A New Model to Calculate the Drying of Concrete

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ABSTRACT

The paper presents the theory for a design tool to calculate drying of concrete, from green condition to flooring. The degree of hydration, the cement ratio of the concrete, the temperature and the moisture state are taken into account. The moisture calculations are based on the use of Kirchhoff potentials. Calculation examples and comparison with experiments are also given in the paper.

KEYWORDS

Concrete drying, material data.

INTRODUCTION

Moisture transport in concrete is a complicated non-linear process, which may vary strongly with a number of parameters such as temperature, moisture state, water cement ratio, degree of hydration. Models to calculate moisture flow have been developed during the past. The theoretical basis for one class of models started in late 1950s by Philip and de Vries (1957), and later Luikow (1966), Vos and van Minnen (1966), and Vos and Tammes (1969). These models were based on two driving potentials, temperature and moisture content, and the combined heat and moisture flow was calculated by two governing partial differential equations. The theory has been used and further developed by van der Kooi (1971) and Nielsson (1974). Another commonly used approach is to use moisture content (or pore water pressure) and vapour content as driving potentials for the moisture flow. (Krischer, 1963; Sandberg, 1973; Kiessl, 1983, Pedersen, 1990; Künzel, 1995; Burch, 1997, Grunewald, Janssen, H., Blocken, B. & Carmeliet 2005 etc) Here, the moisture flow is more directly related to water vapour diffusion and to pressure-driven capillary flow.

This paper deals with a model for moisture transport based on Kirchhoff potentials, Arfvidsson and Claesson (2000), that has been combined with a material model for concrete. The material model determines the transport properties and the sorption isotherms taking into account the degree of hydration, the cement ratio of the concrete, the temperature level and the moisture state.

THEORY

Kirchhoff potential

The algorithm developed in this work uses the Kirchhoff potential devised to simplify the differential equation of diffusion in the case where the diffusion coefficient is a function of moisture content.

The Kirchhoff potential is developed as follows. Let g (kg m^{-2} s^{-1}) denote moisture flux and w (kg m^{-3}) moisture content mass by volume. In the case of one-dimensional isothermal moisture transport we have.

$$g = -D_w \frac{\partial w}{\partial x} \tag{1}$$

Kirchhoff introduced a potential [4] defined as

$$\psi = \int_{w_{ref}}^{w} D_w dw \tag{2}$$

The reference value w_{ref} can be chosen arbitrarily. At the reference value, ψ_{ref} is set to zero i.e.

$$\psi(w_{ref}) = \psi_{ref} = 0 \tag{3}$$

The diffusion coefficient D_w is from (2) the derivative of the Kirchhoff potential ψ with respect to w, i.e.

$$D_w = \frac{d\psi}{dw} \tag{4}$$

We now have, from equations (1) and (4)

$$g = -D_w \frac{\partial w}{\partial x} = -\frac{d\psi}{dw}\frac{\partial w}{dx} = -\frac{\partial \psi}{\partial x} \tag{5}$$

i.e. with this transformation, moisture flux becomes simply the gradient of the Kirchhoff potential ψ.

The moisture balance equation has the following simple form:

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x}(g) = \frac{\partial^2 \psi}{\partial x^2} \tag{6}$$

A more complete presentation of the use of the Kirchhoff potential can be found in Arfvidsson and Claesson (2000).

Moisture transport properties

The moisture transport coefficient, expressed as moisture permeability (δ_v), varies strongly with the water cement ratio (w/c) or the water binder ratio (wbr) of the concrete and also with the “age” of the concrete (the degree of hydration). Besides the moisture permeability decreases with increased drying, as dry concrete transport moisture more poorly than wet. This means that for each concrete that dries, the different moisture permeabilities governs the drying process during different stages.

The starting point is the moisture permeability given in Table 1. Four different types of concrete are presented. They are all very mature. A more complete description of the different types of concrete and the underlying experiments are given in Hedenblad (1993).

Table 1. Moisture permeability of mature concrete as function of RH. Hedenblad (1993).

