Determination of the Effects of Moisture on the Thermal Transmissivity of Cellulose Fiber Loose-Fill Insulation

P.I. Sandberg, Ph.D.

ABSTRACT

This report presents the results of measurements and calculations of thermal transmissivity, temperatures, and heat flows in moist loose-fill cellulose fiber thermal insulation.

The measurements were made and analyzed in accordance with the principles and instructions given in ISO/DIS 10 051, "Thermal Insulation - Moisture Effects on Heat Transfer—Determination of Thermal Transmissiviry of a Moist Material." The results showed that for the cellulose fiber that was the subject of the tests, the effect of moisture on the thermal transmissivity was on the order of 0.001 W/(m·K) within the hygroscopic range (moisture content in equilibrium with 98% RH or lower).

Computer calculations using a simple model indicated good correlation between measured and calculated values of temperatures and heat flows.

BACKGROUND

The Swedish National Board of Housing, Building and Planning rules for approval of thermal insulation include standard allowances for the effect of moisture on the thermal transmissivity of the material. These allowances are based on data in the literature from various scientific reports. As determination of the thermal transmissivity of moist materials is complicated, it is not unreasonable to be wary of the reliability of the values given. In addition, for certain types of materials, only a few results are given. The board therefore allows manufacturers to quote better values (i.e., with lower standard margins) if they can demonstrate, by means of tests, that such values are justified. Therefore, there is reason to develop methods of measuring the thermal transmissivity of moist materials.

An ISO working group (IS0/TC163/SC1/WG9) has been engaged for some years in investigating the principles of determination of thermal transmissivity of moist materials. Its results have now been published as ISO/DIS 10 051, "Thermal Insulation—Moisture Effects on Heat Transfer—Determination of Thermal Transmissivity of a Moist Material." It is important, for continued development of this ISO work, that the proposed principles be tested in practical measurements.

As a result of the above, the Swedish National Testing and Research Institute (SP) has started work on gathering experience of this type of tests. This report presents the results of such work for cellulose fiber loose-fill insulation.

THE ISO STANDARD

ISO/DIS 10 051 sets out the principles for determination of the thermal transmissivity of moist materials; λ^*.λ^* is defined as the thermal transmissivity under steady-state conditions, i.e., it is affected by the moisture content but does not include the effects of moisture migration or phase changes, e.g., of evaporation or condensation. This property of the material can be used together with knowledge of the actual moisture conditions in building structures to determine the safety margin needed for various materials in different environments.

The standard assumes that the measurements are made at a temperature above 0°C in a hot plate apparatus of conventional type: either a heat flow meter apparatus (HFM) as specified by ISO 8301 or a guarded hot plate (GHP) as specified by ISO 8302. We have used a 600 × 600 mm heat flow meter with heat flux transducers on both the warm and cold sides.

The ISO standard draws attention to two complications that occur in connection with measurement of moist materials:

1. There is always some migration of moisture during measurement as a result of subjecting the sample to a temperature gradient. This means that the true moisture distribution during the test is not known.
2. The migration of moisture means that the effects of phase changes (latent heat of evaporation and of condensation) affect the result. The definition of λ^* requires that these effects not be included in the measured value result. It is necessary, therefore, either to ensure that the effects of phase changes are negligible or to determine their magnitude and apply corrections for them.

For cellulose fiber thermal insulation, we chose to perform the tests during what the ISO standard refers to as Phase C, i.e., when moisture migration has ceased and

Per Ingvar Sandberg is head of the Division of Building Physics at the Swedish National Testing and Research Institute, Borås, Sweden.

