EXAMPLES OF NONISOTHERMAL MOISTURE MOVEMENT IN WOOD

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(Received August 1989)

ABSTRACT

Moisture content gradients in wood samples subjected to nonisothermal conditions were monitored over time in two separate experiments using sample material from 1) green ash and 2) southern yellow pine. The warm and cold environment temperatures were maintained at 80 F and −40 F for both experiments. The warm environment relative humidity was maintained at 40% during the ash experiment, and 70% during the southern yellow pine experiment. The cold environment relative humidity was not controlled, but was presumed to be nearly 100%. The temperature gradient through the samples was measured using embedded Type-T thermocouples, and the moisture content profile from the warm to cold surface was determined by sectioning sample material.

Total average moisture content generally increased as a function of time, indicating that moisture flux into the sample through the warm surface was greater than flux out of the sample at the cold surface. Moisture accumulated toward the warm surface for the southern yellow pine, but was generally more evenly distributed through the depth for the ash samples. These differences were attributed to different warm environment relative humidity conditions maintained between the two experiments.

Keywords: Nonisothermal moisture movement, moisture profile.

INTRODUCTION

Several publications have suggested that an imposed temperature gradient could significantly influence moisture diffusion in wood. Some of the earliest research in this area was reported by Voigt et al. (1940) and Choong (1963). Wengert (1975) theorized that wood subjected to a large temperature gradient would experience nonisothermal moisture diffusion, but concluded that such diffusion would be important only under transient conditions.

More recent articles have been concerned with determining the driving force for moisture diffusion under nonisothermal conditions. Bramhall (1978) con-

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Published as Scientific Journal Series Paper No. 16,246 of the scientific journal series of the Minnesota Agricultural Experiment Station on research conducted under Minnesota Agricultural Experiment Station Project No. 43-64 supported by McIntire-Stennis funds. This work was also supported by a Research Fellowship awarded to the senior author by the Graduate School, University of Minnesota. The research was conducted by the senior author as part of the Ph.D. requirements at the University of Minnesota. The authors gratefully acknowledge the cooperation of others in the Department of Forest Products, University of Minnesota.

Wood and Fiber Science, 22(3), 1990, pp. 314–325

cluded that both isothermal and nonisothermal diffusion resulted from a "spreading pressure." In a series of articles, Siau (1980, 1983) and Skaar and Siau (1981) presented and discussed equations that described moisture movement in wood under nonisothermal conditions. These equations used one or more basic potentials as the driving force for moisture movement, and included gradients of chemical potential or activated moisture content. Siau and Avramidis, with others (Siau and Babiak 1983; Siau and Jin 1985; Siau et al. 1986; Avramidis et al. 1987; Avramidis and Siau 1987), have subsequently published a series of articles that reported on experiments designed to evaluate the predictive ability of these equations. In these experiments transverse grain moisture flux was monitored under conditions of varying temperature, relative humidity, and relative vapor pressure on each side of the test specimen. In addition, Stanish (1986) developed a mathematical expression for combined bound water and water vapor diffusion under nonisothermal conditions that utilized an expression for chemical potential derived from fundamental thermodynamic equations. Nelson (1986) also described a model for nonisothermal diffusion in wood based on nonequilibrium thermodynamics.

In addition to the more theoretical work already discussed, some applied problems have been addressed from a nonisothermal diffusion perspective. Tuomi and Temple (1975) investigated the truss arching (ceiling separation) problem from such a perspective, although indirectly. They coated green sample material on all surfaces except for one narrow edge, thereby creating a moisture gradient in the sample since all drying was forced to occur through the uncoated surface. This drying procedure induced a moisture content gradient, and consequently a shrinkage gradient. The presumption was that a moisture content gradient could also result from an imposed temperature gradient. Results indicated that the induced shrinkage gradient produced noticeable warp (crook), and that the amount of crook was a function of the slope of grain.

