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MEASUREMENTS OF CONDENSATION IN SOLID FLAT ROOFS OF CELLULAR CONCRETE

Moisture distributions measured by gamma-ray-attenuation methods and temperature gradient factor calculated by computer

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MEDDELELSE NR 27

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Condensation in solid flat roofs has interested many researchers, but in most cases only the mean moisture content has been measured and at the end of the experiment the moisture distribution. There has been a special interest for experiments with constant temperature and humidity because the measurement of the moisture distribution during the experiment is difficult.

VOS [5] has made a theory of the condensation and the equilibrium moisture content and the time to reach equilibrium. One of his experiments is shown in fig. 1. HANSON [1] has also made experiments of condensation, see fig. 2. The moisture content in both cases is found by cutting the specimen into peices and drying them.

From such experiments Hanson has shown that it is possible to calculate the moisture diffusivity from the equilibrium moisture content. This is done by using the equation:

$$g = -d \text{ grad } p - k \text{ grad } u$$

g is the density of mass flow-rate (g/m^2h)
d is the vapour conductivity $(g/m\ h\ mmHg)$
p is the vapour pressure $(mmHg)$
k is the water transfer coefficient $(g/m\ h\ \%vol)$
u is the moisture content $(\%vol/m)$

At the beginning grad $u \sim 0$, therefore the vapour conductivity (d) can be calculated as the moisture flow and grad p is known.

At the end of the experiment when equilibrium is obtained the moisture flow rate is zero:

$$0 = d \text{ grad } p + k \text{ grad } u$$

When p, u and d are known $k = k(u)$ can be calculated. This is done under the assumption that the vapour conductivity is constant, which we doubt.

We would suggest a new way for evaluating the results. This can be done by using the equation:

$$\frac{q_m}{\rho} = -D \text{ grad } \psi - K' \text{ grad } T$$

q_m is the density of mass flow-rate $(kg/m^2 s)$
ρ is the density of water (kg/m^3)
D is the water diffusivity (m^2/s)
ψ is the moisture content (m^3/m^3)
K' is the thermal moisture diffusivity $(m/s\ {}^\circ K)$
T is the temperature $({}^\circ C)$

In equilibrium, where $q_m = 0$, the temperature gradient factor can be calculated:

$$\varepsilon = \frac{K'}{D} = \frac{-\text{grad } \psi}{\text{grad } T}$$

Another way of finding the temperature gradient factor is to take a specimen with all surfaces wrapped completely moisture tight and place it between a cold and a warm plate. Then an equilibrium between transfer by temperature and by moisture content would occur. This method has been suggested by LYKOW [2], and some experiments on cellular concrete have been done by VAN DER KOOI [4]. He has calculated the temperature gradient factor, see fig. 3.

We would then draw your attention to the possibility of using non-stationary experiments for determining the transfer factors. This can be done if one of the factors D, K or ε is known and the temperature and the moisture distributions are known.

If D for instance is found from a *drying-out* experiment, the non-stationary condensation experiment makes it possible to calculate $K' = K'(\psi)$ and $\varepsilon = \varepsilon(\psi)$. The measurements of the moisture distributions *must* be *non-destructive* and with great accuracy if the results should be reasonable. The gamma-ray-attenuation method as described in NIELSEN [3] would be satisfactory.

Results of own experiment

You will only find a short description of one selected experiment, as a more comprehensive paper will appear in a year. The condensation experiment has been done on specimen no. 162, data:

dry density	564,0 kg/m^3
σ (dry density)	3,8 kg/m^3
height	50,3 mm
diameter	121,2 mm

The conditions have been:

air temperature	29,8 °C
air dew-point temperature	17,1 °C
cold plate temperature	6,4 °C

These temperatures and the temperatures in the five layers of the specimen were measured hourly and stored in computer cards. By this it is easy to find how the conditions were during the experiment. An example of a computer drawing of the temperature is shown in fig. 6.

