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Nilsson, Lars-Olof

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

MOISTURE TRANSPORT UNDER A TEMPERATURE GRADIENT – SOME OLD AND NEW STUDIES

L.-O. Nilsson

University of Lund, Sweden

ABSTRACT

Moisture transport in concrete under a temperature gradient is a topic that has challenged researchers for at least some 60 years. No conclusions are still drawn on how to describe it theoretically and how to quantify it experimentally. In this paper some of the theoretical and experimental work done is summarized. A description of the flux of moisture by the relative humidity and the water vapour content as the two transport potentials is proposed. A comparison with laboratory and field data is given and the consequences in some applications are discussed.

1 INTRODUCTION

The topic of the paper is a topic that has been thoroughly discussed with professor Sellevold at several occasions during a number of years, without any final conclusion being drawn. Now, theoretical aspects and various experimental studies are summarized to show our present knowledge within the topic.

Moisture transport in concrete under a temperature gradient is of major importance in a limited number of applications, simply because temperature gradients in concrete are usually small and disappear quickly. Concrete is a good heat conductor, which means that the heat resistance of a concrete structure with a reasonable thickness is small, compared to

many other materials. If concrete is combined with any type of heat insulating material the temperature gradient in the concrete will be negligible, except for short periods of time if the concrete is temporarily heated or cooled, for instance by solar radiation or rain, respectively. Even without any heat insulation most of the temperature difference between the two sides of a concrete structure will occur between the concrete surfaces and the surrounding air, since the heat resistance of 0.3 m concrete is approximately the same as the resistances at the surfaces.

Where significant temperature gradients really occur in concrete for longer periods of time are in a limited number of applications such as

- the first couple of days after casting if the concrete surfaces are not covered by heat insulation, due to the heat released from the binder reactions,
- through nuclear power reactor containment walls where a high temperature inside the containment occur for months and years with little interruptions,
- through hydro power dam walls where the temperature of the water on the upstream side has small annual variations but the temperature of the air on the downstream side varies from very low levels in wintertime and very high levels in summertime,
- in hydro power dam walls next to the water table in wintertime where the air temperature may by very low during the whole winter but the water is not frozen,
- in concrete floor slabs with cast-in heating cables or tubes.

2 THEORY

Moisture in concrete is mostly adsorbed or interlayer water in the reaction products and capillary condensed water bound by menisci in the capillary pores. A very small amount of moisture is present as water vapour in the pores that are not fully saturated. Temperature gradients may force water into the air voids as well due to condensation.

The mechanisms for transport of this moisture are, traditionally, thought of as diffusion of water vapour due to vapour content v differences in partly empty pores and liquid water transport due to differences in pore water pressure P_w. A flux description with these transport potentials is

$$g = -\delta_{v,P}\frac{\partial v}{\partial x} - k_{P,v}\frac{\partial P_w}{\partial x} \tag{1}$$

where $\delta_{v,P}$ is the water vapour transport coefficient when a second term includes P and $k_{P,v}$ is the water permeability when a second term includes v. The two moisture transport coefficients are of course no constants but significantly moisture dependent.

At isothermal conditions, without a temperature gradient, the pore water pressure can be expressed, from the Kelvin equation, as a function of vapour content in a unique equation

$$P_w = \frac{RT\rho}{M}\ln\varphi = \frac{RT\rho}{M}\ln\left(\frac{v}{v_s}\right) \tag{2}$$

where R is the gas constant, T is the absolute temperature [K], ρ is the density of water, M is the molar weight of water, φ is the relative humidity RH and v_s is the vapour content at saturation at the temperature T.

Consequently, only one term is then required to describe the flux of moisture. A number of alternative moisture transport potentials are the moisture content w, the relative humidity φ and the water vapour pressure p. Isothermal moisture flow may then be described with any of these flux equations

$$g = -\delta_v\frac{\partial v}{\partial x} = -\delta_p\frac{\partial p}{\partial x} = -\delta_{RH}\frac{\partial \varphi}{\partial x} = -k_P\frac{\partial P_w}{\partial x} = -D_w\frac{\partial w}{\partial x} \tag{3}$$

The transport potentials are all equally possible to express as functions of each other and, therefore, the transport coefficients can be translated into each other. The translation when the moisture content w is used involves the slope of the sorption isotherm, which makes the relationships more complicated and not unique. The slope of the sorption isotherm depends on the moisture history, whether the conditions were wetter or drier before.

