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EXPERIMENTAL DETERMINATION OF THE DIFFUSIVITIES OF MOISTURE IN POROUS MATERIALS IN CAPILLARY AND SORPTION MOISTENING

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Experimental data on the moisture distribution in porous materials, obtained with the gamma method in different regimes of moistening, have been given. The moisture diffusivity of steam-cured aerated concrete in a wide range of humidities of the material has been determined.

Introduction. Experimental investigations of the basic humidity characteristics of a material are necessary for the development of computational methods of the process of moisture transfer in porous materials. One determining characteristic is the diffusivity of moisture; it characterizes the intensity of the process of moisture transfer in a material. One usually considers two basic methods of moistening of a porous material: (1) direct contact of the material with water — capillary impregnation; (2) moisture saturation of the material through the sorption of moisture from air — sorption moistening.

The rates and intensities of moistening and moisture transfer and accordingly the diffusivities of moisture differ significantly. Therefore, one must have information on the coefficients of moisture transfer of different porous materials in different regimes of moistening for calculations of the processes of moisture transfer.

Determination of the diffusivity of moisture D of porous materials by the standard methods [1–4] requires lengthy and laborious measurements. One can avoid this using the methods of nuclear magnetic resonance (NMR), those of neutron raying of materials [5–8], and the gamma method [9–11]. With these methods, one can determine the moisture distribution in a material on short notice and without destroying it, thus eliminating the errors caused by the disturbance of the material structure.

The present work seeks to experimentally determine the effective diffusivity of moisture in porous materials in the regimes of sorption moistening and capillary impregnation.

Method of Investigation. The diffusivity of moisture of porous materials was investigated by the gamma method, which is based on the use of a gamma densimeter for obtaining the moisture distribution in a porous specimen with time; from this distribution, we can determine the diffusivity of moisture in a material. The operating principle of a gamma densimeter lies in determining the density of a material from the attenuation of the gamma intensity whose attenuation in a moist material depends on its density in a dry state and the moisture content in the material [9]

$$I_{\text{moist}} = I_{\text{dr}} \exp\left(-\mu_{\text{w}}\rho_{\text{dr}}W_{\text{m}}d\right) . \tag{1}$$

Thus, knowing the attenuation of the radiation in the dry specimen and in the specimen after moistening, we can determine its relative mass humidity:

$$W_{\text{m}} = \frac{1}{\mu_{\text{w}}\rho_{\text{dr}}d} \ln\left[\frac{I_{\text{dr}}}{I_{\text{moist}}}\right] . \tag{2}$$

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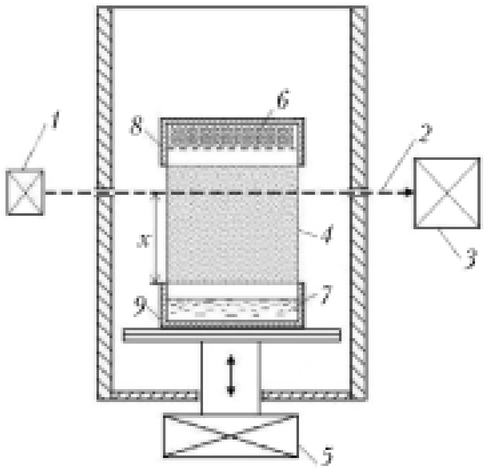


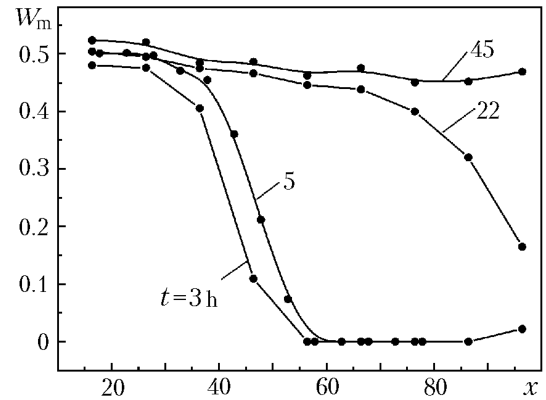


Fig. 1. Diagram of the experimental bench: 1) gamma source (cesium-137 isotope); 2) gamma-quantum beam; 3) scintillation detector; 4) specimen of the material; 5) coordinate device; 6) sorbent; 7) water; 8) upper chamber; 9) lower chamber.

