DRYING OF LIGHTWEIGHT AGGREGATE CONCRETE - A COMPARISON OF THREE DIFFERENT AGGREGATES

Mats Rodhe
M.Sc

Division of Building Materials
Chalmers University of Technology
S-412 96 Gothenburg, Sweden

ABSTRACT

The influence of three different types of aggregate, two of them lightweight aggregates, on the drying process of concrete has been studied by using laboratory experiments. The results are analyzed in a developed model. The analyses point out the main important factors influencing the drying process and show that it is possible to obtain good correlation between measured and calculated results. The behavior of the three aggregates where the moisture transport is concerned are completely different. The explanation for this is found in the different properties of the interstitial zone between the aggregate and mortar phase.

Key words: Lightweight aggregate, moisture transport, drying

1. INTRODUCTION

Drying modelling of porous composite materials, such as concrete, is a difficult task involving several nonlinear transport mechanisms in both the liquid and vapour phases. For lightweight aggregate concrete the drying process is even more complicated. If the aggregate itself initially has an excessive moisture content the drying process will be at least a two dimensional problem and the composite will consist of at least three phases, i.e. the mortar phase, the aggregate phase and the interstitial zone between those two phases. The properties of the interstitial zone depend on many factors such as content and distribution of moisture inside the aggregate when mixing, the w_0/C ratio used, additives such as air entraining agents, mixing order and chemical reactions between aggregate and mortar.

The model formulated here has been simplified to include one transport coefficient with the moisture concentration as the driving potential. The moisture transport is regarded as a one dimensional problem combined with some approximate assumptions regarding the effective diffusion coefficient for the whole composite system. The number of phases considered is reduced to two where the interstitial zone between aggregate and mortar is included as a part of the aggregate phase.

2. DRYING MODEL FORMULATION

The model is based on the diffusion equation in one dimension. For concrete at early ages the hydration process will immobilize a part of the moisture concentration U. The diffusion equation is modified for this, and becomes

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial U}{\partial x}\right) - \frac{\partial S}{\partial t} \tag{1}$$

U	=	the actual concentration of evaporable moisture
D [m²/s]	=	the total moisture transport coefficient
S	=	the concentration of immobilized water due to hydration

The actual concentration of evaporable moisture, c, is expressed by

$$U = \frac{w_e - w_{eq}}{w_{e0} - w_{eq0}} \tag{2}$$

w_e	[kg/m^3]	=	actual evaporable moisture content
w_{eq}	[kg/m^3]	=	actual equilibrium moisture content
w_{e0}	[kg/m^3]	=	initial evaporable moisture content
w_{eq0}	[kg/m^3]	=	initial equilibrium moisture content

The concentration of immobilized water, s, due to hydration is separated into two terms. One is due to the increase in the non-evaporable water, w_n. The other is due to the increase in the concentration of equilibrium moisture content, w_{eq}.

$$S = \frac{(w_n - w_{n0}) + (w_{eq} - w_{eq0})}{w_{e0} - w_{eq0}} \tag{3}$$

w_n	[kg/m^3]	=	actual non-evaporable water content
w_{n0}	[kg/m^3]	=	initial non-evaporable water content

The transport coefficient D(s,t) is a function of the age of concrete as well as of the degree of moisture saturation in the pore system. Two other time-dependent factors to consider are the degree of hydration and the quantity of moisture in equilibrium with the actual drying climate.

The development of the degree of hydration, α, is approximated by the following equation:

$$\alpha = \alpha_{\infty} \cdot e^{a \cdot t^{b}} \tag{4}$$

α_{∞} = final degree of hydration
a, b = constants depending on the material and the environmental conditions, c<0 was suggested by /1/
t [days] = age of the concrete

Good agreement with literature data for concrete older than 3 days was achieved with α_{∞}=0.80, a=b=-1 for w_0/C 0.55-0.65 and with α_{∞}=0.70, a=-0.6, b=-1 for w_0/C=0.45.

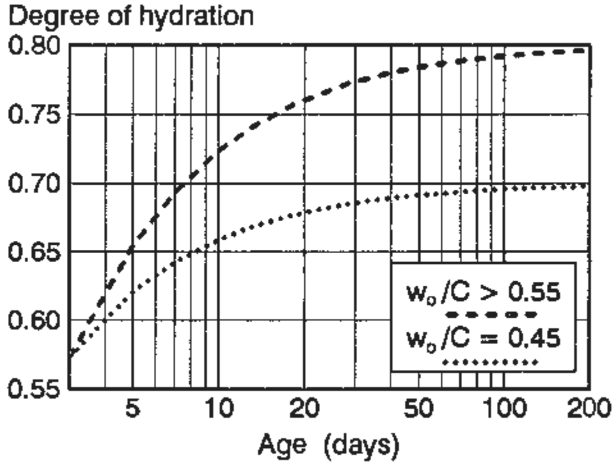

Figure 1 Assumed hydration development, equation (4).