In fig. 4 the moisture distributions are shown at different hours. It is clearly seen that the condensation first occurs at the cold side and then gradually in the other layers. In equilibrium the layers nearest to the cold side have nearly the same moisture content. Fig. 5 shows the moisture content versus time. The layer nearest to the warm side is the one which takes the most time to reach to equilibrium because the heat conductivity is dependent of the moisture content. The mean moisture content was almost constant when the experiment was stopped.

From the temperature- and the moisture distributions in equilibrium the temperature gradient factor was calculated. The result for this specimen and others is shown in fig. 7. The temperature gradient factor has a maximum at about 8% vol.

The non-stationary method mentioned on page 2 has been used for some calculations of the transfer factors, and it seems that it should be possible to get interesting results.

Correlation with earlier experiments

A comparison of own experiments and van der Kooi's show that the temperature gradient factor has a maximum value at about 8% vol. The forms of the curves are almost alike. There is some difference in the numerical value for the same moisture content, but that is not surprising, as the dry density and probably also the pore size distribution are unequal.

From the experiments of Vos (fig. 1) and Hanson (fig. 2) it is possible to calculate the temperature gradient factor. The moisture curve from Hanson could not be used as it is not the best fit. From polynomial regression the best fit was found and used for the calculation. The temperature gradient factors from the known experiments are shown in fig. 8. It is evident that the values all are in the same range for different types of cellular concrete.

Correlation with theory by Vos

VOS [5, appendix 2] has calculated the temperature gradient factor theoretically as:

$$\varepsilon = \frac{\varphi \, \dfrac{\ln \varphi}{\sigma} \, \dfrac{d\sigma}{dT}}{\dfrac{d\varphi}{d\psi}}$$

φ is the relative humidity (-)
σ is the surface tension (Pa m)
T is the temperature (°K)
ψ is the moisture content (m^3/m^3)

The result of this calculation has also been shown in fig. 8. It is evident that the theoretical values are different from what is found by experiments (a factor 100 or so). On the other hand it is quite interesting that the theoretical curve also has a maximum and has the same shape as the measured. The high value at 22% vol only origins from the problem of defining the sorption curve at very high moisture contents.

It is possible that the strange results of the calculation of the non-isothermal moisture transfer in VOS [6] could also be explained from these differences between theory and measurements. It is necessary to measure the pore size distributions for the materials if we want to get a better explanation of the moisture transfer. It is possible that the proposed Poiseille-flow is not the truth, for tubes it is also possible to have Knudsen-flow. Besides, the pore form is not necessarily cylinders. Other pore forms could give other values of the theoretical temperature gradient factor.

Conclusion

The use of the gamma-ray-attenuation method makes it possible to measure moisture distributions under non-isothermal conditions.

The use of computer calculations could give much more results from the same experiment and open the possibility of using statistical methods.

It is shown that the temperature gradient factor could be calculated from roof condensation experiments.

It is mentioned that it is possible to use non-stationary experiments to determine the moisture transfer factors.

References

[1] HANSON, R.: Fuktegenskaper hos lättbetong och tegel. Byggmästaren, B1, 1958.

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[3] NIELSEN, A. F.: Gamma-Ray-Attenuation Used for Measuring the Moisture Content and Homogeneity of Porous Concrete. Building Science, Vol. 7, pp. 257-263, 1972.

[4] VAN DER KOOI: Moisture Transport in Cellular Concrete Roofs. Delft 1971.

[5] VOS, B. H.: Condensation in Structures, report BI 67-33, Delft 1967.

