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Moisture performance through fresh concrete at different environmental conditions

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Abstract

The evaporation of water from fresh concrete exposed to different environmental conditions was investigated theoretically. Meteorological data for three cities, Alexandria (31°N), Cairo (30°N), and Aswan (24°N), were considered as the input data. A computer program was developed to calculate the solar radiation, evaporation rate, heat and mass transfer numbers, and moisture transfer during the four seasons. The results show that the evaporation rate and Gukhman number increased as the latitude decreased. The results also show that a greater part of the mixing water evaporated during the first drying period, and that water must be prevented from escaping and replaced by water from outside to complete the hydration process of cement. The curing method depends on the location and season and is necessary as one moved from the north to the south in Egypt. The results demonstrated that Gukhman number plays a significant role in choosing the curing method of fresh concrete exposed to external climatic conditions. Also, the four curing methods investigated were dependent on the values of Gukhman number.

Keywords: Fresh concrete; Humidity; Drying; Durability; Physical properties

1. Introduction

1.1. Introductory remarks

Concrete, as a commonly used engineering material, is produced under different environmental conditions. The external climatic conditions during the casting process of concrete adversely affect the properties of concrete. Hot weather conditions (high air and concrete temperatures, variable relative humidity, intense solar radiation, and high wind speed) are associated with a high rate of evaporation in porous concrete [1–3]: air can enter to replace expelled moisture. High evaporation rate usually causes: (1) a reduction in the water/cement ratio of the surface parts of concrete; (2) a disadvantageous influence on strength caused by drying, shrinkage, and creep of hardened concrete; (3) an increased rate of salt crystallization within the pores that might cause an appreciable degree of deterioration of concrete; (4) an accelerated rate of hydration and stiffening of the mix at high temperature (which has a very pronounced effect on the time of transition from the stage of rapid linear shrinkage to that of restrained shrinkage); and (5) a plastic cracking appearing above a certain limit of evaporation and even causing a stoppage in the hydration process of cement [4,5]. The necessity of curing arises from the fact that at a water/cement ratio higher than about 0.38, all cement can hydrate and capillary pores will also be present and contain the excessive amounts of mixing water [6,7]. Hence, loss of water from concrete due to evaporation, in addition to self-desiccation caused by the consumption of water during hydration, must be prevented and replaced by water from outside [8]. There are two main types of curing, namely: (1) the continuous frequent application of water through pounding, sprays, steam, or cotton mats, earth, sand, sawdust, and straw; and (2) the prevention of excessive loss of water from concrete by means of materials such as sheets of reinforced paper or plastic or by the application of membrane that forms a curing compound for the fresh concrete [9,10].

1.2. Analytical background to program

Water can be held in fresh concrete in four ways: hydration of set cement compounds, water absorbed in gel formed by set cement structure, water present in capillary voids in the set cement structure, and water present in capillary voids existing between the set cement and aggregates [11,12].

As concrete dries, three stages of moisture movement may be distinguished as shown in Fig. 1. In the first stage,

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the moisture flows as a liquid under a hydraulic gradient. Initially the pores are full but gradually air pockets appear to replace the moisture lost. The length of this period is dependent on the water/cement ratio as well as the external climatic conditions. In the second stage at the beginning of setting and hardening, the moisture has withdrawn to the pore walls, and moisture can migrate either by creeping along the capillary walls or by successive evaporation and condensation between liquid bridges. In the final stage, a description-resorption process takes place (i.e., any moisture that vaporizes is recondensed) and the concrete is in a hygrothermal equilibrium with its environment [13,14,15].

Clearly, no single theory can be applied to all these modes of transfer. Early studies revealed that the drying rate can be divided into two periods, an initial period and a terminal drying period. In the case of concrete, the initial drying period consists of two evaporation stages. The evaporation rate values depend on climatic conditions, because at the beginning of casting water exists at the surface of the concrete (bleeding water). Also the moisture movement within the solid is rapid enough to maintain a saturated condition on the surface. The mechanism of moisture removal during the first stage is equivalent to evaporation from a liquid water surface and is essentially independent of the nature of concrete. The heat and mass transfer relationships for the drying rate is written as shown in Eq. (1) [2]:

$$R_c = h_c(T_{da} - T_{wa})/L = h_m M_B(H_s - H_a) \quad (1)$$

The error obtained in determining the temperature of surface affects the driving force or wet bulb depression coefficient ($T_{da} - T_{wa}$) much less than the effect of mass transfer; therefore, it is preferable to use the heat transfer equation.

