Walldry—A Computer Model that Simulates Moisture Migration through Wood Frame Walls—Comparison to Field Data

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ABSTRACT

WALLDRY simulates heat, air, and moisture flow through wood frame walls using a finite difference method. A description of the model was presented in the third conference in this series (Schuyler et al, 1987). This paper presents examples of runs performed to compare the model to full-scale field and laboratory results. Further results are presented, showing the development of design strategies to ensure adequate wall performance in resisting moisture damage.

INTRODUCTION

The purpose of the research program that has resulted in this computer simulation was to create a design tool that could be used to determine the adequacy of wall designs in resisting moisture problems. The current steady-state models can be used to grade the performance of wall systems. However, they cannot be used to determine whether or not a wall system is adequate for its environment. This takes a more detailed model that can react to the actual conditions that the wall will encounter in its service life. WALLDRY has been created to respond to external weather conditions including temperature, relative humidity (RH), wind direction, wind speed, and solar conditions.

There has been a long history of moisture problems in the Canadian maritimes. The two major reasons for the problems appear to be high moisture loading from the inside and a lack of good drying weather to rid the wall of the moisture. As a companion project, a full-scale test hut monitoring program (CMHC/CHBA 1988) was initiated to investigate the performance of various wall systems in a maritime climate. The program used three test huts: one each in St. John's, Newfoundland; Halifax, Nova Scotia; and Fredericton, New Brunswick. The measurements from these huts from March 1986 to March 1987 comprise a set of data that has been used to validate the computer model.

Prior to this validation using field data, a laboratory validation was performed. Two wall samples were installed in an atmospheric test chamber and monitored over a drying period of several days. The walls were initially conditioned to a high moisture content, and the impressed conditions were such that a positive drying potential was created. The wall samples and imposed conditions were simulated by the computer model for comparison with the laboratory measurements.

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Before beginning the validation, the model was modified to make it more usable to the uninitiated user. In addition to this, the ability of the model to handle air leakage was enhanced. After the validation was performed, using the test hut data, the program was then used to investigate the effects of sheathing performance, vapor barrier permeance, and air leakage on wall moisture content using the same weather data used in the validation.

MODEL DESCRIPTION

General

In the interests of economy, the basic heat, moisture, and air movement mechanisms were analyzed at the beginning of the project to determine if the model could be reduced from a general three-dimensional model to something more compact. It was determined that a two-dimensional section through the wall could be modeled that would illustrate all the basic properties necessary. The conditions could be varied in such a model to represent any vertical section of a wall.

The basic reasoning that allowed this simplification was that a wall is essentially a layered system where lateral gradients are low compared to gradients through the wall. The only area where this does not work well is airflow. By handling the air circulation within the wall as a lateral flow model in conjunction with a series of sources and sinks, this limitation was overcome.

The model was further simplified with what we consider little loss in generality by dividing the two-dimensional wall section into a vertical stack of one-dimensional horizontal heat and moisture flow wall model elements joined by a one-dimensional vertical airflow model in the air space between the siding and the sheathing. This physical arrangement within the wall is used with two scalar field models (temperature and moisture content) and the vector field model of air velocity in the air space behind the siding.

The model lacks a detailed model of airflow in the insulation cavity. Instead, airflow paths must be defined as inputs to determine the effects of air leakage on performance. Convection currents within the insulation cavity are ignored.

The Heat Transfer Model

To accommodate any number of heat sources and sinks in the wall (e.g., latent heat gains or losses at any element), and to accommodate the transport of heat in the air space, a series of simultaneous equations were set up to model the heat balance through all elements from inside to outside while accounting for latent heat and sensible heat storage effects of every element. Thus, quantities of latent heat calculated in the moisture flow model can be treated as a heat source/sink in the thermal model. The vertical transport of heat in the air space is treated by the one-dimensional heat transfer model as an air change heat loss or gain at the air space element.

The general information of the energy balance of each element is an expression of continuity of energy:

Net heat transfer through the element by conduction	=	Heat gain + heat losses by other means

Among the "heat gains and losses" treated are:

-- radiant heat (e.g., for the siding element or exterior air film)
-- latent heat (from evaporation and condensation melting and freezing of water)
-- sensible heat (stored in the element by a change in temperature from the previous hour)
-- air change heat transport in the air space.

These heat gains and losses are calculated for each element for each hour. There is one equation for each element. The equations, when written out, form a "banded" matrix of heat loss factors multiplied by element temperatures on the left side of the matrix. These equal the net heat generation or less on the right-hand side. The generalized expression is solved by a standard matrix solution of simultaneous equations.

Airflow Model

The mass flows and pressure drops are calculated sequentially, using the principle of continuity of mass and a generalized form of the friction pressure drop term. The continuity of mass is of the first order, and the pressure drop terms are represented as polynomials with experimental terms $n = 0.5$ and $n = 1$. The weighting of each of the two terms is determined by the Reynolds number of the flow and the surface characteristics of the flow path.

The weighting has been assigned, based on our own experiments, to determine the actual flow conditions for a number of siding types and air space thicknesses.

Moisture Transfer Model

We have assumed that the hourly time step must be preserved in the moisture transport model to make the system integrations between thermal, moisture, and airflow models manageable. Relative to the size of an hour interval, the moisture content in the elements can be assumed to be constant over that hour. The moisture properties of these elements can thus be used as fixed boundary conditions to the flow calculations applied to adjacent air elements over one hour.

Again relative to the hour calculation interval, those elements involving air (e.g., the moving air space) can be assumed to have reached steady-state conditions with their boundaries very early within the hour. The problem is thus reduced to calculating equilibrium moisture conditions of air relative to its boundaries given a set of temperatures and boundary conditions for the hour. The total rate of moisture taken/deposited in the boundary (water film, ice, wood) is the quantity of water that flows as a result of those equilibrium conditions.

The transport of vapor from the boundaries to the air space is treated as a pure vapor pressure equation. The absolute mass of the water is substituted for the vapor pressure using the perfect gas law.

Inputs

The running of the program requires a "wall" file, which describes the wall in terms of materials, thicknesses, opening dimensions, etc. Table 1 is an example of the wall file. The first line of Table 1 is simply a title that gives a brief description of the wall. The reference to the Halifax south wall indicates that the preprocessed hourly weather data is for a south-facing wall located in Halifax. The appropriate data file is specified within the table. A prompt in the program asks if weather data are to be used. If no, it asks for a set of fixed weather conditions and ignores the weather data file named in the table.