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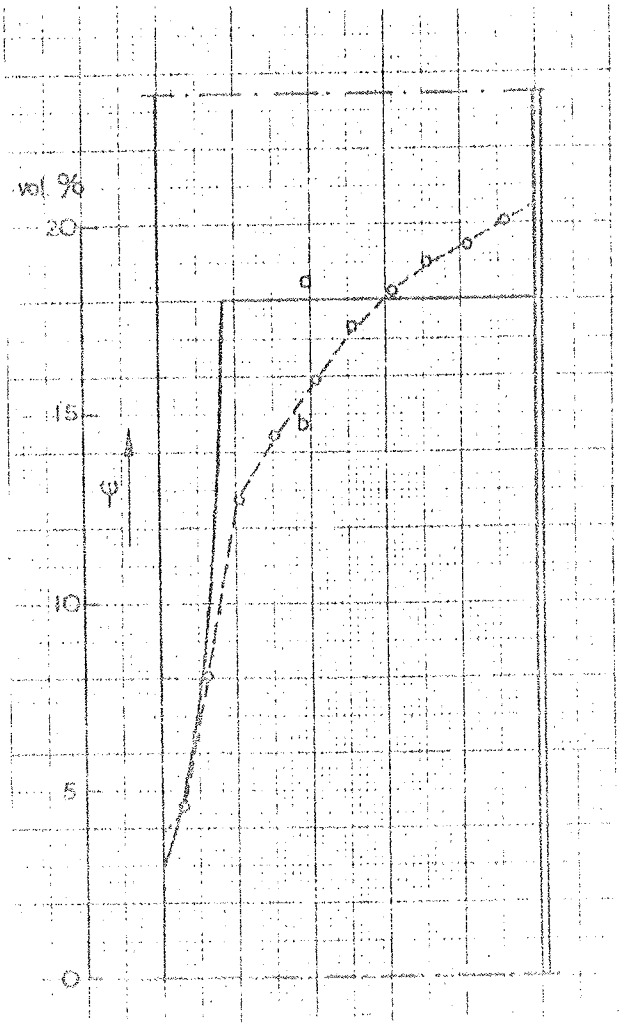

Fig. 1. Moisture distribution in a roof of cellular concrete in equilibrium. (Vos)

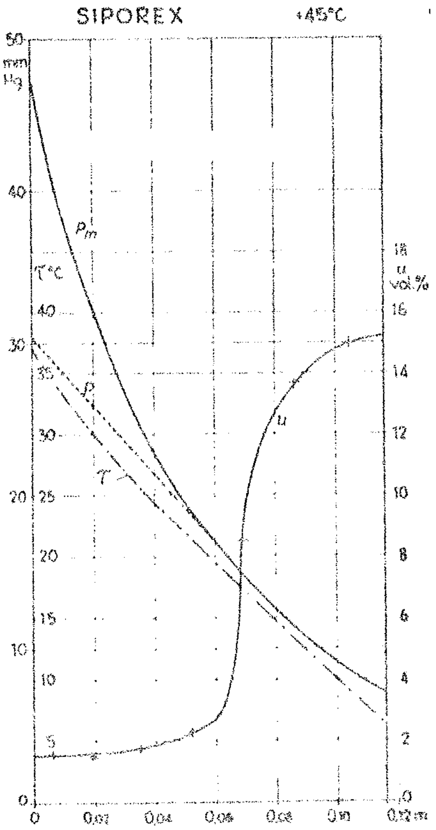

Fig. 2. Moisture distribution in a roof of cellular concrete in equilibrium.

(Hanson)

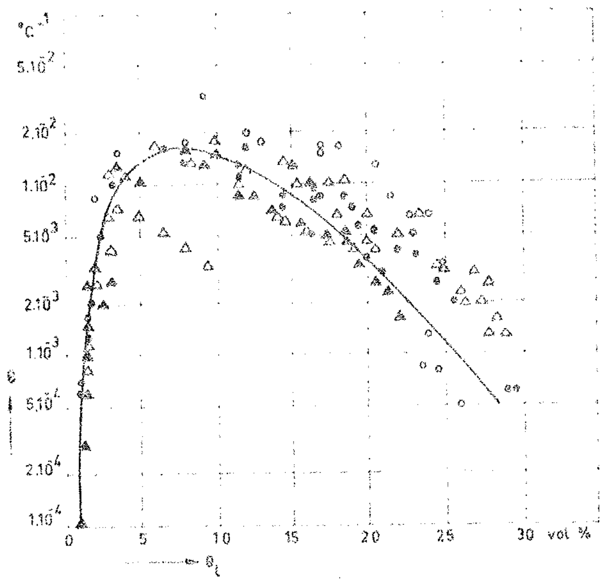

Fig. 3.21
Temperature gradient factor, ε (= D_T/D_θ), for cellular concrete determined from moisture distributions in the stationary state. ○, △ – from distributions found after one month. ⊛, ▲ – from distributions found after two months.

