CAUSES OF MOISTURE IN BUILDING STRUCTURES

B. H. Vos

Head of the Heat and Moisture Transport Section of Institute TNO for Building Materials and Building Structures, Delft (Netherlands)

SUMMARY

In this report an outline of the factors involved in the wetting of building structures is considered. Hygroscopic moisture, rain penetration, condensation and ground moisture are dealt with successively. The report finishes with a short description of the measuring methods for the determination of the moisture content and the moisture distribution in situ.

INTRODUCTION

In the following an attempt will be made to discuss briefly the factors involved in the wetting of building structures. In view of the necessary brevity of this paper and the short time for preparation, it is impossible to do more than just write down what is known at present on the subject. Because of this the problem is first estimated theoretically, and if it is necessary and possible illustrated by examples. Therefore I must be bounded by very strict limits whereas this report could be expanded to fill a book. In view of the age of the majority of monuments, the building moisture present can be eliminated as a cause.

I hope this report can contribute to a profitable discussion.

Delft, August 1967 B. H. V.

HYGROSCOPIC MOISTURE.

If a completely dry material is placed in an environment with a certain relative humidity, it appears that the material absorbs moisture from the air, and more so if the relative humidity is higher. After some time equilibrium is reached. The moisture content of the material at equilibrium is called the hygroscopic moisture content. Fig. 1 shows schematically how the hygroscopic moisture content depends on the relative humidity of the air. In virtually all cases the curve takes this form; the height of the curve varies considerably from material to material. An explanation of the s-form of the curve is not given in this paper. The explanation of this and the variance in size of the curve is given, for example, in references [1,2,3] .

In table 1 is given the hygroscopic moisture content of a number of materials at different relative humidities of the air. These values must not be taken as being exact but as the mean values of a great spread. The values are taken from literature, and our own investigations.

The low moisture content of brick is remarkable.

Table 1 - Hygroscopic moisture content of a number of building materials

material	mass per unit vol. kg/m^3	Moisture content in vol. % for relative humidity of		
		40%	65%	95%
wood	800	10	15	26
brick	1800	0	0	1
sand limestone	1900	2	4	10
gypsum	1400	0	1	3
concrete	2300	3	4	8
cellular concrete	700	2	3	5
cement mortar 1:3	2000	6	9	14
chalk mortar 1:3	1800	1	2	5

Often one is speaking about "air-dry" materials. This concept is a little vague, but it means that the moisture content of these materials is about hygroscopic at normal relative humidities of the air.

For the sake of completeness, it must be mentioned that temperature also will have a small effect on the hygroscopic moisture content [2] and that hysteresis may occur, as for example for wood [4] and concrete [5] as stated. In normal building practices this is so small that it need not be taken into account.