TABLE 1
WALL CONSTRUCTION FIELD

HALIFAX SOUTH WALL: M Air Space, M Opening at the Top, 3 iterations

NUMBER OF ELEMENTS UP THE WALL (N) AND LAYERS THROUGH THE WALL (N) 9,12

SELECTION OF MATERIALS FOR EACH LAYER (SEE PROPERTIES DATABASE FOR #)1,15,16,16,16,4,5,6,7,8,9

THICKNESS OF EACH LAYER (M0
1,0.002,0.005,0.005,0.002,0.02,0.002,0.0005,0.005,0.095,1

WALL HEIGHT (m), WALL LENGTH (m)
6,9

SIDING GAP CHARACTERISTICS: WIDTH (m), FLOW PATH LENGTH (m), FLOW EXPONENT 0.0020,0.02,0.8

AIR SPACE CHARACTERISTICS: NUMBER OF THE LAYER, FLOW EXPONENT
7,0.8

WIND PRESSURE COEFFICIENTS FROM BOTTOM TO TOP (9 elements + UPPER-MOST OPENING)
0.1,0.2,0.3,0.4,0.5,0.5,0.4,0.3,0.2,0.1

WALL ORIENTATION (DEGREES FROM NORTH):N:360,E:90,S:180,W:270 180

NAME OF THE WEATHER DATA FILE (INCLUDE THE DRIVE SPEC: e.g. A:D WEATHER.SOU) A:HAL.SOU

MOISTURE SOURCE STRENGTH IN kg/hr, & LOCATION:LAYER # & ELEMENT NUMBER 0,7,3

SIMULATION START AND END (DAY OF YEAR)1,365

NUMBER OF ITERATIONS BETWEEN THE 3 MAJOR SUB MODELS 3

The hourly weather data file includes temperatures, relative humidity, wind speed, wind direction, and direct and diffuse solar radiation. The file is preprocessed to represent a particular wall orientation. Cloud cover and atmospheric transmittance data are used to compute direct and diffuse solar radiation. At present, the weather data are available for the year 1974 at the following Canadian locations: St. John's, NF; Montreal, PQ; Toronto, ON; Windsor, ON; Winnipeg, MB; Calgary, AB; Revelstoke, BC; Vancouver, BC; and Whitehorse, YT.

Material properties used in the model include thermal resistivity, density, heat capacity, and diffusion resistivity. All properties are handbook values subject to modification by the user.

VALIDATION

Comparison with Laboratory Test Wall

General. The intended purpose of the validation was to assess the model's ability to predict wetting and drying behavior of a wall under controlled by arbitrary test conditions. The task was performed by comparing model-simulated moisture contents in the sheathing and studs with corresponding measured values on a full-size wall segment constructed in the laboratory. Although the materials and fabrication procedure were typical of walls constructed in the field, the care taken in erecting the laboratory wall was probably greater. Also, the weather conditions imposed on this test wall in the laboratory were not intended to be, nor were they, representative of conditions expected in the field.

Validation Procedure. The following steps were performed as part of the validation procedure:

(i) Characteristics of the test wall were entered into the wall specifications file of the WALLDRY program.

(ii) The weather file required by WALLDRY that normally contains hour-by-hour weather data for a specific location (Halifax, for instance) was replaced by a file of measured conditions (temperature, wind speed, RH) on the exterior side of the test wall. This file was generated using data measured over the course of the test. Two additional hourly inputs not normally available in a weather file - indoor temperature and indoor RH - were also included in this file.

(iii) The initial moisture contents of the sheathing and studs were specified, in the wall specification file of step (i), to be those measured at the start of the test. The siding moisture content was not measured and was therefore assumed to be the same moisture content as that of the sheathing at the start of the test.

Comparison of Computer Simulations and Test Results. The two test specimens were 4 ft wide, 8 ft high, and of standard wood frame construction. Starting from the interior surface, they consisted of 1/2-in. gypsum board, 2 by 4 studs on 16-in. centers with 31/2-in. glass fiber batt insulation, 1/2-in. wood fiber sheathing, and horizontal wood fiber siding. The siding was spaced 3/16-in. from the sheathing surface with vertical furring strips. This is the 5 mm air space referred to in the figures. One specimen had sheathing paper while the other did not. The temperature and humidity conditions imposed on the wall are shown in Figure 1. For economic reasons, the walls were not exposed to solar gains, but an arbitrary pressure pattern was impressed upon the exterior surface using a fan and baffle arrangement. Pressure difference across the wall was not monitored since the air barrier was virtually perfect and the average pressure difference was kept small. The pressure distribution over the outside face of the wall was a steady-state condition achieved by forcing air vertically up the wall past several flow resistance baffles.

Measurement of moisture content was accomplished using a resistance moisture meter. Moisture pins were inserted in wood members in several locations and monitored hourly during the test period.

Sheathing Drying

The simulated drying rate of the sheathing is compared with measured values on Figure 2 for the case with sheathing paper. The drying rate was uniform from the bottom of the wall to the top, and this uniformity was also observed in the test data. The simulated bottom, mid-height, and top drying curves are so close that they do not require differentiation.

Figure 2 indicates that there is a mismatch between the model and the specimen in both drying rate and the equilibrium moisture level.

The underpredicted equilibrium moisture content could be due to:

-- actual moisture retention curves of the wood and sheathing being different than published values,

-- the calibration of the moisture sensors being high by about 1.5 moisture content points, i.e., moisture values were incorrectly adjusted for the wood species, or

-- instrument accuracy degrading for low-moisture-content measurements.

Any one of these requires an adjustment before comparisons of the drying rates can be made fairly. No conclusions can be drawn as to which source of error would be most dominant in this case, but it is the opinion of the authors that the last is most likely. This adjustment was made in the second comparison.

The mismatch in the rate of drying for this case with sheathing paper is even more clearly defined when the shift in moisture content is made as shown in Figure 3.

It was postulated that the slower simulated drying rate may be due to:

-- modeled value of sheathing paper permeance too low,

-- not enough simulated airflow behind the siding, or

-- air circulation around the sheathing paper may be reducing its effect.

The uniformity of the drying rate of the sheathing suggests that the simulated airflow behind the siding is adequate. This points to either low permeance in the model or possible airflow behind the paper in the test. Examination of the test results for the half of the wall without sheathing paper (Figure 4) shows virtually identical drying rate as the half with sheathing paper. This suggests that air could have been short-circuiting the building paper. The good agreement between actual and simulated results, shown in Figure 5, further supports the conclusion that the sheathing paper was ineffective.

Drying of the Studs

Since the drying of the studs is in series with the drying of the sheathing, it would be expected that the simulated drying rates of the studs would also be slower than tested in the case with sheathing paper. This is in fact the case, as shown in Figure 5, although the discrepancy was smaller than the one indicated for the sheathing.

Again, by comparison of the test results with and without sheathing paper (Figures 5 and 6) we see that the sheathing paper must have been short-circuited, since the measured results for the two cases are nearly identical. The simulation without the paper agrees very well with the "no-paper" results of Figure 6.

Comparison with Field Study

Methodology. As mentioned in the introduction, the field tests were performed at three maritime locations. For this validation, the Halifax location was arbitrarily chosen. The input information for the Halifax test hut wall sections was obtained from the descriptions of the test huts found in Reference 2. A schematic of the wall samples is shown in Figure 7. The monitoring methods are described in CMHC/CHBA (1988).

