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The Thermal Mass-Transfer Coefficient and Equilibrium Moisture Content of Insulating Materials

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ABSTRACT

Since moisture can diminish the thermal performance of an insulating system, it is necessary to understand the mechanisms involved in moisture behavior in insulating materials. Toward this end, this research project studied two parameters of hygroscopic moisture transfer: (1) the equilibrium moisture content (EMC) and (2) the thermogradient coefficient. EMC is dependent on the temperature and humidity of the surrounding air, and a plot of EMC versus humidity is known as an isotherm. Isotherms were determined for two densities of glass fiberboard 8.63 and 6.31 lb/ft^3 (138 and 101 kg/m^3) at 86°F (30°C) and 104°F (40°C). It was found that the EMC is greater for desorption than for sorption, decreases with an increase in temperature, and is greater for higher density fiberboard. The EMC for glass fiberboard is less than 1.5% by weight for temperatures above 86°F (30°C) and humidities below 90%. A sample of 8.63 lbs/ft^3 (138 kg/m^3) density glass fiberboard was subjected to a thermal gradient of 47F° (26C°). The results showed that the temperature versus moisture distribution of the sample was linear and that the thermogradient coefficient in the hygroscopic zone was on the order of 0.01 to 0.017 lbs/lbF° (0.02 to 0.03 kg/kgC°). The coefficient is dependent on the average moisture content, increasing with increasing moisture.

INTRODUCTION

With the increase in energy costs has come increased interest in conserving energy through the use of insulation. Over the last decade, a number of new insulations and insulation systems came into use. As a result of this expanded use and development, the need for research concerning factors affecting insulation systems has increased. One of the major factors is moisture. Moisture can have profound effect on the performance of insulation systems. Moisture intrusion into a system either during construction or during service, can lead to dimensional change, deterioration, increased water intrusion, and reduced thermal efficiency. A considerable amount of research is being done on the effects of moisture on the thermal conductivity of insulation.[1-6] But to design these systems properly, understanding the mechanisms involved in moisture migration is necessary.

Most insulation can be classified as porous(closed or open celled) or fibrous media. There has been extensive research on simultaneous heat transfer and mass transfer in porous media, but the vast majority of experimental work has been done on moist soils; very little has been done on fibrous materials and insulations in the hygroscopic zone.[7-10] The objective of this research is to study moisture behavior in insulating materials and to determine the parameters associated with this behavior. The initial work is being done in the hygroscopic zone of moisture content (0 to 5% by weight) where mass transfer occurs almost exclusively in the vapor phase. Some current theories suggest that

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vapor-phase transfer is the major factor in moisture transfer, even at high moisture contents.[11] At the low moisture content, the gravitational and capillary forces of mass transfer can be assumed to be negligible, allowing for the direct determination of the thermal mass-transfer coefficient. The equilibrium moisture content of insulation is useful in determining the boundary conditions for insulation exposed to air and in determining moisture potential. Using these results as a basis allows the study to be extended into higher moisture contents.

Equilibrium Moisture Content

Water can be retained in a substance by a number of different mechanisms - - chemical, adsorption, and mechanical.[12] When dealing with the equilibrium moisture in insulations, it is the moisture that adsorbs or condenses on the internal surfaces that is important. The EMC is the moisture content of a material attained when the water vapor pressure is in equilibrium with the liquid phase on the pore or fiber surface. The EMC is dependent on the temperature and humidity of the air and on the method by which equilibrium was attained (sorption or desorption) For each temperature, a graph of EMC versus air humidity (called an isotherm) can be obtained. The EMC isotherm for most materials is a S-shaped curve with a rapid change in EMC for relative humidities between 0 and 20% and above 80%. The curve can be broken into three regions: (1) in the 0 to 20% humidity range, a monolayer of water collects on the surface of the capillaries or fibers; (2) in the 30 to 80% humidity range, a polymolecular layer of water covers the surface; and (3) in the 80 to 100% humidity range, water condenses on the surface of the fibers or capillary walls.[13] In the 20 to 100% humidity range there can be a hysteresis effect. The EMC obtained for a particular humidity will be higher if equilibrium was reached by desorption than if reached by sorption. This effect is not totally understood but may be attributable to the fact that during desorption the interior surfaces of the material are already wetted, allowing a greater capillary surface area for polymolecular water formation.[14] A number of empirical relationships have been derived for estimating the EMC of building materials,[15-17] but little has been done to predict the EMC of insulating materials. Some data are available for glass wool,[18] so, to allow comparison, glass fiberboard was the initial test material. The EMC is essential in predicting moisture behavior because it establishes the boundary conditions between the air and the insulation and determines moisture potential.