In the second stage the evaporation rate is always less than that of surface free water and the moisture migration becomes progressively more sluggish as it closes to the critical-moisture content.

The values of heat transfer coefficient (h_c) obtained for drying moist bodies are greater than those obtained from bone-dry bodies under similar conditions of air flow and temperature potential [16] (cf. Appendix). It is important to note that the heat transfer coefficient is an approximate value, because it is dependent on the geometry of the material, the temperature conditions, and the characteristic of air stream. The moisture movement in the flat slab of concrete in one dimension can be represented as seen in Eq. (2) [13]:

$$\frac{\partial^2 M}{\partial x^2} = \frac{1}{D_e}\frac{\partial M}{\partial \tau} \quad (2)$$

By taking into consideration the boundary conditions, the simple solution of Eq. (2) can be written as Eq. (3):

$$M = M_o + \frac{R_c b}{\rho_s D_e}\left[\frac{1}{6} - \frac{1}{2}\left(\frac{x}{b}\right)^2 - \frac{D_e \tau}{b^2}\right] \quad (3)$$

The parameter ($D_e\tau/b^2$) is the Fourier number (F_o), which represents the relative time of drying. At the critical point, the moisture content at the surface is equal to zero ($M_{surface} = 0$), consequently [see Eq. (4)]:

$$F_{o_{cr}} = \frac{D_e \rho_s M_o}{R_c b} - \frac{1}{3} \quad (4)$$

Substituting Eq. (4) in Eq. (3), we get the critical moisture content M_{cr} as seen in Eq. (5):

$$M_{cr} = R_c b / 3 D_e \rho_s \quad (5)$$

In this physical model the critical moisture content is not a specific property for a given substance, but depends on the initial drying rate (R_c), the material thickness (b), and the moisture diffusion (D_e). True diffusion in porous material (D_e) is given by ($D_e = D_{AB}/\mu_D$) where D_{AB} is the diffusion of moisture vapour in free air and μ_D is the diffusion coefficient ($\mu_D = 3\Psi^{-3/2}$, where Ψ is the porosity.

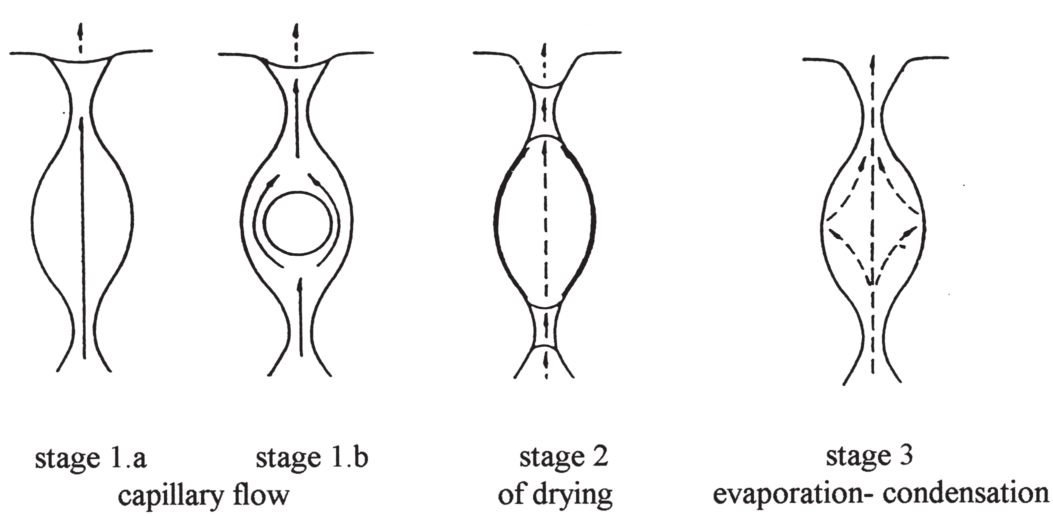

Fig. 1. Moisture movement at various stages of the concrete drying.