Halifax weather data for the period in which the test hut was monitored were formatted into the hourly weather data format used by the WALLDRY computer program. The weather file covered a one-year period starting in March 1986. With this weather file the weather occurring during the actual testing could be used for the computer simulation.

The Halifax test hut consisted of a single-room structure measuring 26 ft by 36 ft, the longer sides facing north and south. Along the north and south sides eight test panels measuring 4 ft wide by 8 ft high were fitted side by side, with identical wall panel systems on each of the north and south walls. The orientation of the normal lines to the north and south walls were 9° and 189°, respectively, clockwise from true north.

Halifax test hut panels 1 and 5 were modeled with the WALLDRY computer program. These panels were surfaced with vinyl siding on the outside and were surfaced on the inside with gypsum board. The Panel 1 wall section used waferboard sheathing and Panel 5 used an extruded polystyrene foam sheathing.

The north- and south-facing wall sections designated Panel 1 and the south-facing Panel 5 wall section were modeled with WALLDRY. By specifying the wall orientation the computer program takes into account differences in the amount of solar radiation falling on the wall. In addition to this, different rates of air movement beneath the exterior siding occur for walls with different orientations to the wind.

The initial moisture content levels of the wood studs and sheathing and the initial test dates were taken directly from the graphs of corrected moisture content given in Appendices 2 and 4 of CMHC/CHBA (1988). On inspection of the moisture content data derived from the test hut, it was found that extremely large, unexplained swings in moisture content would occur whenever the moisture content was above about 40%. It was concluded that no moisture content data above this value could be considered trustworthy. The starting time of the comparison and the initial values of moisture content were therefore adjusted to match the point where all further readings were below 40%.

The stud moisture content in each panel of the Halifax test hut was monitored at two positions on the stud-- one near the top of the stud and the other near the bottom. One limitation of the program is that only one uniform initial moisture content value over each of the program's nine vertical stud elements can be set. Since we were forced to discard test hut data from the beginning of the monitoring period, the moisture content was no longer uniform at the beginning of the comparison. Therefore, two test runs were performed-- one setting the initial moisture content of the stud elements to the value given by the lower moisture sensor, and a second setting the initial moisture content to that given by the upper moisture sensor.

Results. The drying curves of the wood studs and sheathing from the WALLDRY program runs are compared graphically with the field study drying curves in Figures 8, 9, and 10.

Figure 8 shows the drying curves for Panel 1 (waferboard sheathing) on the south side of the test hut. The initial moisture contents of the top and bottom of the studs were 37% and 20%, respectively. The graph shows that the bottom of the wood studs only dried to a moisture content of 17%. The top of the studs dried from a moisture content of 37% to the same moisture content as the bottom of the wood stud. Over the test period most of the drying in the Panel 1 wood stud occurred at the top of the wood stud.

In comparison to this the WALLDRY drying curves for the top and bottom of the wood stud bracket the results of the actual test case. The drying curves bracket the field test results because the program is limited to setting one initial moisture content throughout the entire wood stud. This was a modification made to the program to reduce the complexity of the inputs. The WALLDRY test case for the top of the wood stud dried more slowly than the field test because by setting the initial moisture content in the wood stud to 37% the amount of moisture in the lower portion of the wood stud was overstated. This excess moisture in the lower portion of the wood stud resulted in the wood stud drying more slowly than the actual test hut wood stud. The opposite is true for the case run for the bottom of the wood stud with the initial moisture content throughout the wood stud set at 20%.

Figure 9 compares the drying curves for Panel 1 on the north face of the test hut. The initial moisture contents for the top and bottom portions of the wood stud are 41%. The figure shows that the predicted value of the moisture content in the wood studs essentially lies between the actual values for the top and bottom of the stud. The moisture content in the entire wood stud is well predicted in this case, as it matches the average of the top and bottom values given by the test hut over the duration of the test period.

Figure 10 compares the drying curves for the south exposure Panel 5 (extruded polystyrene foam sheathing). The initial moisture contents for the top and bottom of the wood studs are 39% and 41%, respectively.

It should be noted that no effort was made to modify the performance of the model to improve agreement between field data and predictions. The parameters used as inputs to represent the wall samples were those present in the program's data base. The WALLDRY program models the trends of the drying process in the wood studs very well, as evidenced by Figures 8, 9, and 10.

PERFORMANCE COMPARISON

Methodology

Since the validations show very good agreement between predicted and measured values, it is appropriate to use the model to investigate the effects of various varying wall parameters.

The Panel 5 construction, used in the validation, was used as the standard wall section. Individual components of this wall section were varied in the model for each of the comparison test cases. This wall section consisted of: vinyl siding, sheathing paper, 1.5 in. of extruded polystyrene foam sheathing, 2 in. by 4 in. studs with glass fiber batt insulation in the stud space, an internal vapor barrier, and 0.5 in. of gypsum board. A cross section of this wall panel is shown in Figure 7. The only change to the validation wall panel was to add an air leakage path that could conduct air from the indoor space through the insulated cavity space to outdoors or vice versa. The Halifax test hut panels were well sealed to the indoors, tighter than a wall section used in normal construction practice.

Two of the variables in the wall section that are believed to have a significant impact on the moisture movement in the wall system are permeability of the sheathing layer and permeability of the internal vapor barrier. For this reason, tests on the standard wall section were performed with two higher values of permeability specified for the foam sheathing. The standard foam sheathing had a permeance of 40 ng/Pa.s.m2. In one test case the permeance was set at 80 ng/Pa.s.m2 and in another test case it was set at 100 ng/Pa.s.m2. In a fourth test case the standard wall section's internal vapor barrier was removed. This only affected the permeance of the inner wall since air leakage was modeled separately. For comparative purposes the standard wall section's foam sheathing was replaced with 3/8-in. waterboard sheathing in one case, and expanded polystyrene foam (beadboard) sheathing in another test case. Altogether six test runs were completed.

Each of the wall sections was simulated for one year. The moisture content in the wood studs was set to an initial moisture content of 35%. A moisture level of 35% was chosen to represent the moisture content values expected from the stockyards of building supply dealers. The same Halifax meteorological data used in the validation were used for each of the six test cases.

Results

Figure 11 shows the drying curves for the six test runs. The drying curves show the average moisture content of the entire wood stud for the one-year duration of testing. Five of the six curves show similar drying curves. The wood studs in these five wall sections dry most quickly from March to June and then dry at a slower rate during the summer (June to August). After the summer, these wall sections begin to dry at a faster rate. The only exception to this is the standard wall section without an internal vapor barrier.

This wall section dries at almost a constant rate from the 35% moisture content level to the 22% level. Around the 22% level the studs in this wall section begin to dry more slowly. The no-vapor-barrier case is the fastest-drying wall section during the summer months and the slowest in the winter. This is to be expected.