When quantifying the moisture transport coefficients, it is not possible to separate the moisture into flux of water vapour, flux of pore water, flux of adsorbed water and flux of interlayer water. The total flux is measured.

Therefore it is natural to express the moisture transport properties with only one coefficient and the flux of moisture with only one term.

Moisture transport in concrete under a temperature gradient is, however, different. The transport mechanisms behave differently under a temperature gradient and the flux of water vapour and the flux of pore water may very well have different directions! Consequently, at least two terms are needed in a flux equation.

Moisture transport under a temperature gradient is a topic that has challenged researchers for at least some 60 years. Lykow (1958) used the temperature itself as the moisture transport potential in the second term. Lykow used the moisture ratio u as transport potential; with the moisture content instead his equation will be

$$g = -D_{w,T}\frac{\partial w}{\partial x} - D_{T,w}\frac{\partial T}{\partial x} \tag{4}$$

Several other alternative expressions have been used with different combinations of transport potentials.

Next, some experimental observations from laboratory studies and field studies are shown, starting from a hypothetical, simple case to real concrete structures in laboratory and filed conditions.

3 MOISTURE TRANSPORT IN A TWO PORE-SIZE SYSTEM

The most simple case to use for understanding some of the mechanisms involved when moisture flow occurs under a temperature gradient is a two pore-size system with vapour flow in the larger pores and capillary suction in the smaller pores. A hypothetical example is constructed and a real case where measurements were done is shown.

3.1 A hypothetical example

A simple example shows the complication with moisture flow under a temperature gradient, cf. figure 1.

In the example in figure 1 RH is very close to 100 % at the right hand side and the temperature is +17°C. Consequently, the menisci in small pores

that are water filled are flat. The pore water pressure is close to 0. The water vapour content at saturation is equal to the vapour content at saturation at +17°C, i.e. 14.5 g/m^3. Very large pores are empty.

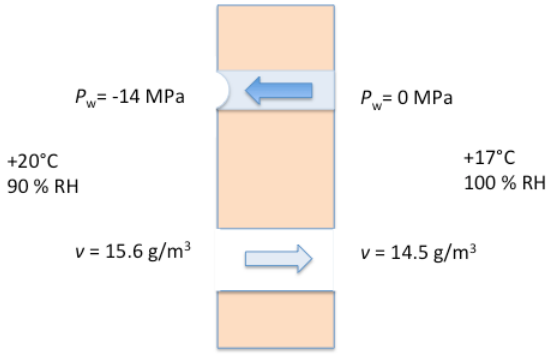

Figure 1 – Example: direction of the fluxes of moisture under a temperature gradient in a two pore-size system

On the left hand side the temperature is +20°C and RH is kept at 90 %. Consequently the menisci in the small pores are curved and the pore water pressure is -14 MPa. The water vapour content is 90 % of the vapour content at saturation at +20°C, i.e. 15.6 g/m^3.

In this example, the vapour content is higher on the left hand side than on the right hand side. Consequently, vapour diffusion will occur from left to right. The pore water pressure, however, is lower on the left hand side. Liquid flow in the small pores will then occur in the opposite direction to the vapour flow.

3.2 A real two pore-size system: a bed of expanded clay particles

Common practice for concrete-slabs-on-grade during the 1970's in Sweden was the use of a layer of expanded clay particles as underlying heat insulation under a concrete floor slab in small houses. The expanded clay particles were supposed to act as a capillary breaking material to prevent soil moisture from being sucked up from the ground. The quality of the particles varied a lot; sometimes they had significant capillary suction abilities. Since they anyway produced a temperature gradient, moisture transport through a bed of these particles could have vapour diffusion in one direction and capillary suction in the other.

Some examples are shown in figure 2, with measurements of the distributions of temperature (with thermocouples) and RH (on samples).