Thermal Mass-Transfer Coefficient

Moisture, as either vapor or liquid, can move through porous and fibrous material by five main mechanisms:

1. Mass diffusion resulting from a concentration gradient (vapor pressure gradient)
2. Mass diffusion resulting from a temperature gradient
3. Liquid transfer resulting from capillary potential
4. Liquid transfer resulting from gravity
5. Vapor diffusion resulting from a pressure gradient.

In the hygroscopic zone (moisture content less than the maximum EMC), the third and fourth mechanisms are negligible for relative humidities below 80%. Thus, if the pressure is equalized, moisture transfer in most of the hygroscopic zone will occur only as a result of concentration and temperature gradients. The formula for this is

$$J = -\rho_s D (\nabla U + \delta \nabla T) \tag{1}$$

where

J = the mass flux, lb/ft^2s

ρ_S = the density of the porous material lb/ft^3

D = the mass diffusivity coefficient for moisture, ft^2/s

U = the moisture content, lb/lb

δ = the thermogradient coefficient, lb/lbF°

T = the temperature, °F

As is evident from the equation, the thermogradient coefficient is defined as the coefficient for moisture transfer resulting from a temperature gradient. If the system is closed (Jm = 0) and transfer is one dimensional, the TMTC can be expressed as a ratio of distributions:

$$\delta = - (\Delta U/ \Delta X)/ (\Delta T/ \Delta X) = - \Delta U/ \Delta T \qquad (2)$$

where

X = the distance in the direction of flow, ft. Thus, the coefficient can be determined by measuring the moisture and temperature distribution in a sealed test sample. This is the approach used in this project.

Some work has been done in measuring the thermogradient coefficient, but primarily that work is for moist soils and building materials. In the experimental work done by Luikov on soils and building materials, the coefficient usually reached a maximum in the low-moisture-content range (10 to 30% weight) and decreased to zero as the maximum moisture content was approached.[19-20] Eckert and Faghri used a computer model to describe thermal moisture behavior,[21] and Philip and de Vries developed a theory to explain discordant experimental results for thermogradient coefficients.[22] But very little experimental data are available on the coefficients of insulating materials.

In most studies of moisture migration in porous materials, the thermal gradient contribution has been neglected. When compared to normal mass transfer, this assumption is correct for most systems. But with a closed system such as a built-up roof (BUR), the thermal gradient effect can become predominant. In a BUR, the insulation is trapped between the membrane and a vapor barrier or the structural deck, and moisture transfer out of the system is restricted. The thermal gradient imposed by the diurnal cycle causes moisture to be redistributed through the insulation continually. As was shown by Powell and Robinson, this moisture distribution has a profound effect upon the thermal performance of the insulation.[23] Simulating this behavior requires more thermogradient coefficient data.

EXPERIMENTAL DESIGN AND TEST PROCEDURE

Since two different physical properties were studied, the work plan consisted of two separate parts: (1) the equilibrium moisture content and (2) the thermal mass-transfer experiments. Initially the insulating materials tested fiberboard of two densities.