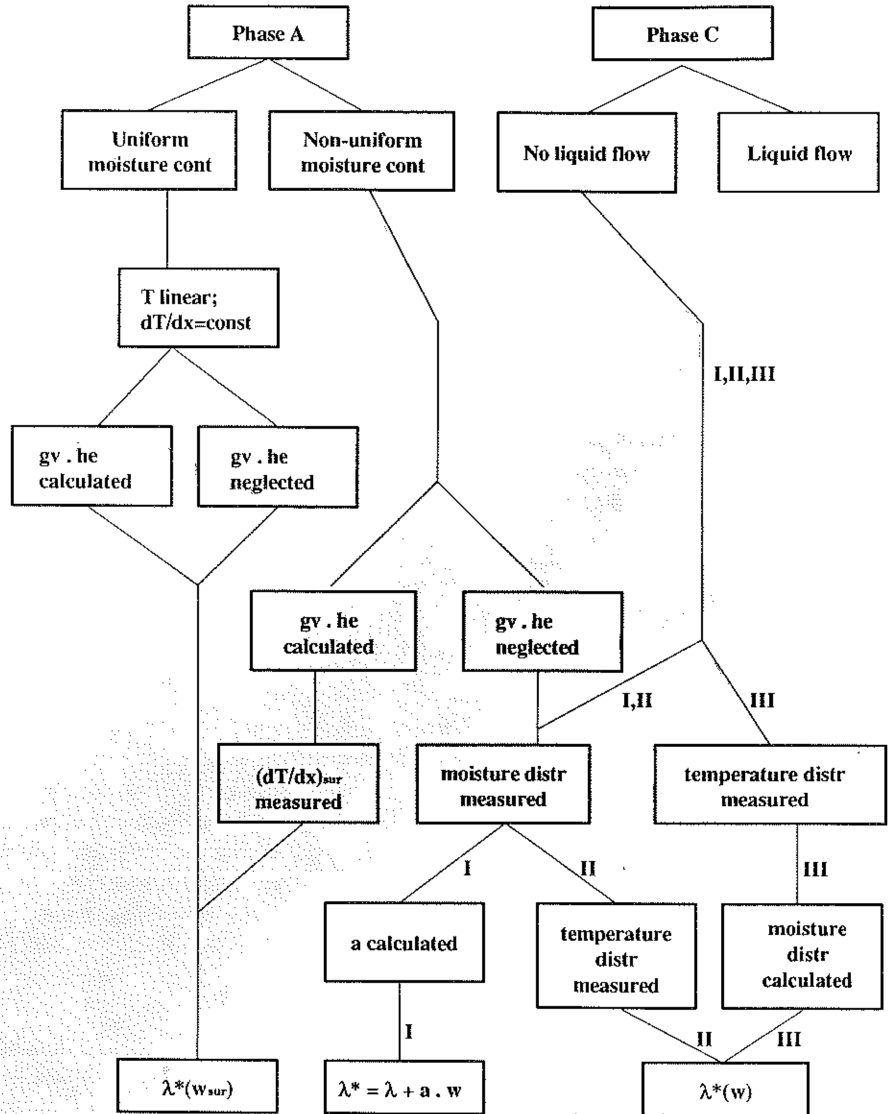

Figure 1 *The flow diagram from ISO/DP 10 051 that describes various paths to follow in order to determine λ*. Paths I, II, and III are marked.*

steady-state moisture conditions have been established. This is possible because cellulose fiber is a permeable material and steady-state moisture conditions are established within a reasonable time, which avoids the problems associated with (2) above. The problem with (1) above is solved by ascertaining the moisture distribution in the sample at the conclusion of measurements or by calculation. Both methods have been used, and the results have been compared.

The temperature distribution in the sample has been determined. The thermal transmissivity can be determined both with and without knowing the temperature distribution. A problem in connection with determination of temperature distribution has been uncertainty in knowing the exact positions of the temperature sensors with respect to their distances from the warm or cold plates. We have therefore complemented the measurements of moist materials with measurements of dry materials in the same test apparatus. This procedure is described below.

The ISO standard specifies different ways of following a flow diagram. Our evaluation compared three different paths (see Figure 1).

Path I involves

- measurement of the moisture distribution,
- determination of the equation $\lambda^* = \lambda_{dry} + a \cdot w$

where

λ = thermal transmissivity for moist material,
w = moisture content.

Path II involves

- measurement of moisture distribution,
- measurement of temperature distribution,
- determination of λ^* as a function of moisture content.

Path III involves

- measurement of temperature distribution,
- calculation of moisture distribution,
- determination of λ^* as a function of moisture content.

In other words, the departure from the ISO standard is (as mentioned above) the fact that in paths II and III, it is not λ^* that has been determined but $\Delta\lambda_{moist} = \lambda^* - \lambda_{dry}$, as a function of the moisture content.

TEST SPECIMEN PREPARATION

The material—a cellulose fiber intended for use as a loose-fill insulation in roof spaces—was blown into a cardboard box in the laboratory using a spray gun. It was then loaded by hand into test frames, as shown in Figure 2, where it was distributed as evenly as possible.

The test frames have sides of extruded foamed polystyrene, with a bottom of thin, finely woven fabric. The density of the insulation (27 kg/m^3 dry density) was checked by weighing. As used in the rest of this report, "frame" shall be taken to mean the physical frame itself, the fabric bottom, and the filling of insulation under test.

Earlier experience had shown that it is essential to know the positions of the temperature sensors with considerable accuracy and to be certain that their positions do not change while testing is in progress. Pt 100 temperature sensors were therefore positioned at the boundaries between the frames in the center of the measuring area (see Figure 3). Each sensor was secured to a steel wire, with thermal contact mastic between it and the wire, and the wire was then fastened to a spacer of extruded polystyrene, to ensure a known, constant position for each sensor. The sensors were calibrated with an accuracy of better than 0.1 K.