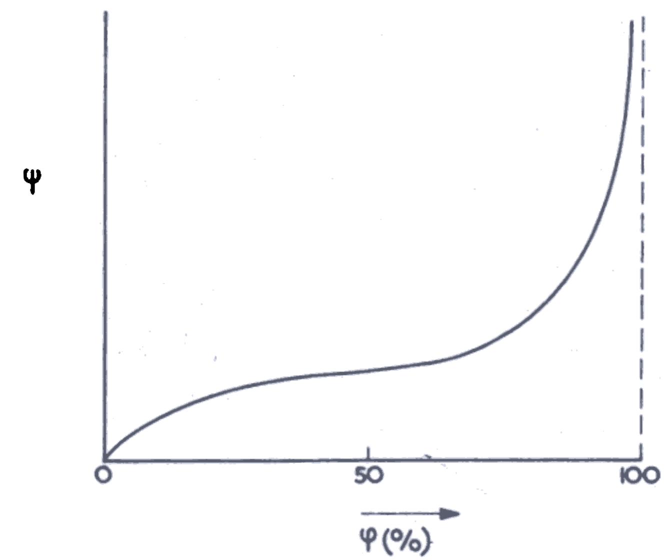


fig.1

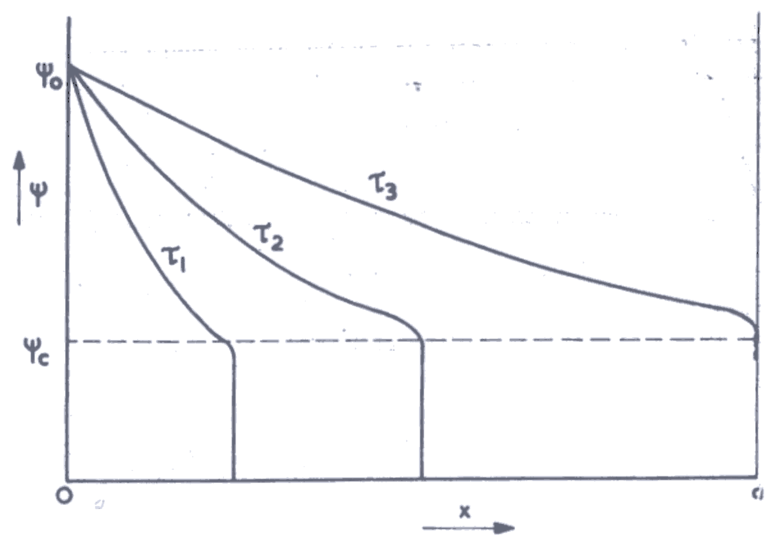


fig. 2

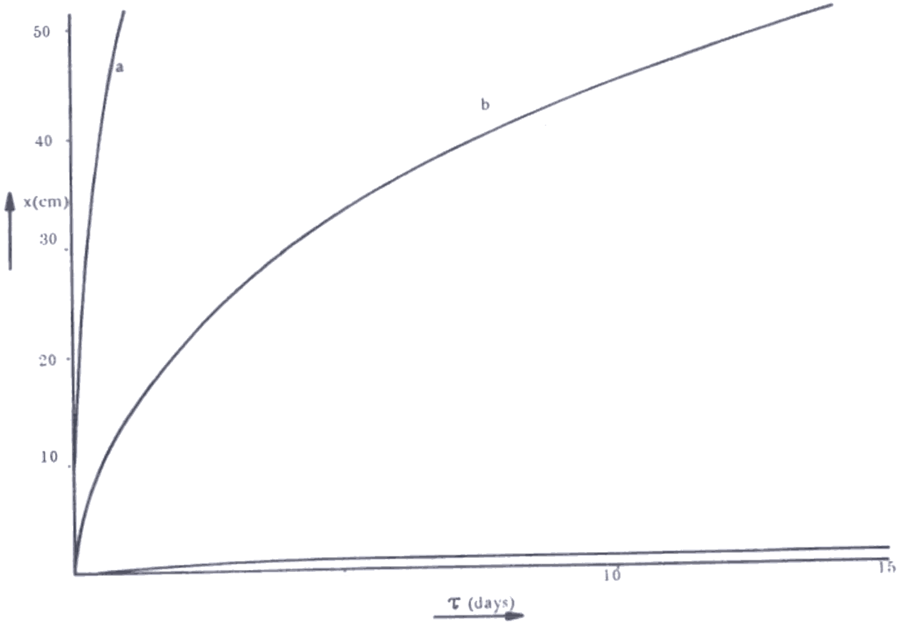


fig. 3

RAIN PENETRATION.

Another cause for the wetting of structures is rain-water penetration. When rain falls on a wall there is penetration to the inner side in two possible ways.

In the first place it is possible that the material used in the building absorbs the water. Nearly all building materials have this absorption property to more or less an extent. Here the capillary forces determined by the internal structure play an important part [6]. Next, there is penetration by the cracks and crevices or, in the case of masonry, via the joints which may not be caused by capillary sunction but is determined by the wind pressure.

We will first speak about capillary absorption in building materials. The water depth (x), when a waterfilm is present flowing over the surface, can be given to a first approximation by the following equation [7, 8] :

$$x = B\sqrt{\tau} \qquad (1$$

where τ represents the time, and the coefficient B is the water-absorption coefficient.

Fig. 2 gives the water distribution (ψ) in the wall at different times (τ_1, τ_2 and τ_3). There is usually a fairly sharp water front present; the water content [9] . At time 3 the front has reached the inner side (x = d).

The speed with which the water front moves through the material (v) can be calculated from :

$$v = \frac{B}{2\sqrt{\tau}} = \frac{B^2}{2x} \qquad (2)$$

The speed of the absorption process is determined by the values of B. The lower B is the more compact is the material. The B-value of brick is, dependent on the quality and sort, between about 5 x 10^{-4} and 20 x 10^{-4} m/s^{0,5}. For good Dutch brick and heavy weight concrete a value in the order of 10^{-5} to 10^{-6} m/s^{0,5} is found. This also holds for a good cement mortar.

Fig. 3 shows how the front varies with time, as calculated from equation (1). We see that for a good quality brick wall 50 cm thick, moisture will penetrate through in about 14 days. For a lower quality wall of the same thickness it can happen in about 24 hours, for concrete with a B-value of 10^{-5} m/s^{0,5} after 14 days the front has passed through only about 1 cm.

One wonders to what an extent the evaporation of the water from the interior to the inside effects this penetration phenomenon. One can show that this is never or hardly ever the case for brick [10], as opposed to heavy weight concrete. Here in general the evaporation of the water will compensate the penetration when the water path is about 1 cm. If one is speaking about watertight concrete structures one understands the word "waterproof" in this context.

The foregoing was in reference to a structure with a waterfilm on the outside. Such a situation will seldom or never occur longer than one or two days (e.g. this was the case during the heavy "driving rain" period in December 1965 in Britain and Netherlands [11]. Usually after this, however, a period of drying occurs. This is generally a notably slower process than the wetting by water in fluid form. After the water front has withdrawn from the outside to the interior, evaporation must come from the interior, whereby the diffusion resistance of the material must be overcome [1]. Fig. 4 illustrates this. This figure starts at the moment τ_2 (fig. 2), when the waterfilm supposedly disappeared.

