Fire resistance of circular steel columns filled with bar- reinforced concrete

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Moisture Diffusivity of Cellulose Insulation

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ABSTRACT: Test specimens of blown cellulose insulation were placed in contact with water to initiate an isothermal moisture intake process in which liquid water was allowed to enter freely against gravity into the specimens. The transient moisture distribution in the specimens was determined using the gamma-ray attenuation method over a period of 10 days. The results indicate that, as with most porous systems, the specimens first establish a characteristic water retention curve and then undergo a unique secondary moisture transport process. This paper presents the experimental data from the investigation. The data were used to derive information on the moisture diffusivity of cellulose insulation, in relation to the secondary moisture transport process undergone by the test specimens.

INTRODUCTION

A RECENT SURVEY CONDUCTED as part of the activities of an International Energy Agency Annex on "Heat, Air and Moisture Transport in Insulated Envelope Parts" has resulted in information on many computer models used by various building physicists to simulate long-term performance of various components of building envelopes, such as walls and roofs [1]. With the rapid advance in computer technology and better understanding of the physical principles that govern combined heat, air and moisture transport through building materials, these models will become powerful tools for optimizing the design of new as well as retrofitted building envelopes. For example, several applications of a computer model called TCCC2D (Transient, Coupled, Conduction and Convection in 2 Dimensions) reported during the past three years [2–5] demonstrate the role of computer models in building technology.

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As a rule, all computer models that can simulate combined heat, air and moisture transport depend on reliable information on a set of material properties that define the transport processes. Thermal conductivity, water vapour permeability and air permeability are well known examples of such properties. Standard test methods [6–9] are available for the determination of the above three properties.

Among the three transport processes, moisture transport is much more complex than the other two for reasons such as:

- moisture undergoes phase transitions within the building material
- building materials interact with moisture through sorption and interstitial condensation
- moisture can be transported either as liquid or as vapour at a significant rate

Also, the three transport processes interact in a rather complex way. Hence, the information that is necessary to reliably model moisture transport is understandably complex. Unfortunately, the existing information on moisture transport properties of building materials is grossly incomplete.

One of the moisture transport properties used in most of the computer models is called moisture diffusivity, denoted by D_w (m^2/s). It stems from the moisture transport equation:

$$J_m = -\varrho_o D_w \text{ grad } u \tag{1}$$

where

J_m = moisture flux [($kg/(m^2 \cdot s)$]
ϱ_o = density of dry building material (kg/m^3)
u = moisture content (kg/kg)

In Equation (1), moisture content is expressed as mass of moisture per unit mass of the dry material. If the moisture content is expressed as a concentration, c (kg/m^3), or mass of moisture per unit volume of the dry material, the transport equation becomes:

$$J_m = -D_w \text{ grad } c \tag{2}$$

If the transport is restricted to one-dimension, Equations (1) and (2) become:

$$J_m = -\varrho_o D_w (du/dx) \tag{3}$$

$$J_m = -D_w(dc/dx) \tag{4}$$

respectively, where x (m) is distance along the direction of transport.

The moisture diffusivity as defined in Equations (1) to (4) has a considerable practical significance because it is related to an easily realizable and measurable quantity viz. moisture concentration. At the same time, experience shows that it is often a complex function of the moisture concentration. The moisture concentration of building materials may vary from that of a perfectly dry state to a fully saturated state. For example, in a sample of a medium density ($\approx$ 50 kg/m^3) mineral fiber insulation, the moisture concentration may vary between 0 and 970 kg/m^3. It has been shown [10] that for such a material, the moisture diffusivity may change its value by two or three orders of magnitude as a function of the local moisture concentration. Hence, for any practical use of Equations (1) to (4), one has to know the moisture diffusivity for the entire range of moisture concentration between the dry and fully saturated state of the material. This is not an easy exercise, from an experimental point of view. Unfortunately, there is no way to determine this other than by experiments. Often such experiments are very slow and require very sophisticated measurement techniques. One such experiment, based on a method reported by Bruce and Klute [11] for the measurement of soil moisture diffusivity, was designed at the Institute for Research in construction for determining the moisture diffusivity of building materials. A brief description of the method is given below. Further details of the experimental and analytical procedures were reported earlier [12,13]. This paper reports the application of the method to determine the moisture diffusivity of cellulose insulation.