After the material had been loaded into the frames, the frames were placed in a ventilated oven at a temperature of 70°C to dry them out completely. After about a week, their weights had ceased to change, and they were taken out and quickly placed in a pile, one on top of the other, with a plastic film placed on top of the uppermost frame.

Four frames were used, giving a total sample thickness of 164 mm. As mentioned above, the outer dimensions of the frames are 600 mm × 600 mm, and the measurement area of the heat flow meter apparatus is 250 mm × 250 mm.

TESTS OF DRY MATE

The stack of frames was loaded into the heat flow meter apparatus. A plastic film was placed beneath the lowest frame to protect the apparatus from condensation. The temperature of the upper plate was about 20°C and that of the lower plate about 0°C.

Steady-state heat flux conditions were achieved after about one to two days. When steady-state conditions had been established, temperature distribution through the sample was determined by reading the temperatures indicated by the temperature sensors embedded in the sample and of the warm and cold plates. Table 1 shows the indicated temperatures and the heat fluxes. The heat fluxes past temperature sensors 1-3 have been linearly interpolated between the measured heat flows at the warm and cold plates.

The thermal transmissivity in each frame can be calculated, assuming that each of the temperature sensors is correctly positioned, i.e., that the distance between them is 41 mm (see Table 2). All the values ought reasonably to lie around the measured dry value for the entire sample. The slight deviations can be safely accounted for by the fact that the true thickness of the material in each of the frames is

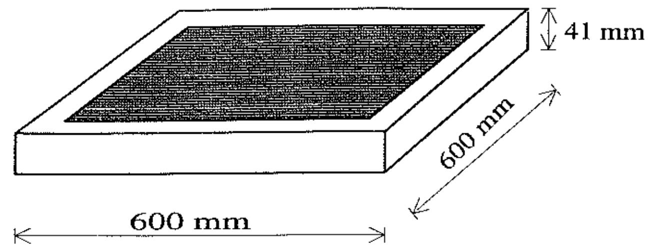

Figure 2 *The frame in which the material was loaded during the tests.*

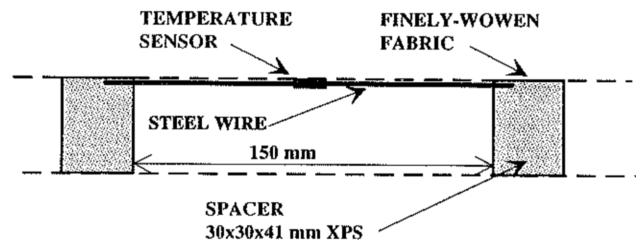

Figure 3 *Positioning and fixing of temperature sensors.*

TABLE 1
Temperature Distribution (°C) and Heat Flow (W/m^2) for Test of Dry Material

Position	Temperature	Heat flow
Warm plate	20.09	4.46
Sensor 1	15.07	4.49
Sensor 2	9.99	4.53
Sensor 3	5.05	4.56
Cold plate	0.03	4.59

TABLE 2
Calculated Thermal Transmissivity (W/[m·K]) for the Material in Each Frame When Testing Dry Material

Frame	Thermal transmissivity
1	0.0365
2	0.0364
3	0.0377
4	0.0373
Entire sample	0.0370

uncertain. Each millimeter difference in thickness is equivalent to a difference of about 0.001 in the value of λ for the frame concerned. Errors in measurement of temperature difference and heat flux result in a further uncertainty of the same order of magnitude.

During an earlier project, the same material was tested using a similar method (Sandberg 1991). The values for the dry material in that project are shown in Table 3. The spread between the different frames is greater than for this project because the temperature sensors were not fixed as carefully in position and the thickness of the individual frames was not so well defined.

TESTS OF MOIST MATERIAL

After testing the dry samples, the stack of frames was carefully removed from the apparatus without separating the individual frames, and water was sprayed onto the upper surface as evenly as possible across the sample. The quantity of water amounted to about 0.110 kg, equivalent to 0.10 kg/kg for the entire stack of frames.

The stack was then reloaded into the heat flow meter apparatus at the same temperatures as used for testing the dry material. This time, it took almost a week for steady-state conditions to be reached (see Figure 4).

When steady-state conditions had been established, temperature distribution through the sample was determined by reading the temperatures of the sensors embedded in the sample and of the warm and cold plates. Table 4 shows the temperatures and the heat fluxes. The heat fluxes past temperature sensors 1-3 have been linearly interpolated between the measured heat flows at the warm and cold plates.