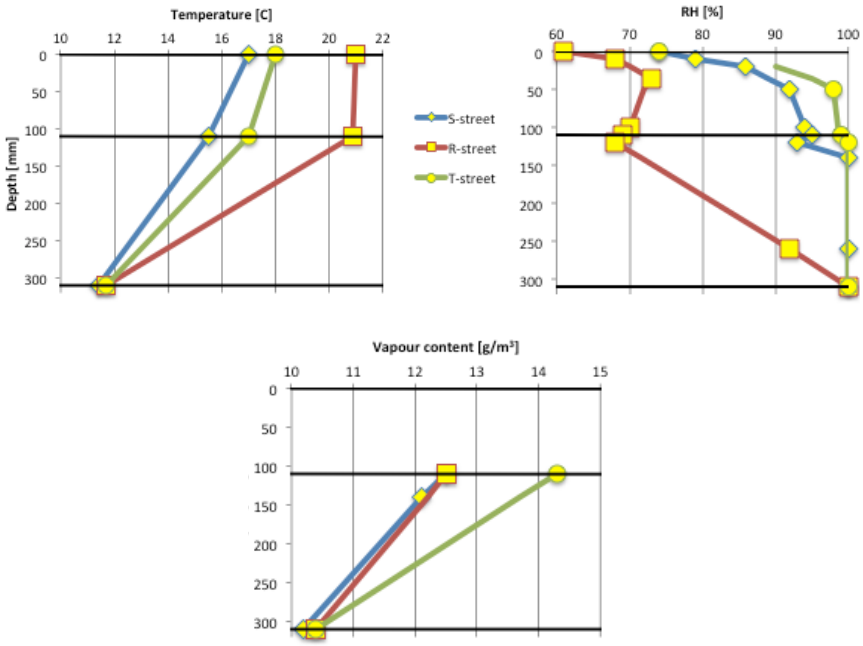

Figure 2 – Temperature, RH and vapour content distributions in three concrete floor slabs on grade with underlying heat insulation of expanded clay particles, Nilsson (1976).

In S-street and T-street the expanded clay particles are sucking water upwards. This explains why the temperature gradients are much smaller. Because of the temperature gradient, the vapour content profiles show a gradient downwards, i.e. there is vapour diffusion downwards, in the space between the particles.

In R –street the clay particles do not suck water very much. Consequently, there is no water transport upwards through the particle bed. The RH and T-measurements show that there is vapour diffusion downwards; the concrete slab is drying downwards.

This is a real example of the two-size pore system in section 3.1.

4 ADSORBED MOISTURE FLOW WITH A T-GRADIENT

In concrete a significant portion of the moisture flow is the transport of adsorbed and interlayer water, especially for low-w/c systems. In cement-based materials it is not easy to study this flow separately and few studies are found in literature. Observations made on wood could, however, give some ideas on adsorbed water flow.

In the hygroscopic range, almost all of the resistance to moisture flow in wood is in the cell walls. The pores between the cell walls, the lumen, are so large that they contain almost no water at RH < 99 %. In these large pores the transport is pure vapour diffusion with little resistance.

A recent study on moisture transport under a temperature gradient in wooden specimens was performed by Segerholm (2007). He made experiments with the cup method, with and without temperature gradients, and quantified the steady-state flux of moisture through thin specimens.

Segerholm tested his results against two alternative flux equations, the first one being similar to the equation by Lykow (1958),

$$g = -D_w \cdot \rho \cdot \left(\frac{\partial u}{\partial x} + \varepsilon_{uT} \cdot \frac{\partial T}{\partial x} \right) \tag{5}$$

$$g = -D_w \cdot \rho \cdot \left(\frac{\partial v}{\partial x} + \varepsilon_{vT} \cdot \frac{\partial T}{\partial x} \right) \tag{6}$$

and found the results shown in table I.