Erickson et al. (1981) also approached the truss arching problem from such a perspective. In this study wood was exposed to a severe temperature gradient, and the warm-edge to cold-edge moisture content profile was determined periodically. The authors conjectured that by monitoring the development of the moisture profile, they would be able to ascertain whether a differential longitudinal dimensional change in the tension chord of the truss could cause upward bowing of the truss. This scenario was deemed even more plausible due to the increased use of high longitudinal shrinkage lumber in trusses. Although somewhat variable, the results indicated that moisture movement did result from the imposed temperature gradient.

The results presented in this paper represent a continuation of the research reported by Erickson et al. (1981). The objective of the current research was to determine if, under controlled nonisothermal conditions, a moisture content gradient would develop which could account for the proposed dimensional changes (caused by a shrinkage gradient) in the tension chord.

MATERIALS AND METHODS

Sample preparation

Green ash (*Fraxinus pennsylvanica*) was employed in the first experiment and southern yellow pine (SYP) (*Pinus* spp.) in the second. The ash samples were prepared from two never-dried 4/4 boards that had been stored in the laboratory coldroom. The SYP samples were prepared from a 10-foot nominal 2 by 8, purchased at a local lumberyard.

The two flatsawn ash boards were edged, planed on both surfaces to ¾-inch thickness and then ripped and jointer surfaced to approximately a 3¾-inch width. End-matched samples were obtained by crosscutting the boards at 2-inch intervals and the samples were then equilibrated to a uniform moisture content (MC) of 19.8% at a dry-bulb temperature (DBT) of 80 F and a relative humidity (RH) of 88%.

The flatsawn pine 2 by 8 was planed on both surfaces to a ¾-inch thickness and then ripped into two boards, each approximately 3¾ inches wide. End-matched samples were obtained by crosscutting the boards at 2-inch intervals. The 40 samples were then equilibrated to a uniform MC of 17.4% at a DBT of 70 F and an RH of 81%.

Following equilibration, and just prior to testing, each sample was coated with a resin sealer plus an aluminum foil overlay on both its tangential and end grain surfaces. The purpose of the coatings was to insure that during testing any moisture flux would occur in the tangential direction.

Sample exposure

The desired test conditions were obtained by utilizing a chest-type freezer in a controlled environment room. The hinged freezer top was replaced by a 4-inch-thick sheet of extruded styrofoam insulation, and the samples were inserted into rectangular slots cut into the sheet with the 3¾-inch tangential dimension oriented vertically. Before insertion into the slots, the coated surfaces of the samples were wrapped in a thin layer of fiberglass insulation plus a piece of nylon cloth, to ensure a snug fit in the styrofoam.

A completely randomized block design was utilized for the ash samples, with each of the two parent boards considered a block. Two MC samples were removed at a given sampling time, one sample for each block for a total of 32 MC samples. Two temperature gradient samples remained in place throughout the experiment. Twelve Type-T thermocouples were inserted into the bottom of holes drilled half way through the 2-inch width. The outermost thermocouples were located approximately ⅛-inch from each exposed surface and thermocouples were spaced about $^{5}\!/_{16}$-inch apart.

In the SYP experiment, one-half of the underside of the styrofoam freezer top was covered with an approximately 2-inch thick layer of fiberglass insulation (without backing) and the other half was exposed to the freezer air. The insulation was used to simulate conditions in an attic where the tension chord of a truss is completely covered. Each member of the 20 end-matched pairs of samples was randomly allocated either to the half of the freezer with insulation or to the half without. The matched samples were randomly removed as a pair during the course of the experiment. Thus a randomized design was again utilized but without blocking. There was a temperature gradient sample for each half of the freezer cover comparable to that described earlier for the ash samples. However, in addition to the 12 thermocouples equally spaced through the sample depth, special surface mounted thermocouples were attached directly to the warm and cold surfaces.