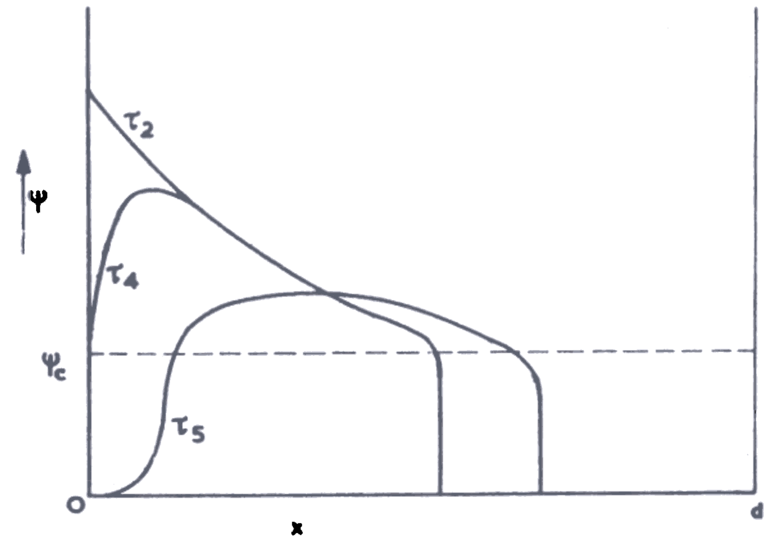
The process of water penetration and drying, whereby the latter as well as to the inside as to the outside can occur, is very complicated. It makes an exact description impossible. Besides this, what happens depends much upon the location and the associated climate. Particularly structures on the North-West shore of Europe (affected by storms and rain in autumn and winter) show much penetration damages. It is appropriate to show that just here the cavity wall is widely used.

The influence of external forces, such as wind pressure difference and the hydrostatic pressure of the water in the wall, is always comparatively small in respect to the influence of the capillary forces in the material itself. This is different if cracks or crevices are present in the structure. In such cases in the first instance the wind pressure appears to be responsible for the rain penetration. This is always the case when rain streams out of the inner side of the wall. The capillary forces can, as internal forces, bring the water just as far as the inner side !

The quantity of water that streams out can be calculated from :

$$g = \frac{\rho \Delta p}{wd} \qquad (3)$$

g = quantity of water that streams out (kg/m^{2}s)
ρ = specific mass of water (kg/m^3)