Table I - Results from four series of steady-state moisture flow measurements on wood, Segerholm (2007)

Series	-du/dx	$-\varepsilon_{uT}dT/dx$	-dv/dx	$-\varepsilon_{vT}dT/dx$
1	0.41	0.92	0.37	0.16
2	0.31	1.57	0.32	0.35
3	0.46	1.88	0.37	0.33
4	0.39	2.33	0.39	0.28

From table I it is obvious that the second term in the "Lykow-equation", equation (5), is much larger than the first term. The second term could be seen as a form of "correction" of the first term, which is frequently used for moisture transport without a temperature gradient. Using the water vapour content as the main transport potential, equation (6), seems to be better; the first term is smaller or of the same size as the second term.

One complication in wood is the two-size type pore system with large, air-filled pores in-between the cell walls with no pores at all but the space occupied by adsorbed water. A temperature gradient over such a material will produce a 2D temperature field with smaller temperature gradients in the cell walls than in the larger pores in the lumen. To understand moisture transport under a temperature gradient in wood the 2D temperature-field must be quantified to separate the T-gradients for the adsorbed water flow in the cell walls.

6 MOISTURE FLOW IN HEATED CONCRETE FLOORS

The moisture conditions in a concrete floor with cast-in heating cables were studied by Sjöberg & Nilsson (2003). They tested their measurements against equation (1), with different emphasis on the first and second term. The predicted RH-distributions are shown in figure 3 for two very different assumptions, the second term being zero and the second term being dominating, respectively.

The difference is extremely large. When the vapour content is used in a one-term flux equation as the sole transport potential there will be significantly lower RH closer to the cables. This follows of course from the 2D-temperature distribution with much higher temperatures around the heating cables than between the cables.

With the second term being dominating, with the pore water pressure as the main transport potential, RH will be almost equal everywhere. That means that RH would be a good alternative transport potential; the absolute temperature in equation (2) does not change the relationship between RH and P_w very much in this small temperature interval.

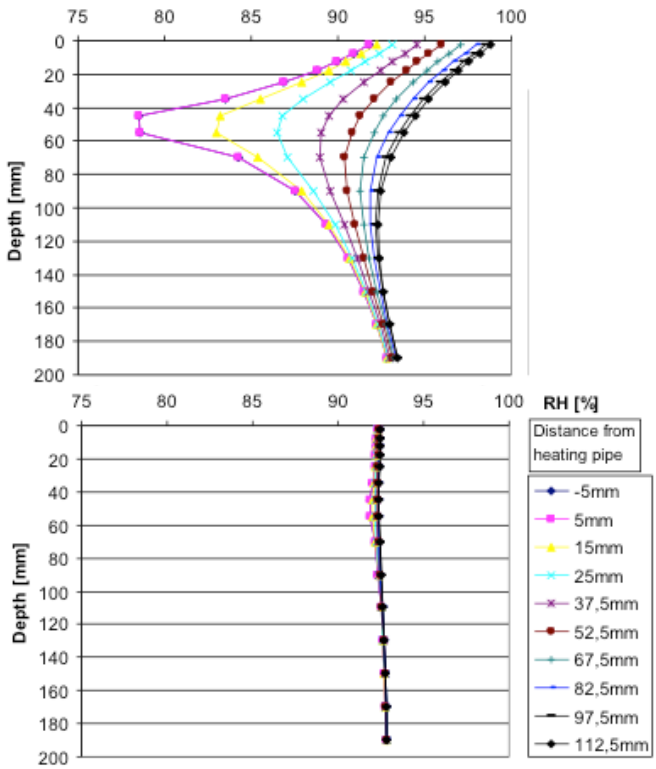

Figure 3 – Calculated RH-distributions between heating cables at a depth of 50 mm after redistribution of moisture in a 200 mm thick concrete floor slab by using equation (1), with the second term being zero (top) and the second term being dominating (bottom), Sjöberg & Nilsson (2003)

In laboratory tests, samples for RH-measurements were taken close to the heating cables and in the middle between the cables at the same level as the cables. According to figure 3 a comparison between these RH-values should reveal what assumptions that are most correct. The results are shown in figure 4.