For both experiments, the freezer temperature was maintained at −40 F. There was no attempt to monitor the humidity conditions in the freezer but air saturation was assumed. This was evidenced by the accumulation of ice on the freezer walls during the experiment. For both experiments the DBT in the environment room was maintained at 80 to 82 F. In the ash experiment the room was maintained at 40% RH, while for the SYP experiment it was maintained at approximately 70% RH. The SYP experiment was conducted after completing the ash experiment and the higher RH condition was used to determine the effect of a more severe condition on the MC profiles. Environment room conditions were monitored daily.

Sample removal and MC determination

The MC samples were most commonly removed at 3-day intervals. However, there were occasional sampling intervals of up to 6 days. Immediately after removing the sample, a plug made from the styrofoam insulation board was inserted in the slot.

A bandsaw was used to remove the foil layers from the tangential and end grain surfaces. Approximately ⅛-inch was removed in the process, leaving a sample ½-inch thick, 1¾ inches along the grain and with its original depth of 3¾ inches. A metal template was then positioned on a tangential face of the sample and 13 parallel lines were drawn, spaced approximately $\frac{9}{32}$-inch apart. Figure 1 shows the template, the foil covered sample and the MC sections.

For the ash samples, the following method of subdividing the sample was employed. First, a ⅛-inch-thick section was bandsawed from the top and bottom surfaces. The remainder of the sample was wrapped in aluminum foil and temporarily set aside for approximately 10 minutes. Each ⅛-inch-thick section was then subdivided into two $\frac{1}{16}$-inch-thick sections by use of a single-edge razor blade. This subdivision was facilitated by first crosscutting the ⅛-inch-thick sections into two equal lengths. Each subdivided section was immediately placed in weighing bottles. The remainder of the original sample was then removed from the aluminum foil and bandsawed into 12 MC sections. The final thickness for each of these 12 sections was about $\frac{7}{32}$-inch.

A modified procedure was used to obtain the surface MC of the SYP. The portion used for surface MC determination was left as an integral part of sections 1 and 12, respectively. Sections 1 and 12 were then crosscut into two equal parts and one part from each section was placed in a sliding microtome. Eight consecutive slices of approximately 0.012-inches in thickness were removed from the surfaces exposed to room and freezer air. Consequently, sections 1 and 12 had a final thickness of approximately $\frac{10}{32}$-inch. The microtome was used in the SYP experiment in order to improve near surface MC profile information. Each of the remaining sections (numbers 2 through 11) had an after-sawing thickness of about $\frac{7}{32}$-inch (the same as those in the ash experiment).

Processing of the MC sections was done as rapidly as possible and with due attention to minimizing drying, especially for microtome slices. As previously mentioned, weighing bottles were used for all MC samples. Weighings were to the nearest 0.0001 gram and samples were oven-dried at 218 F to constant mass. Moisture contents were determined on the basis of oven-dry mass.