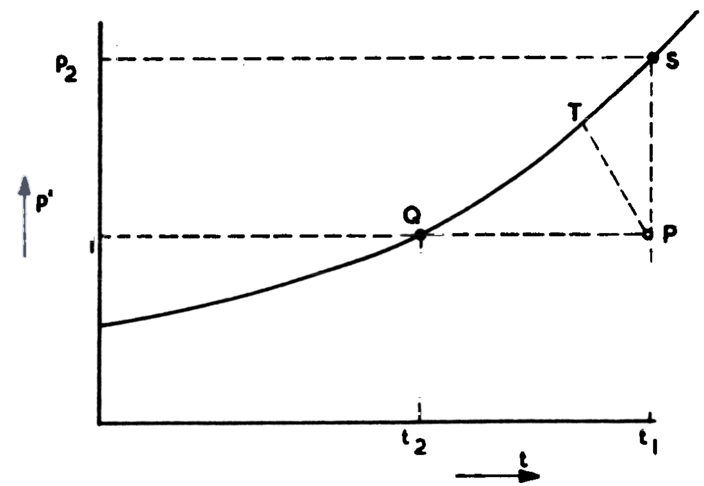


fig. 5

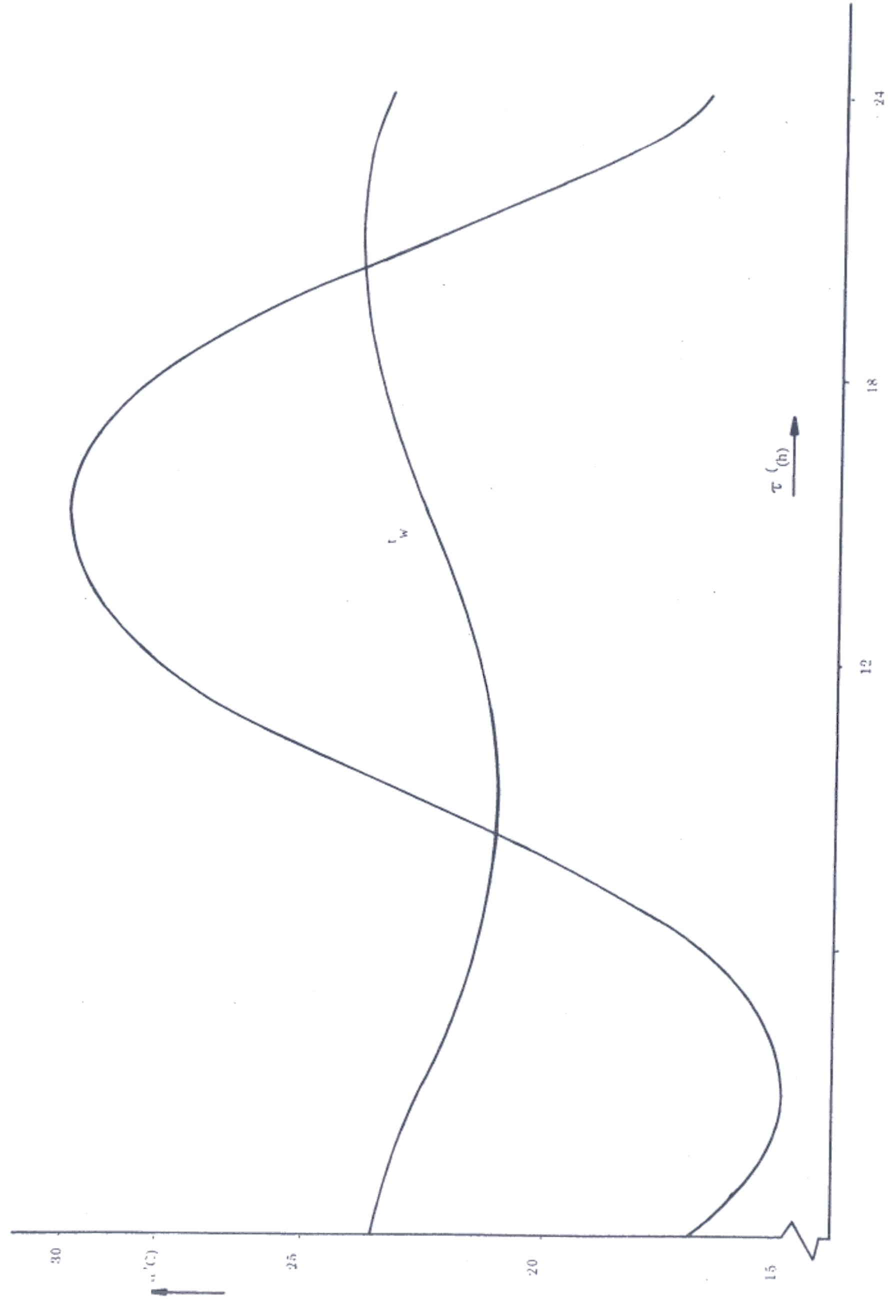


fig. 6

d = thickness of the wall (m)
Δ p = wind pressure difference over the wall (N/m^2)
w = specific resistance to liquid flow (Ns/m^4)

Equation (3) can be applied to the material that the wall is made up of, as well as possible cracks and crevices, while, of course, also taking the total wall structure into account.

Hereby another value for the specific resistance to liquid flow must be taken.

For normal brick this w-value is 3 to $10 \times 10^{10} Ns/m^4$; for concrete and "trass layer bricks" 10^{13} to 10^{14}. These latter values are appropriate to a good quality mortar. For example we can take a wall, 30 cm thick, with w = 5×10^{10} Ns/m^4. The wind pressure difference is 200 N/m^2. This gives :

$$g = \frac{10^3 \times 200}{5 \times 10^{10} \times 0,3} = 13,0 \times 10^{-6}\ kg/m^2s = 50\ g/m^2\ h$$

CONDENSATION.

Condensation will occur if the water-vapour pressure of the air is or will be higher than the maximum vapour pressure. This can happen on the boundary surface of the structure as well as in the interior. In the first case we are talking of surface condensation ; and in the second of internal condensation. We start by dealing with the first phenomenon.

SURFACE CONDENSATION

Condensation at the surface occurs when the dewpoint of the air is higher than the temperature of the surface concerned. See fig. 5. This shows how maximum water-vapour pressure (p') depends on the temperature. Point P represents a certain situation of the air : vapour pressure p_1; temperature t_1. If this air touches a surface with a temperature greater than t_2, then this air remains unsaturated. If, however, the temperature is lower than t_2, then p_1 would be higher than p' (point Q). Then water vapour will condense. The surface concerned becomes wet. Another method of obtaining saturation is to increase the relative humidity φ (= p/p'), by adding water vapour. At point S the relative humidity is 100%. Naturally, every combination of both factors can lead to condensation (T).

Condensation at a wall surface therefore originates from

1. A high relative humidity in the room
2. A low surface temperature of the wall.

When no moisture production takes place inside a building, as a result of natural ventilation, the vapour pressure inside will equal the vapour pressure outside. When the temperature inside is higher than that outside the relative humidity here is lower. In the other case the relative humidity inside will be higher. Under steady-state conditions condensation at the inside of the wall will occur in neither summer nor winter.

In structures with a high heat capacity - thick walls - such a steady-state situation will be seldom realised, especially in summer. Fig. 6 shows the daily variation of the external temperature (t_e) and the temperature of the walls inside (t_w). For the greater part of the day the latter temperature is lower than the temperature outside. Condensation can occur according to the level of the relative humidity outside. Because the moisture is usually absorbed in the wall, evaporation will contribute to the drying to a small extent during the period that the inside temperature is higher than that outside (in evening and at night). Namely, water in liquid form enters the wall more easily than evaporation can occur from it.

The amount of vapour that condenses can be calculated from the formula 1 :

$$g_c = \beta \, (p_i - p'_w) \qquad (4)$$

where :

g_c =	amount of condensing vapour	(kg/m²m)
β =	surface coefficient of water-vapour transfer	(s/m)
p_i =	water-vapour pressure inside	(N/m²)
p'_w =	maximum water-vapour pressure at t_w	(N/m²)

The β-value under practically calm conditions, as is always the case inside, is about 20×10^{-9} s/m [12] .

EXAMPLE.

We look at the temperature diagram sketched in fig. 6. In fig. 7 is shown how the maximum vapour pressure at these temperatures (p'_e and p'_w) varies with the hour of the day. The location of the building determines mainly if the real vapour pressure of the air outside (p_e) deviates slightly from the pressure inside (p_i), which at normal ventilation of the building will be higher than p'_w .