The thermal transmissivity in each frame can be calculated, assuming that each of the temrerature sensors is correctly positioned, i.e., that the distance between them is 41 mm (see Table 5). The corresponding values from the earlier project are given in Table 6. Note that the value for each individual frame is uncertain, reflecting the uncertainty in determining the thickness of the material in each frame.

The stack of frames was removed from the heat flow meter apparatus and the individual frames separated. Two

TABLE 3
Calculated Thermal Transmissivity (W/[m·K]) When Testing Dry Material in an Earlier Project (Sandberg 1991)

Frame	Group 1	Group 2	Group 3
1	0.040	0.040	0.039
2	0.036	0.041	0.037
3	0.034	0.034	0.038
4	0.043	0.039	0.038
5	0.035	0.035	0.037
Entire sample	0.0374	0.0374	0.0377

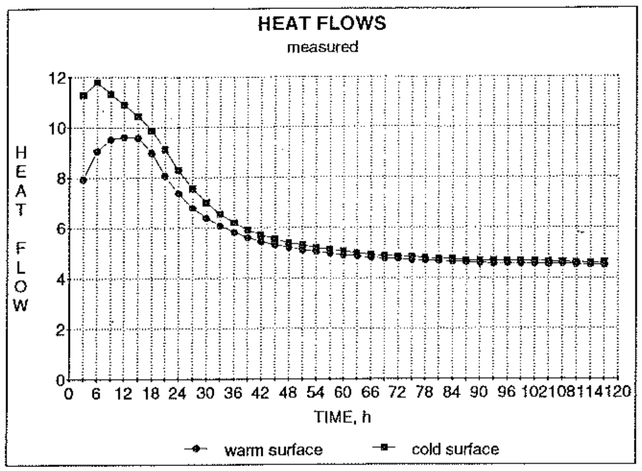

Figure 4 *Heat flux at the upper and lower plates as a function of time when testing the moist material.*

samples of the material were then taken from each frame for determination of the moisture content (mass by mass). One sample was taken from the middle of the frame, i.e., in the measurement zone of the heat flow meter apparatus, while the other sample was taken at the edge of the frame. All eight samples were weighed, dried at 70 °C until

TABLE 4
Temperature Distribution (°C) and Heat Flux (W/m²) for Tests of Moist Material

Position	Temperature	Heat flow
Warm plate	20.09	4.54
Sensor 1	14.96	4.56
Sensor 2	9.88	4.58
Sensor 3	4.98	4.60
Cold plate	0.08	4.62

TABLE 5
Calculated Thermal Transmissivity (W/[m·K]) for the Material in Each Frame When Testing Moist Material

Frame	Thermal transmissivity
1	0.0364
2	0.0369
3	0.0384
4	0.0386
Entire sample	0.0375

TABLE 6
Calculated Thermal Transmissivity (W/[m·K]) for the Material in Each Frame When Testing Moist Material in an Earlier Project

Frame	Group 1	Group 2	Group 3
1	0.040	0.041	0.038
2	0.037	0.042	0.038
3	0.034	0.035	0.038
4	0.044	0.039	0.040
5	0.036	0.035	0.039
Entire sample	0.0378	0.0381	0.0385

TABLE 7
Steady-State Moisture Contents (Mass by Mass) in the Material in Each Frame (kg/kg)

Frame	Centre	Edge
1	0.069	0.069
2	0.083	0.083
3	0.101	0.099
4	0.165	0.162

steady-state conditions were reached, and then weighed again. The moisture content was calculated; Table 7 shows the results. The accuracy of the determination of moisture content was estimated as better than $\pm$ 0.005 kg/kg.

The values show no significant difference between the samples taken in the center of the frames and those taken at the edge, indicating that any horizontal migration of moisture and loss through the frame can be ignored. The measured mean moisture ratio in the middle of the frames is 0.104 kg/kg. This value should be compared with the amount of water added—0.10 kg/kg.

EVALUATION

The above results have been evaluated in three different ways, referred to here as Paths I, II, and III.

Path I

The moisture distribution is determined (see Table 7). Assuming that the relationship between thermal transmissivity and the mass by mass moisture content is linear and that the temperature dependence of the thermal transmissivity is negligible,

$$\lambda_i^* = \lambda_{dry} + a \cdot u_i \qquad (1)$$

where

λ^* = the thermal transmissivity of moist material, W/(m·K);
u = moisture content, kg/kg;
a = coefficient;
i = indication of any arbitrary frame.