RH	δ_v (m^2/s)			
(%)	w/c 0.5	w/c 0.6	w/c 0.7	w/c 0.8
33 – 65	$0.14 \cdot 10^{-6}$	$0.15 \cdot 10^{-6}$	$0.18 \cdot 10^{-6}$	$0.18 \cdot 10^{-6}$
80	0.33	0.38	0.40	0.37
86	0.59	0.83	0.77	0.60
90	1.0	1.7	1.4	1.3
93	1.7	3.5	2.7	3.3
95	2.8	7.5	7.5	7.5
96	4.2	8.5	9.5	11
97	9.0	14	17.5	26
97,6	-	22	28	42
98	-	-	38	63
98,5	-	-	-	130

Table 1 is valid for concrete made of the Swedish cement; Slite Std.

The results in Table 1 clearly show that w/c in the range 0.6 to 0.8, has no, or little, influence on δ_v up to about 95 % RH. This is a surprising result and one explanation can be that the interface between the aggregates and the cement paste is much more permeable than the cement paste. Over about 95 % RH, δ_v depends strongly on w/c. Maximum δ_v is about $130 \cdot 10^{-6}$ m^2/s for w/c 0.8 and about $20 \cdot 10^{-6}$ m^2/s for w/c 0.6.

Gilliland et al (1958) have shown, for isobutane at 0 °C, that the plot of the surface flow versus the (surface concentration)^2/gas-phase pressure gives a straight line, see Figure 1 to Figure 3. The surface flow in Figure 3 is evaluated, in Figure 1, as the total flow minus the gas-phase flow (marked with line of short dashes). Both adsorption and desorption are considered in Figure 3.

Instead of (surface concentration)^2/gas-phase pressure on the X-axis one can use (moisture content mass by volume)^2/vapour density. A more complete presentation is given in Hedenblad (1993).

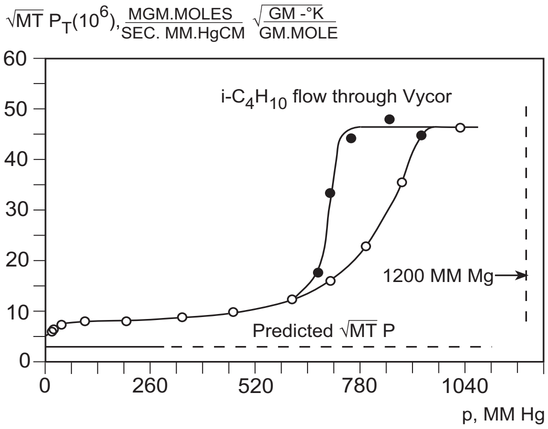

Figure 1. Isobutane flow through Vycor glass, after Gilliland et al (1958)

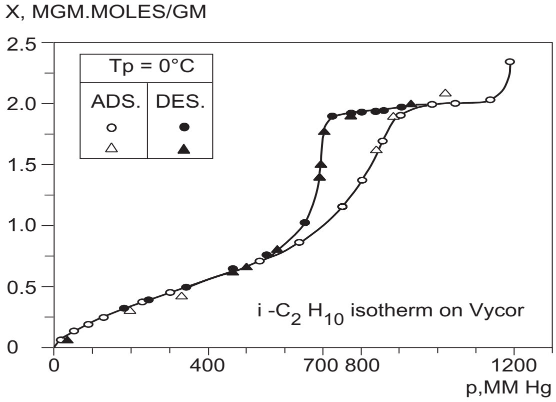

Figure 2. Sorption isotherm for isobutene on Vycor glass, after Gilliland et al (1958).

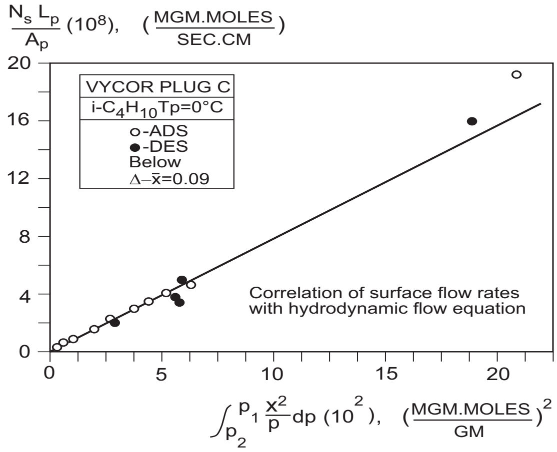

Figure 3. Correlation of surface flow and (surface conc.)^2/gas-phase pressure,Gilliland et al (1958).