We also note that none of the drying curves actually reverse, even with no vapor barrier. The curves represent the average moisture content of the studs over their entire height. In the lower half of the stud the curve does reverse during the summer months. Since these curves represent the average of the entire stud, the reaction time is much slower than the surface layer of the stud. Figure 12 illustrates that a reversal does take place in the surface layer of the stud. The figure depicts moisture content at three vertical locations up the wall. Location 1 is at the bottom and 5 is at mid-height. The change in moisture content, even in the surface layer, is fairly slow, taking more than a month to rise or fall.

The sheathing moisture content, shown in Figure 13, is in marked contrast to the studs. The same three vertical positions are shown in this figure (i.e., 1, 2, and 5). Location 2 is directly across from the hole. One can see that is responds rapidly, loading up with moisture during the winter. It reaches the limiting value of 120% by weight in December of the second winter. At that point the model allows water to drain from the element to the element below.

Element 1 responds much more slowly than Element 2 because it is not in direct contact with the leak. It does follow the same general trend as Element 2. Note that the element slowly rises during the second winter until drainage of water from the element above dries it to saturation.

Element 5 shows a response to the wetting and drying influences, with a steady trend upward. It appears that it too would eventually reach saturation and start to drain.

The differences between the stud and the sheathing performance point out an extremely important aspect of wall performance that has been borne out many times in field investigations. <u>The studs do not pick up moisture directly in quantities sufficient to cause problems. Problem conditions occur when air leakage loads the sheathing, causing water to drain to the sill plate and, through wicking, enter the studs.</u> Both of these aspects (i.e., heavy wetting found directly opposite an air leak, and wet sill plate and bottom of stud) have been documented in past field studies.

CONCLUSIONS

WALLDRY has been shown to reproduce measured moisture content data from both laboratory and field investigations. It combines heat, moisture, and air transport to provide realistic conditions in wood frame walls. As a design tool, it allows a researcher to investigate the effects of various parameters, including geographic location, on the ability of a wall system to dry and remain dry.

The ability of the model to realistically reproduce air leakage and drainage effects allows a designer much greater understanding of the wall's performance as it pertains to durability.

REFERENCES

Schuyler, G.; Swinton, M.; and Smith, B. 1987. "A model of the moisture balance in the outer portion of wood frame walls". Presented to "Thermal Performance of Exterior Envelopes III," Fort Worth, TX.

CMHC/CHBA. 1988. Task force on moisture problems in Atlantic Canada. Canadian Mortgage and Housing Corporation, Canadian Home Builders' Association.

