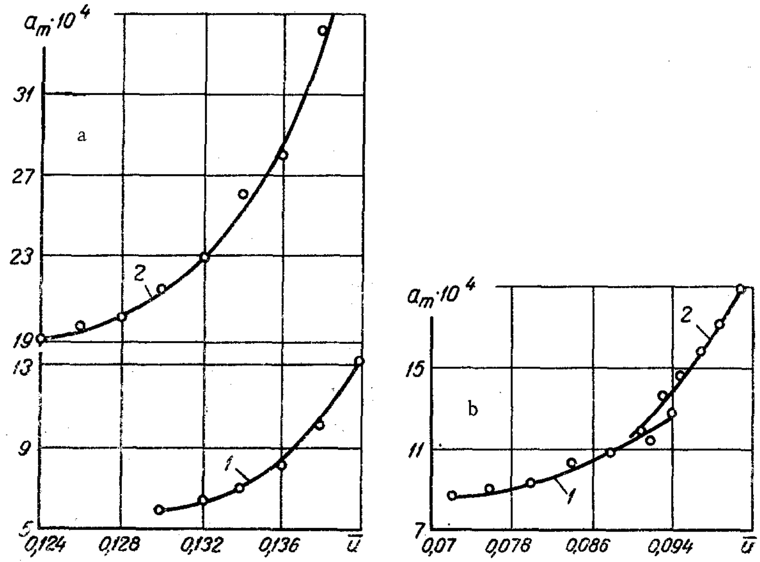

Fig. 3. Moisture-diffusion coefficient a_m as a function of the moisture content of the cement solution (a) and of that of the concrete (b): 1) electromagnetic heat treatment; 2) vapor-heat treatment.

In the case of vapor heat treatment the flow of heat at the beginning is directed from the outside to the inside of the reinforced concrete product. The water-vapor condensate which thus forms at the surface of the item migrates to the inside of the concrete, exerting a destructive effect on the skeleton of the forming structure of the cement stone, which is not yet sufficiently strong. It is natural that the surface layers of the concrete are subject to particularly strong action of this type.

As follows from the experimental data, with this procedure for the supply of heat there is an increase in the moisture content of the cement solution (Fig. 1Aa) and for the concrete [2] in comparison with the initial moisture content $\bar{u}_0$. This leads to an increase of the internal pressures that have not been relieved by the displacement of the moisture. With an increase in the moisture content and in the internal excess pressures a volume stressed state arises, with tensile and shearing stresses resulting in the deformability of the concrete structure and in the appearance of microcracks.

Toward the end of period III, in the case of vapor heat treatment, when the internal liberation of heat in the concrete – as a consequence of the cement hydration reaction – reaches its maximum, the flow of heat, as well as the flow of moisture, reverse direction, i.e., from the inside to the outside. It is precisely during this period that there is an increase in the rate of moisture migration.

The transport mechanisms for heat and moisture in the heat treatment in an electromagnetic field are fundamentally different in nature. From the very beginning and to the very end of the temperature regime, the flow of heat is directed from the inside to the outside of the specimens. There is no condensate formation nor any migration of the moisture to the inside of the concrete. The magnitude of the internal excess pressures in this case is substantially smaller than in the case of vapor heat treatment. The moisture-content gradient in this case is also smaller. We should therefore expect a reduction in the deformability of reinforced-concrete products that have been heat treated in an electromagnetic field, which is borne out by the results of the experimental research [5]. To confirm the above from the research results, we determined one of the basic criteria of mass transfer – the Kirpichev number

$$\mathrm{Ki}_m = \frac{j_m R_v}{a_m \gamma_0 \bar{u}_0}, \tag{5}$$

which can describe the deformability (primarily, resistance to crack formation) of a hardening concrete as it is subjected to heat and moisture treatment. As follows from Table 2, the Ki_m number determined for the same period of isothermal treatment varies for concrete from 0.024 to 0.120 and from 0.0235 to 0.042 for the cement solution.