In Table 2 the transport coefficients are given as Kirchhoff potential. The values in Table 2 are in g/(m·day), they can be expressed in kg/(m·s) by mulitiplying the values with $11.57 \cdot 10^{-9}$

Table 2. Kirchoff potential of mature concrete as function of RH.

RF	ψ (g/m·day)			
(%)	Wc 0.5	Wc 0.6	Wc 0.7	Wc 0.8
35	0	0	0	0
50	0.039	0.039	0.036	0.046
60	0.061	0.061	0.063	0.071
65	0.072	0.072	0.073	0.083
70	0.084	0.088	0.088	0.099
75	0.098	0.104	0.104	0.115
80	0.118	0.124	0.128	0.139
84	0.142	0.151	0.160	0.165
86	0.156	0.173	0.174	0.182
88	0.175	0.202	0.200	0.203
90	0.201	0.243	0.235	0.231
92	0.239	0.304	0.294	0.288
94	0.295	0.423	0.384	0.389
95	0.335	0.506	0.407	0.448
96	(0.380)	(0.596)	0.491	0.812
97	(0.480)	(0.744)	(0.650)	1.213
97.6	-	(0.975)		
98	-	-	(1.162)	(1.666)
98.5	-	-	-	(2.227)

Sorption isotherms

Nilsson (1980) published desorption isotherms for mature cement paste with different w/c. The isotherms go up to 100 % RH. Some revisions of the isotherms have been made by Hedenblad (1988), so that the alkalies in the cement determine the maximum RH (lower than 100 %). Figure 4 shows the desorption isotherms, from Hedenblad (1988).

The desorption isotherms in Figure 4 must be multiplied by the content of cement in the concrete or the cement mortar to get the isotherm for the material.

For concrete with a degree of hydration different from Figure 4, a mathematical model is used which are developed by Hedberg (1994) and used by Norling Mjörnell (1997). The model is expressed by the following equation.

$$w(\phi,\alpha) = w_{gel}(\phi,\alpha) + w_{cap}(\phi,\alpha) \qquad (7)$$

w_{gel} = the maximum amount of water in the gel pores of the cement paste
w_{cap} = the maximum amount of water in the capillary pores of the cement paste.
w_{gel} = the maximum amount of water in the gel pores of the cement paste Norling Mjörnell (1997).
w_{cap} = the maximum amount of water in the capillary pores of the cement paste.For further details, see

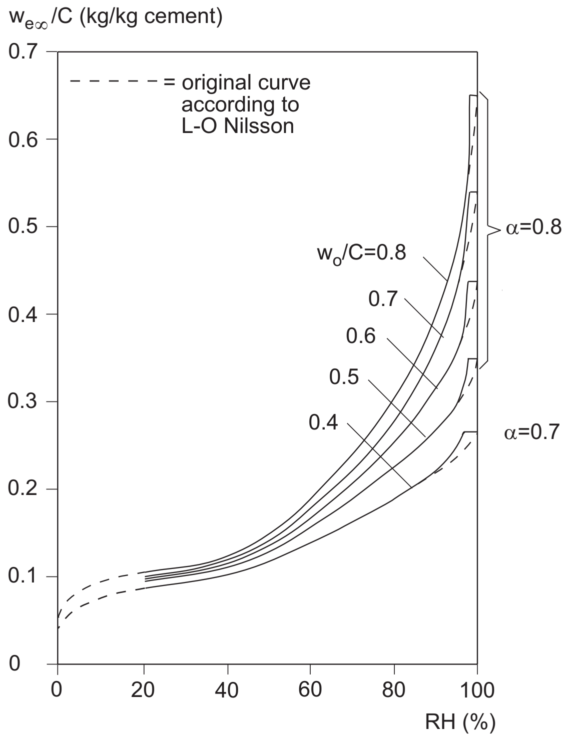

Figure 4. Desorption isotherms for mature cement paste with different w/c and degrees of hydration. Based on isotherms according to Nilsson (1980).