For both the ash and SYP experiments, isothermal MC samples were left un-

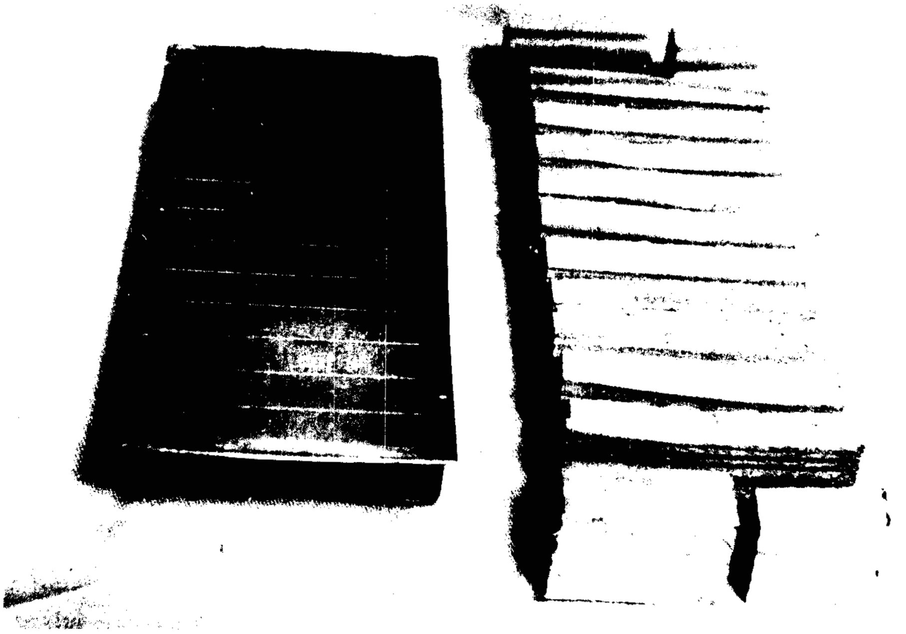

FIG. 1. Illustration of the cutting template, the foil covered sample and the moisture content sections that were obtained by bandsawing.

disturbed in the environment room for the course of each experiment. One ash and two SYP isothermal samples were subdivided at the end of the respective experiments. The procedures used for subdividing were the same as those described earlier for the nonisothermal ash and SYP samples.

In the SYP experiment, samples were suspended in the freezer air for the purpose of determining the equilibrium moisture content (EMC). Such samples were not used in the ash experiment, but since the freezer temperature was −40 F in both experiments, presumably equivalent air conditions prevailed and consequently comparable EMCs.

RESULTS AND DISCUSSION

Analysis of variance was conducted on the ash and SYP MC data. In these analyses, the sampling sequence (time) and depth (slice number) were considered as treatments. For both species, time and depth were statistically significant ($p < 0.01$), indicating that the MC profiles were changing with respect to time.

An MC profile was generated for each sample by plotting slice MC against sample depth. For each species the general shape of the overall MC profile was quite consistent from sample to sample. However, between sample variability in absolute MC values by depth interfered with verifying what appeared to be a trend for the level of the MC profiles to increase with time. Consequently, sequential samples were averaged in order to minimize the effect of random variation. The 16 sampling sequences for the ash experiment were combined to yield three time periods, and consequently, only three MC profiles. Similarly, the 18 sampling sequences for the SYP experiment were combined to yield three time periods.

Partial vapor pressure was calculated as a function of slice number (depth). It was assumed that at a given sampling time the entire MC section was at an EMC equal to its determined MC, and that the measured temperature for the given section was representative of its uniform temperature. Spacing of thermocouples in the sample was closely comparable to the spacing of sections obtained for MC analysis. The procedure developed by Simpson (1971) was used to calculate RH from the assumed EMC and the known DBT. Psychrometric relationships from the ASHRAE Fundamentals Handbook (Anonymous 1981) were also used. The complete procedure used to determine vapor pressure was given by Quarles (1985).

The results obtained from the SYP samples where the bottom surfaces were in contact with fiberglass insulation on the freezer side will be discussed first. Figure 2 graphically summarizes the MC, temperature and calculated vapor pressure data. The uniform initial MC of these samples was 17.4%. It was apparent from the subsequent MC curves that there was a moisture redistribution relative to the initial profile. In order to determine if there was an overall absolute increase in MC over time, the area under each curve was calculated. These calculations showed that the average MC of the samples increased over time. The average MC of the 972–1,786 hour samples was 8.8% greater than the initial profile (18.9% MC versus 17.4% MC).