MATERIAL

The test specimens used for this investigation were prepared from a 58 cm $\times$ 58 cm $\times$ 13 cm slab of blown cellulose insulation, manufactured out of recycled newsprint. The bulk density of the insulation was 41 kg/m^3. The thermal conductivity of the slab was measured at 0.0386 W/(m·K), at a mean temperature of 24°C, according to ASTM method C518 [7].

EXPERIMENTAL PROCEDURE

The moisture transport process selected for determining the moisture diffusivity is schematically shown in Figure 1. Three rectangular test specimens are prepared from a sample of the building material of interest. The specimens are approximately 25 to 30 cm long and 5 cm wide. The thickness of

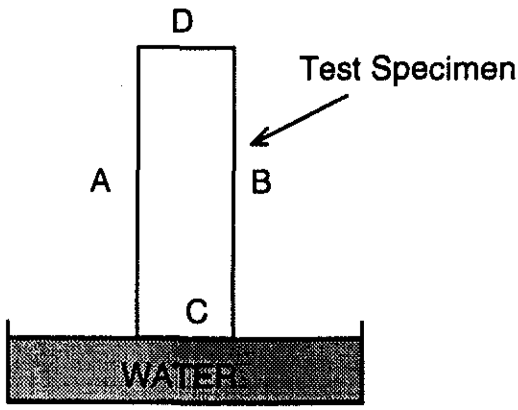

FIGURE 1. Schematic drawing of the moisture intake process. All four longitudinal surfaces, such as A and B, of the test specimen are coated with epoxy resin. Surface C is in contact with water and open. Surface D is open to the ambient air. The test specimens are scanned at successive 2-mm intervals [13], centrally on the specimen.

the specimen depends on the density of the material because, for a given thickness, denser materials attenuate the gamma radiation used in the measurements (see later) at a faster rate as it traverses through the material and reduces the number of gamma-photons available for subsequent analysis. For the gamma-ray equipment at the Institute for Research in Construction for dense materials such as brick and concrete the optimum thickness is approximately 1 to 2 cm. For wood, it is between 3 and 5 cm. For light insulating materials, 5 to 10 cm is an appropriate thickness. If the specimens are rigid, as most of the building materials are, they are dried for 2 to 3 days in an oven held at 50°C to attain constant mass, the thickness is accurately measured and then encapsulated using a water vapour resistant epoxy resin. The thickness of the epoxy coating is usually about 0.2 mm. The resin is allowed to set, and fresh surfaces are opened at the ends of the specimens by slicing the coating. They are then mounted vertically with the opened ends at the top and bottom in gamma-ray equipment [14]. The middle 1 cm across the 5 cm width of each specimen is then scanned from top to bottom at successive 2-mm layers to determine the gamma ray attenuation due to the measured thickness of the dry material.

After scanning the dry test specimen, the bottom surfaces of the test specimens are placed in contact with water in a shallow container (about 2 to 4 mm of the material will be below the water surface). The water level in the container is held at a constant height. The time at which the specimen and water surfaces meet is recorded as the zero time of the process. This initiates moisture transport into the test specimens. The test specimens are repeatedly scanned in the gamma-ray equipment during selected intervals. The change in the attenuation in each of the 2-mm layer, in relation to the corresponding dry scan, gives the moisture concentration in that layer [13]. The gamma-ray equipment also records the relative height of each layer scanned (the distance between the lowest point of the gamma scan and the specimen/water interface is measured manually within 1 mm to calculate the absolute height at which each other scan is made). As the measurements are repeated, they result in the transient moisture distribution in the specimens during the moisture intake process. The 25 to 30 cm length is selected such that the resultant water vapour transport across the specimen is negligible; this is a requirement for deriving the moisture diffusivity from the data on transient moisture distribution [13]. The ambient temperature and relative humidity are usually maintained at 20°C and 50%, respectively. The scanning continues until the moisture profile just becomes measurable (about 0.02 g/cm^3) at half way through the specimens. That means that the upper halves of the specimens still remain dry and minimise the vapour transport across the specimen.