Fig. 2. Humidity distribution over the specimen's height in capillary impregnation.

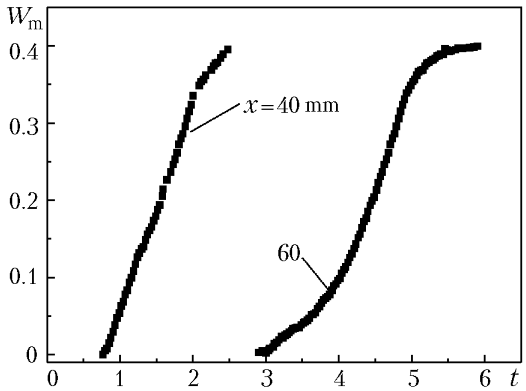
Experimental Bench. A diagram of the experimental bench for determination of the diffusivities of moisture in a material is shown in Fig. 1. It represented a metal casing inside which a test specimen was placed. The upper and lower parts of the specimen were in hermetic chambers. The specimen was rayed by a gamma-ray beam (diameter 4 mm) whose output intensity was recorded by a scintillation detector. A cesium-137 isotope with a gamma-quantum energy of 662 keV (μ_w = 0.00862 m^2/kg]12]) was used as the gamma-ray source. The possibility of displacing the specimen vertically relative to the gamma beam enabled us to obtain the humidity distribution over its height.

We used steam-cured aerated concrete of density 600 kg/m^3 and porosity about 80% as the porous material under study. The specimens of aerated concrete had the shape of a parallelepiped with a cross section of 100 × 100 mm and a height of 80–100 mm. Before the experiment, we placed the specimen in a vacuum drying cabinet and dried it to a constant mass at a temperature of 105^oC. Then we insulated the lateral surfaces of the specimen to attain the one-dimensionality of the moisture transfer. Thereafter the specimen was placed in the experimental bench.

The experiments were carried out under isothermal conditions at a constant temperature of the ambient air of 20^oC. The instant of creation of a constant concentration of moisture at the lower boundary of the specimen was considered to be the beginning of the experiment. We determined the humidity over the specimen's height at certain time intervals. The calculations and results of test measurements showed that the error in determining it was $\Delta W_m = (12W_m + 1)\cdot 10^{-3}$.

The processes of moisture transfer were investigated in two different regimes of moistening: capillary impregnation and sorption moistening.

Capillary Impregnation. In the regime of capillary impregnation, the lower specimen surface came in contact with water. Free access of the ambient air, which had a relative humidity of 30% and a temperature of 20^oC during the experiments, was provided to the upper boundary of the specimen. The data (obtained in the experiments) on the change in the humidity distribution over the specimen's height with time are presented in Fig. 2. The specimen's height is plotted on the abscissa axis, beginning from the lower boundary, and the relative mass humidity of the material is plotted on the ordinate axis. It follows from the figure that the moisture distribution over the specimen's height changed with time — we had step-by-step moistening from the bottom upward. The humidity profiles corresponding to 3 and 5 h from the beginning of moistening show the advance of the humidity front in the specimen. The humidity front reached the upper boundary of the specimen by the end of the first day, and the process of moistening of the specimen was completed over its entire height, in practice, on the second day.