Equilibrium Moisture Content (EMC)

To determine their EMC of the insulating materials, the two samples were placed in an airtight test chamber in which air of constant temperature and humidity was circulated (Fig. 1). Air passed through filters and was sent through one or both of two lines. In one line, the air's moisture content is unaltered, in the other, the air passes through a water bath to raise its humidity. Combining the unaltered air with the moist air provided a wide range of humidities. A humidity probe in the test chamber was used to monitor humidity. A constant air temperature was maintained by a proportional feedback controller, and a thermistor in the test chamber supplied the feedback signal to the controller. The controller in turn adjusted the current to a tape heater. Since heating air reduces its relative humidity, the water bath was heated to just below the desired temperature, allowing humidities approaching 80% to be reached in tests. For humidities above 80%, the samples were placed in a sealed chamber containing a salt solution in equilibrium with the air at the desired humidity. The range tested was 0 to 90% relative humidity at (86° and 104°F (30° and 40°C) temperature. The humidity probe is accurate to 1%, and the controller system can maintain a temperature to within 1.8F° (1C°). The test was started at 15% relative humidity, increased to maximum humidity, and then decreased to 15%. The two samples were removed periodically and weighed ($\pm$ 1 X 10^{-6} lb) immediately to determine moist weights and the point at which steady state is reached. The samples were oven dried at 221°F (105°C) for 1 hour to dry the samples out completely. Since the test uses moving air, the time needed to reach steady state was considerably less than that needed with static air. The sorption isotherm can differ from that of desorption, so tests were run with increasing and decreasing humidities. The difference between dry density, void fraction, percent age of bonding material, and fiber size distribution were measured for each sample and taken into consideration. The bonding material is a phenolic compound. The specifications on the two samples are:

	Sample 1	Sample 2
Density, lb/ft^3	8.63	6.31
Void fraction	0.937	0.954
Mean fiber size, μm	10.3	11.6
Surface area to volume, ft^{-1}	7.46 X 10^3	4.88 X 10^3
Percent bonding, wt. %	11.2	10.7
Sample size, in.	1 1/8 X 1 3/8 X 2 5/8	1 1/2 X 1 1/2 X 2

Thermal Mass Transfer

To measure the thermogradient (thermal mass-transfer) coefficient for moisture in insulation, the test sample was sliced into five 1/4 inch thick layers, moistened by exposure to air of constant humidity, and placed perpendicular to the moisture flow in an airtight test chamber (Fig. 2). This method is similar to that used by Thomas, et al.[24] Extra insulation was placed around the edges of each slice to separate the test section from the walls. The slices were arranged slightly offset to prevent the formation of a channel for vapor transfer. Thermocouples were inserted into each layer to measure the temperature profile. The sample was then subjected to a thermal gradient by maintaining the top and bottom surfaces of the sample at constant temperatures over a number of days. A method similar to that used in the EMC experiment was used to maintain the surface temperatures. Water passing through a water-tight container was the heating/cooling medium, and 1/4 inch copper plates were placed on the top and the bottom of the sample to ensure uniform temperature. Proportional controllers having thermistor feedback regulated the heat output of the line heaters. The sides of the chamber were heavily insulated to prevent lateral migration and heat losses. Once steady state had been reached, each layer was immediately placed in a plastic bag (to prevent moisture loss to air) and was then weighed, dried, and reweighed to determine moisture content.

Steady state was reached by running the test for a number of days, taking the data, and then restarting the experiment from time zero. The number of days per run was increased until the results were unchanged from run to run. Collectively, the slices provided the moisture distribution of the entire sample. Since the thermogradient coefficient is a function of moisture and temperature distribution, the value of the coefficient was then calculated using Eq 2. To test for gravity effects, some of the experiments will be repeated with the thermal gradient of 47F° (26 C°). The sample material was the same as sample 1 in the EMC experiment.