ANALYTICAL PROCEDURE

The transient moisture distribution calculated from the gamma-ray attenuation measurements can be used to derive the moisture diffusivity through Boltzmann transformation of the data. The transient moisture distribution data give moisture concentration in the specimen as a function of time and height from the specimen/water interface.

An example of such a set of data obtained on a specimen of spruce, with the moisture transport in the longitudinal direction, is given in Figure 2. As the data in Figure 2 are subjected to the Boltzmann transformation:

$$z = x/\sqrt{t} \qquad (5)$$

where

z = Boltzmann factor (m/s$^{1/2}$)
x = distance from specimen/water interface (m) and
t = time (s),

the six separate curves collapse to form one single curve, shown in Figure 3. This can be called a "characteristic curve" for the test specimen that repre-

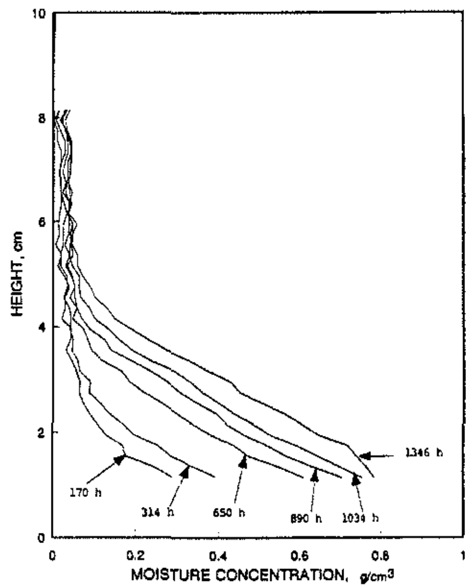

FIGURE 2. Moisture distribution in a test specimen of spruce, subjected to the process shown in Figure 1 in the longitudinal direction.

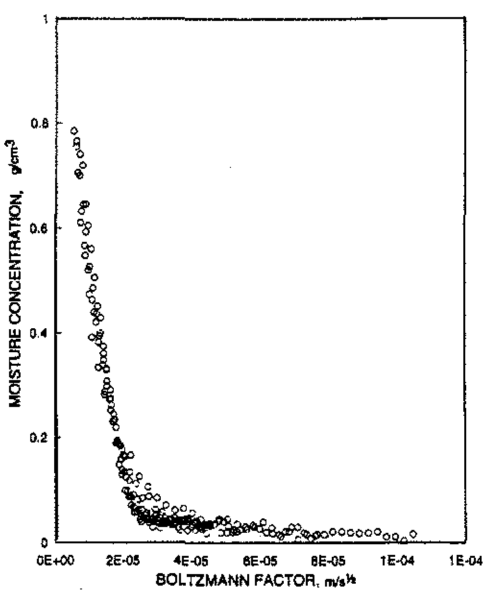

FIGURE 3. The data in Figure 2 were subjected to the Boltzmann Transformation, which resulted in a "characteristic curve" for the test specimen.

sents the transport of moisture and shows the moisture concentration in the specimen as a function of time and position. This characteristic curve can be analysed to derive $D_w(c)$, for any given value of c in Figure 3 [13] as:

$$D_w(c) = \frac{-1/2 \text{ (the area enclosed by the curve between moisture concentrations 0 and } c)}{\text{(the slope of the curve at } c)} \quad (6)$$

The integral and the slope (derivative) in Equation (6), as illustrated in Figure 4, can be generated as a function of c, either numerically or analytically, and $D_w(c)$ can be calculated. Figure 5 shows $D_w(c)$ for the specimen of spruce as obtained from the characteristic curve in Figure 3.