Fig. 3. Temperature gradient factor. (van der Kooi)

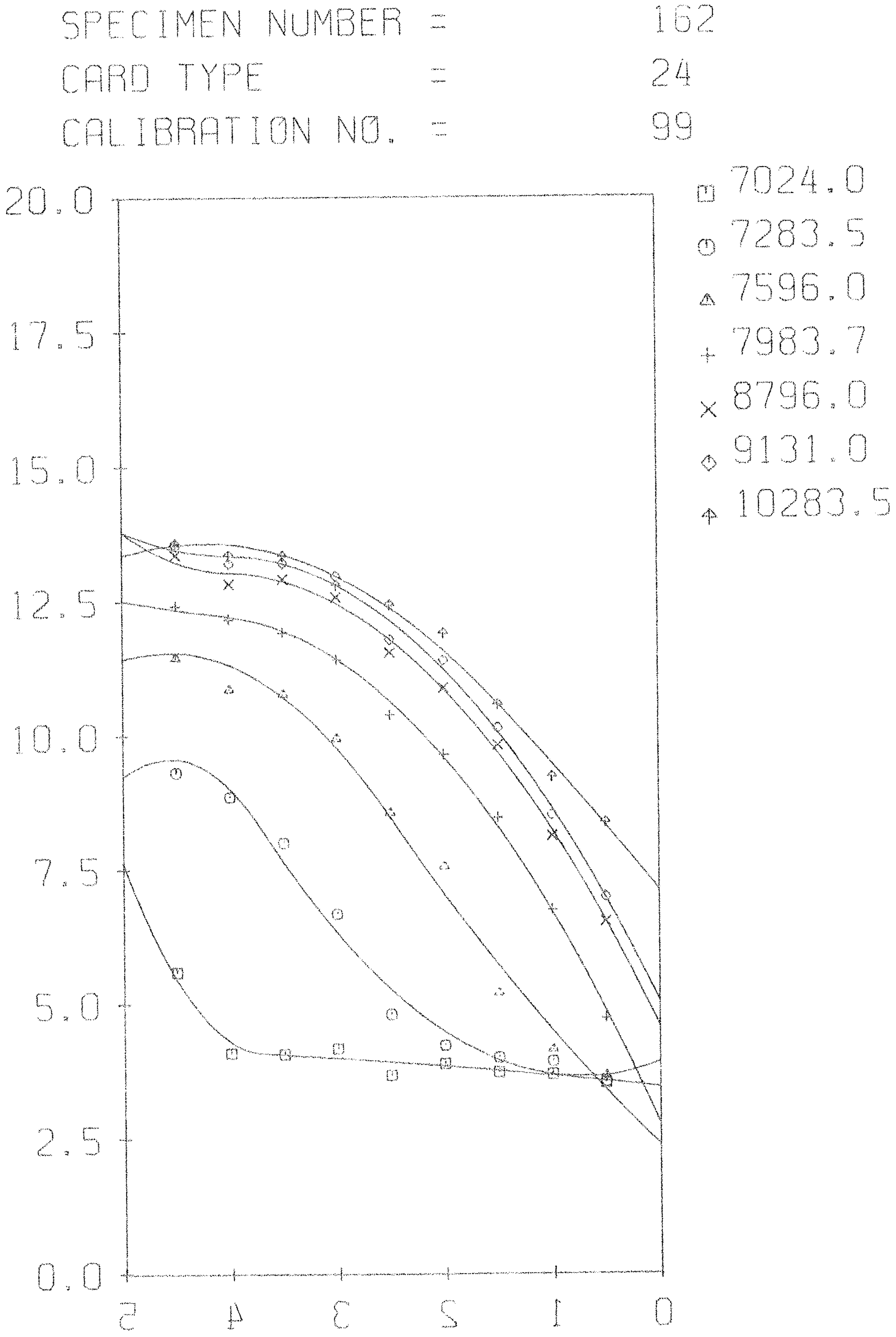

Fig. 4. Moisture distributions in condensation experiment (sample 162). Moisture content (%vol) versus distance (cm) from the open (warm) side. To the right the symbols of the measured values at the experimental time (hours). AFN 1973