The transport coefficient, D(s,t), decreases with the age of the concrete. There are very few data in literature available that describe its time-dependence. The function used is a function of the degree of hydration and is based on data from /2/.

There is more information available about the influence of the moisture concentration on D. Based on literature data, D is divided into three phases. The assumptions regarding the shape of each phase are that phase 1 and 2 are described by the following expression, /2/:

$$D=D_o(1+cs^{d}) \tag{5}$$

D = diffusion coefficient at actual concentration
D_o = diffusion coefficient at low moisture contents
s = degree of saturation
c,d= constants

In phase 3 the diffusion coefficient is considered constant, see fig 2.

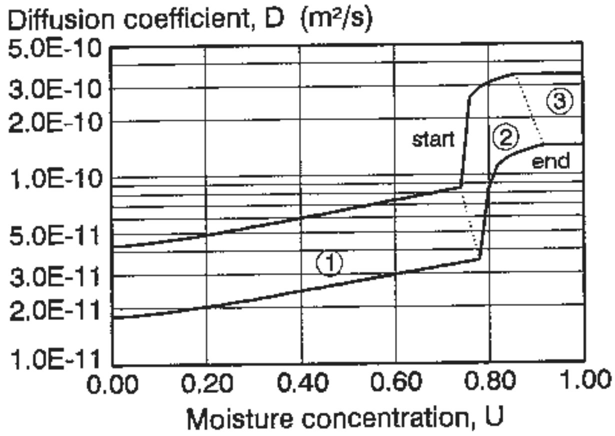

Figure 2 Example on curves showing the diffusion coefficient versus moisture concentration at the start of the 5 day, and at the end of the drying process. Mortar with $w_0/C = 0.55$.

For the three types of aggregates used the diffusion coefficient is considered constant. The interstitial zone between the aggregate and mortar has been included as part of the discontinuous aggregate phase.

The composite model used is based on a model by Jefferson, Witzell and Sibbert (1958) and is described in /3/. They consider the composite medium to be divided into a number of cubes, each having a sphere of the discontinuous phase at its centre. A one dimensional flow is assumed. It means, among other things, that the flow from the discontinuous phase only goes in one direction. This is not true of course, especially if the diffusion coefficient is lowest in the discontinuous phase.

The equilibrium moisture content in the material depends on the cement content, the w_0/C ratio, the aggregate and the degree of hydration. The equilibrium moisture content of the aggregates and of some of the concrete mixes were measured experimentally. The results are compared with desorption isotherms found in literature, /2/, and are shown in Fig 3 and Fig 4.

The time-dependence of the equilibrium moisture content for the drying climates used, RH 50% and RH 65%, is assumed to be proportional to the degree of hydration. Based on those test results the diffusion coefficient, D_c, for the continuous mortar phase is approximated in the way that it will remain constant until all moisture in the aggregate has dried out. Drying of the resulting part of the evaporable moisture in a plane perpendicular to the flow will influence the diffusion coefficient of the mortar phase according to figure 2. This is the normal case, when D is greater in the discontinuous phase of the aggregate and interstitial zone than in the continuous mortar phase. In the case of pumice concrete where the interstitial zone seems to become more and more dense, the diffusion coefficient of the discontinuous phase will decrease and be even lower than in the continuous phase. If this is the case the diffusion coefficient of the mortar will be considered equal to the one of the aggregate as long as the diffusion coefficient of the aggregate is greater than D_o in the mortar phase.

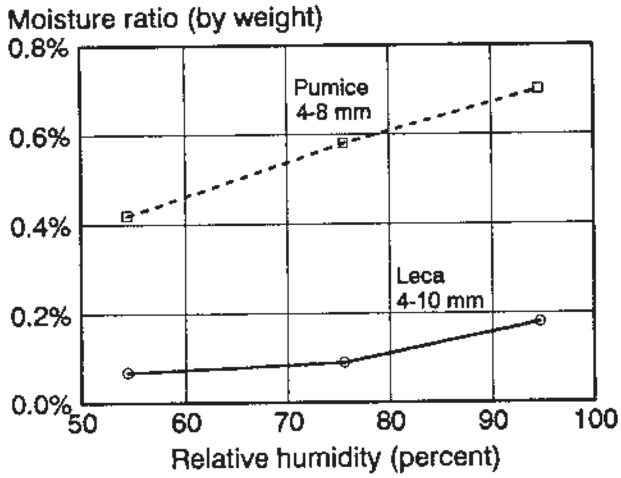

Figure 3 Desorption isotherms for lightweight aggregates used in the experiments.