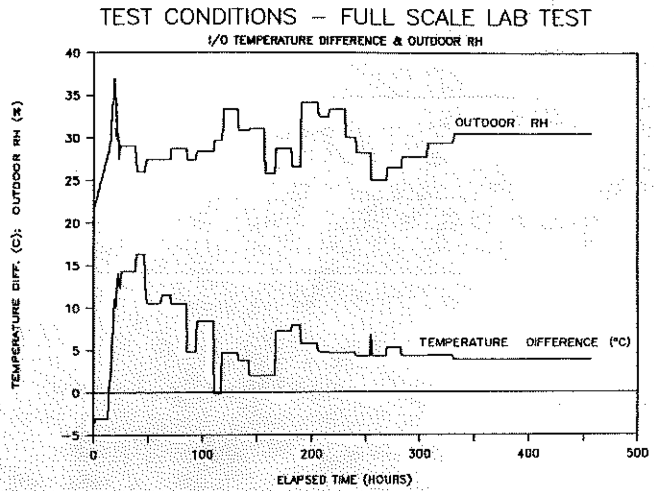

Figure 1. *Laboratory test conditions*

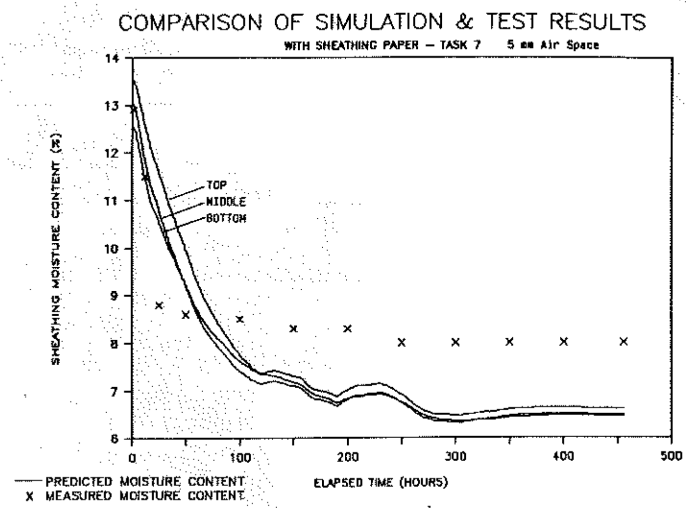

Figure 2. *Initial comparison of sheathing results with sheathing paper*

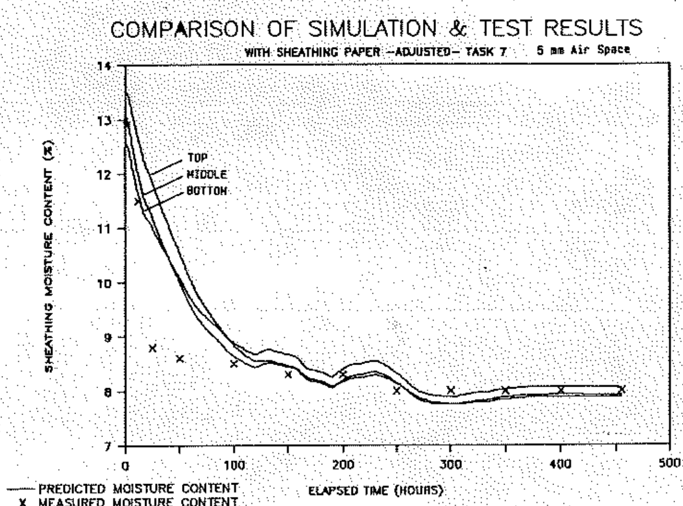

Figure 3. *Adjusted comparison with sheathing paper*