All building material specimens need not be as homogeneous as the one that corresponds to the data in Figure 2. For example, the data obtained on a specimen of gypsum board are shown in Figure 6. As the data on three test specimens prepared from one board are subjected to the Boltzmann transformation, Figure 7 results. The shape of the characteristic curve is not well-defined due to the large scatter of the data. Most of the scatter can be attributed to local differences in the rates of the liquid and vapour transport process due to the inhomogenity of the test specimens. Also, as the moisture concentration becomes smaller and smaller, the statistical variation in the incident gamma-ray [15] adds to the uncertainty. The gamma-ray attenuation method, though it gives an excellent picture of the overall transient moisture profile in the test specimen during the transport process, will not give the individual moisture concentrations better than 0.01 g/cm^3. However, because of the abundance of the data available, an appropriate averaging method can be developed to filter the effect of the inhomogenity. For example, as the data in Figure 7 are subjected to a "running average" calculation, as described below, Figure 8 results. It can now be seen that the shape of the characteristic curve is very well defined. Such a curve will give $D_w(c)$, as shown in Figure 9.

The running average is calculated through the following steps. The data on z vs c are sorted in an ascending (or descending) order with respect to z. Then the average values for both z and c are calculated for successive blocks of 11 data pairs. At every step, 10 entries from the previous step are retained by eliminating only the uppermost pair. Then a new pair is added at the bottom of the block to form the 11 entries for averaging. Due to the large number of measurements, the values for z do not change significantly in one block while the scatter in c is smoothened out (depending on the range of the scatter in a figure such as Figure 7, the number of data pairs in a block may vary between 6 to 11 for different building materials). This technique works remarkably well for all highly inhomogeneous materials.

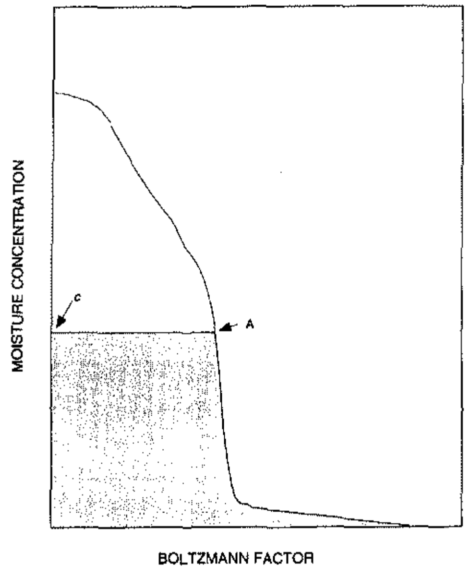

FIGURE 4. Graphic explanation for the relation (6) in the text. The diffusivity that corresponds to the moisture concentration c is calculated by using the shaded part as the area and the derivative of the "characteristic curve" at A as the slope.

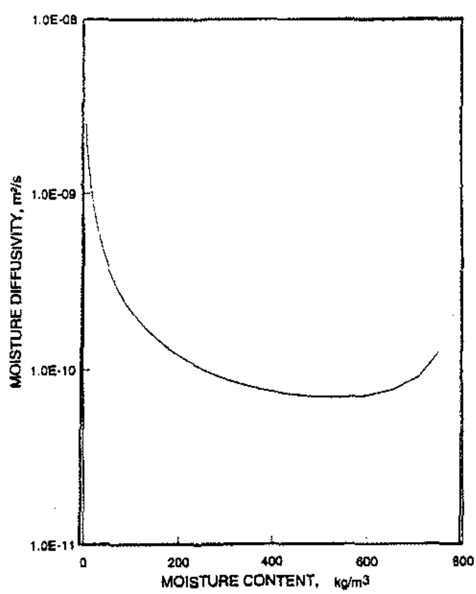

FIGURE 5. Moisture diffusivity of spruce according to the characteristic curve in Figure 3.

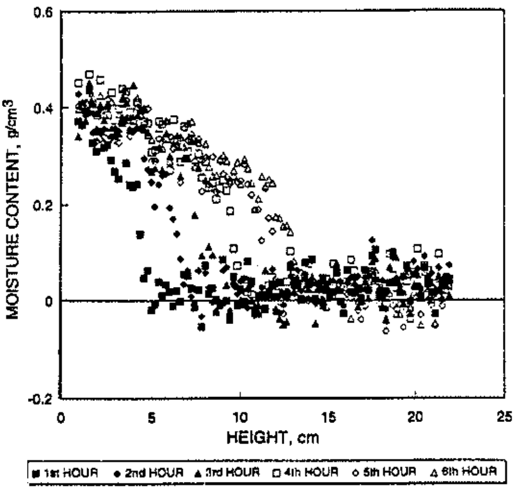

FIGURE 6. Moisture distribution in a test specimen of gypsum board during the process shown in Figure 1.