In a maritime climate there is a large amount of evaporation. The absolute vapour pressure increases quickly with rising

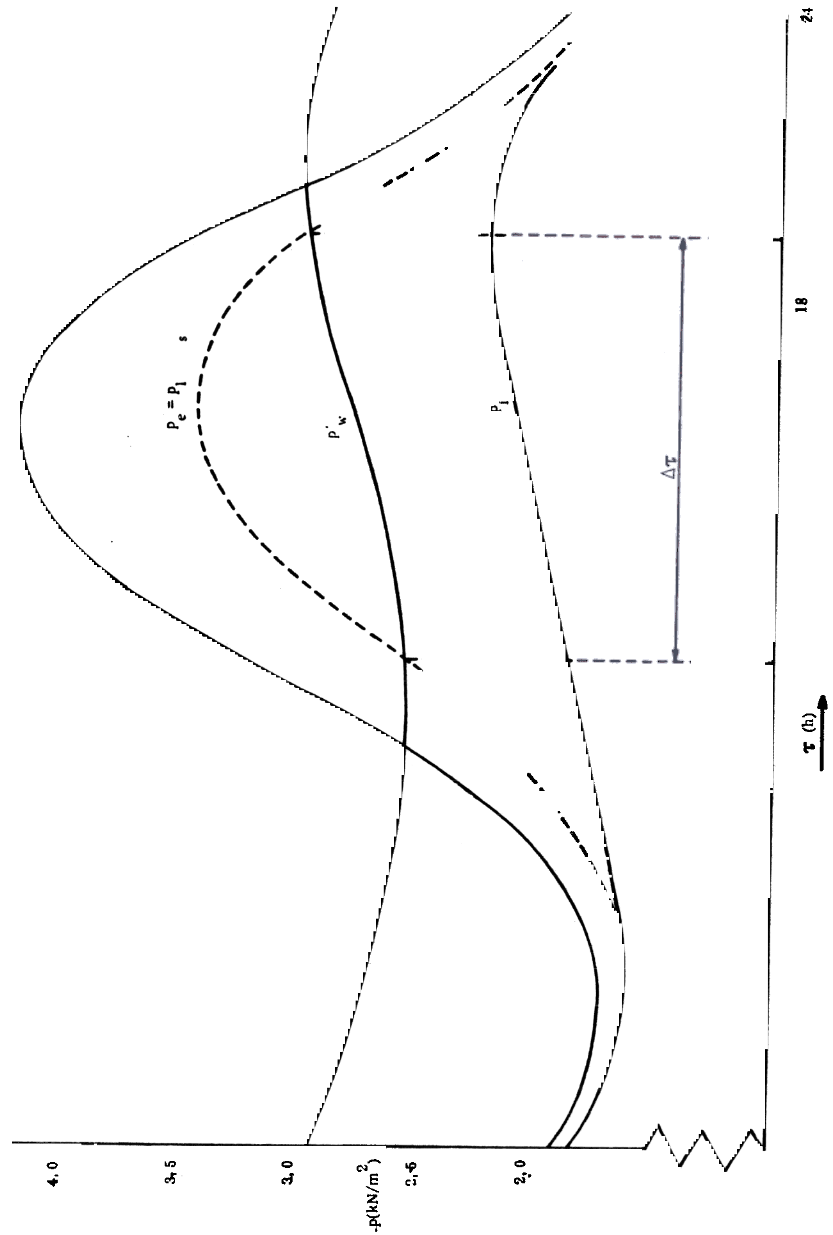


fig. 7

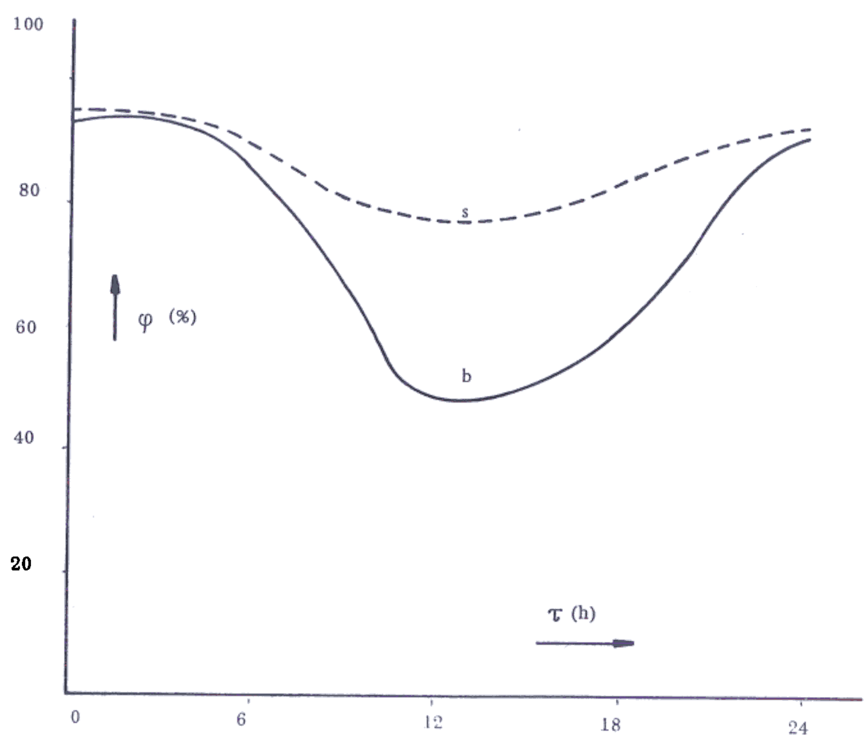


fig. 8

temperature while the relative humidity decreases only slightly (*) (p_i = p_e = s in fig. 7). In a more continental climate where only a little water can evaporate, the vapour pressure will increase only slightly (p_i = p_e = ℓ) while the relative humidity decreases greatly. Fig. 8 shows approximately the daily course in both cases.