The total thermal resistance of the sample can be expressed as the sum of the thermal resistances of the individual frames, i.e.,

$$q = (t_{warm} - t_{cold}) / \sum [d_i(\lambda_{dry} + a \cdot u_i)] \qquad (2)$$

where

q = heat flux through the sample, W/m^2;
t_{warm} = temperature of the warm plate, °C;
t_{cold} = temperature of the cold plate, °C;
d_i = thickness of the respective frame, m.

In this equation, the a term is the only unknown, and so the equation can be solved for it; a has been determined by trial and error in a spreadsheet program. The value of heat flux used has been the mean value of the measured fluxes at the warm and cold sides.

The value of the a term was found to be 0.005. Figure 5 shows λ^* as a function of the mass by mass moisture content. For comparison, the figure also shows the results from the earlier project, working with the same material and evaluating it in the same way.

Path II

The moisture distribution is determined (see Table 7). According to the ISO standard, the next step would be to determine λ^* for the various frames by means of the measured temperatures and heat fluxes, in the same way as was done for Table 5. However, as the actual thickness of the frames is not known exactly, we decided to express λ^* as (λ_{dry} + $\Delta\lambda_{moist}$), where the value used for λ_{dry} is that for the whole stack, as shown in Table 2, and where

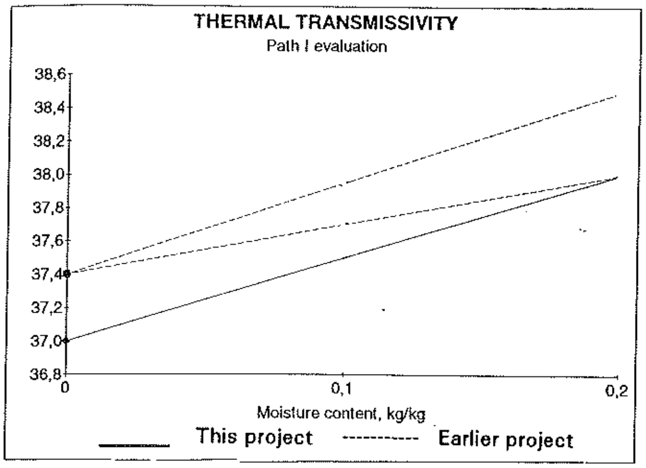

Figure 5 λ^* *as a function of the mass by mass moisture content, calculated by Path I; values from this project and an earlier project.*

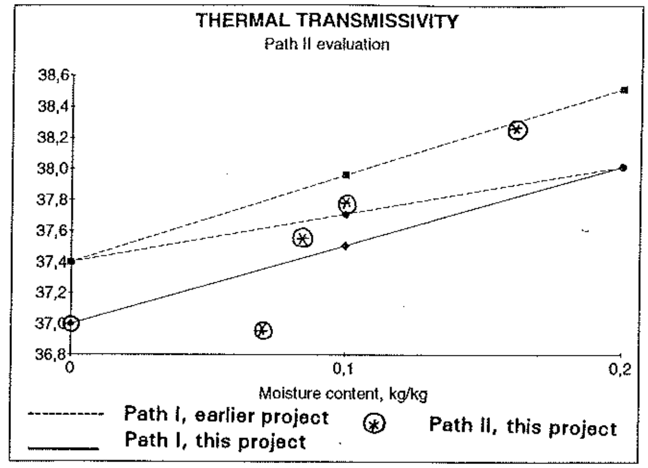

Figure 6 λ^* *as a function of the mass by mass moisture content, evaluated according to Path II.*

TABLE 8

Difference in Thermal Transmissivity for the Respective Frames When Determining the Values Thereof for Moist and Dry Material, $\Delta\lambda_{moist} = \lambda^* - \lambda_{dry}$, W/(m·K)

Frame	$\Delta\lambda_{moist}$	$\lambda^* = \lambda_{dry} + \Delta\lambda_{moist}$
1	-0.0001	0.0369
2	0.0005	0.0375
3	0.0007	0.0377
4	0.0013	0.0383
Entire sample	0.0005	0.0375

$\Delta\lambda_{moist}$ is given by the difference of the values in Tables 5 and 2 (see Table 8). Since Table 8 shows the difference in measured values between two sets of measurements, the systematic errors in temperature difference and heat flux should be eliminated. Most of the error due to uncertainty of determination of thickness is also avoided by using the differences between the values.

Unfortunately, the effect of the amount of moisture added to this material is very slight and of the same order as the measurement uncertainty. The relationship between λ^* and u as determined by the Path II evaluation is shown in Figure 6, which should be compared with Figure 5. With the exception of the value for Frame 1, agreement is very good. The discrepancy in the value for frame 1 can be at least partly explained. After testing the moist material, a slight settling of the material in frame 1 (amounting to some tenths of a millimeter) was noted, so that contact between the material in the frame and the hot plate was no longer perfect. This increased contact resistance affects the calculated value of λ^*.