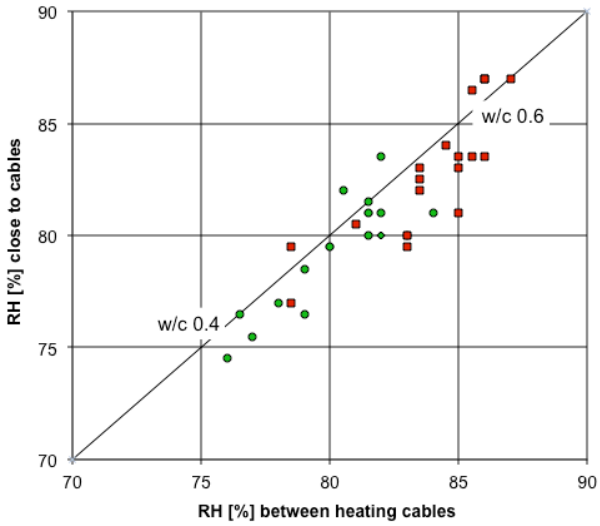

Figure 4 – RH-values measured in a series of heated concrete floor slabs on samples taken close to the heating cables and in the middle between the cables at the same level, after one year of redistribution, Sjöberg & Nilsson (2003).

From figure 4 it is quite obvious that the experimental results support the assumption that the second term in equation (1) is dominating. The results are very close to the predicted distribution is the bottom diagram in figure 3, where RH is almost the same close to the cables and in the middle between the cables.

7 MOISTURE FLOW IN CONCRETE CONTAINMENTS

A series of recent studies was made in Sweden on drying of nuclear power reactor containments. The walls of these containments are very thick, around some 0.8 m of pre-stressed concrete, a steel liner and a 0.2-0.3 m thick concrete inside the liner. Most of these containments are today some 30-40 years old and they are still far from dried out, because of the large dimensions and the one-way drying.

In a first study, Nilsson & Johansson (2006), a model was tested against field data from a BWR-containment (BWR = Boiling Water Reactor). The model had a flux equation with only one term and the vapour content as the transport potential. The model considered the significant temperature dependency of the desorption isotherm, especially important because the

temperatures varied from some +25°C in the bottom and +50°C at the top of the containment.

The model was shown to predict the moisture conditions very well, when compared to field data from a 30 year old BWR-containment. One reason for this could be that the walls of a BWR-containment have almost no temperature gradient through the walls, only a small gradient between top and bottom.

The same model was also used for PWR-containment walls (PWR = Pressurized Water Reactor). The predictions of temperature and moisture distributions after 15 and 30 years are shown in figure 5.

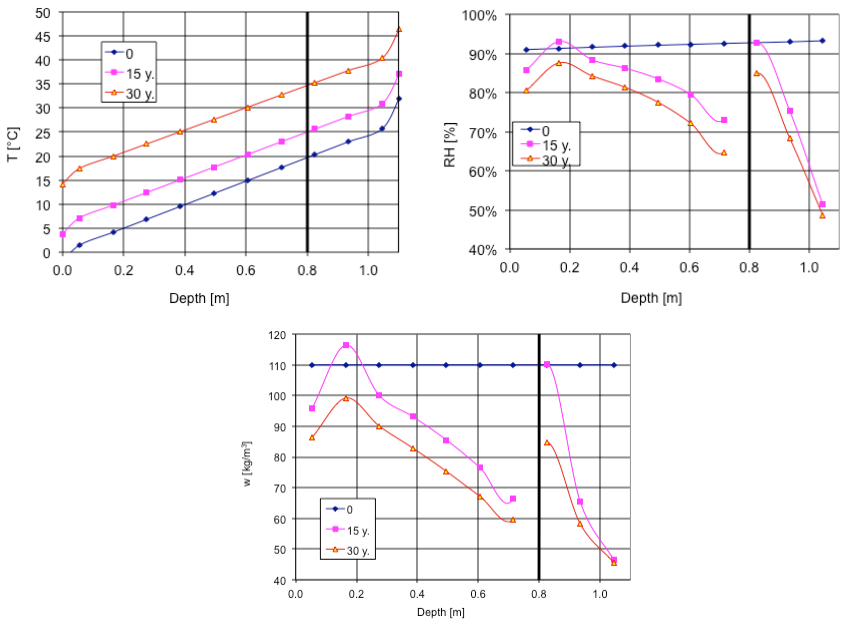

Figure 5 – Predicted moisture distributions after 15 and 30 years in a PWR nuclear reactor containment wall by using one term with vapour content as the moisture transport potential, Nilsson & Johansson (2006)

A PWR-containment is exposed to natural weather at the outer surface. The reactor keeps the inner parts at a high temperature, with a small annual temperature variation. This creates significant temperature gradients through the walls, with some annual variations.