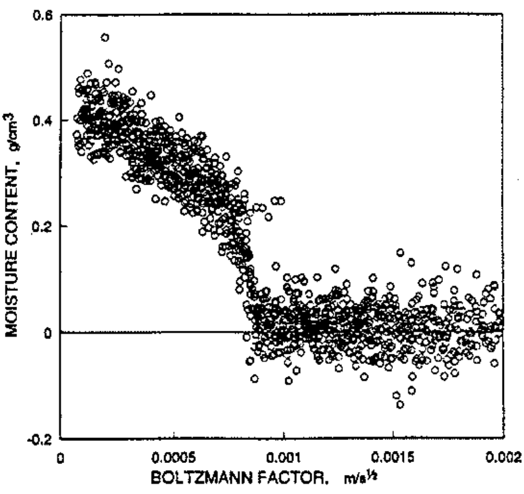

FIGURE 7. The data obtained from measurements on three test specimens of gypsum board were subjected to the Boltzmann transformation and resulted only in a crude "characteristic curve."

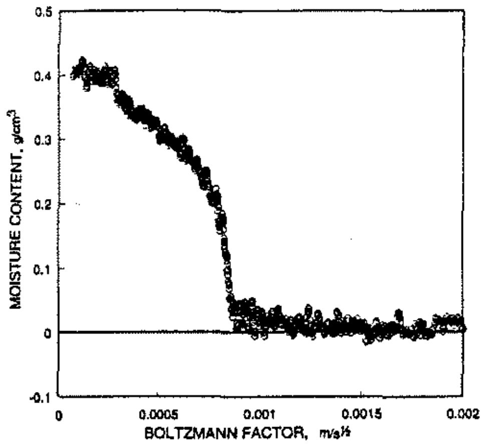

FIGURE 8. The data in Figure 7 were smoothed out by taking a running average, resulting in a well-defined characteristic curve for gypsum board.

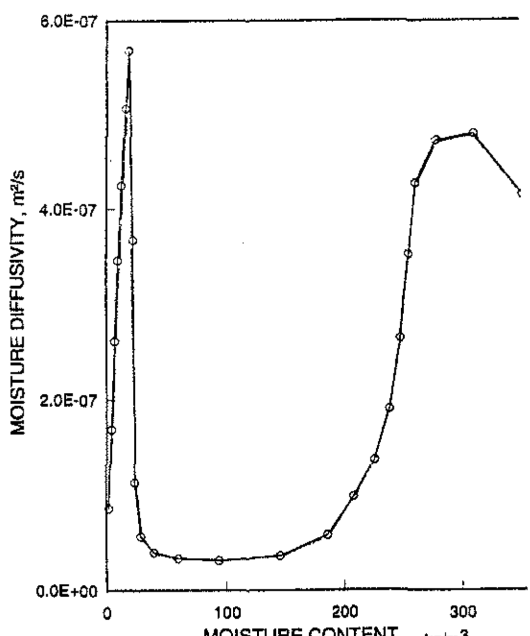

FIGURE 9. The moisture diffusivity of gypsum board that corresponds to the characteristic curve in Figure 8.