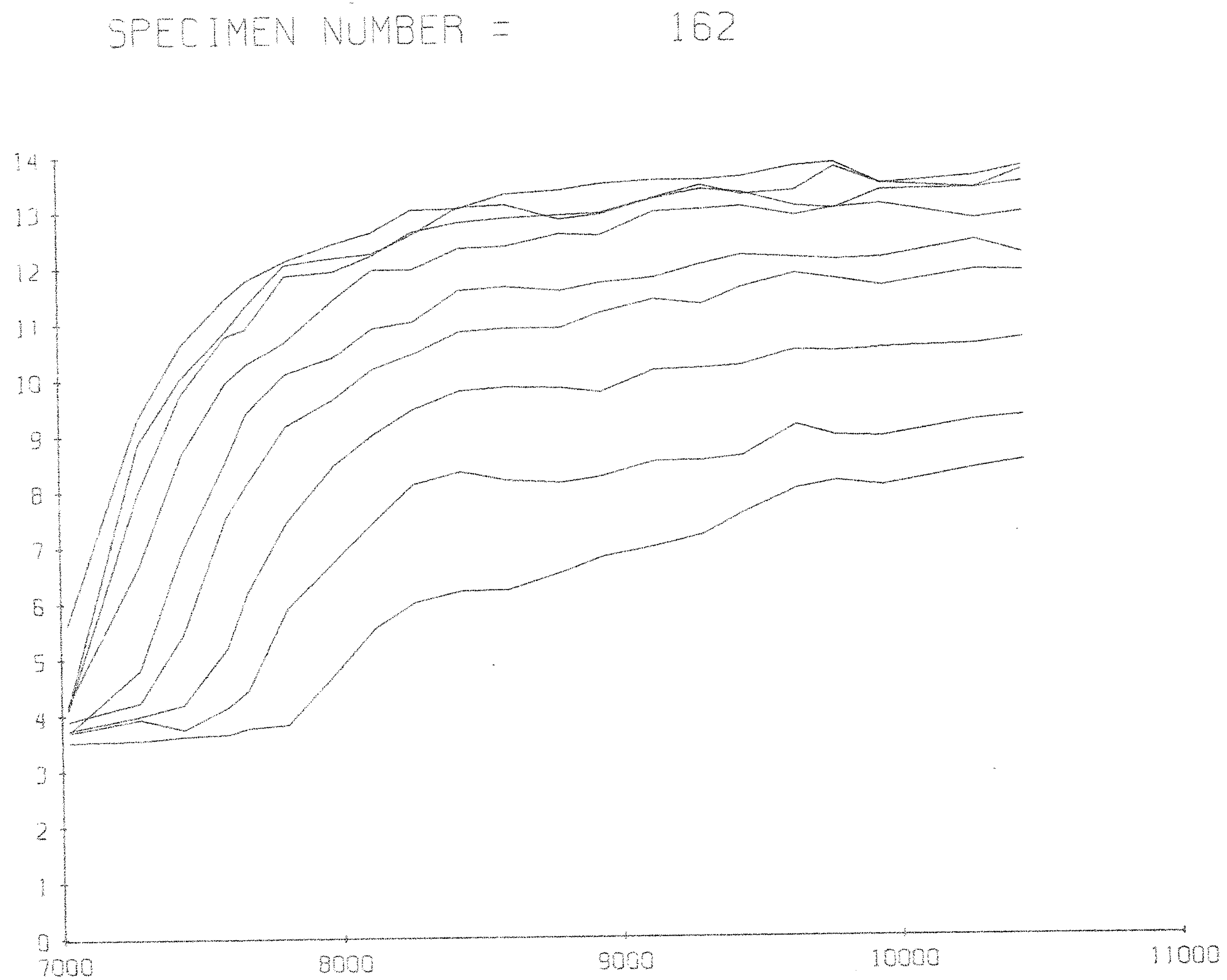

Fig. 5. Moisture distributions in condensation experiment (sample 162). Moisture content (%vol) versus time (hours). The curves have been plotted between values measured in the same height in the specimen.