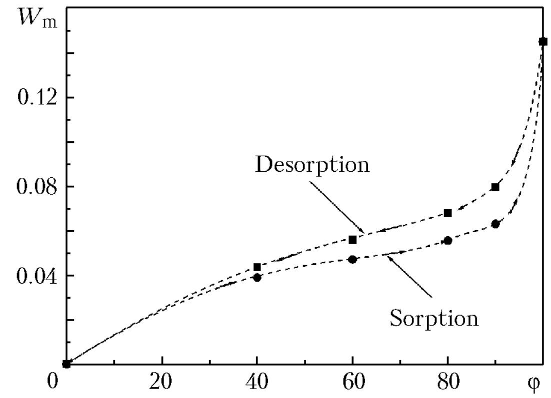
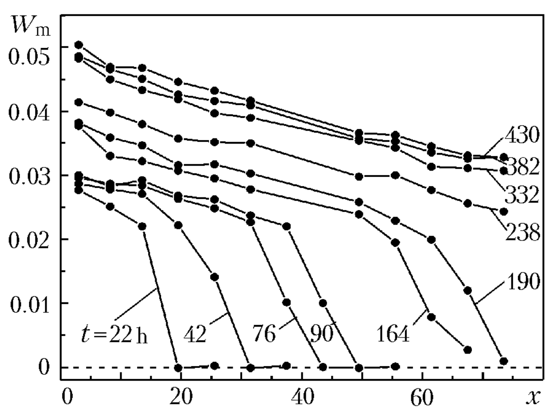


Fig. 3. Change in the humidity of the material with time in capillary impregnation.

Fig. 4. Isotherm of sorption and desorption of steam-cured aerated concrete of density 600 kg/m^3.



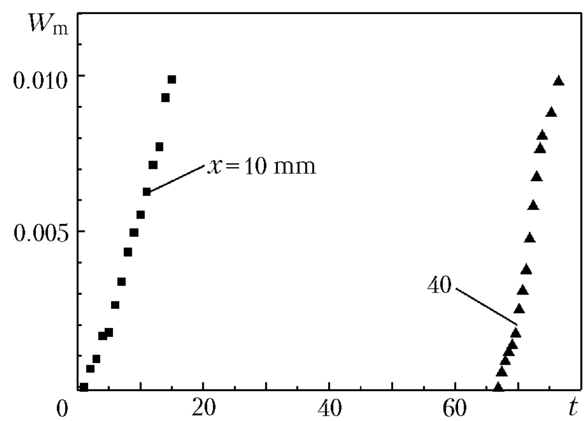


Fig. 5. Humidity distribution over the specimen's height in sorption moistening.

Fig. 6. Change in the humidity of the specimen with time in sorption moistening.

Also, we measured the humidity in fixed cross sections of the specimens with time (Fig. 3) in the experiments. The time from the beginning of the experiment is plotted on the abscissa axis in Fig. 3. The results presented in the figure show that the humidity in a cross section of 40 mm increased already within 30 min after the beginning of the experiment, whereas that in a cross section of 60 mm increased only after 3 h. Furthermore, it is seen that the rate of moistening of the material is dissimilar in these cross sections.

It is noteworthy that in capillary impregnation, the process of moistening is more intense and the relative humidity of the material attains values higher than 50%.

Sorption Moistening. A material can also be moistened without contact with water due to the absorption of moisture from the surrounding air. The humidity of the material will depend on the relative humidity of the surrounding air. This dependence is described by the isotherm of sorption or desorption. It was obtained experimentally for the material under study. The measurements were carried out by the exsiccator method [13] at a temperature of 20^{o}C for three months. As is seen in Fig. 4, the maximum sorption humidity for this aerated concrete amounts to about 15%.

In the experiments on sorption moistening, the lower part of the specimen was above the free water surface in a hermetic chamber, i.e., under conditions of 100% relative air humidity, whereas its upper part was in another hermetic chamber inside which a vessel with a sorbent was placed. As a result, the upper surface of the specimen was at a zero relative air humidity, in practice (Figs. 5 and 6).