RESULTS AND DISCUSSION

The results consist of equilibrium moisture curves for two densities of glass fiberboard at two temperatures (Figs. 3-8) and the temperature versus moisture distribution for a sample of fiberboard under a thermal gradient (Fig. 9). In Figs. 3 and 4 the EMC curves for 8.63 and 6.31/lb ft^3 (138 and 101 kg/m^3)-density glass fiberboard at 86°F (30°C) are shown. For relative humidities above 95% for 86°F (30°C) and above 85% for 104°F (40°C), the EMC increased dramatically (the EMC at 104°F (40°C) and 96% is above 2.5% by weight) making measurements in this region very difficult to obtain since a slight change in humidity produces a sharp change in EMC. The sorption and desorption curves in the humidity range of 10 to 95% differ appreciably. The reasons for this hysteresis were discussed earlier. The same effect can be seen in Fig. 5 for 8.63 lb/ft^3 for (138 kg/m^3) fiberboard at 104°F (40°C) though it is more pronounced. More tests at different temperatures are necessary to determine whether temperature has a significant effect on the magnitude of the hysteresis. Preliminary results at 50°F (10°C) support the trend of decreasing hysteresis with decreasing temperature. The EMC values for the glass fiberboards agree well with values shown by Luikov for glass wool.[25] Figures 6 and 7 show the differences between the sorption curves of the two fiberboard densities at 86 and 104°F (30 and 40°C), respectively. The higher density material has the higher moisture content by weight, because of the increased surface area available for moisture adsorption and condensation; in the higher density material, the surface area to volume ratio is 54% greater. In Fig. 8, the sorption EMC for the 8.63 lb/ft^3 (138 $kg.m^3$)-density material is shown to be greater at 86°F (30°C) than at 104°F (40°C). There is no theory that directly addresses this effect, but the reduction in EMC with an increase in temperature may be the result of the decrease in surface tension with an increase in temperature. As the surface tension decreases, the capillary pressure decreases.

Figure 9 refers to the thermal mass-transfer experiment and shows the temperature-versus-moisture distribution for the 8.63 lb/ft^3 (138 kg/m^3) glass fiberboard at two average moisture contents (0.96% and 1.13% by weight). The sample was exposed to a temperature gradient of 47F°(26C°) with a water temperature of 108°F (42°C) on the top and 61°F (16°C) on the bottom. The temperatures shown in Fig. 9 are at the midpoint of each slice, and the total sample thickness was 1 1/2 inches (34 mm). As mentioned earlier, in a closed system the thermogradient coefficient is equal to the change in moisture content divided by the change in temperature through the sample (Eq 2). This is simply the slope of each line in Fig. 9. The thermogradient coefficient is 0.011 lb/lb F° (0.020 kg/kg°C), for an average moisture content of 0.96% and 0.016 lb/lb F° (0.0288 kg/kg C°) for 1.13%. Though coefficient values are available for some soils and building materials, they are much higher moisture contents, and the differences in structure would preclude any comparison. It has been shown that the coefficient is a strong function of moisture content (as indicated by the results) but not of temperature,[26] making it hard to obtain an exact value for the coefficient because the moisture content can change with position. A number of tests are still needed to determine how sensitive the coefficient is to average moisture content, localized moisture content, average temperature, and thermal gradient, as well as to physical properties.

CONCLUSIONS

1. The EMC curves for glass fiberboard show a hysteresis between the sorption and desorption curves, with the desorption values being higher.

2. The EMC curve for fiberboard decreases with an increase in temperature, perhaps as a result of decreased surface tension.

3. The EMC curve is higher for higher density fiberboard because

of the greater available surface area.

4. The EMC for fiberboard is less than 1.5% by weight for temperatures above 86°F (30°C) and humidities below 90%.

5. The thermogradient coefficient for glass fiberboard (138 kg/m^3) in the hygroscopic zone is on the order of 0.01 to 0.017 lb/lbF° (0.02 to 0.03 kg/kgC°) and is a function of moisture content.