<u>Influence of alkalies in the cement</u>

When a material contains different kinds of salts, e.g. sodium chloride (NaCl) or sodium hydroxide (NaOH), the isothermal equilibrium is affected. In the case of cement products, it is above all the contents of alkali metal compounds, chiefly as potassium hydroxide (KOH) and sodium hydroxide (NaOH), which can affect the humidity equilibrium curve. Peterson (1987) has calculated, for Slite Standard cement (Slite Std) for which TorkaS is made, that the content of alkali metal hydroxides is about 0.34 moles per kg cement, mainly as KOH. Different types of cement, and also from different factories, contains different amounts of alkali. The effect on the sorption isotherm is that for the same moisture content (kg water per m^3 concrete) so decreases the relative humidity. For completely saturated concrete, RH will be lower than 100%. The more alkalies there are in the concrete the lower will RH be at saturation. For a more complete presentation, see Hedenblad (1988) and Hedenblad & Janz (1994).

<u>Degree of hydration</u>

At the calculation of the moisture transport properties and the sorption isotherms you must know the progress of the hydration (chemical reaction between cement and water) both for silica fume and for the cement. This varies with temperature, relative humidity and water binder ratio but it also varies with the type of cement. Experimental data taken from Norling Mjörnell (1997) is used. Examples of such measurements, on cement paste without silica fume, are shown in Figure 5 and Figure 6. Degrees of hydration, used in TorkaS are shown in Table 3.

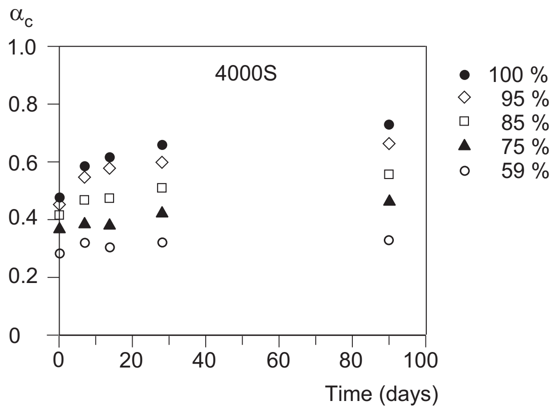

Figure 5. Degree of hydration for cement paste with w/c 0.4, Different RH, after Norling Mjörnell [1997].

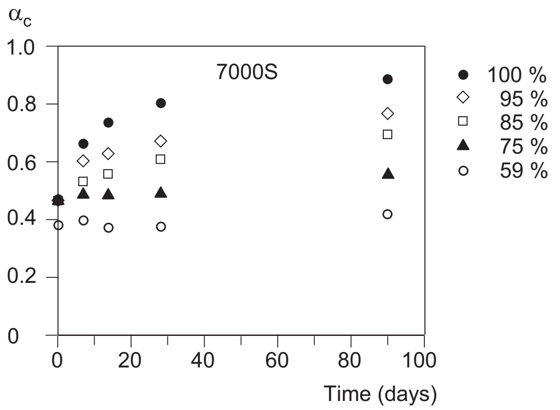

Figure 6. Degree of hydration for cement paste with w/c 0.7, Different RH, after Norling Mjörnell [1997].

Table 3. In TorkaS used degree of hydration at +20 °oC for concrete with different w/c.The values is calculated for the case: 100 % RH.

Time (days)	W/c 0.4	W/c 0.5	W/c 0.6	W/c 0.7
<0.2	0	0	0	0
1	0,42	0,42	0,42	0,42
7	0,54	0,57	0,60	0,62
14	0,60	0,64	0,67	0,71
28	0,64	0,69	0,74	0,78
56	0,69	0,75	0,80	0,86
90	0,72	0,78	0,85	0,90

The influence of the relative humidity on the degree of hydration is shown in Figure 5 and Figure 6. This influence is shown as a factor of correction to the degree of hydration at 100 % RH. The factor is shown in Figure 7.