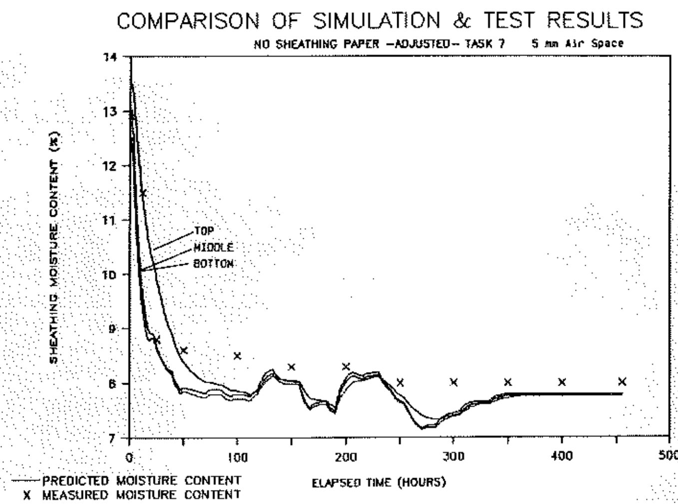

Figure 4. *Adjusted comparison without sheathing paper*

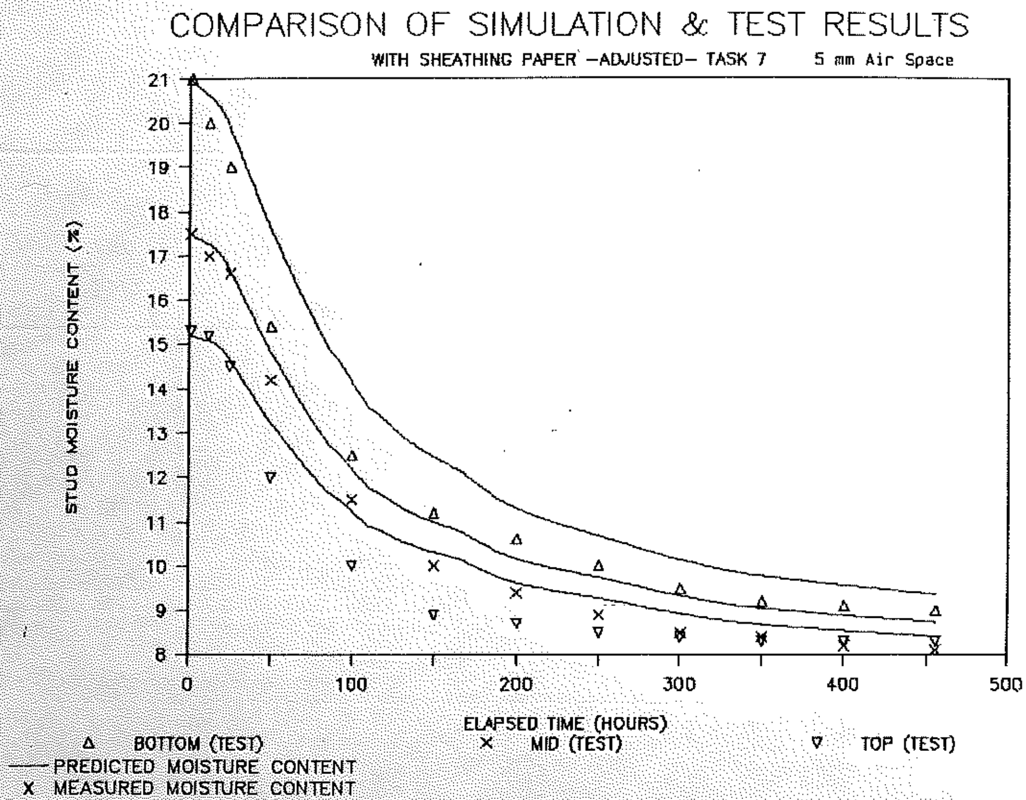

Figure 5. Stud moisture content adjusted comparison with sheathing paper

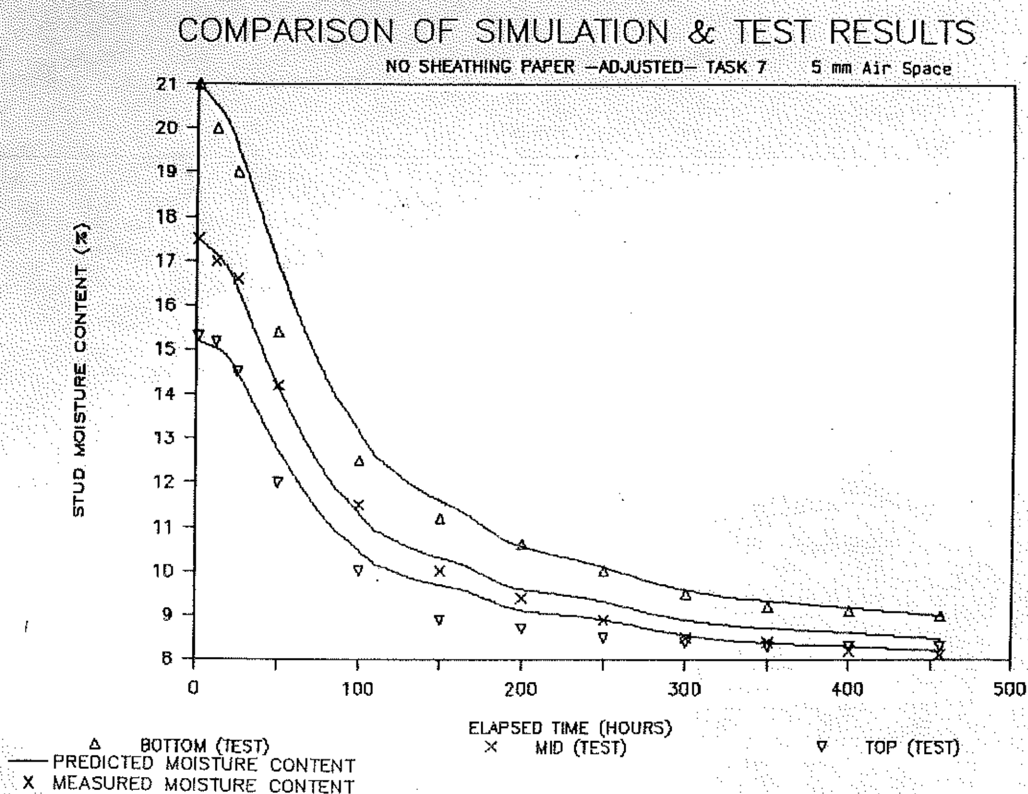

Figure 6. Stud moisture content adjusted comparison without sheathing paper