2. Results and discussion

Table 1 shows the estimated average drying time (F_{ocr}), critical moisture content (M_{cr}), and Gukhman number (Gu). The table illustrates that the critical moisture content through the exposed concrete slabs reached small values in the three cities during the year. This is due to the loss of most of the free water during the first drying period. It can be seen that the average drying time reached a lowest value of about 12.6 h in Aswan city. This value indicated that most of casting water was removed through the concrete in liquid phase. It can be seen that the Gukhman number increases as the average drying time decreases. For this reason the Gukhman number plays a significant role in the water-curing methods. Also, the average drying time (F_{cor}) indicated that curing methods must be applied at the end of this time.

Fig. 2 shows the variations of the drying rate and Gukhman number from wet concrete surface with time under the external climatic conditions of the three cities in Egypt during the year. The figure shows that both evaporation drying rate and Gukhman number increase from north to south and also increase from winter to summer and decrease during autumn. Fig. 2. (A1, A2, and A3, corresponding to winter season) show that the evaporation drying rate in Alexandria, Cairo, and Aswan reached about 150, 205, and 250 g/m^2 · h, respectively, while Gukhman number reached about 20, 20, and 30, respectively. These figures show that 3 h time lag is noticed between the maximum of evaporating rate and Gukhman number; this is due to the time lag effect of solar radiation on the outdoor air temperature. During the spring, the evaporation rate reached to 300, 350, and 400 g/m^2h, respectively, for the three cities. Also, the Gukhman number of the three cities, Alexandria, Cairo, and Aswan, reached 30, 45, and 65, respectively (as shown in Fig. 2, B1, B2, and B3). Fig. 2 (C1, C2, and C3) illustrate that evaporation rate reached about 325, 350, and 450 g/m^2 · h, respectively, for the three cities, while the Gukhman numbers reached about 20, 50, and 70, respectively, during the summer. The curves show a decrease in the evaporation rate and Gukhman number with autumn as shown in Fig. 2. (D1, D2, and D3).

Fig. 3 illustrates the computed moisture content profiles across a 100-mm thick slab of concrete exposed to external periodic climatic variations of the three cities in Egypt during the first 2 days from casting for the four seasons. The shaded area under the curves represents the residual moisture content in the concrete slab after the first 2 days from casting. The figure shows that the residual moisture content decreases from north to south and also decreases from winter to summer. For the winter, Fig. 3 (A1, A2, and A3) shows that the moisture content increases gradually with increasing depth, and moisture loss is rapid and large in quantity in the neighborhood of the drying surface; but in the interior of concrete, it is rather slow and of small quantity. Larger quantities of residual water during the winter season is found after 1 day from casting and the moisture becomes progressively more sluggish in the concrete slab during the second day from casting in all three cities. This is due to the moisture progress during the second day by the evaporation and condensation through the concrete. Fig. 3 (B1, B2, and B3, related to spring) shows that the moisture loss is increased from north to south and the concrete exposed to the climate of Aswan city reached a harmful value after 1 day of casting compared with those in the two other cities. This is due to the effect of temperature and wind speed during this season. During the summer season, Fig. 3 (C1, C2, and C3) shows that the moisture loss varies according to the distance from the drying surface. Also, the moisture loss is more rapid from the lower part of concrete slab and curing methods must be applied. Fig. 3 (D1, D2, and D3) shows the same performance as during the summer under the external climatic conditions of autumn.

From the above results it can be noticed that the evaporation rate and Gukhman number increase as the latitude decreases. The Gukhman number characterized the effect of mass transfer on heat transfer. The Gukhman number plays a significant role in choosing the curing method of fresh concrete exposed to external climatic conditions. Four curing methods were investigated in this study, namely: covering the concrete surface with material saturated with water, spraying concrete surface in the evening and the morning, spraying the concrete in the evening, and the case without any treatment. The study led to the following findings:

1. For the maximum value of $0 < Gu < 0.15$ (i.e., the drying rate is less than 100 $g/m^2/h$), the fresh concrete is not sensitive to external climatic conditions. Curing

Table 1
Average drying time (F_{ocr}), critical moisture content (M_{cr}), and Gukhman number (Gu) for the three cities during the year