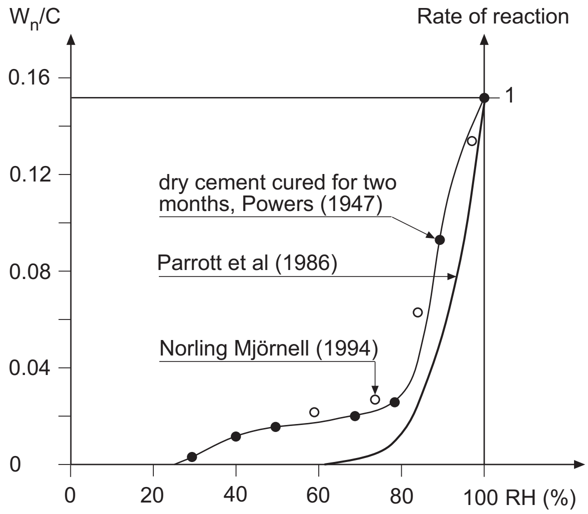

Figure 7. Influence of RH on the degree of hydration, after Norling Mjörnell [1997]

The numerical algorithm

The numerical modelling becomes particularly simple, when Kirchhoff's potential is used. The method of explicit forward differences is used in the discrete numerical models.

The one-dimensional process occurs along the x-axis. The material is divided in thin slabs or cells. The thickness of cell i is Δx_i and its centre lies at x_i. See Figure 8. The moisture state variables at the centre of the cell are denoted w_i, ϕ_i and ψ_i at the considered time-step. The moisture state is given in all cells at the start t=0. We use a time-step Δt and calculate the moisture state in all cells i for each time-step at times $t=\Delta t$, $t=2\cdot\Delta t$, etc.

The moisture mass balance per unit area perpendicular to the x-axis in the one-dimensional discrete approximation using explicit forward differences is now:

$$(w_i^{new} - w_i)\cdot 1\cdot \Delta x_i = (g_{i-½} - g_{i+½})\cdot 1\cdot \Delta t \qquad (8)$$

Here w_i^{new} denotes the new moisture content of cell i at the next time-step. The moisture flux from i-1 to i is $g_{i-½}$ (kg/(m^2,s)). Multiplication with the area (1m^2) and the time Δt gives the total moisture inflow. The second term on the right hand side involving $g_{i+½}$ gives the moisture flux from cell i to cell $i+1$.

The moisture flux $g_{i-½}$ between cell i-1 and i is given by a discrete approximation of Fick's law. Let us first consider a conventional approach with ϕ as gradient and $D_\phi(\phi)$ as flow coefficient. We have from Fick's law (1):

$$g_{i-½} = -D^{av}_{\phi,i-½}\cdot\frac{\phi_i-\phi_{i-1}}{x_i-x_{i-1}} \qquad (9)$$

The denominator is the distance between cell i and cell i-1:

$$x_i - x_{i-1} = \frac{\Delta x_{i-1}}{2} + \frac{\Delta x_i}{2} \qquad (10)$$

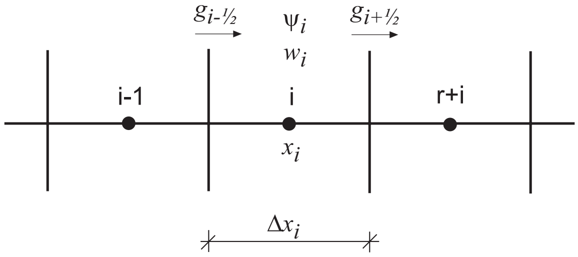

Figure 8. Discrete approximation in the one-dimensional case. Cell i has the width Δx_i.

In (9), a suitable average of $D_\phi(\phi)$ in the interval ϕ_{i-1} to ϕ_i has to be determined and used. If D_ϕ is constant or modestly varying in the interval, the value of D_ϕ at $(\phi_{i-1}+\phi_i)/2$ should be quite good. Problems occur when D_ϕ varies strongly in the interval. This interpolation problem occurs in the same way when $D_w(w)$ is used.