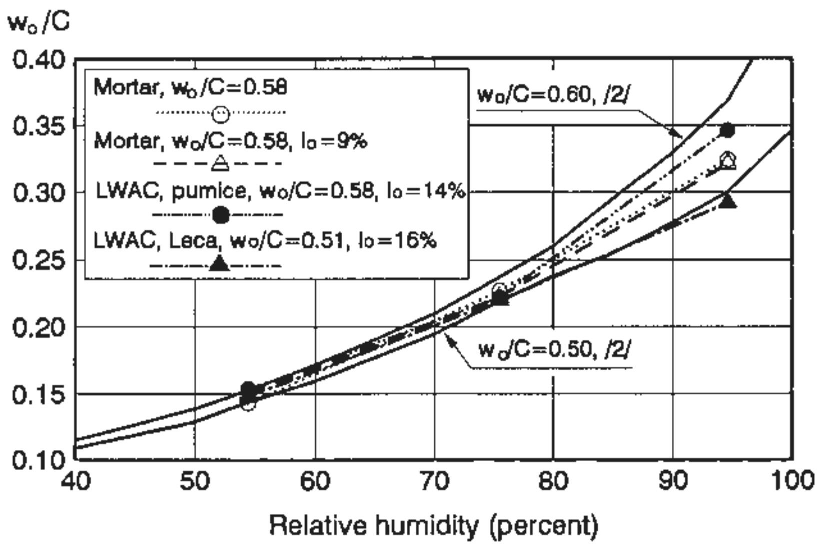

Figure 4 Desorption isotherms for 4 different types of concrete compared to curves based on literature /2/. l_o=air content

Based on the results from laboratory tests the moisture concentration U_m can be calculated. U_m is defined as the average residual amount of moisture that will dry out from the pore system divided by the total amount of moisture that has dried out when the material has reached its equilibrium moisture content.

$$U_m = \frac{\overline{w}_e - \overline{w}_{eq\infty} - (\overline{w}_{n\infty} - \overline{w}_n)}{\overline{w}_{e0} - \overline{w}_{eq\infty} - (\overline{w}_{n\infty} - \overline{w}_{n0})} \qquad (6)$$

$\overline{w}_e$	[kg/m$_3$]	=	average moisture content at actual degree of hydration
$\overline{w}_{eq\infty}$	[kg/m^3]	=	average equilibrium moisture content at final degree of hydration
$\overline{w}_{e0}$	[kg/m^3]	=	average moisture content at initial degree of hydration
$\overline{w}_n$	[kg/m^3]	=	average non evaporable water content at actual degree of hydration
$\overline{w}_{n\infty}$	[kg/m^3]	=	average non evaporable water content at final degree of hydration
$\overline{w}_{n0}$	[kg/m^3]	=	average non evaporable water content at initial degree of hydration

The parameter U_m has been used in the analyses to describe the drying course for comparison between the laboratory tests and the calculated results.

3. NUMERICAL SOLUTION

The partial differential equation (1) has been solved numerically by the use of the finite difference method (FDM) in explicit form, /4/.

$$U_j^{n+1} - U_j^n = \frac{\Delta t}{2(\Delta x)^2} \Big[[D(s_{j+1}^n, t^{n+0.5}) + D(s_j^n, t^{n+0.5})] [U_{j+1}^n - U_j^n] -$$

$$- [D(s_{j-1}^n, t^{n+0.5}) + D(s_j^n, t^{n+0.5})] [U_j^n - U_{j-1}^n] \Big] -$$

$$- \frac{C \cdot 0.25 [\alpha(t^{n+1}) - \alpha(t^n)] + w_{eq}(t^{n+1}) - w_{eq}(t^n)}{w_e(t^0) - w_{eq}(t^0)} \qquad (7)$$

U	= moisture concentration
n	= time step number
j	= element number
Δx	= grid spacing
Δt	= time step
t^i	= age at step i
D(s,t)	= moisture transport coefficient as a function of moisture saturation (s) and age of the concrete
C	= cement content
$\alpha(t^i)$	= degree of hydration at the age t^i
$w_{eq}(t^i)$	= equilibrium moisture content at the age t^i
$w_e(t^i)$	= evaporable moisture content at the age t^i

The number of grids chosen is 20, equally sized. The outer cell is placed with half the grid inside the specimen and its concentration was put at zero after the first time step.

The boundary conditions for U(x,t) are

$$U(x>0,0) = 1$$
$$U(0,t) = 0$$

$\lim_{x\to 0} U(x,t) \neq \lim_{t\to 0} U(x,t)$ shows that $U(0,0) = 0.5$, /4/

There are few existing analytical solutions to equation (1), even with no existing therm for chemical reaction. However, the solutions from the numerical method described above have been compared with analytical solutions for constant diffusion coefficient and results presented in literature for moisture distribution during sorption in a semi-infinite medium with linear variation of the concentration dependent diffusion coefficient.