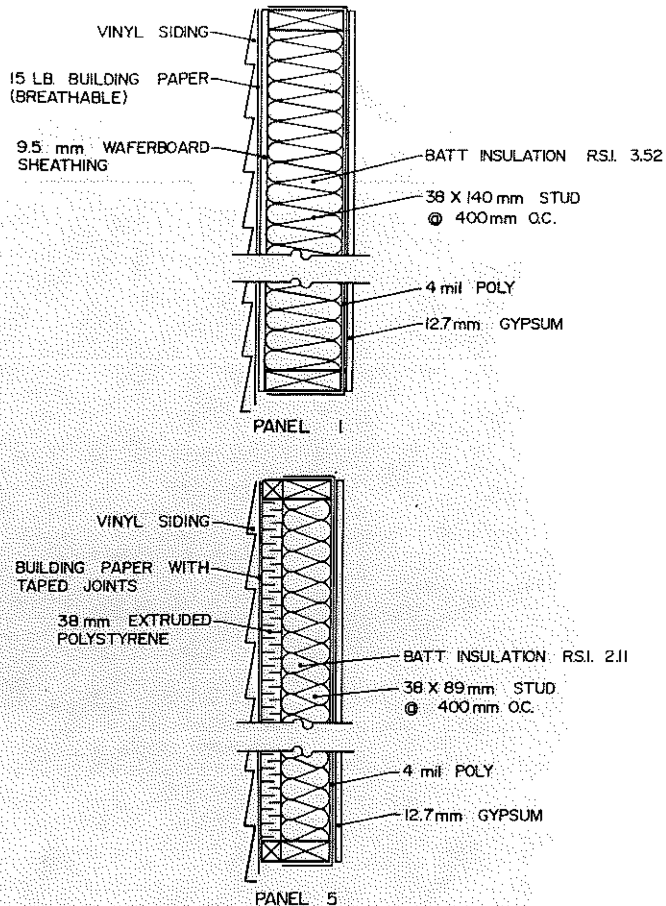

Figure 7. *Cross section of test panels*

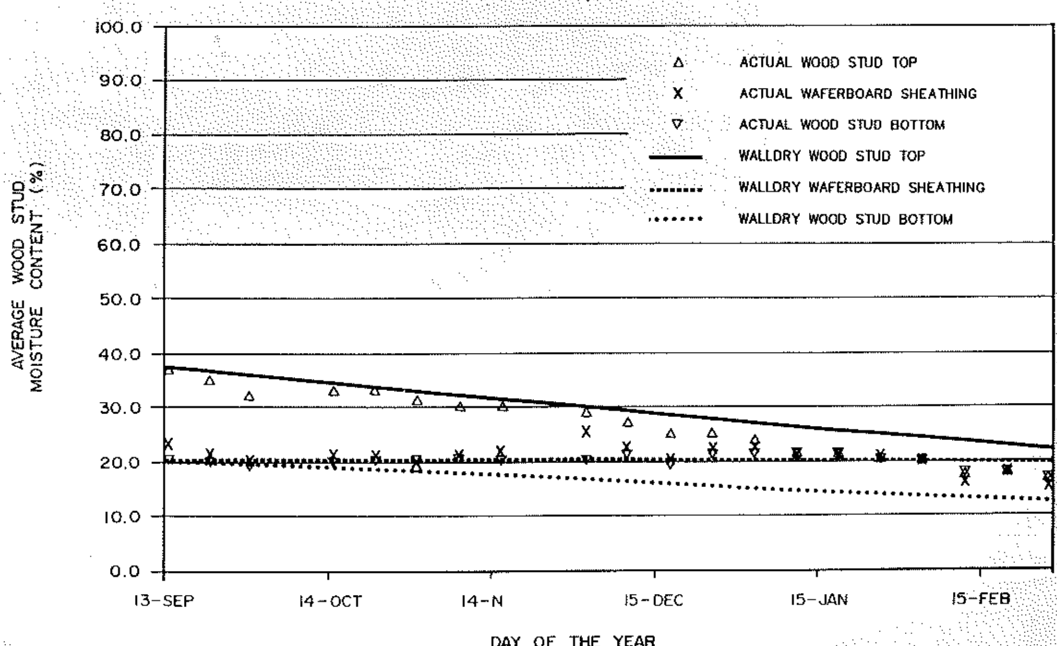

Figure 8. *Field data comparison panel 1—south*

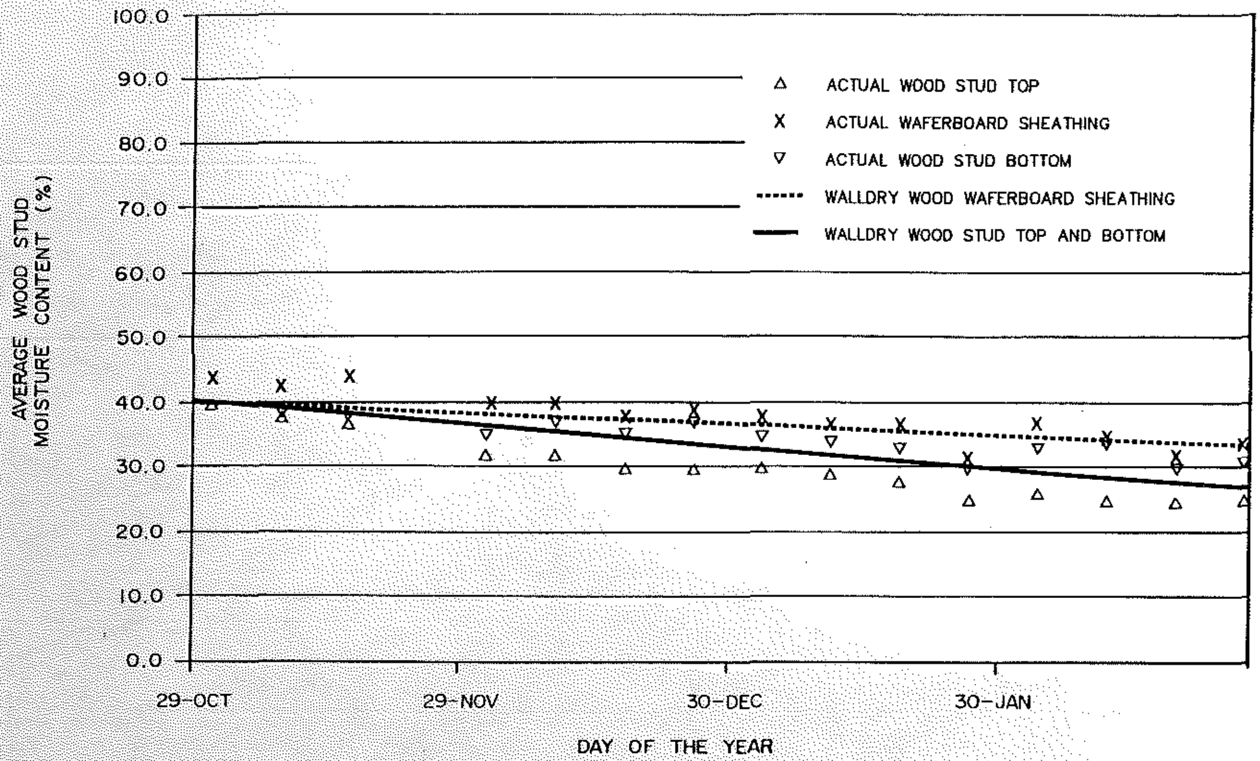

Figure 9. Field data comparison panel 1—north

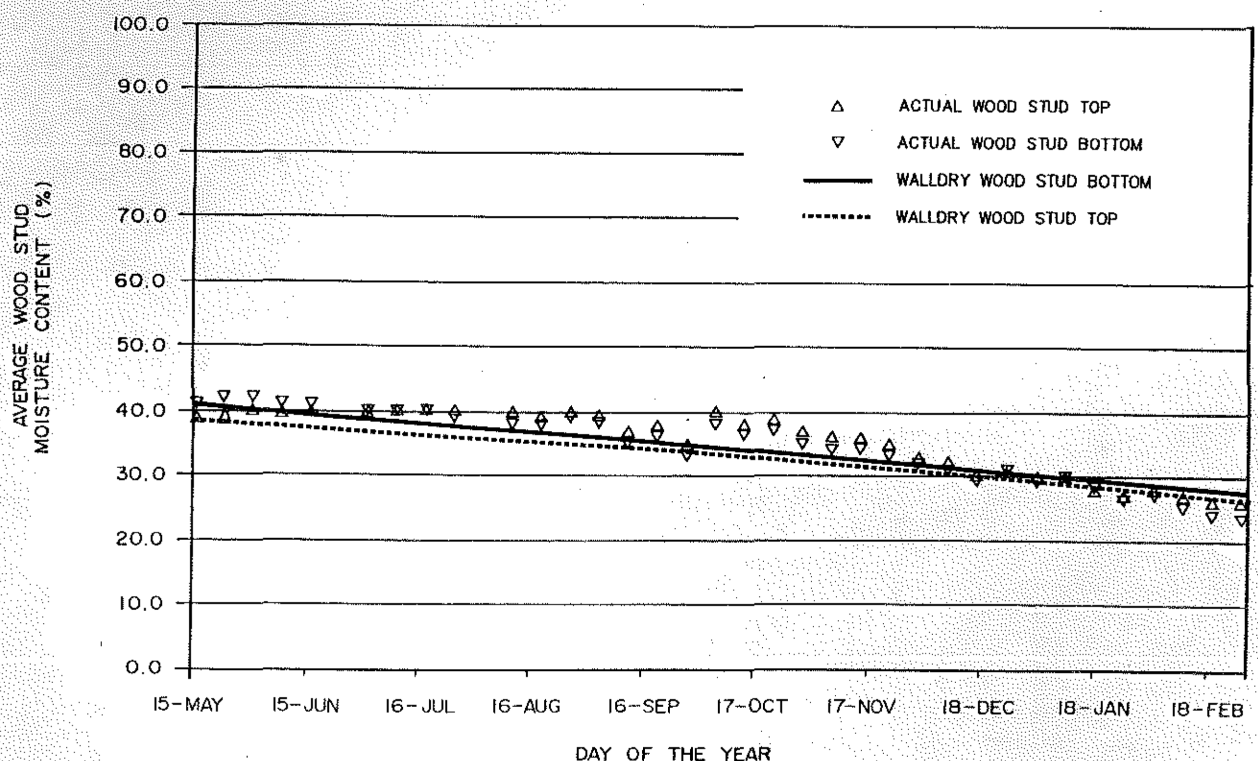