Let us consider an exact solution. We have from (1) for the considered (quasi steady-state) situation:

$$g_{i-½} = -D_\phi(\phi)\frac{d\phi}{dx}$$

$$\phi(x_{i-1}) = \phi_{i-1} \qquad \phi(x_i) = \phi_i \qquad (11)$$

Integration over $x_{i-1} < x < x_i$ gives, since $g_{i-½}$ is constant:

$$g_{i-½} \cdot (x_i - x_{i-1}) = -\int_{\phi_{i-1}}^{\phi_i} D_\phi(\phi')\, d\phi' \qquad (12)$$

Combining (9) and (12), we have the exact average which should be used in calculations:

$$D^{av}_{\phi.i-½} = \frac{1}{\phi_i - \phi_{i-1}} \int_{\phi_{i-1}}^{\phi_i} D_\phi(\phi')\, d\phi' == \frac{\psi_i - \psi_{i-1}}{\phi_i - \phi_{i-1}} \qquad (13)$$

Combining (9) and (13), we have, since ϕ_i - ϕ_{i-1} cancels:

$$g_{i-½} = -\frac{\psi_i - \psi_{i-1}}{x_i - x_{i-1}} \qquad (14)$$

This is our relation for the flow using Kirchhoff's potential. We could of course have written this down directly.

Let us summarise the calculation procedure using Kirchhoff's potential. The moisture fluxes are given by differences in ψ; i.e. ψ_i-ψ_{i-1}, divided by the distance x_i-x_{i-1} between the cell centres. Combining (8) and (14), we have the simplest possible numerical procedure:

$$w_i^{new} = w_i + \left(\frac{\psi_{i-1} - \psi_i}{x_i - x_{i-1}} + \frac{\psi_{i+1} - \psi_i}{x_{i+1} - x_i}\right) \cdot \frac{\Delta t}{\Delta x_i} \qquad (15)$$

Initially at time $t=0$ the moisture content w_i is known in all cells. The material model described in 2.2 gives $\psi_i = \psi(w_i)$ for all cells. The moisture flow between adjacent cells is then calculated using equation (14). When all flows to and from a cell are known, the moisture content w_i^{new} one time-step Δt later is calculated from (8) or directly from (15). From w_i^{new}, the Kirchhoff potentials ψ_i^{new} are, as before, determined from the material model. This procedure is repeated time-step after time-step throughout the simulation time.

EXPERIMENTAL

To validate the model a number of experimental runs were undertaken. Cylindrical specimens with a diameter of 300 mm and a height of 180 mm were cast in plastic tubes. In this way a one-dimensional flow system was established by sealing all sides of the specimen except the two flat faces. In the big tube, small tubes were fastened at different depths and sealed with rubber plugs. In these tubes the relative humidity was measured, see Figure 9.

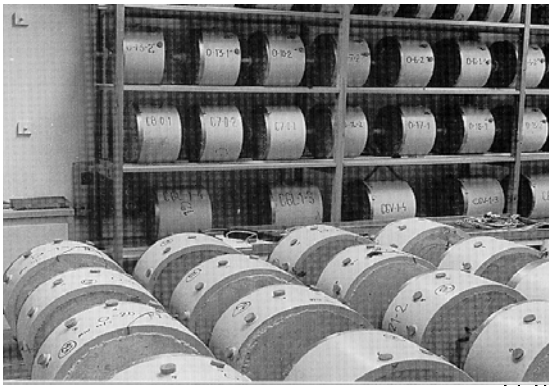

Figure 9. Photo of some concrete specimens.