We calculate the amount of moisture condensing in the maritime region from relation (4): The average vapour-pressure difference between 10 and 19 hours is about 0,45 kN/m^2. Thus :

$$g_c = 20 \times 10^{-9} \times 0\ 45 \times 10^3 = 10^{5}\ \mathrm{kg/m^2s}$$

In 24 hours this amounts to 300 g/m^2.

Such a quantity is not large. In the long run, however, especially under unfavourable drying conditions, the percentage of moisture cannot be neglected.

If moisture production takes place, then in steady-state conditions in winter, condensation will also occur; the chances for this are greater in the coastal region than inland.

Now a word about the influence of the thickness of the wall. The thicker the wall, the greater the heat insulation and also the greater the heat capacity. In the summer the magnitude of the latter is determining. The greater the heat capacity the greater the difference in amplitude between t_e and t_w. The chance for condensation in summer increases with this as a result of this damping.

In winter, however, the heat resistance is more important. This determines namely the wall temperature t_w. The chance of condensation in winter will decrease while the thickness of the wall increases.

INTERNAL CONDENSATION.

Condensation can occur not only at the surface, but also in the interior of the structure. In this case two distinctions must be made.

1. The homogeneous structure

Fig. 9a shows the temperature variations under steady-state conditions in a homogeneous structure. This temperature course also determines the maximum vapour pressure (p') as drawn in

(*) In the urban agglomeration of Holland for example the relative humidity seldom decreases below 70% in summer. The average relative humidity in this season is 80%.

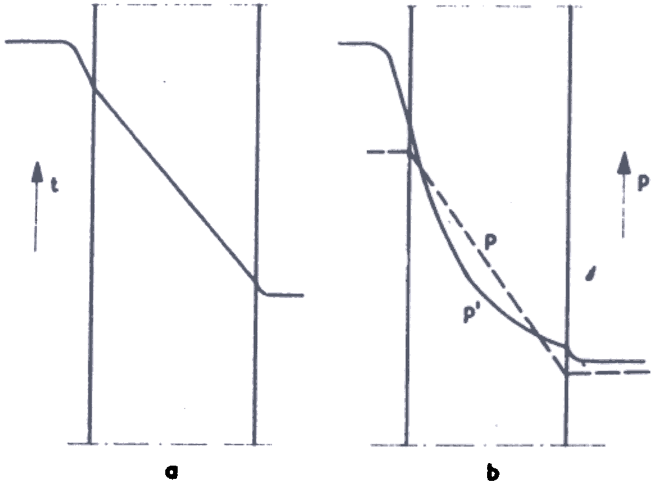


fig. 9

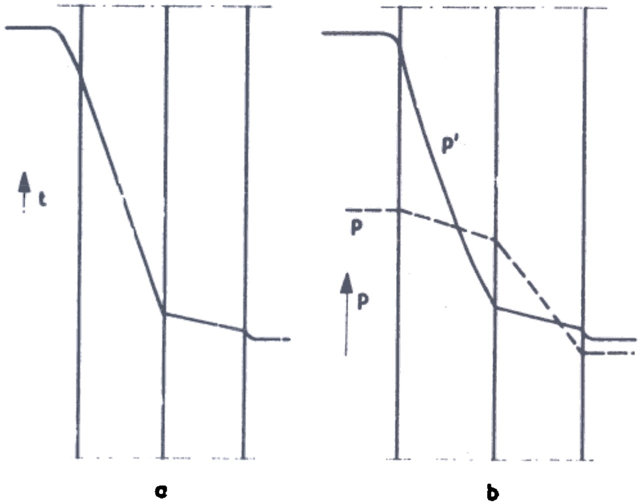


fig. 10

fig. 9b. Because the maximum vapour pressure increases more than linearly with the temperature (see fig. 5) a curved p'-line arises. The p-line on the other hand - that is the line that gives the real vapour pressure if no condensation takes place - is straight. The chances are that the lines will cross and thus over a certain section p would be greater than p'. This is impossible. Therefore anywhere in the interior of the structure condensation will take place. The course the vapour pressure follows in reality will not be dealt with here [13] , also not the method of calculating the quantity of condensed moisture or the occurrence of the moisture distribution in equilibrium [10]

From the figure however it can be seen that such a situation as described here can only occur at high relative humidities.