If the moisture flux were equal to zero, and only moisture redistribution had occurred, one would have expected a buildup of moisture at or near the cold face (as indicated by the Soret Effect). Instead, the moisture profiles showed an accumulation of moisture toward the warm surface, with the maximum at a depth of about 0.5 inches. Although moisture flux was not measured, it is unlikely that the flux was zero since the integration results indicated an absolute increase in MC over time. Since the overall MC increased over time, moisture flux through the warm and cold surfaces must have been unequal, and because of the experimental environmental conditions, it was likely that the inward flux through the warm face was greater than the outward flux through the cold face. The fact that moisture accumulated near the warm face indicated that the flux was a function of the location in the wood.

As depicted in the side blocks shown in Fig. 2, the isothermal sample kept in the environmental room attained a uniform MC of 12.72%, while the average warm surface MCs for the 0–515, 516–971 and 972–1,786 hour profiles were 13.97, 19.04 and 16.86%, respectively. Therefore the warm surface MCs were higher than the MC of the warm isothermal sample throughout the experiment, as would be expected because of the temperature differences. However, the trend of increasing surface MC with time supports the argument for increased flux in the near warm surface region.

The average cold surface MCs for the three profiles, in the same order, were 7.97, 7.83, and 8.91%, whereas the average MC of the samples suspended in the freezer was 17.6%. This order of MC difference would also be expected due to the temperature differences between the wood surface and ambient air.

According to Stanish (1986) total diffusion in wood is comprised of a bound water component, driven by a gradient of chemical potential, and water vapor diffusion, driven by a gradient of the mole fraction of water in the gas phase. The