The test program comprised about 40 different concrete qualities, ranging from wbr 0.8 to 0.31. For all the types of concrete the water binder ratio or the water cement ratio has been used as the main parameter. This was done because the drying time of concrete is mainly dependent on its construction water content and its imperviousness. These properties are determined by the w/c ratio and not by the strength class. For "conventional" concrete the w/c ratio ranged from 0.8 to 0.4, with in principal the same structure for each w/c ratio

For rapid drying/self desiccating concrete the wbr ratio ranged from 0.49 to 0.31, divided in steps of

0.03. For this type of concrete, totally 15 different concrete compositions were used.

Seven different typical cases were investigated, namely

- Case a: Normal case. Rain during the first 2 weeks after casting, followed by very high RH in the ambient air for 2 weeks. After this, drying starts in a climate of +18oC and 60 %RH.
- Case b: Short curing period. After curing in formwork for one day, drying takes place at +18 oC and 60 % RH.
- Case c: Continuous rain for 2 weeks. This is followed by drying at +18 oC and 60 % RH.
- Case d: Air of high RH for 4 weeks. During the first 4 weeks after casting, the ambient air has a very high RH. Drying then takes place at +18 oC and 60 % RH.
- Case e: Continuous rain for 4 weeks. It is raining during the first 4 weeks after casting. Then drying takes place at +18 oC and 60 % RH.
- Case f: Continuous rain for 2 months. It is raining during the first 2 month after casting. Then drying takes place at +18 oC and 60 % RH.
- Case g: Rain again after some drying. Normal conditions (Case a) during the first 2 months, followed by rain for two weeks. Then drying takes place at +18 oC and 60 % RH.

All the different cases have not been used for every concrete quality, but case a, the normal case, has been used for most of the different concrete compositions.

Case e, continuous rain for 4 weeks, has been used to calibrate the “suction” parameters in TorkaS. All the other cases have not been used at the mathematical modelling in TorkaS. It means that in this cases only an comparison have been made by calculated and measured drying.

RESULTS AND DISCUSSION

The theory described in this paper has been implemented in a computer program, TorkaS, aimed to be a design tool for the building industry in Sweden. It is only valid for Swedish Slite Std cement. The program is very easy to use and the result can be used to make prognosis for the drying of a concrete slab on the ground or an intermediate floor. By knowing the drying time for different constructions it is possible to take the result into the planning and prevent moisture related problems in floors. The program is freely available in Sweden on the internet and so far over 3000 users have been registered.

To be sure that the program gives reasonable good results a number of comparisons between measurements and calculation results have been made. About 50 different comparisons have been made and reported in Hedenblad [1998]. Some of the comparisons are shown in TABLE 4 and TABLE 5. The comparisons are made at 20 % of the thickness of the specimen (drying from both sides) or 40 % of the thickness of the specimen (drying from one side only). Comparisons between measurements made on the building site and calculations made with TorkaS have been carried out by a construction company. The agreement was very good.

TABLE 4 Comparison between calculated and measured RH. Case b: Short curing period.

w/c	Time (months)								
	0	1	2	3	4	5	6	7	8
0.75 calc.	96	92	90	88,5	87,5	86,5	86	85,5	85
meas	97	93	90,5	88,5	87	86	-	-	-
0.60, calc.	95,5	91,5	89,5	88	87	86,5	85,5	85	-
meas.	96	90,5	88,5	87,5	-	-	-	-	-
0.50, calc.	95	90,5	88,5	87,5	86,5	85,5	85	-	-
meas.	92	89	87	85	-	-	-	-	-
0.40, calc.	93	89	86,5	85,5	84	-	-	-	
meas.	88.5	85	-	-	-	-	-	-	-

TABLE 5 Comparison between calculated and measured RH. Case e: Continuous rain for 4 weeks.

w/c	Time (months)								
	0	1	2	3	4	5	6	7	8
0.75, calc.	96,5	93	92	91	90	89	88	87,5	87
meas.	96	94,5	92,5	91	90	89	88	-	-
0.60, calc.	96	93	91	90	89	88	87,5	87	86
meas.	95	93	91,5	90	89,5	-	-	-	-
0.50, calc.	93	91	89	88	87	86	85,5	84,5	-
meas.	92	90	88						
0.40, calc.	90	88,5	86,5	85,5	84,5	-	-	-	-
meas.	90	87	-	-	-	-	-	-	-

CONCLUSION

The comparison between measured and calculated values shows good agreement. The material model seems to work well for the cement used (Slite Std cement).

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