	Alex			Cairo			Aswan		
Season	F_{ocr}	Gu × 100	M_{cr}	F_{ocr}	Gu × 100	M_{cr}	F_{ocr}	Gu × 100	M_{cr}
Winter	42.3	11.3	0.2	41.4	15.4	0.2	31.2	23.9	0.2
Spring	21.5	21.0	0.3	15.5	32.5	0.4	12.6	51.7	0.4
Summer	36.9	14.5	0.3	33.4	27.1	0.3	17.7	51.7	0.3
Autumn	54.2	14.0	0.2	48.8	20.9	0.2	15.5	38.8	0.3

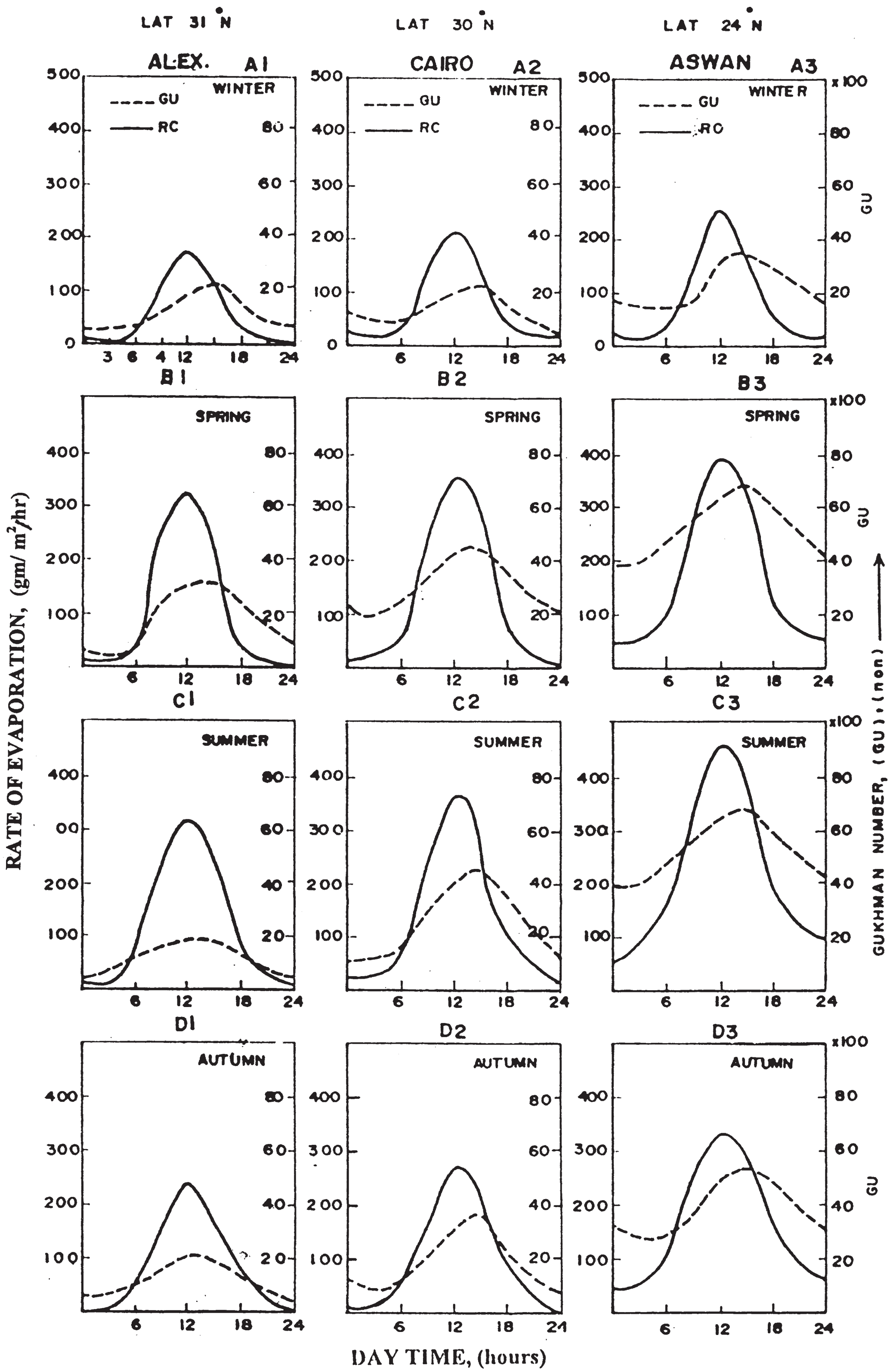

Fig. 2. Variation of the drying rate from wet concrete surface with time under the external climatic conditions of three cities in Egypt during the year.