Path III

We start by determining $\Delta\lambda_{moist} = \lambda^* - \lambda_{dry}$ as above (see Table 8).

We determine moisture distribution approximately by assuming that moisture transport in the material can be described by the equation

$$g = \delta_v \cdot dv/dx \tag{3}$$

where

g = density of moisture flow rate, kg/(m^2·s);
δ = vapor permeability, m^2/s;
v = humidity by volume, kg/m^3.

For the majority of insulating materials, this assumption provides a good approximation of moisture transport for moderate moisture levels. When moisture equilibrium is achieved, the humidity by volume of the sample is constant and equal to the saturation value at the cold plate. The temperature distribution is known, and so the saturation value of the vapor in each frame can be calculated. The relative humidity in each frame can also be calculated and the mass by mass moisture content estimated from a sorption curve. Figure 7 shows the principle of the various steps, while Figure 8 shows the results after determination of a sorption curve.

The values shown in Figure 8 are for absorption from dry material (over a period of three weeks) and for desorption from a mass by mass moisture content of about 0.5 kg/kg (over a period of seven weeks). Only one sample was used at each value of relative humidity, which means that the values may not be entirely reliable. Table 9 shows the associated calculations.

NOTE: Instead of using humidity by volume as the driving force for moisture transport, the partial pressure of water vapor can also be used. This procedure gives the same results.

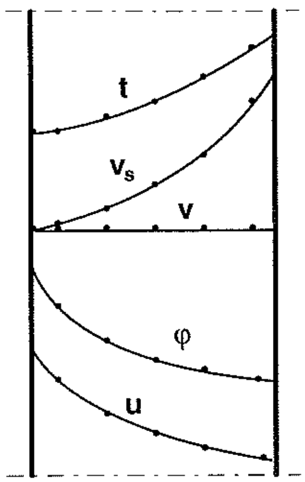

Figure 7 Schematic representation of temperature, saturated humidity by volume, humidity by volume, relative humidity, and mass by mass moisture content.

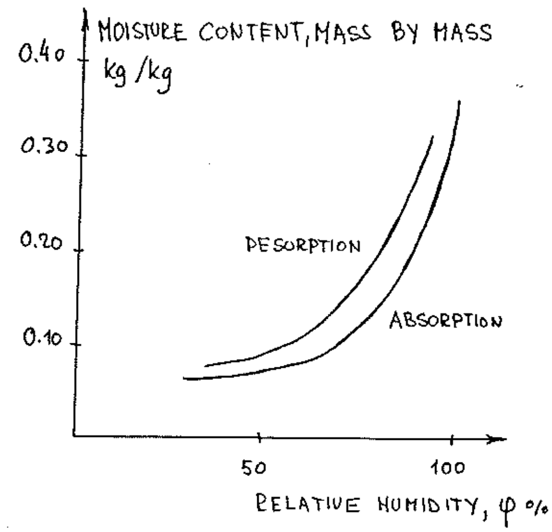

Figure 8 Measured sorption curves for the material. Absorption was obtained using a dry material and covers a period of three weeks, while desorption was obtained using a sample having an initial moisture content of 0.5 kg/kg and covers a period of seven weeks.

The estimated values have been expressed as an interval corresponding to the area between the absorption and desorption curves. Determination of the distribution of moisture content in this way requires a true sorption curve and a correct description of moisture transport in order to be able to estimate the equilibrium state. We often lack both these items of information, which means that, in the absence of measured values, determination of the moisture content by calculation must be regarded as a rough estimate.

COMPUTER CALCULATIONS

Simulations have been run, using a computer model, in order to obtain a better understanding of the moisture and temperature redistribution processes occurring during the tests and to verify the validity of theoretical models. The program was described in detail by Sandberg (1983). The model describes single-dimensional heat and moisture transport in a hot plate apparatus and allows for the effects of phase changes and the convective transport of heat. It is assumed that moisture transport can be described by purely vapor transport mechanisms in accordance with Equation 3.

The material characteristics that are used are as follows:

- thermal transmissivity $\lambda^* =$

$$0.037 + 0.0002 \cdot w \text{ (W/m,K)} \tag{4}$$

where

$w =$ the mass by volume moisture content of the material in kg/m^3.