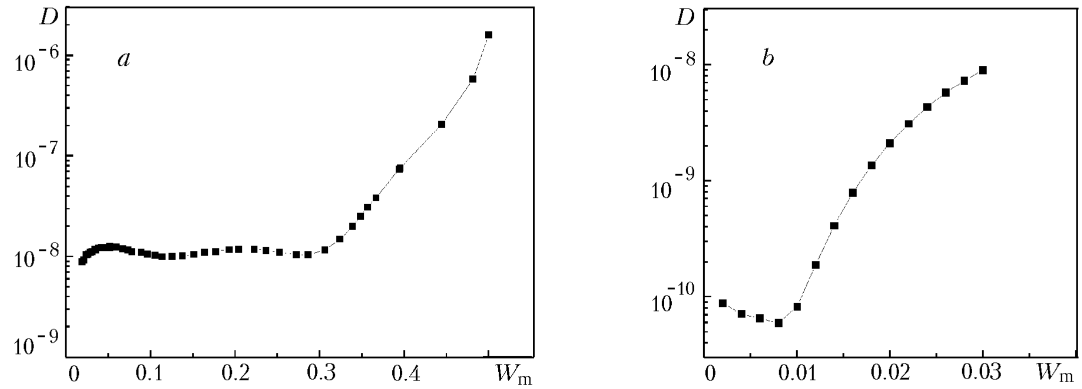


Fig. 7. Diffusivity of moisture of aerated concrete vs. humidity in sorption moistening (a) and in capillary impregnation (b).

It follows from the data of Fig. 5 that, in sorption moistening, the shape of the moisture distribution in the specimen changed with time. In the first period of time (up to 90 h), the humidity at the lower boundary amounted to about 3% and was constant, in practice; we observed only the advance of its front into the specimen with time. The process of moistening was slow: after 430 h from the beginning of the experiment, the humidity near the lower boundary of the specimen amounted to only 5% and decreased to 4% near the upper boundary, i.e., over the period of the experiment it attained about 1/3 of its maximum sorption value.

Figure 6 shows the manner in which the material is moistened in several cross sections of the specimen with time. It is seen in the figure that, for example, in a cross section of 40 mm, the humidity of the material begins to change only after three days and attains a value of about 1% in 10 h.

Thus, the results of the experiments have shown that the processes of moisture saturation in sorption moistening were not very intense and the content of moisture in the material did not attain high values.

Processing of Experimental Results. The effective diffusivity of moisture *D* as a function of the humidity of the material was determined with the use of the humidity profiles obtained in the experiments. For this purpose we used the Boltzmann–Matano method [14]. This method is based on solution of the unsteady diffusion equation for a semiinfinite body in the one-dimensional formulation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\,\frac{\partial c}{\partial x}\right). \tag{3}$$

For Eq. (3), we have the initial conditions

$$0 < x < \infty \quad \text{and} \quad t = 0: \quad c = c_0 = 0\,,$$

and the boundary conditions

$$x = 0 \quad \text{and} \quad t \ge 0: \quad c = c_1\,; \quad x \to \infty \quad \text{and} \quad t \ge 0: \quad c = c_0\,, \quad \partial c/\partial x = 0\,.$$

To solve Eq. (3) we introduce a new time- and coordinate-dependent variable $\lambda = x/t^{0.5}$. Substituting it into the diffusion equation and applying the Boltzmann transformation, we pass from the partial derivatives in (3) to total derivatives:

$$2\,\frac{d}{d\lambda}\left(D\,\frac{dc}{d\lambda}\right) + \lambda\,\frac{dc}{d\lambda} = 0\,, \tag{4}$$

the initial and boundary conditions have the form

$$\lambda = 0: \quad c = c_1\,; \quad \lambda \to \infty: \quad c = c_0\,, \quad \partial c/\partial\lambda = 0\,.$$

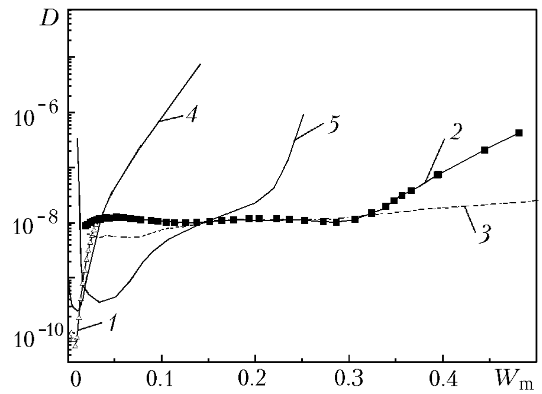


Fig. 8. Moisture diffusivity vs. humidity: 1) aerated concrete (experiments of the present work on sorption moistening); 2) aerated concrete (experiments of the present work on capillary impregnation); 3) calculated data, aerated concrete [15]; 4) experiment, brick [5]; 5) experiment, gypsum [5].