From figure 5 it is easy to see the predicted effect of the simple flux equation. With the vapour content as the sole moisture transport potential, the very large water vapour content gradient, because of the temperature gradient, will drive the moisture at all depths towards the outer surface. RH and the moisture content will drop in the inner parts to equalize the vapour content. The predictions in figure 5 show significant RH- and *w*-gradients in the opposite direction to the moisture flow.

It has not been possible to check, until now, whether these predictions were correct or not. Oxfall (2013) recently had the opportunity to take moisture samples from a PWR-containment wall when a generator was to be replaced. He has made his preliminary results available and they are shown in figure 6, as degrees of capillary saturation S_{cap}. The wall has the liner at a depth of 0.8 m and is drying towards the left hand side, the outdoor climate, with significant temperature gradients from the high inside temperatures to the much lower outdoor temperatures.

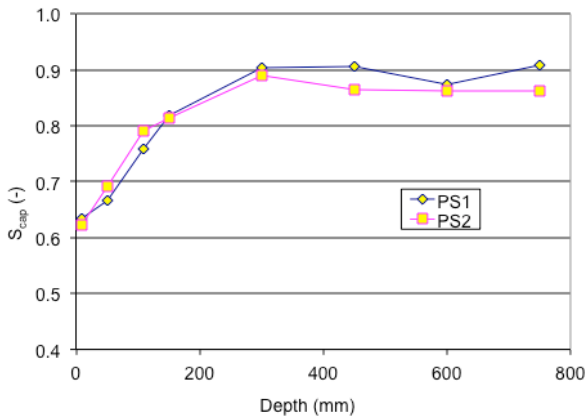

Figure 6 – Measured moisture distribution on two cores, as S_{cap}, in a PWR nuclear reactor containment wall after 35 years of drying under a temperature gradient, Oxfall (2013)

The predictions in figure 5 are obviously not correct! A single term with the water vapour content is simply not correct when there is a significant temperature gradient. The profiles in figure 6 show that the moisture content or, better, the RH, would be a much better selection of moisture transport potential. Obviously, it seems as if equation (1) is a good alternative to describe flux of moisture under temperature gradients.

8 DISCUSSION AND CONCLUSION

From the examples given in this paper it is quite obvious that the flux of moisture due to different transport mechanisms may occur in different directions, depending on the conditions, when there is a temperature gradient. In materials with a two pore-size system liquid and vapour may very well flow in opposite directions if there is a temperature difference.

In concrete a significant part of the resistance to moisture flow is in the reaction products. The natural transport potential for adsorbed water and interlayer water is not obvious, even if RH as a measure of the state of that water is a good candidate. To couple the local transport mechanisms to the total, macroscopic flux, a pore model is required. Such a model remains to be developed and validated.

In the meantime we must rely upon measurements. Since we cannot separate the fluxes of the different types of water, but can only measure the effects of the total moisture flow, alternative mathematical expressions for the flux of moisture must be tested against carefully performed measurements. This is not an easy task and literature is full of attempts that did not work very well. Here a few fairly good examples have been shown. They point towards a flux description with two terms where the dominating term has the pore water pressure or RH as the transport potential. With RH as the main moisture transport potential, the transport of liquid, adsorbed and interlayer water have a natural transport potential. The transport of water vapour does occur in some pores and air voids and requires a transport description with the water vapour content as the transport potential.

To conclude: equation (1) seems to be a good candidate for a flux equation in concrete. The two coefficients, and their moisture dependency remain to be quantified and modelled as functions of the concrete composition, using a material science approach.

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