TABLE 9
Estimate of Approximate Moisture Content Distribution

	Frame 1	Frame 2	Frame 3	Frame 4	Cold plate
Temperature, °C	17.5	12.4	7.4	2.5	0.1
Saturation humidity by volume, kg/m^3	0.0149	0.0109	0.0080	0.0058	0.0049
Humidity by volume, kg/m^3	0.0049	0.0049	0.0049	0.0049	0.0049
Relative humidity, %	33	45	61	84	100
Moisture content, kg/kg, estimated	0.06-0.07	0.07-0.09	0.08-0.11	0.17-0.21	
Moisture content, kg/kg, measured	0.07	0.08	0.10	0.16	

The computer program expresses the moisture level as mass by volume moisture content, and this convention has been followed in this section. In the other parts of this report, moisture level has been referred to as mass by mass moisture content, u kg/kg, which is more suitable for a loose-fill material. For the density used in this project, the relationship between u and w is given by $w = u \cdot 27$.

- Thermal capacity $C =$
$$54000 + 4200 \cdot w \text{ (W·s/K·m}^3\text{)}. \tag{5}$$

The sorption curve is as shown in Figure 8 but approximated to two straight lines.

- Vapor permeability, δ_v. The vapor permeability for dry material was taken as $200 \cdot 10^{-7}$ (80% of the value of δ_v in air), with a quadratic increase to 250×10^{-7} (δ_v in air) at the boundary of the hygroscopic zone, where the moisture content is about 8 kg/m^3. In previous calculations, these values have given acceptable agreement between calculations and measurements (see Sandberg [1991]). The high values that are needed for agreement indicate that transport in the liquid phase (capillary attraction) plays an important part in moisture transport, which is not unexpected in a material of this type, particularly not at higher moisture contents.

Calculated values of the heat flow at the hot and cold plates are shown in Figure 9, from which it can be seen that agreement with measured values, as shown in Figure 4, is good. The measured values indicate a somewhat higher heat flow at the cold plate during the first few hours. This can perhaps be partly explained by the fact that the temperature of the lower frames of the sample rises somewhat when the stack of frames is removed from the hot plate apparatus and water is sprayed on the upper surface.

A comparison of the calculated and measured values of temperature distribution indicates good agreement. Figure 10 shows the measured values, and Figure 11 shows the calculated temperatures at three different levels in the sample.

Finally, we have also plotted the moisture distribution as it changes with time (Figure 12). Tendencies to a temporary "storage" of moisture in the sample can be noted before most of the moisture migrates to the cold side. This is due to the fact that the gradient of the saturation value of humidity by volume—and therefore also the humidity by volume gradient—is higher at higher temperatures. Vapor transport to the interior of the sample is therefore higher than transport out to the cold surface, with the result that a temporary accumulation occurs. Kumaran (1988) has measured similar moisture distribution behavior in connection with measurement of moisture movement through cellulose fiber insulation.