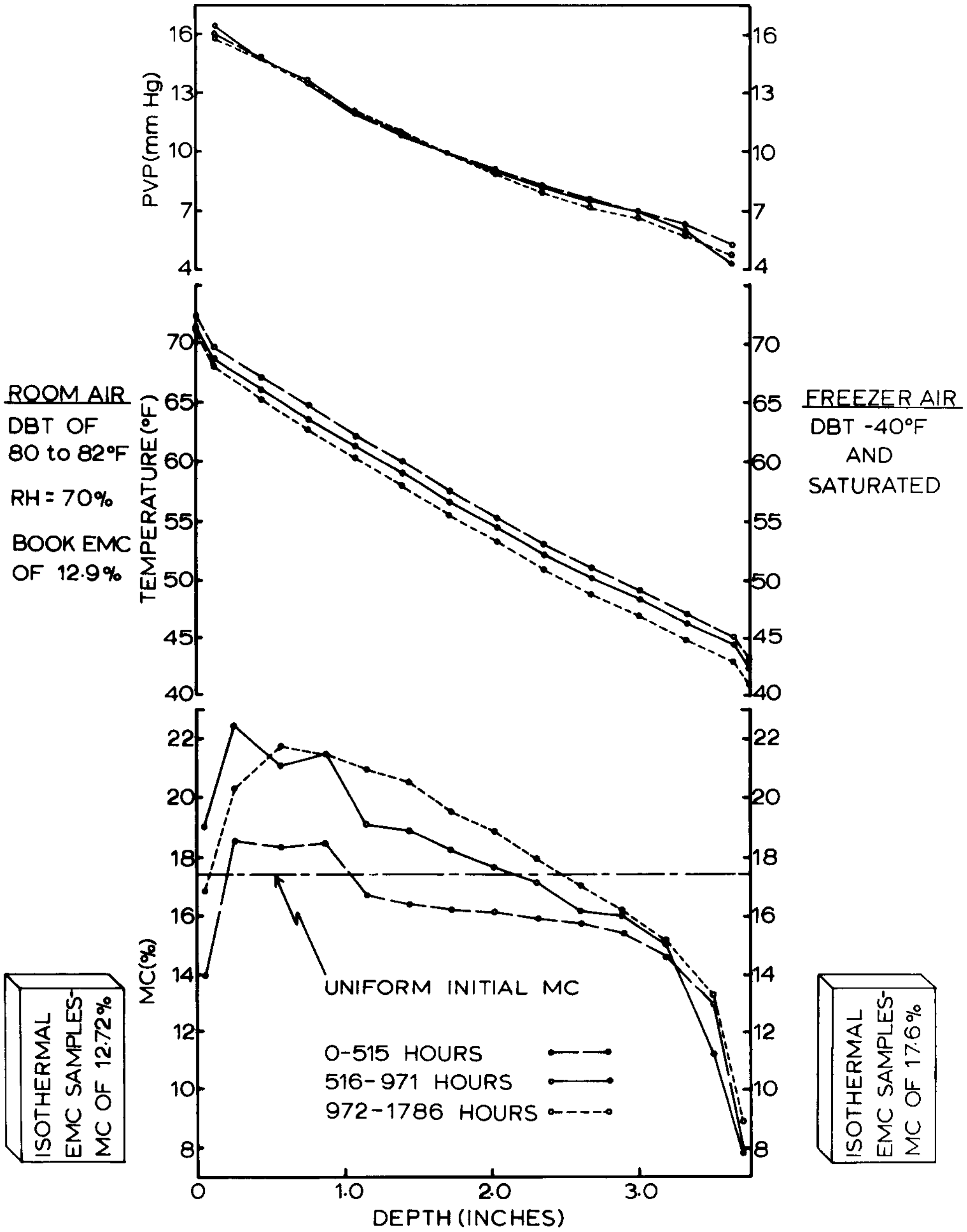

FIG. 2. Summary of the moisture content, temperature and partial vapor pressure profile data that were obtained with the insulated southern yellow pine samples.

contribution of the temperature gradient to the driving force arises from the gradient of chemical potential alone. Therefore moisture flux between two points would be a function of the temperature and vapor pressure gradient.

If flux is a function of the temperature and vapor pressure gradients, then it should be possible to describe the changes in the moisture profiles by these gradients. The measured internal temperature gradient was consistently linear, ex-

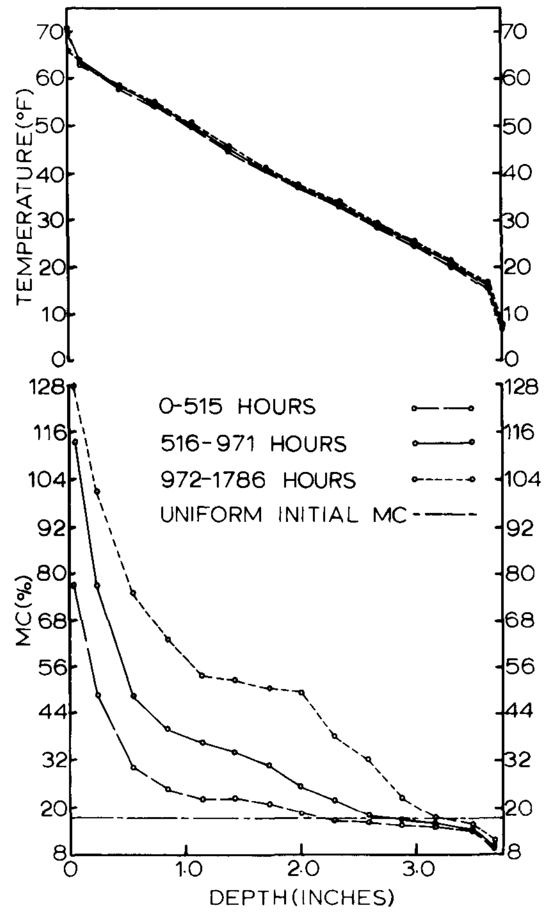

FIG. 3. Summary of the moisture content and temperature data that were obtained with the uninsulated southern yellow pine samples.