6. The techniques outlined in this paper are valid, but considerably more data are needed to determine the factors affecting the thermogradient coefficient.

NOMENCLATURE

D = mass diffusivity coefficient for moisture, ft^2/s

J = mass flux, lb/ft^2

T = temperature, °F

U = moisture content, lb/lb

X = the distance through the material, ft

δ = the thermogradient coefficient, lb/lbF°

ρ_s = the density of the porous material, lb/ft^3

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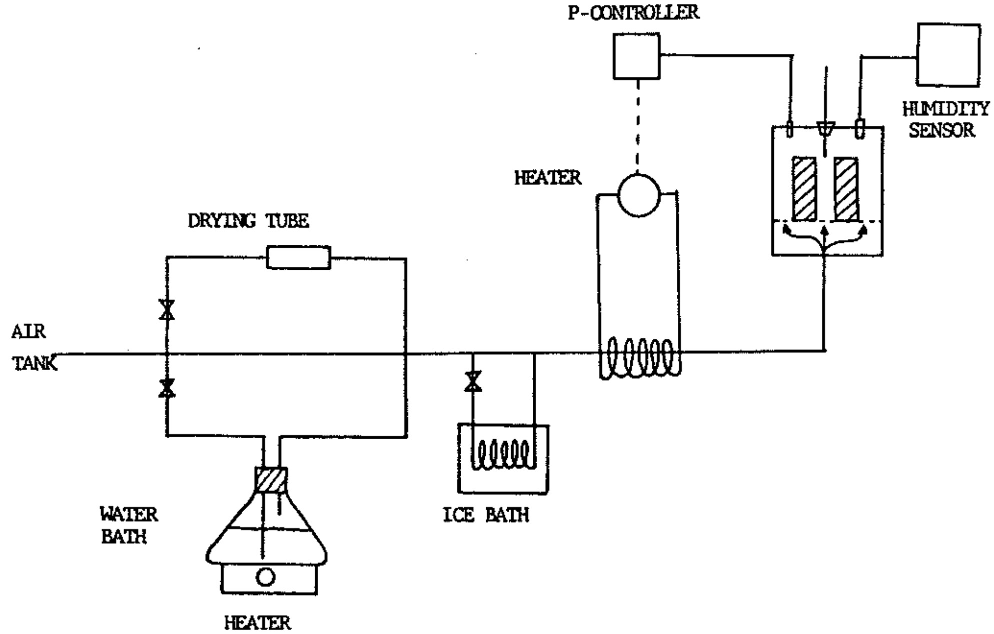