Analytical solutions to the diffusion equation when the diffusion coefficient is constant are presented in literature for many shapes of bodies and under different boundary conditions /3/. The boundary conditions described above, the falling rate period with the surface at its equilibrium moisture content and uniform initial moisture distribution, result in the solution to equation (8) shown in equation (9), /5/.

$$\frac{\partial U}{\partial t} = D \frac{\partial^2 U}{\partial x^2} \tag{8}$$

$$U_m = \frac{8}{\pi^2}\left(e^{-Dt(\pi/2h)^2} + \frac{1}{9}e^{-9Dt(\pi/2h)^2} + \frac{1}{25}e^{-25Dt(\pi/2h)^2} + \dots\right) \tag{9}$$

h = thickness of the layer through which diffusion occurs. In the case of diffusion through two opposite sides the thickness is 2h.

The results from the comparison between the analytical and numerical solution are shown in Fig 5. In the numerical solution the moisture concentration has been plotted after the first loop and in concentrations from 90% down to 2% of the initial concentration, in steps of 2%. The results show good agreement between the two methods of calculation.

Solutions with variable diffusion coefficient found in literature, /4/, have been used for comparison by other researchers /6/. The solution is obtained by Shampine (1973) when using the numerical method by Runge-Kutta. The conditions concern absorption in an initially dry semi-infinite medium.

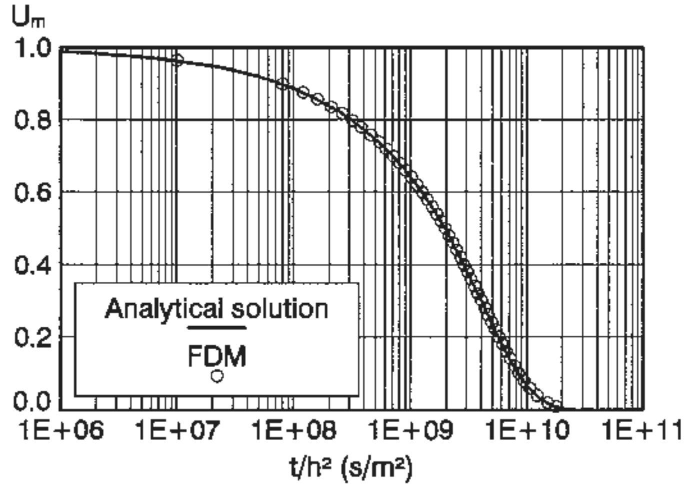

Figure 5 Drying course with constant diffusion coefficient. Comparison between analytical and FDM method. $D=10^{-10}$ m^2/s

The variation of the diffusion coefficient is linear proportional to the moisture saturation, see equation (10).

$$D = D_o(1 + as) \tag{10}$$

s = actual ratio of moisture saturation, s=1 at complete saturation.

In the FDM solution the results of the moisture concentration are plotted for every second grid point, a total of 10 points. This is carried out in moisture concentrations of 10% to 90% of the final concentration. The step in concentration change between each plot is 10%. The results show good agreement between the two solution methods, see Fig 6.

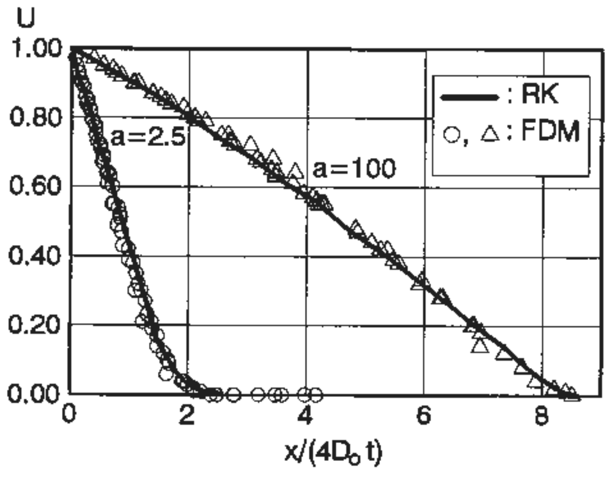

Figure 6 Concentration-distance curves according to equation (10). Numbers on curves are values of a. Comparision between FDM and Runge-Kutta (RK).

4. EXPERIMENTS

4.1 Making concrete and sample preparation

Mortar compositions, mixed in batches of 50 l, were divided into five parts by weight. Washed aggregate of different types and amounts was added to four of these parts. All the five mixes were cast in forms 10x10x50 cm. The concrete composition of each mix was determined based on density and moisture contents of the components added and on the measured density of the mix. The forms were stripped after one day moisture curing and the density of the beams was measured by weighing in air and water. Based on the results from density measurements in fresh and one day old material the volume changes caused by bleeding and/or moisture absorption into the porous aggregates were estimated.

The beams were sealed with two layers of epoxy with an alumina folie between the layers. The second day specimens of different thicknesses, mainly 50 mm, were cut out from the beams. The thickness of each specimen was determined by measuring the distance between the mid-points of the cut surfaces. In order to simulate double thickness one cut side was covered for part of the specimens. The prepared samples were sealed in double plastic bags and stored in the climate where the drying procedure was supposed to take place.