After the transformation of Eq. (4) we can obtain the expression for determination of the moisture diffusivity:

$$D(c) = -\frac{1}{2}\frac{1}{\frac{dc}{d\lambda}}\int_{c_0}^{c}\lambda dc\,. \tag{5}$$

The humidity profiles obtained in the experiments were processed with the use of formula (5). As a result, we determined the dependences of D of aerated concrete in sorption moistening (Fig. 7a) and capillary impregnation (Fig. 7b).

Processing of the experimental results (Fig. 7a) in sorption moistening of aerated concrete enabled us to obtain D as a function of the humidity of the material in the region of low humidity. These data show that a certain minimum of D of the order of 10^{-10} m^2/sec is observed with a humidity of about 1%. Then, as the humidity increases to 3%, we have a sharp increase to 10^{-8} m^2/sec in D.

An analysis of the change in the moisture diffusivity D in capillary impregnation shows that, with a relative humidity of the aerated concrete lower than 30%, the value of D was approximately constant and was about 10^{-8} m^2/sec. As the humidity increased above 30%, we observed a sharp increase in D to values of the order of 10^{-6} m^2/sec. Probably, the reason for this phenomenon is that, when the humidity is high, all the pores of the material, in practice, are filled with water and the process of moisture transfer is intensified by the action of capillary forces.

The general dependence of D on the humidity of the material, obtained from the experiments on capillary impregnation and sorption moistening, is presented in Fig. 8.

As is clear from the figure, the results of both sets of experiments with a humidity of the material of about 3% are in satisfactory agreement, despite dissimilar regimes of moistening.

Figure 8 also plots the calculated data obtained for aerated concrete of density 400 kg/m^3 at a temperature of 20°C [15]. It follows from the plot that the results of our experiments satisfactorily coincide with the calculated data in the humidity range of aerated concrete from 3 to 30%. When the humidity is higher than 30%, the experimental data show a faster growth in D with increase in the humidity of the material than the calculation results do.

Furthermore, Fig. 8 shows the data obtained by the nuclear magnetic resonance method [5] on the change in D for gypsum and brick. As is clear from the figure, different materials have dissimilar values of D, and there are certain features in the character of the dependences. Noteworthy is the fact that the minimum of D in the region of low humidities is present in all these materials. In brick and gypsum, the quantity D first sharply increases from the minimum value with moistening, after which we observe its smooth growth, whereas, in aerated concrete, there is an extended portion (from 3 to 30%) of a constant value of the diffusivity. It is probable that certain differences in the dependences of D on the humidity in different materials are explained by their different porous structure.

CONCLUSIONS

As a result of the experimental work on determination of the moistening of aerated concrete by the gamma method in capillary impregnation, we have obtained the moisture diffusivities in the range of relative humidities of the material from 3 to 50%. It has been shown that, in the range of relative humidities from 3 to 30%, the diffusivity of moisture of steam-cured aerated concrete of density 600 kg/m^3 remains constant, in practice, and is equal to approximately 10^{-8} m^2/sec.

In the experiments on sorption moistening, we have obtained D in the range of humidities of the material from 0.5 to 3%. It has been shown that, in this range, D increases more than 2 orders of magnitude with growth in the humidity of the material.

Good coincidence of the results is observed in comparing the values of D of aerated concrete that have been obtained from the experiments on sorption moistening and capillary impregnation with a humidity of the material of 3%.

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NOTATION

c, concentration of moisture in the specimen, kg/m^3; d, specimen's thickness, m; D, effective diffusivity of moisture, m^2/sec; I, intensity of gamma radiation after transmission by the specimen, sec^{-1}; t, time, h; W_m, relative mass humidity of the material, kg/kg; x, coordinate, mm; φ, relative humidity of air, %; λ, Boltzmann variable, m/sec$^{0.5}$; μ_w, mass coefficient of attenuation of gamma radiation for water, m^2/sec; ρ_{dr}, density of the dry material, kg/m^3. Subscripts: dr, dry; moist, moist; m, mass; w, water; 0, 1, ..., subscripts characterizing different states of the system.

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