2. The composite structure

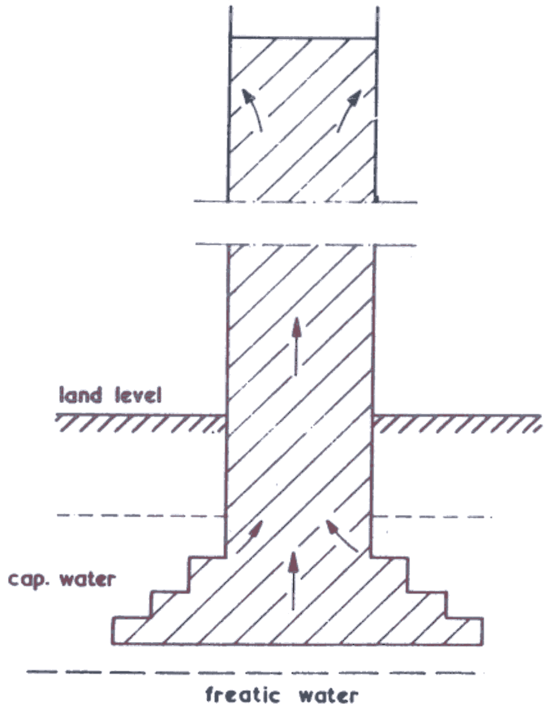
Even if the relative humidity is not particularly high, condensation can still take place at the boundary of two layers. Fig. 10 illustrates this. Here is drawn a structure composed of two layers of which the inner one has good thermal insulation and the outside one bad. On the other hand, the inside layer has a low diffusion resistance, while the outside one is high. Fig. 10a gives the course of the temperature distribution ; fig. 10b the course of the vapour pressure and the maximum vapour pressure. The fact that also here the vapour pressure in part of the structure would be higher than the maximum is not a result of the curved character of the maximum vapour pressure line, but finds its origin in the ratio of the thermal and hygric properties of both layers.

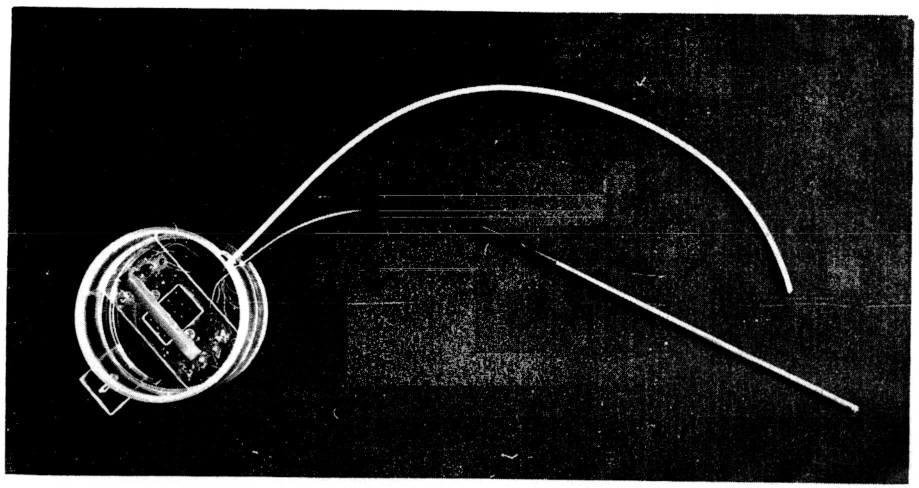
An extreme example of what is described here is found in the flat roof that has a strongly vapour-retarding layer on the outside and also in the massive wall with an outside covering of tiles. The construction is widely considered in [2] .

The quantity of moisture absorbed in the inside of the structure is mostly small as compared with the amount of surface condensation absorbed. The damage however can be greater as this phenomenon is hidded from view. During a number of years a considerable accumulation of water can take place without it being seen. The damage can show itself rather suddenly, for example in form of rotting joisting in a roof, or the frosting off of tiles.

GROUND MOISTURE.

As the last cause of wetting of structures we consider ground moisture. That is to say the moisture that originates in the ground and was drawn into the floor and walls by capillary forces. For this it is necessary that there is direct contact between the capillary water in the ground and the foundations. If these are not sufficiently closed (too high a B-value) then the water can





be absorbed in the walls. The height for capillary absorption in brick is many metres. Under normal conditions however this height of absorption is never reached because evaporation takes place at the wall surfaces (fig. 11). There is a rather sharp waterfront in the wall where the moisture content is about critical [9]. By branching out the water can also be found in the floor.

Here again it appears rather impossible to exactly define the moisture transports. We will not try to do this either.

DETERMINATION OF MOISTURE CONTENT AND MOISTURE DISTRIBUTION.

In many cases at a first glance it is impossible to determine which of the foregoing cases had caused the wetting of the structure. The moisture distribution and its changes in the course of time can however be an indication. Many methods for the determination of this were tried during the course of time.

It is not however the intention of this article to go into this. We want to make an exception in the case of our laboratory developed method, from which particularly favourable results were obtained : the λ-probe method [14,15,16] .

Fig. 12 shows such a probe. In a hollow arm is situated a thin doubled wire (0,3 mm diameter) against which are 9 thermocouples (0,1 mm diameter) which are at distances of 2 cm. If an electric current is passed through the heating wire the temperature increase can be measured with the aid of the thermocouples. From the relation between temperature and time the λ-value (thermal conductivity) can be calculated with the aid of the formula :

$$\lambda = \frac{Q}{1\pi} \frac{d\,\ell n\,\tau}{dt} \quad (J/ms^{\circ}K) \qquad (5)$$

Q is quantity of heat developed per unit length (J/ms)
t is temperature (°C)
τ is time (s)

To eliminate temperature fluctuations due to external causes, the nine cold junctions are put in a second arm of the probe. The two arms are situated 20 cm apart in the wall so that the heater in the hot arm does not effect the cold junctions.

By this method we find the thermal conductivity as a function of depth in the wall. If the relation between the λ-value and the moisture content is known then an idea of the moisture distribution can be found. Fig. 13 shows the results of such a measurement.