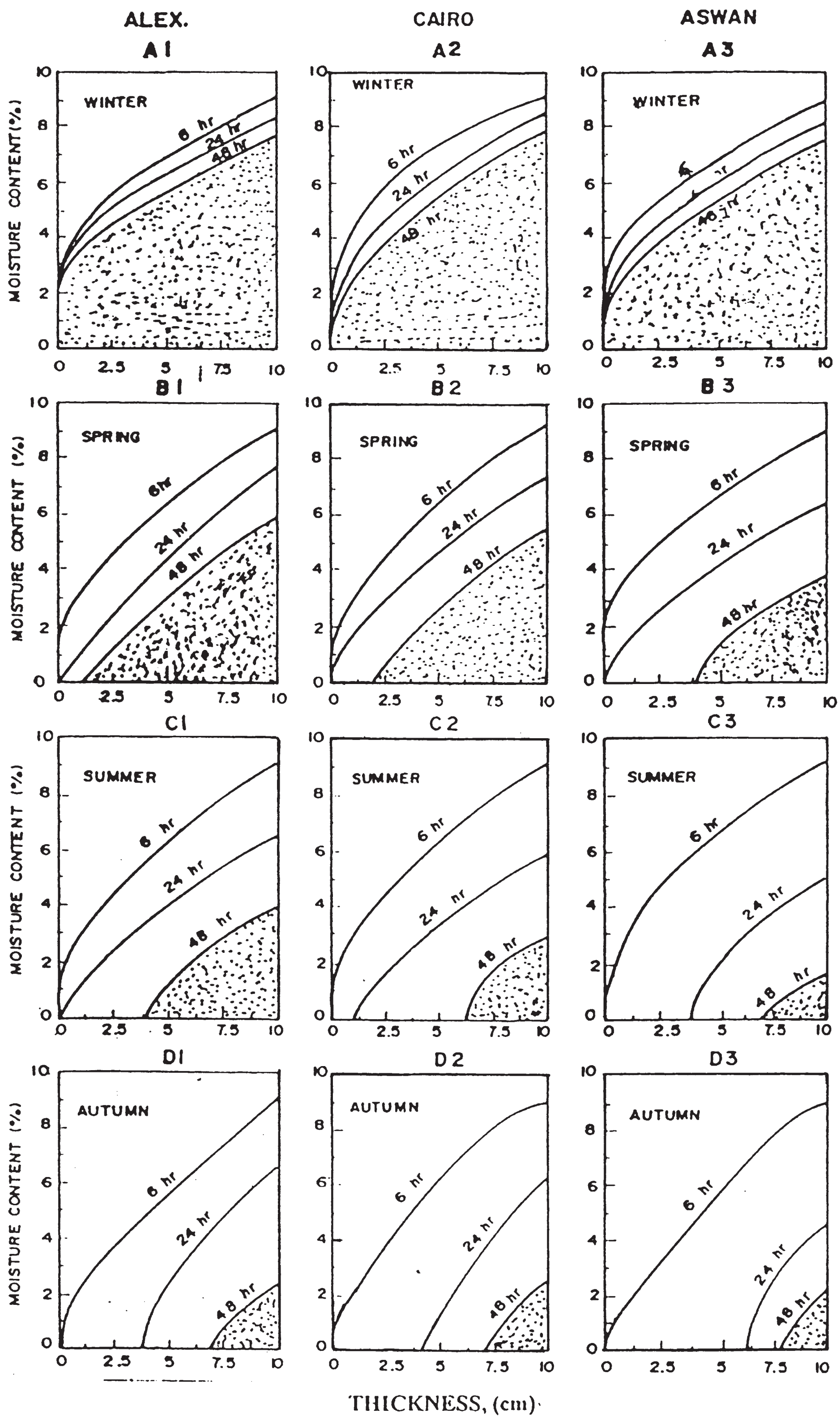

Fig. 3. Computed moisture content profile across a 100-mm concrete slab dried under periodic external climatic conditions of three cities during the first two successive days from casting.