We know [1] that the smaller Ki_m, the lower the resistance to internal mass transfer.

It follows from Fig. 3 and from Table 2 that the resistance to the displacement of moisture in the concrete and in the cement solution, hardening as a result of vapor heat treatment, is substantially less than in the case of electromagnetic heat treatment.

The migration of the moisture in the last case is made difficult by the formation of a denser structure with closed pores and an increase in the pore volume within the microcapillaries. This serves to explain the reduction in the coefficient of moisture diffusion in the concrete which is being hardened by heat treatment in an electromagnetic field.

In vapor–heat treatment, with a reduction in the Ki_m number, there is an increase in the danger of crack formation in reinforced-concrete constructions, since the moisture content u_s of the surface layers is greater than the initial moisture content $\bar{u}_0$ (Fig. 1A), i. e., the concrete swells, and this is follows by a more intensive reduction in moisture content than in the case of electromagnetic heat treatment. This is the reason for the appearance of directed communicating porosity with an increase in the macropores in the forming structure of the hardening concrete, which has been demonstrated by Ivanov [7] and a number of other researchers. In this state the structure of the concrete exhibits minimum capacity to resist the effect of destructive processes (shearing stresses, express pressures, etc.). A structure of this type exhibits elevated permeability, reduced resistance to the effect of the ambient medium (frost resistance, resistance to agressive media, etc.), and as a result, it exhibits a reduced useful life. Research has recently established [8] that the porous structure of concrete is, conversely, impaired after an optimum electromagnetic heat-treatment regime.

Consequently, the diffusion transfer of moisture exerts significant influence on the structure formation of concrete and is directly dependent on the manner in which heat is supplied.

The research results discussed here make it possible to develop an entire range of concepts with regard to the possibility of controlling the processes of concrete structure formation along specified lines.

NOTATION

ΔT is the temperature difference, °C;
$\bar{u}_0$ is the initial mean integral moisture content, kg/kg;
u is the instantaneous moisture content, kg/kg (shown in % in the figures);
u_c is the moisture content of the center layer of the specimen, kg/kg;
u_s is the moisture content of the surface layer of the specimen, kg/kg;
u_1 is the mean integral moisture content of one of the layers of the specimen, kg/kg;
u_{am} is the arithmetic mean of the moisture content, kg/kg;
x is the instantaneous coordinate, mm;
R is the specimen thickness, mm;
R_1 is the thickness of a separate specimen layer, mm;
τ is the time, h;
j_m is the density of the material flow, $kg/m^2 \cdot h$;
R_V is the hydraulic radius, equal to the ratio of the specimen volume V to its side surface F, m;
γ_0 is the bulk weight of absolutely dry material, kg/m^3.

LITERATURE CITED

1. A. V. Lukov, Heat and Mass Transfer in Drying Processes [in Russian], Gosenergoizdat (1956).
2. I. N. Rutskii, S. G. Romanovskii, L. Ya. Volosyan, and A. L. Korsenko, in: Investigation of Convection Heat and Mass Transfer [in Russian], Nauka i Tekh., Minsk (1968).
3. S. G. Romanovskii and L. Ya. Volosyan, in: Structural Thermophysics [in Russian], Energiya (1966).
4. S. R. Ramanouski and L. Ya. Volosyan, Vestsi AN BSSR, Ser. Fiz.-Tekhn. Navuk, No. 4 (1966).
5. L. Ya. Volosyan and S. G. Romanovskii, Vestsi AN BSSR, Ser. Fiz.-Tekhn. Navuk, No. 1 (1968).
6. A. V. Luikov and V. P. Zhuravleva, in: Heat and Mass Transfer [in Russian], Vol. 6, Naukova Dumka (1968).
7. F. M. Ivanov, in: The Physicochemical Mechanics of Disperse Structures [in Russian], Nauka (1966).
8. L. Ya. Volosyan and V. M. Kazanskii, Inzh. Fiz. Zh., 15, No. 5 (1968).