Figure 1. The equilibrium moisture content experimental design

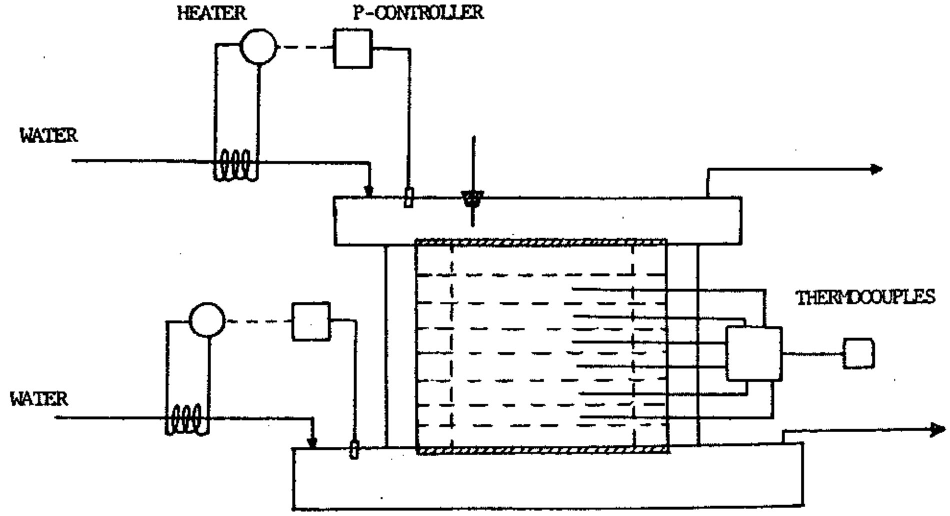

Figure 2. The thermal mass-transfer experimental design

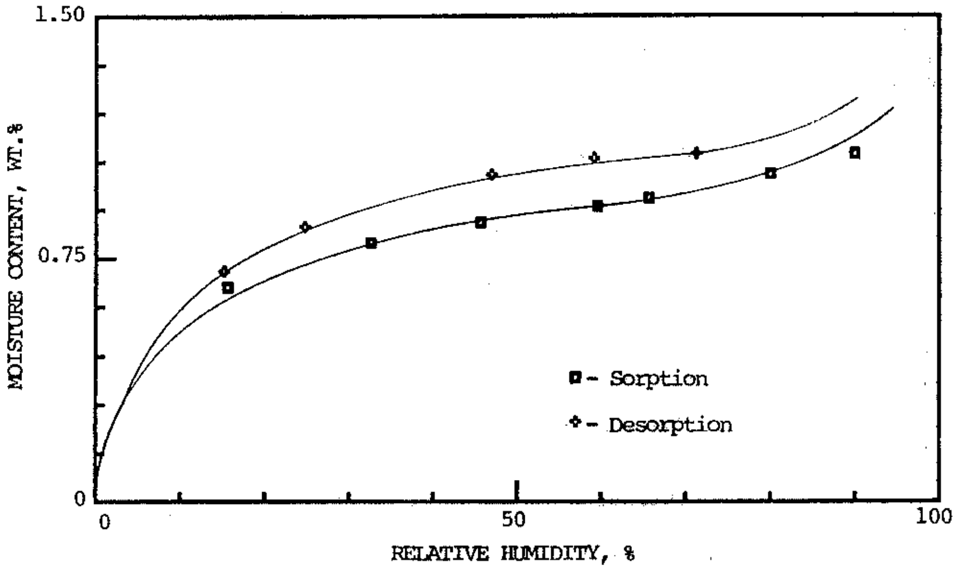

Figure 3. The EMC Curve for 138 kg/m^3 density glass fiberboard at 30^{o}C

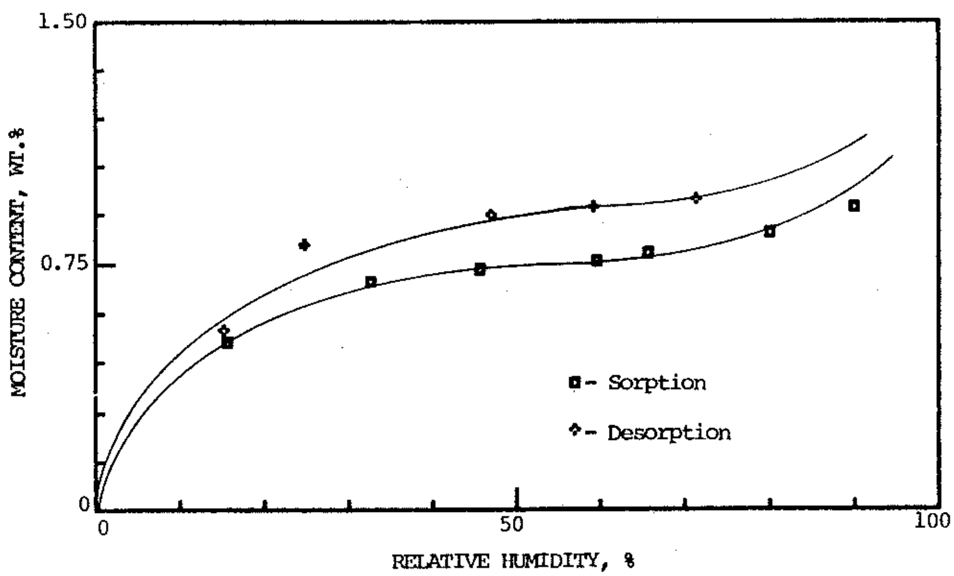