4.2 Drying measurements and calculations

Drying experiments were performed in climate rooms where the climate was kept constant at +20°C RH 50% and +20°C RH 65% respectively. A third series was performed in a climate box at +32°C and RH 55%. The influence of the distance between the drying surfaces and the location of the specimens was studied in a special series in order to obtain equal drying conditions for each specimen. For some of the specimens the dry weight in 105 °C was determined in order to obtain the true moisture content.

The total amount of specimens to be dried out in controlled climatical conditions was about 200. Three different ages of the concrete at the start of the drying process were selected, 3, 5 or 6 and 37 to 55 days. The weight measurements for the main part of the specimens were carried out during one year.

Calculation of the drying rate and the change in moisture concentration is based on the measured weight changes and the results are compared with the numerical calculations. The criteria for testing input data for the numerical solutions are summarized below:

Degree of hydration, α

α_∞	Depending on w_0/C ratio and the age at the start of the drying process, see Fig 1. Minor corrections due to cement content in the mix and moisture content of the aggregate.
$\alpha(t)$	Equal function for the same w_0/C ratio, see Fig 1.

Equilibrium moisture content, w_{eq}/C

$w_{eq\infty}/C$	From desorption isotherm, see Figs 3 and 4.
$W_{eq}(t)/C$	A linear function of $\alpha(t)$

Diffusion coefficient, D (m^2/s)

Continuous phase (mortar)

D_o	Selected to match the experimental data Proportional to vapour pressure at saturation at different temperatures Constant for different ambient RH
D(t)	Equal function for the same w_0/C ratio,
D(s)	Equal functions for the same w_0/C ratio but different courses for air entrained concrete.

Discontinuous phase, D_{dis} , (aggregate+interstitial zone between aggregate and mortar phase)

D_{dis}	Constant for gravel and Leca Depending on the age of the concrete for pumice due to reactions between the aggregate and mortar phase

The age of the specimens

For some of the mixes it was found that the rate of drying was overestimated in early ages with the time dependent functions used to describe the degree of hydration and/or the diffusion coefficient. The reason for this is that the degree of hydration in the early ages depends on so many material and environmental factors that it is difficult to predict the true degree for each sample. For some of the mixes an equivalent age has been used as data input. The residual course has been described with the same functions as the other mixes.

5. RESULTS AND ANALYSES

The results and analyses presented in this article describe the influence of different properties on the drying course and on D_o, the diffusion coefficient of well hydrated material under equilibrium moisture conditions. The main subjects considered are some fundamental influences of w_0/C ratio and entrained air on mortar, the influence of different types of aggregate on the diffusion coefficient of concrete, influence of age at the start of drying for different types of aggregate and influence of the environmental temperature and relative humidity. The percentage values noted in the legends of the Figures after each aggregate are the volume part of the aggregate in the concrete.

5.1 Influence of w_0/C ratio and entrained air

The drying courses for mortar specimens of different w_0/C ratios are shown in Fig 7. The maximum value of the concentration-dependent diffusion coefficient $[D(t)_{max}]$ is in both cases 8 times D_o. The Figure shows good agreement between calculated and measured values for both the thicknesses. Good agreement between measured and calculated values was obtained with an increase in D_o to more than double when w_0/C increases by 0.1. This implies that w_0/C , as for many other properties, is one of the most important variables influencing the drying rate.

The influence of entrained air is shown in Fig 8. The difference in D_o for the two materials has been calculated by using the composite model described earlier. Increase in the air content will increase D_o in the composite. By reducing $[D(t)_{max}]$ to half the value of non-air entrained mortar, and multiplying D_o with 1.3, a good agreement between the model and measured values was obtained.

5.2 Influence of different types of aggregate

In Fig 9, 25% gravel is added to mortar of w_0/C 0.56. A good curve fitting is achieved when the value of D_o for the gravel, including the interstitial zone is $5*10^{-11}$ m^2/s. It means that the diffusion in the concrete will be greater than in its corresponding mortar phase despite the negligible diffusion through the gravel. This result agrees with results from literature /2/.

Results from measurements with Leca and pumice are shown in Figure 10. The w_0/C ratio of the mortar was in this case 0.45. The Leca fraction used here, 4-10 mm, had a very low rate of water absorption. After one week storage in water the moisture ratio was as low as eight percent. As can be seen from the Figure the influence of Leca is very small. Probably most of the moisture was at the surface of the grains when the concrete was cast. Most of this amount of moisture will probably leave the grains at an early stage of the hydration due to the chemical contraction inside the paste. The low water absorption and the low value of the diffusion coefficient for Leca indicate a large number of closed pores in the aggregate.

The effect of pumice addition is completely different. The initial moisture ratio in the pumice aggregates was as high as 102%, theoretically maximum is 115%. Despite the mixing order, this very high moisture content probably changed the w_0/C ratio of the mortar phase. The w_0/C ratio used in the model was 0.50 for 13 vol-% and 0.55 for 25 vol-% pumice addition. The shape of the curves representing pumice concrete indicates great time dependence of the diffusion coefficient. The most probable explanation is that the pozzolanic reaction between pumice and mortar will densify the surface of the pumice grains and reduce the rate of moisture transport from the grains.