APPLICATION OF THE PROCEDURES TO CELLULOSE INSULATION

Five rectangular specimens, approximately 25 cm long with 5 cm × 5 cm cross sections, were cut from the sample of cellulose insulation. The specimens, being non-rigid, could not be encapsulated with the epoxy resin. Hence, the four longitudinal surfaces of each of three of the specimens were made water vapour tight by fitting them inside rectangular boxes with open ends; two of the opposite walls of the boxes were made out of 5-mm thick aluminum and the other two with 3-mm thick Plexiglas sheets. The Plexiglas walls faced the radiation source in the gamma-ray equipment. The cellulose particles were prevented from falling through the bottom, as clamped upright in the equipment, by fastening a copper mesh at the base of the box. The two specimens not fitted in the boxes were dried in an oven at 40°C (relative humidity of the air inside the oven ≈ 15%) for ten days and the changes in mass due to drying were determined to be 5.2% of the dry mass. This corresponds to ≈ 0.02 g/cm³ of moisture concentration as the initial value in all the test specimens. The three test specimens were then scanned in the gamma-ray equipment, as mentioned earlier, for the initial reference attenuation. Then the moisture transport process shown in Figure 1 was initiated and at various intervals the moisture profile in the three specimens was determined for 10 days. All three specimens gave similar results, as shown in Figure 10, where the average moisture concentration from the three specimens corresponding to the layer at the same height is plotted.

DISCUSSION

The results shown in Figure 10 are distinctly different from the results obtained on any other building material investigated in our laboratory. The results on spruce and gypsum board are two types of behaviour shown by building materials in general; the whole moisture profile moves through the specimens as the transport process progresses. In the case of cellulose, an initial profile, characteristic of the pore size distribution, was developed well within the first three hours (probably instantaneously) and most of this profile, the region AB in Figure 10, remained unchanged during the ten days of investigation. The point B corresponds to 3.7 cm from the specimen/water interface and 0.235 g/cm³ moisture concentration. The only change observed after the 3rd hour is above the 3.7 cm level, but the moisture concentration never exceeded the 0.235 g/cm³ value. This is quite unique. Hence, the moisture distribution data cannot be analyzed in the standard way to derive the moisture diffusivity.

An average value for the moisture diffusivity in the range of moisture concentration 0 to 0.235 g/m³ can be estimated using Equation (4) directly. The

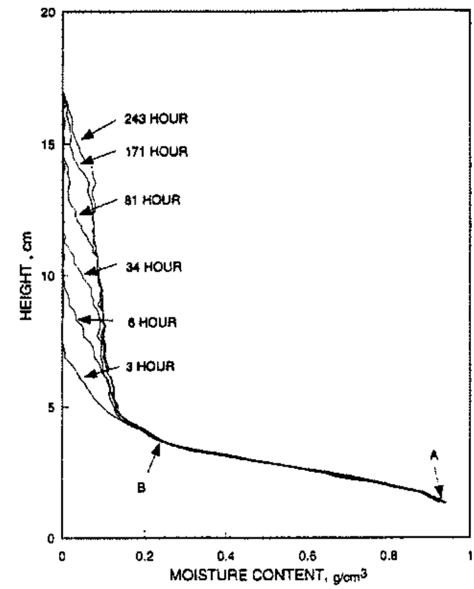

FIGURE 10. Moisture distribution in the cellulose insulation specimens subjected to the process shown in Figure 1; the data are averaged from three separate sets of measurements on three test specimens.

averaged moisture profiles in the specimens after 3 and 243 hours are shown in Figure 11. Therefore, during the 240 hours, the moisture concentration increased within the specimen by an amount that corresponds to the area enclosed by the two profiles. This is calculated by integrating the two curves to be equal to 21.9 g. Such integrations were gravimetrically verified earlier [16] and were always accurate within 1%. The moisture concentration at 16.9 cm, which corresponds to the highest point in the moisture profile after 243 h, is 0.02 g/cm^3. This is equivalent to a moisture concentration gradient of (0.235-0.02)/(16.9-3.7) ($g/cm^3/cm$). This has resulted in an average moisture flux of 21.9 g/(5 cm × 5 cm)/(240 × 3600) s = 1×10^{-5} $kg/m^2/s$. When these values for the moisture flux and moisture concentration gradient are substituted in Equation (4), an average moisture diffusivity of 6.2×10^{-9} m^2/s is obtained.