Figure 4. The EMC Curve for 101 kg/m^3 density glass fiberboard at 30^{o}C

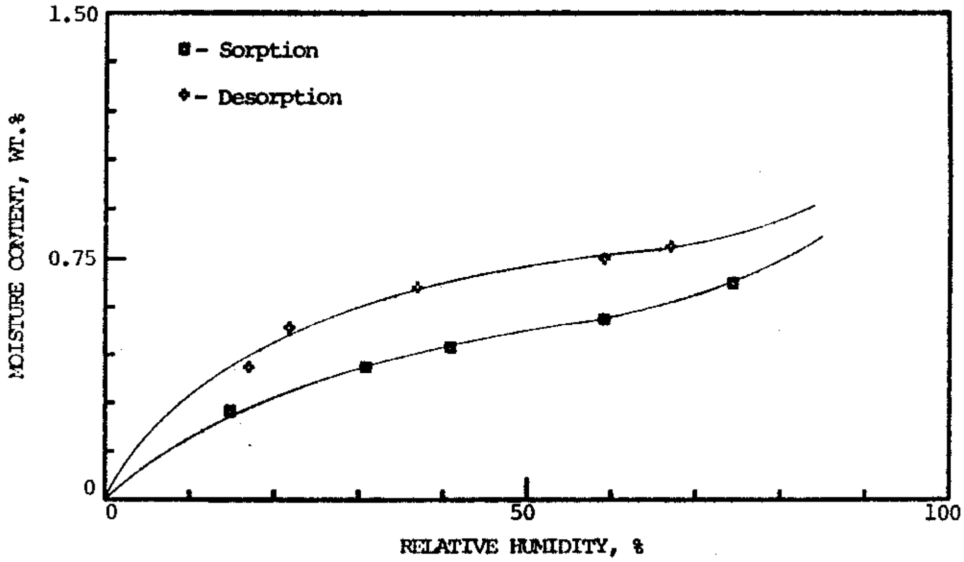

Figure 5. The EMC Curve for 138 kg/m^3 density glass fiberboard at 40°C

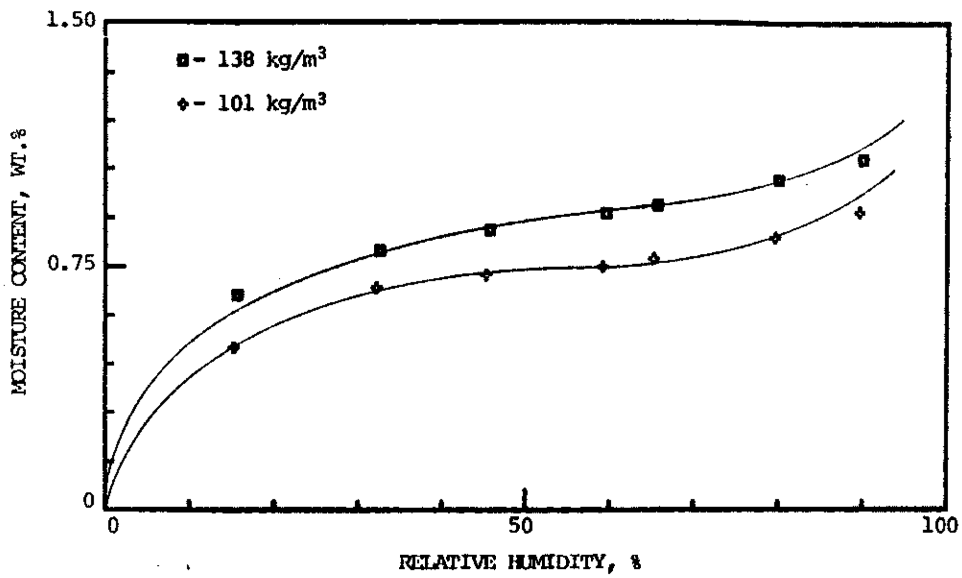

Figure 6. The EMC Sorption Curves for 138 and 101 kg/m^3 density glass fiberboard at 30°C