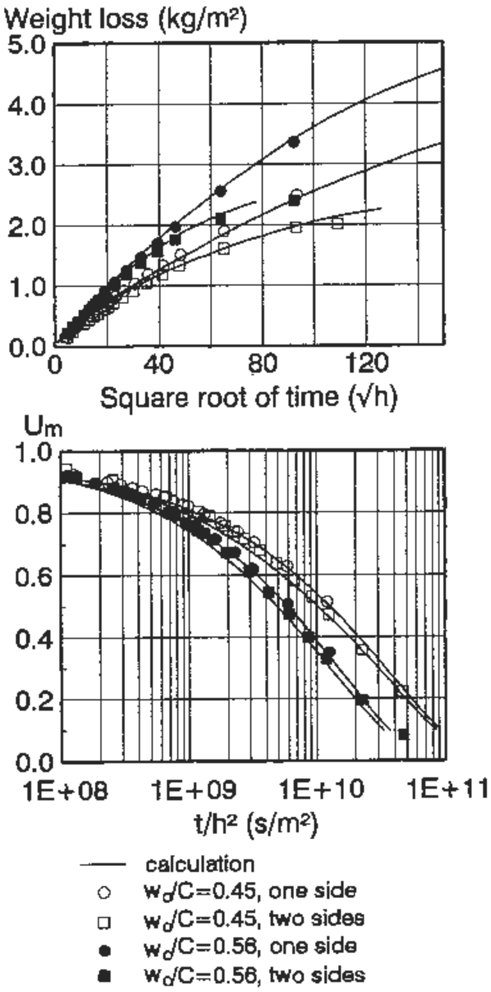

Figure 7 Influence of w_0/C ratio on drying of mortar

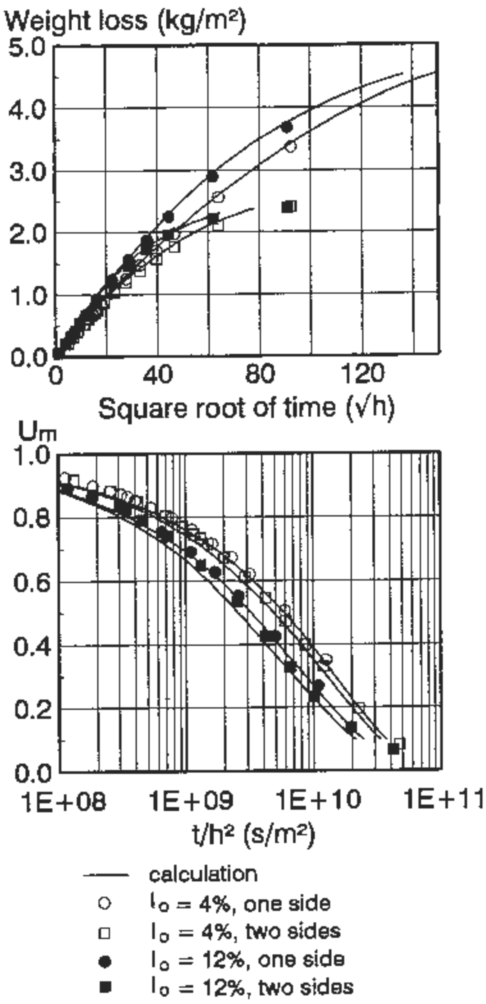

Figure 8 Influence of air content (l_o) on drying of mortar

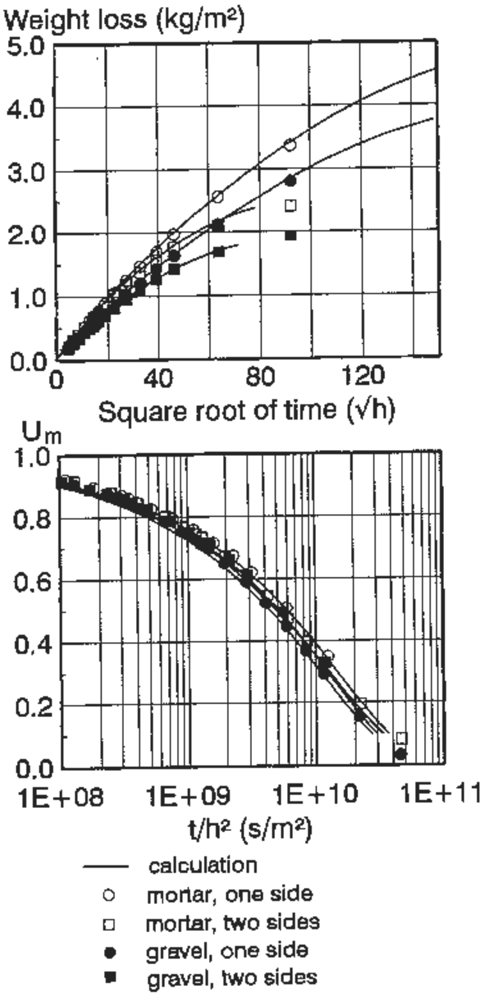

Figure 9 Influence of gravel, 26 vol-%, on drying of mortar.