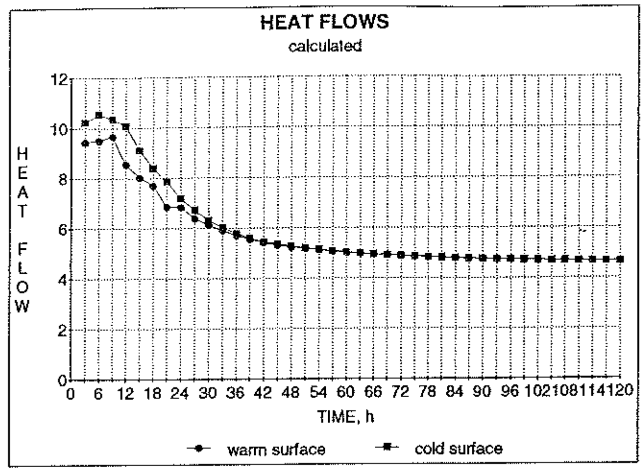

Figure 9 *Calculated values of heat flux at the warm and cold plates.*

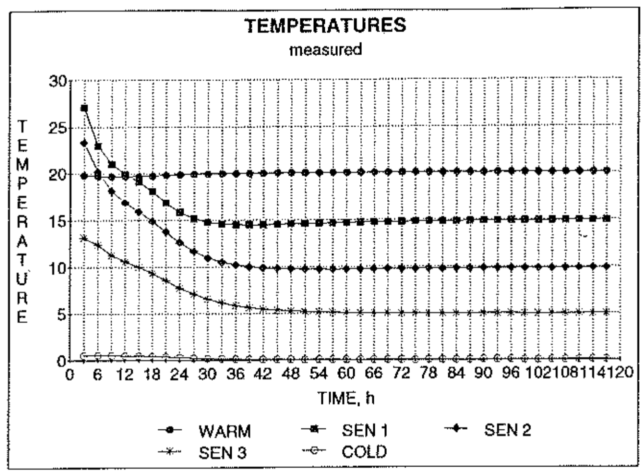

Figure 10 *Measured temperatures in the sample.*

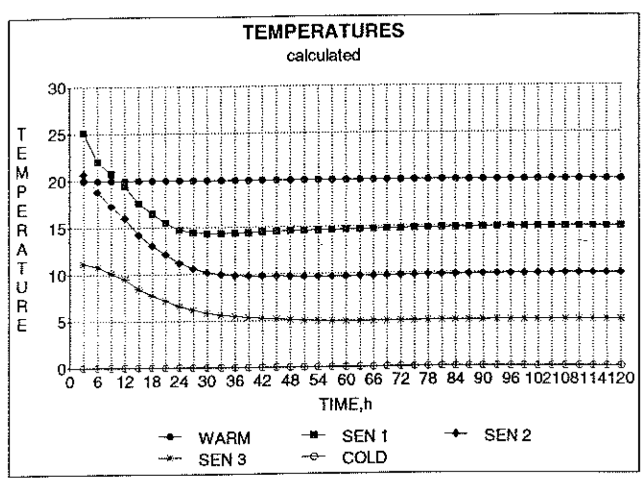

Figure 11 *Calculated temperatures in the sample.*

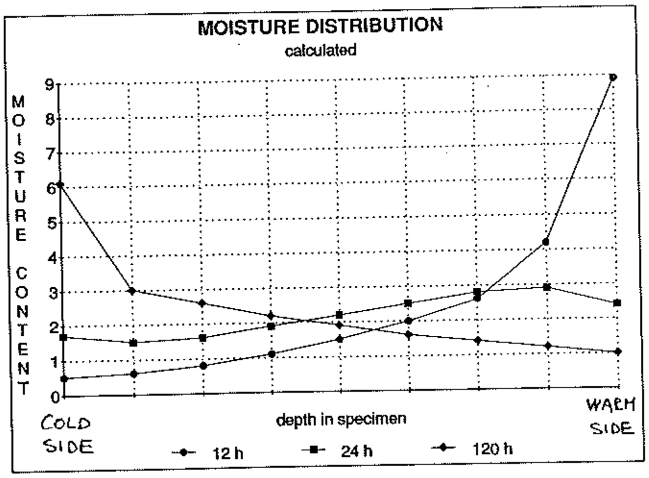

Figure 12 *Calculated moisture distribution through the sample after 12, 24, and 120 hours.*

CONCLUSIONS

Within the hygroscopic range, the increase in thermal transmissivity of the cellulose fiber insulation material used in this investigation was less than 0.001 W/(m·K).

Three different ways of evaluating the results, as described in ISO/DIS 10 051, have been used. All three were practicable and subject to the advantages and drawbacks described below.

Path I requires that

- λ^* increases linearly with moisture content;
- moisture distribution be determined with a certain degree of accuracy. A random error of ±25% should cause an error in a of about 10%.

Path II requires that

- the actual temperature distribution be measured with high accuracy—with the test arrangement described in this report, an error in position of 1 mm (frame thickness) or in value of 0.1 K can each result in an error of about 2.5% or 0.001 in the value of λ^*;
- moisture distribution be determined by measurement.

Path III requires that

- the actual temperature distribution be measured with high accuracy—with the test arrangement described in this report, an error in position of 1 mm (frame thickness) or in value of 0.1 K can each result in an error of about 2.5% or 0.001 in the value of λ^*;
- moisture distribution be determined by calculation, which requires a correct sorption curve and a correct model of moisture transport in the material.

Computer calculations using a simple model of heat and moisture transport have shown acceptable agreement with measured values.

Characteristic features of the material used in these tests are that it is hygroscopic and that capillary attraction plays an important part in moisture transport. In this respect, it differs from mineral wool, which is only very slightly hygroscopic and in which capillary attraction is negligible.

ACKOWLEDGMENTS

This work was sponsored by the Swedish National Testing and Research Institute and the Swedish Council for Building Research.

REFERENCES

Kumaran, M.K. 1988. Comparison of simultaneous heat and moisture transport through glass-fiber and spray-cellulose insulations. *Journal of Thermal Insulation* 12 (July).

Sandberg, P.I. 1983. Thermal resistance of a wet mineral fibre insulation. Paper presented at the CIB W40 Leuven meeting.

Sandberg, P.I. 1991. Determination of the effects of moisture on the thermal transmissivity of cellulose fibre loose fill insulation. Paper presented at the CIB W4O meeting in Lund.