The measurements are completely automatic. Fig. 14 shows a recorder to which 28 probes can be connected. Each mea-

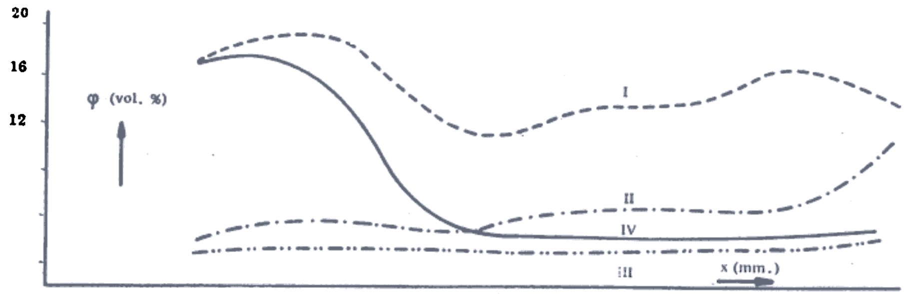


fig. 13

fig. 14

surement (9 measuring points) extends over half an hour. Hereafter a new probe is measured.

SUBSCRIPTS.

1. Hygroscopic moisture content ψ) as a function of relative humidity (ψ); general picture.

2. Water distribution (ψ) in a wall as a function of depth (x) at different times (τ) during rain penetration.

3. Position of waterfront (x) as a function of time (τ) during rain penetration; (a) poor quality brick; (b) good quality brick; (c) concrete.

4. Water distribution (ψ in a wall as a function of thickness (x) at different times (τ) during drying at the outside.

Maximum vapour pressure (p') as a function of temperature (t). P is unsaturated situation; Q is dewpoint; S and T are saturated situations.

Outside temperature (t_e) and temperature of the inner surface of a wall (t_w) show a daily fluctuation.

7. Daily fluctuation of the vapour pressure (p) in the summer.
   - p'_e = maximum vapour pressure outside
   - $p_e = p_i = s$ vapour pressure inside in maritime climate
   - $p_e = p_i = \ell$ ditto in continental climate
   - p'_w maximum vapour pressure on inner surface of wall

8. Daily fluctuation of the relative humidity (φ) in summer; s = maritime climate; ℓ = continental climate.

9. a. Course of temperature (t) in a homogeneous wall; steady-state conditions in winter.
   b. Course of maximum vapour pressure (p') and the theoretical vapour pressure (p). Condensation takes place.

10. a. Temperature course in structure composed of two layers; steady conditions in winter.
    b. Course of maximum vapour pressure (p') and the theoretical vapour pressure (p). Condensation on boundary.

11. Rise of ground moisture in wall.

12. Probe for determining of moisture content and moisture distribution in situ.

13. Moisture distribution (ψ) in a wall as measured by λ-probes.

I. One month after building of the wall
II. Three months afterwards
III. Six months afterwards
IV. After an artificial rain period

x = depth in the wall.

14. Automatic registration of probe measurements.

BIBLIOGRAPHY.

1. Krischer, O.: "Die wissenschaftlichen Grundlagen der Trocknungstechnik" (2nd impression).
Springer Verlag, Berlin/Göttingen/Heidelberg (1963).

2. Vos, B. H.: "Condensation in structures".
Report BI-67-33, Institute TNO for Building Materials and Building Structures, Delft (Neth.) (1967).

3. Romslay, R. R.: "Multimolecular absorption equation".
Am. Inst. Chem. Eng. Journal, 7 (1961), p. 308.

4. Egner, K.: "Feuchtigkeitsdurchgang und Wasserdampfkondensation in Bauten".
Fortschritte im Bauwesen C1 (1950). Frank'sche Verlagshandlung, Stuttgart.

Sereda, P. J. and N. B. Hutcheon: "Moisture equilibrium and migration in building materials".
Techn. paper 205, Div. of Building Research, Ottawa (1965).

Lykow, A. W.: "Transporterscheinungen in kapillarporösen Körpern". Akademie Verlag, Berlin (1958).

7. Jansson, I.: "Testing the rate of water absorption".
RILEM/C. I. B. publication 2.25, Helsinki (1966).

8. Tammes, E. en B. H. Vos : "Vocht in bouwconstructies".
Bouwcentrum Rotterdam (1966).

9. Van Minnen, J. and B. H. Vos : "Distribution and transport of water in porous materials".
Report SBR II:8, Institute TNO for Building Materials and Building Structures, Delft (Neth.), 1965.

10. Vos, B. H.: "Moisture transfer and drying".
Institute TNO for Building Materials and Building Structures, Delft (Neth.); to be published.

11. Lacy, R. E.: "The absorption of water by three weighed walls at Garston".
Int. note In. 14/166, Building Research Station, Garston, Watford, Herts (Eng.), 1966.

2. Illig, W.: "Die Grösse der Wasserdampfübergangszahl bei Diffusionsvorgängen in Wänden".
Ges. Ing., 73 (1952), Heft 7/8, p. 124.

Glaser, H.: "Temperatur- und Dampfdruckverlauf in einer homogenen Wand".
Kältetechnik, 10 (1958), p. 174/179.

14/15 Vos, B.H.: "Warmtegeleidingsmetingen volgens een niet-stationaire methode I en II".
De Ingenieur, 73 (1961) n°. 3, p. 07 et seq. and n°5, p. 013 et seq.

16. Vos, B.H.: "Determination of water content, water distribution and heat resistance of walls I".
Report SBR II:4, Institute TNO for Building Materials and Building Structures, Delft (Neth.). 1965.