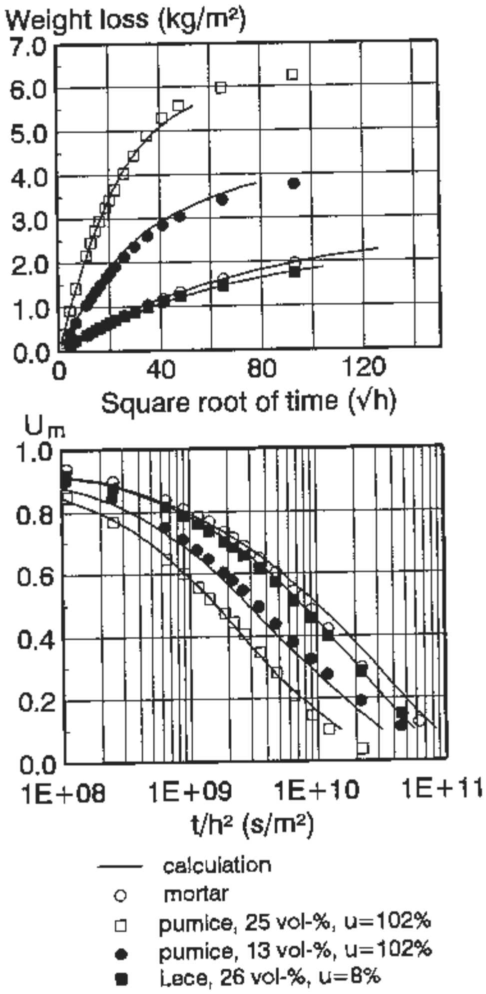

Figure 10 Influence of Leca and pumice

5.3 Influence of age

Fig 11 shows drying of mortar with and without Leca aggregate The ages at the start of drying are 5 and 50 days. The results agree with the equations given for the time dependence of the moisture transport.

The results for pumice compared with the results for Leca are shown in Fig 12. The curves representing pumice concrete show a much greater gap between the two ages. This also indicates that the diffusion through the pumice surfaces is time dependent.