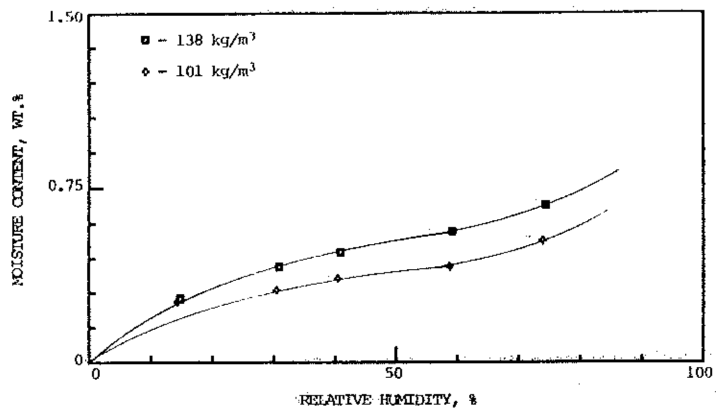

Figure 7. The EMC Sorption Curves for 138 and 101 kg/m^3 density glass fiberboard at 40^{O}C

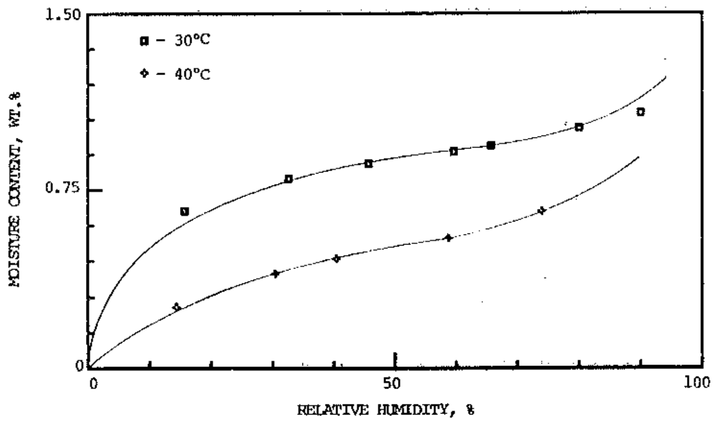

Figure 8. The EMC Sorption Curves for 138 kg/m^3 density glass fiberboard at 30^{O}C and 40^{O}C

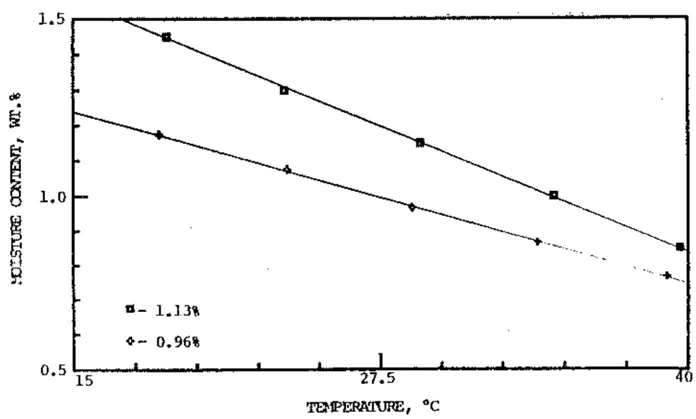

Figure 9. The temperature versus moisture distribution through a sample of 138 kg/m^3 density glass fiberboard with thickness of 30 mm, two average moisture contests, and thermal gradient of 26^{O}C