Figure 10. Field data comparison panel 5—south

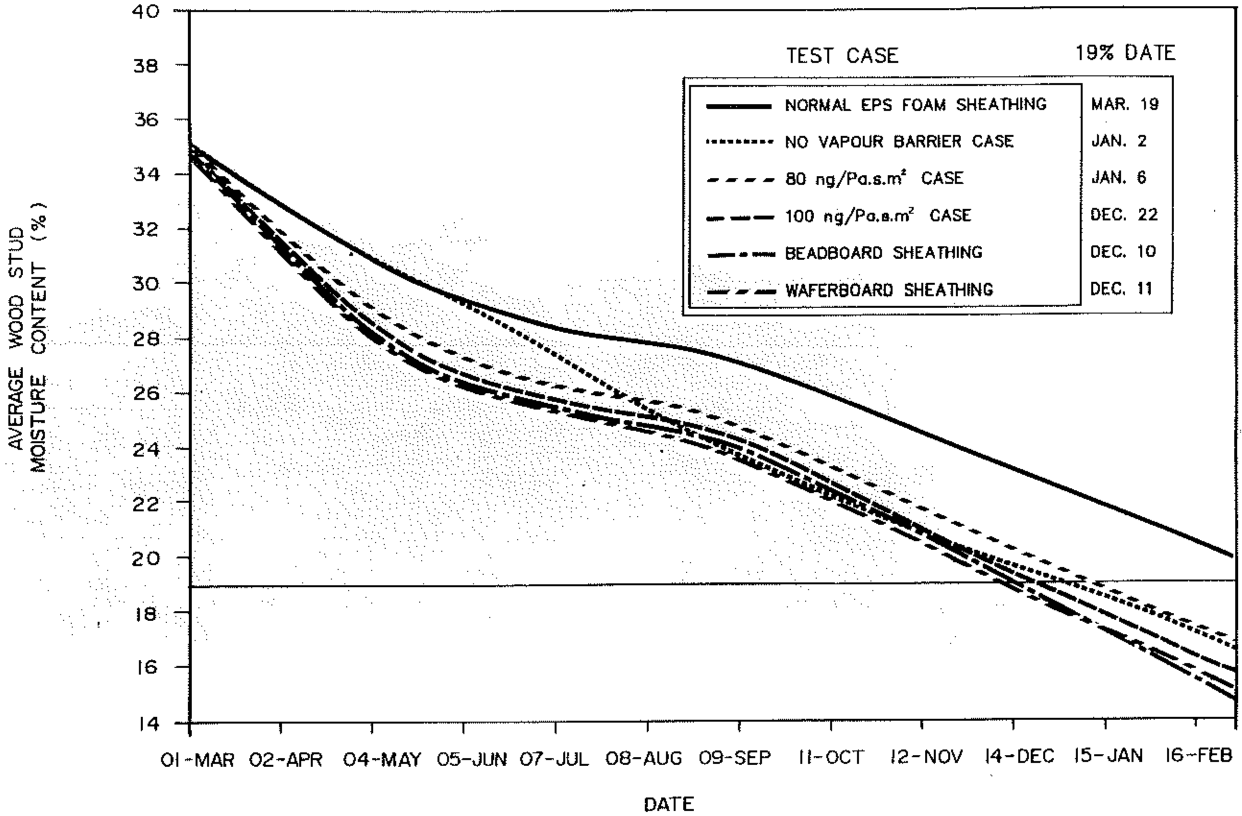

Figure 11. *Performance comparisons*

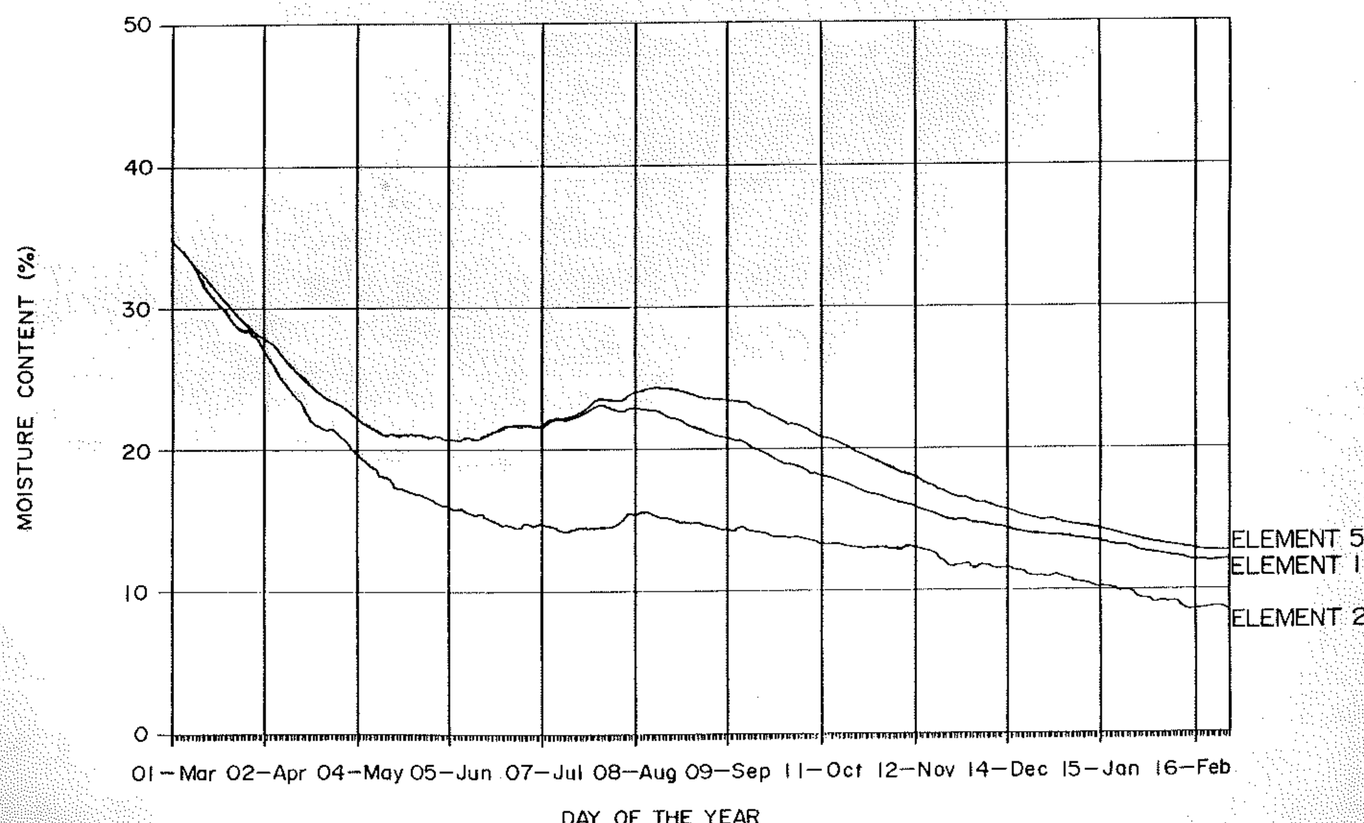

Figure 12. *Stud surface layer moisture content*

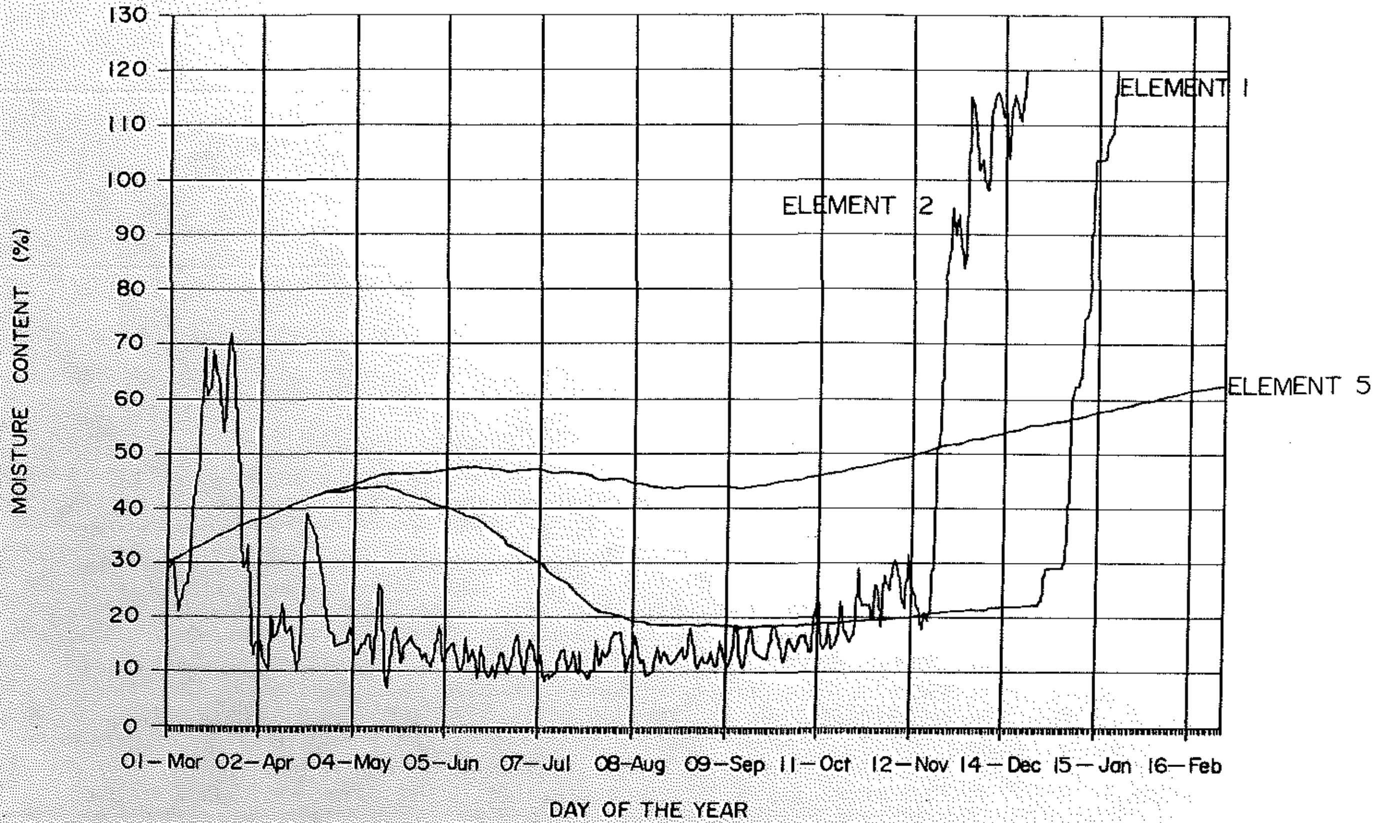

Figure 13. Sheathing surface moisture retention