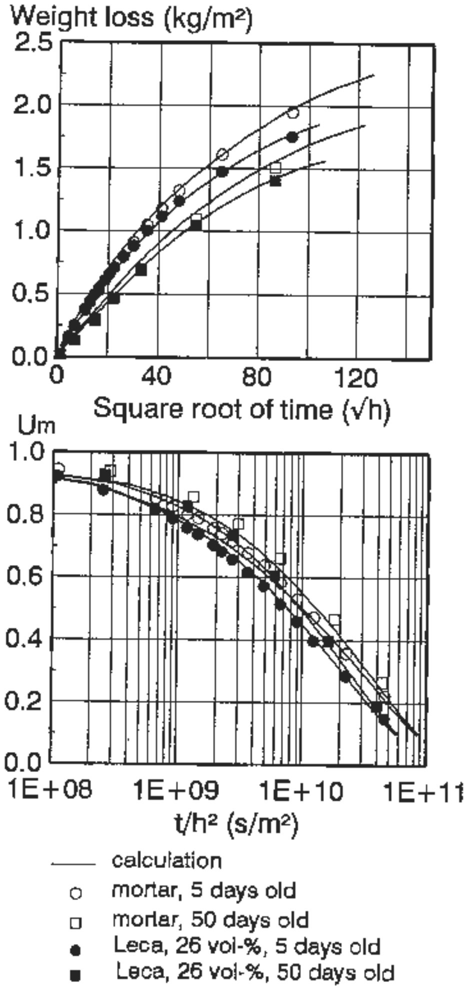

Figure 11 Influence of age. Mortar and Leca,

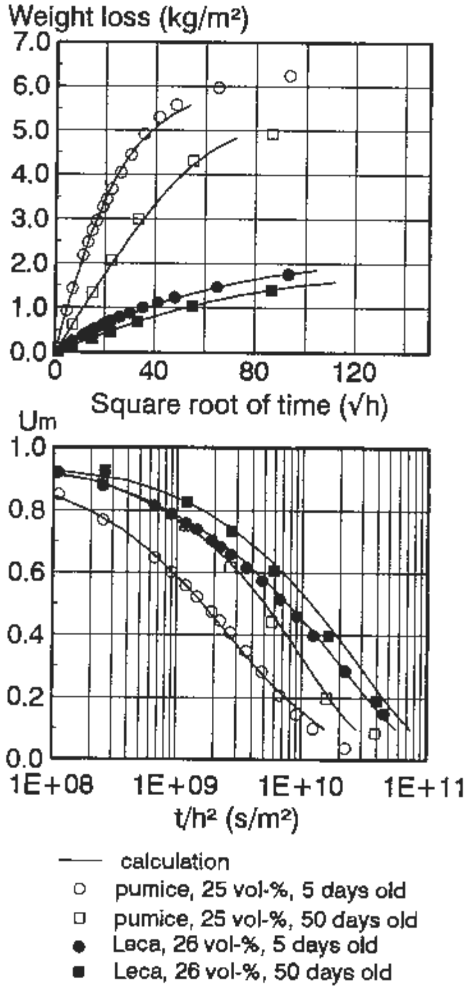

Figure 12 Influence of age. Pumice and Leca

5.4 Influence of drying climate

In Figs 13 and 14 the influence of different climates are shown. A rise in relative humidity will increase the amount of equilibrium moisture content. According to the model the increase of fixed moisture will not change the diffusion coefficient, D, as long as D_0 are considered constant.

The effect of rise in temperature on D_0 is modelled as proportional to the saturated vapour pressures at the different temperatures /2/. The Figures show good agreement between calculated and measured values. The course of the curves representing pumice concrete in the climate +20°C and RH 65% indicates however a short initial period of constant rate and/or unsaturated surface drying.

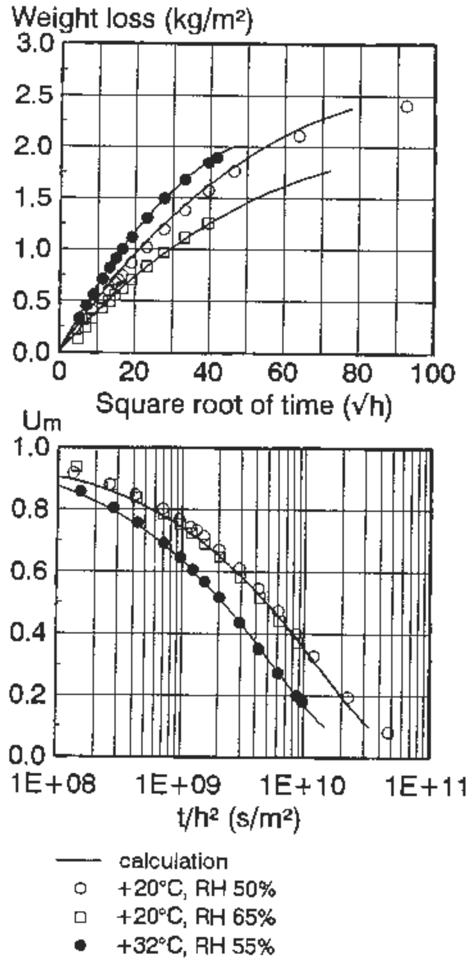

Figure 13 Influence of RH and temperature. Mortar

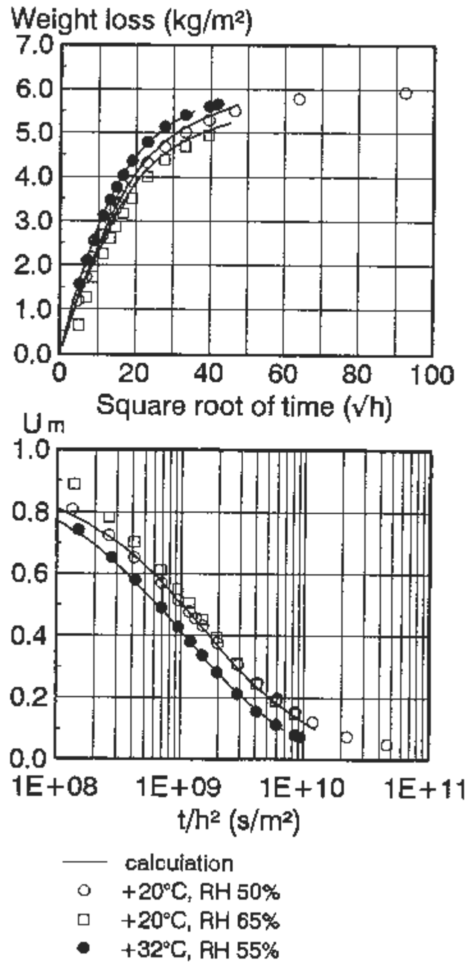

Figure 14 Influence of RH and temperature. Pumice, 25 vol-%

6. CONCLUSIONS

The results and analyses show that it is possible to formulate a model which describes the influence of main factors on the drying process in a complex composite such as lightweight aggregate concrete.

Good correlation has been obtained between calculated and measured values. This has been confirmed as specimens of different thicknesses have been used.

Many of the main influencing factors on the drying process of the mortar phase, previous known among researchers, have been confirmed as having similar influence on lightweight aggregate concrete. The properties of the contact zone between aggregate and concrete could, however, influence the whole drying process in a drastic way. Gravel, Leca and pumice are examples of aggregates which show completely different influences on the drying process.

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