AFN 1973

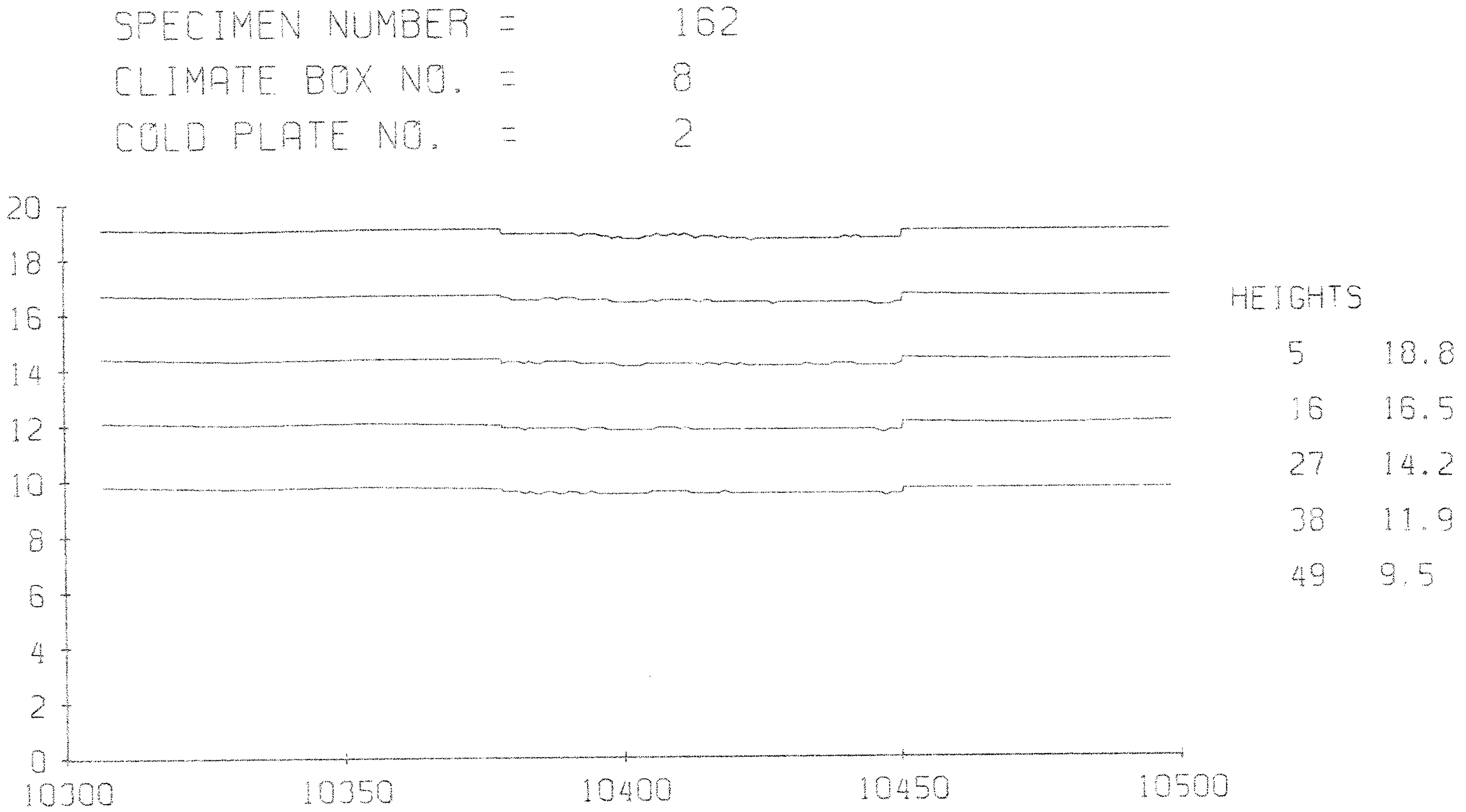

Fig. 6. Temperature distribution in sample 162 of cellular concrete during condensation experiment. Temperature (°C) versus experimental time (hours). To the right the mean values of the temperatures in different heights (mm) from the open side.