Table 2
Values of the constants in the formulae [13,16]

Reynolds number	k	n	m	k'	n'	m'
$1 - 2 \times 10^2$	1.070	0.48	0.175	0.830	0.53	0.135
$3.15 \times 10^3 - 2.2 \times 10^4$	0.510	0.61	0.175	0.490	0.61	0.135
$2.2 \times 10^4 - 3.15 \times 10^5$	0.027	0.90	0.175	0.0248	0.90	0.135

is not essential and the adsorbed water during the nighttime compensates for the water lost during the daytime.

2. In the range of $0.15 < \mathrm{Gu} < 0.25$, the fresh concrete is then sensitive to external climatic conditions during the sunny hours and the increase in the evaporation rate is due to the effect of solar intensity. This means that a small amount of mixing water will have evaporated from the concrete surface during the daytime. The spraying by water in the evening is sufficient as a curing method.
3. If the boundary values are $0.25 < \mathrm{Gu} < 0.4$, the fresh concrete becomes more sensitive to external climatic conditions, as the evaporation drying rate would be nearly equal or greater than 200 $g/m^2/h$. Also, a larger quantity of mixing water will have evaporated from the concrete surface during the daytime. The spraying with water in the evening and early morning hours is sufficient as a curing method.
4. The fresh concrete is highly sensitive to external climatic conditions for the values of $0.4 < \mathrm{Gu} < 1$. Covering the fresh concrete surface with material saturated with water to control the evaporation rate during the hydration process is a must.

3. Conclusions

The investigation showed that most of the evaporating water is lost from fresh concrete surface during the first 2 days from casting. Also, it can be concluded that the Gukhman number plays a significant role in choosing the curing method of fresh concrete. The curing methods of concrete in Egypt are different and dependent on the latitude. The fourth curing method must be applied during the summer season in the southern region of Egypt.

Appendix

Airflow above the surface of concrete has a strong influence on the evaporation drying rate. The influence of airflow is exhibited through the boundary layer thickness and can be measured by Reynolds number (Re), Prandtl number, Schmidt number, and Gukhman number for heat and mass transfers [16]. Nesterenko treated numerous experimental data obtained in studying the evaporation of a liquid from a free surface in adiabatic conditions and forced air convection, and obtained the empirical formulae shown in Eq. (6) and Eq. (7):

$$Nu = kPr^{0.33}Re^{n}Gu^{m} \tag{6}$$

$$Sh = k'Sch^{0.33}Re^{n'}Gu^{m'} \tag{7}$$

The value of constants k, n, m, k', n', and m' in the formulae according to Nesterenko are given in Table 2. When $Re < 200$, the number 2 must be subtracted from Nu and Sh in Eqs. 6 and 7.

4.1. Notation

b = concrete thickness (m)
D_{AB} = moisture diffusivity in medium B (m^2/s)
D_e = effective diffusivity for moisture transfer (m^2/s)
g = gravity (m/s^2)
h_c = convection heat transfer coefficient ($W/m^2 \cdot K$)
h_m = convection mass transfer coefficient (m/s).
H_a = humidity of air at T_{da} temperature (kg H_20/kg air)
H_s = humidity of air at T_{wa} temperature (kg H_20/kg air)
k = thermal conductivity ($W/m \cdot k$)
l = air stream length (m)
L = latent heat vaporization (J/kg)
M = moisture content (kg H_20/kg solid)
M_B = molecular weight of air
R = universal gas constant ($J/kmol \cdot K$)
R_c = evaporation drying rate (kg/m^2s)
T = temperature (°C)
T_{da} = dry bulb temperature (°C)
T_{wa} = bulb temperature (°C)
q = distance (m)

4.2. Greek

α = Thermal diffusivity ($k/\rho c_p$) (m^2/s)
μ = diffusion resistance coefficient
ν = kinematic viscosity (m^2)
τ = time (s)

4.3. Commonly used dimensions groups

Bi = Biot number ($\alpha l/k$)
Fo = Fourier number ($a\tau/l^2$)
Nu = Nusselt number ($h_c l/k$)
Pr = Prandtl number (υ/α)
Re = Reynolds number ($\upsilon l/k$)
Sch = Schmidt number (υ/D_{AB})
Sh = Sherwood number ($h_m l/D_{AB}$)
Gu = Gukhman number = $[(T_{da} - T_{wa})/T_{da}]$

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