On the other hand, if we hypothesise that a secondary transport process in the specimens occurred only above the 3.7 cm level because below that nothing changed during the 240 h, an apparent specimen/water interface can be assumed at the 3.7 cm level. Subsequent Boltzmann transformations and calculations of a running average result in a characteristic curve for the sample of cellulose insulation, as shown in Figure 12. This curve can be well-

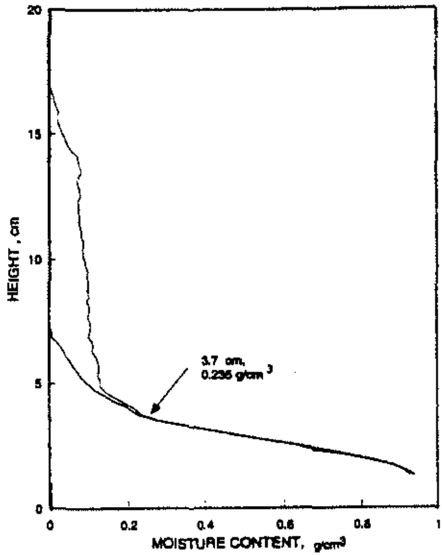

FIGURE 11. Change in the moisture distribution in the cellulose insulation test specimens between 3 and 243 h of moisture intake; the area enclosed by the two curves corresponds to the total moisture intake by each specimen in 240 h.

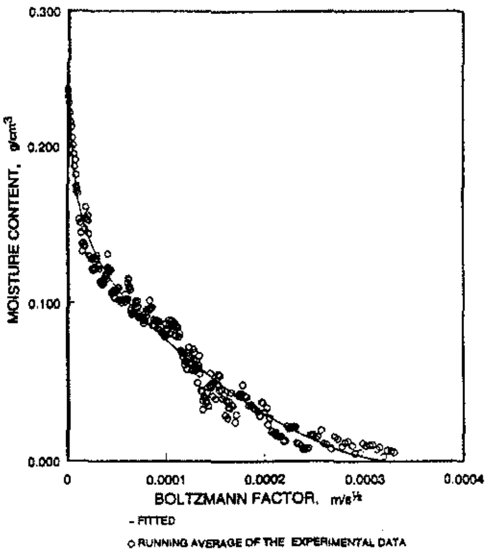

FIGURE 12. A characteristic curve for the cellulose insulation test specimens after Boltzmann transformation of the data in Figure 10; the running average method was used to smooth the data before curve fitting.

represented, as shown by the fitted data in Figure 12, by the analytical equation:

$$c' = A_0 + A_1 \cdot z^{0.5} + A_2 \cdot z + A_3 \cdot z^{1.5} + A_4 \cdot z^2 \tag{7}$$

where c' is the moisture concentration expressed in g/cm³. The numerical values for the coefficients are:

$A_0 = 0.2591$
$A_1 = -39.451$
$A_2 = 4168.2$
$A_3 = -268451$
$A_4 = 6341136$

Equation (7) can be used to numerically calculate the integral and derivative needed in Equation (6) for moisture concentrations between 0 and 0.253 g/cm³, and the corresponding $D_w(c)$ can then be calculated. These results are shown in Figure 13. It may be that the value for the moisture diffusivity approximately calculated, using Equation (4), is a reasonable estimate of the property.

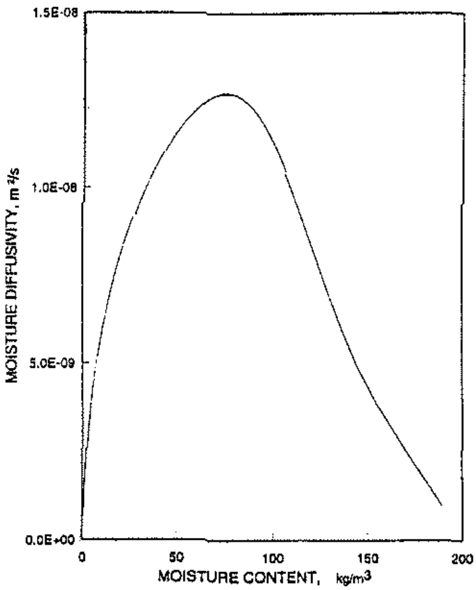

FIGURE 13. Moisture diffusivity of blown cellulose insulation from the characteristic curve in Figure 12.

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