AFN 1973

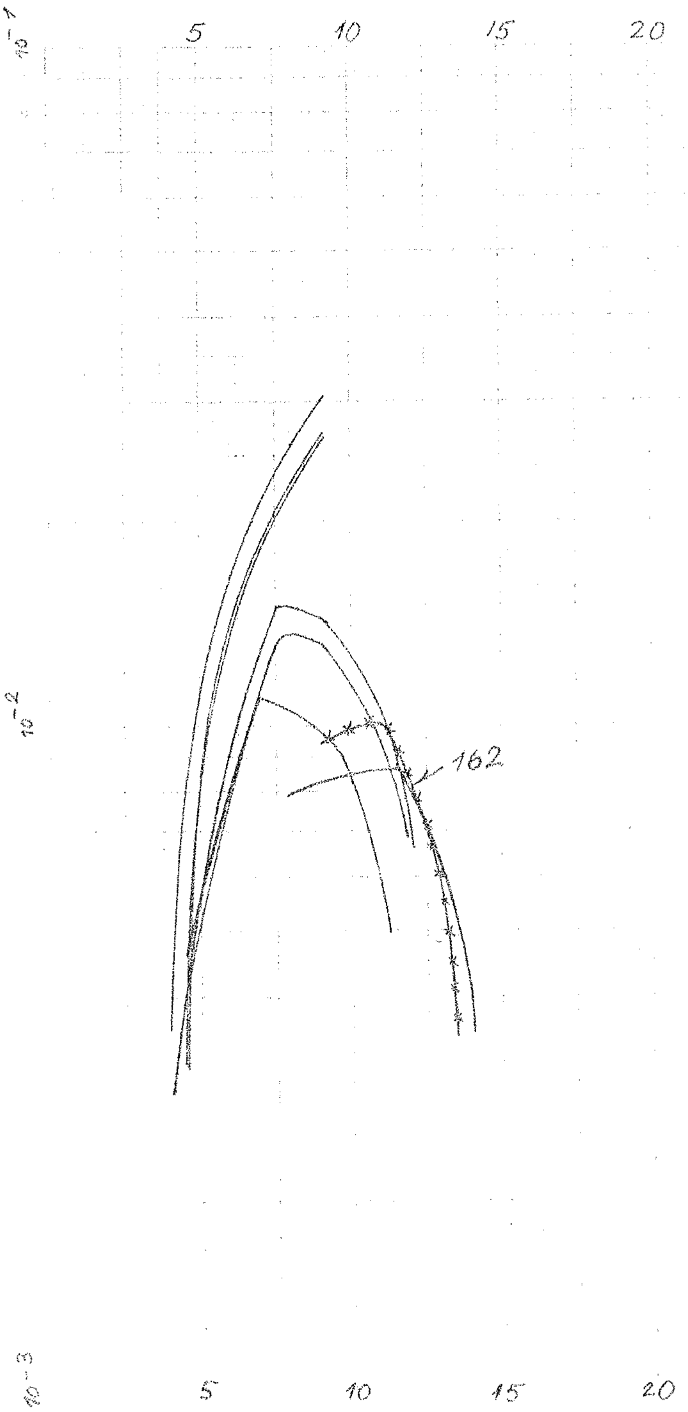

Fig. 7. Temperature gradient factor calculated from equilibrium in roofs of cellular concrete. Each curve represents one experiment. The factor (°C⁻¹) (log-scale) versus moisture content (%vol). AFN 1973

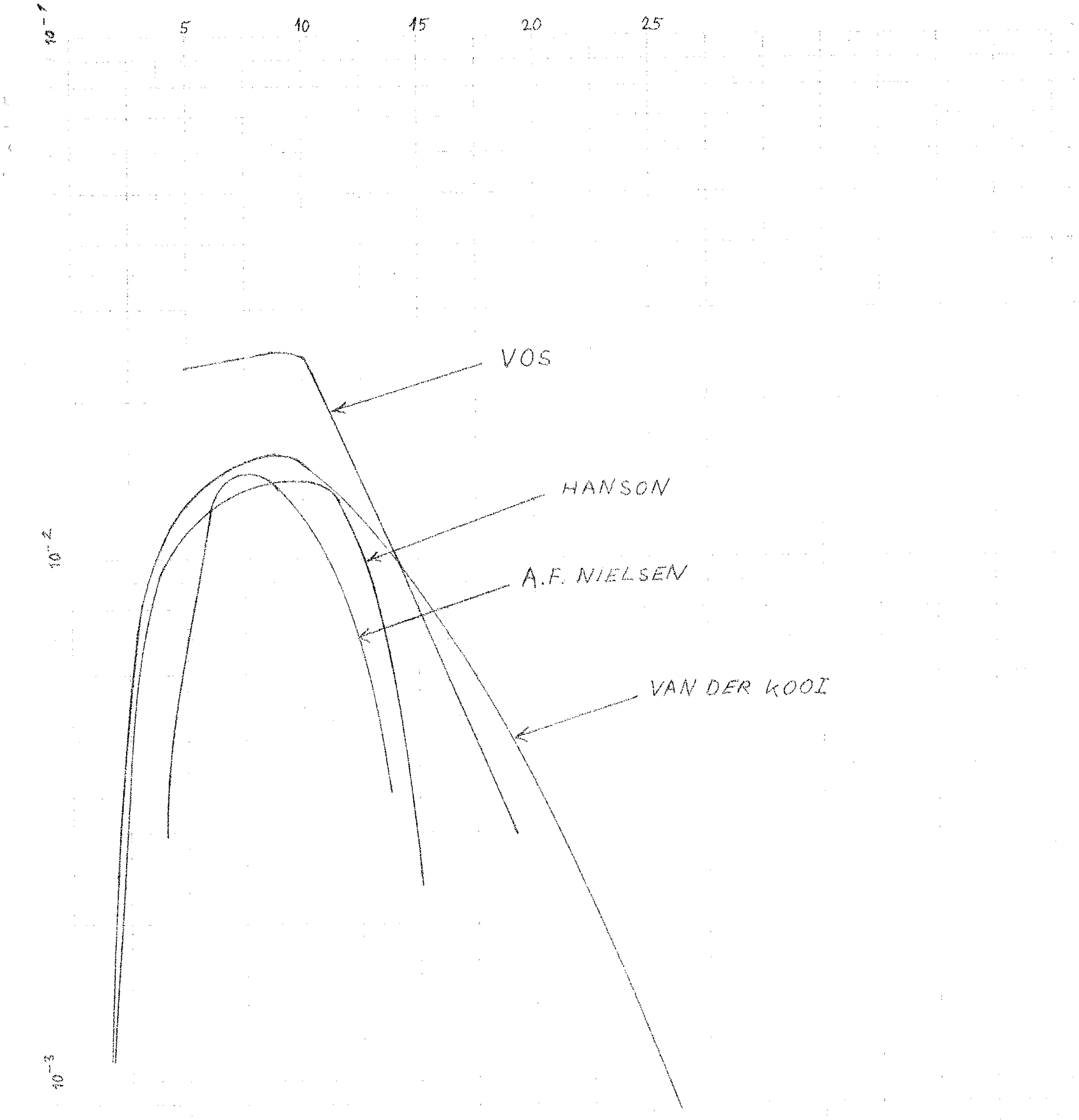

Fig. 8. Temperature gradient factor calculated from equilibrium in roofs of cellular concrete. The factor (°C^{-1}) (log-scale) versus moisture content (%vol). (Vos, Hanson, van der Kooi, AFN, Vos theoretical).