hibiting a common slope and only minor differences in the y-intercepts. The segment of the MC profile exhibiting a negative slope (between approximately 0.5 and 3.5 inches) was also fairly linear, with coefficient of determination values between 0.85 and 0.96 for the three curves. All three curves had different slopes and y-intercepts. Because of the constant temperature and vapor pressure gradients in the warm surface region, it is likely that the moisture flux in that region was also constant. The differences exhibited in moisture storage in the samples, which would cause an accumulation of moisture near the warm surface, would likely be caused by a larger moisture flux in the near surface region. As shown in Fig. 2, the temperature gradient between the warm surface and first internal thermocouples, was steeper relative to the internal gradient, and may have been responsible for the observed accumulation near the warm face. Taylor and Cary (1961) also observed a sharp drop in temperature near the warm surface in an experiment they conducted with soil. However, the abrupt change in slope in the temperature profile could possibly be an artifact related to the use of surface mounted thermocouples (e.g., they either influenced the heat flux at the surface, or sensed a temperature that was between the surface and ambient air temperatures).

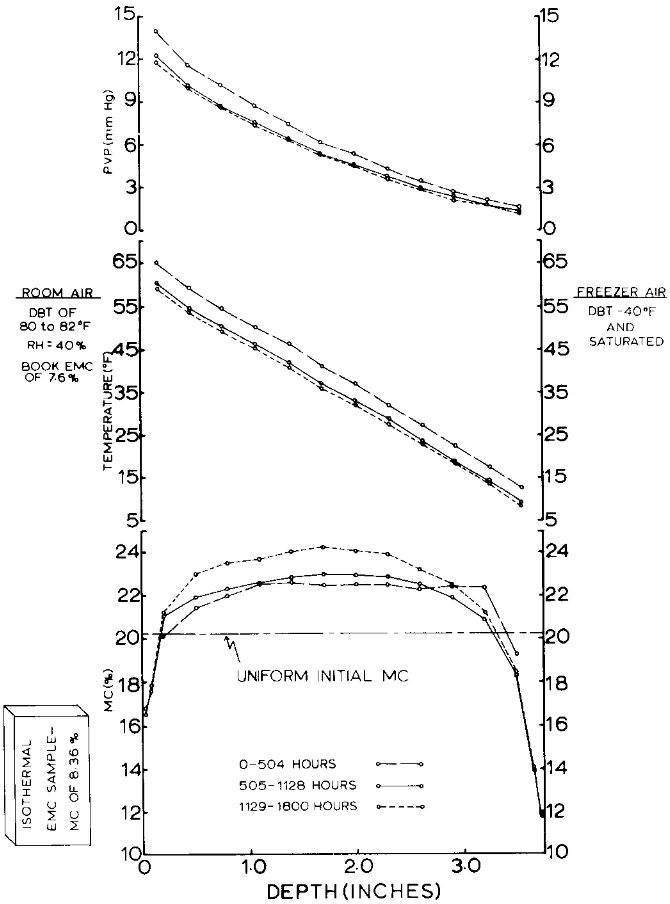

FIG. 4. Summary of the moisture content, temperature and partial vapor pressure profile data that were obtained with the AshI set of samples.

Figure 3 summarizes the results for the uninsulated SYP samples, for which there was an early initiation of condensation on the warm surface. The fact that the warm air RH used in the SYP experiment was 70% enabled the dew point temperature to be attained on the warm surface of the wood. This caused an extremely large increase in warm surface and average MC unrelated to nonisothermal diffusion. Condensation continually occurred on the warm surface of the samples, leading to the extremely high MCs throughout the experiment. In spite of the increasing average MC between the warm surface and a depth of about 3 inches, the cold surface MCs remained in the 10 to 12% range for the entire test period.

Figures 4 and 5 summarize the results obtained with the ash samples. Since the analyses of variance showed a significant block effect, where a block was the individual board that provided one set of end-matched samples, the data from the two sets were analyzed separately, and identified as AshI and AshII.

Results from the ash experiments were similar to that for insulated SYP (Fig. 2). The average increases in MC relative to the initial MC, as determined by integrating the areas under the MC curves, were 4.7%, 12.3%, and 19.7%, re-

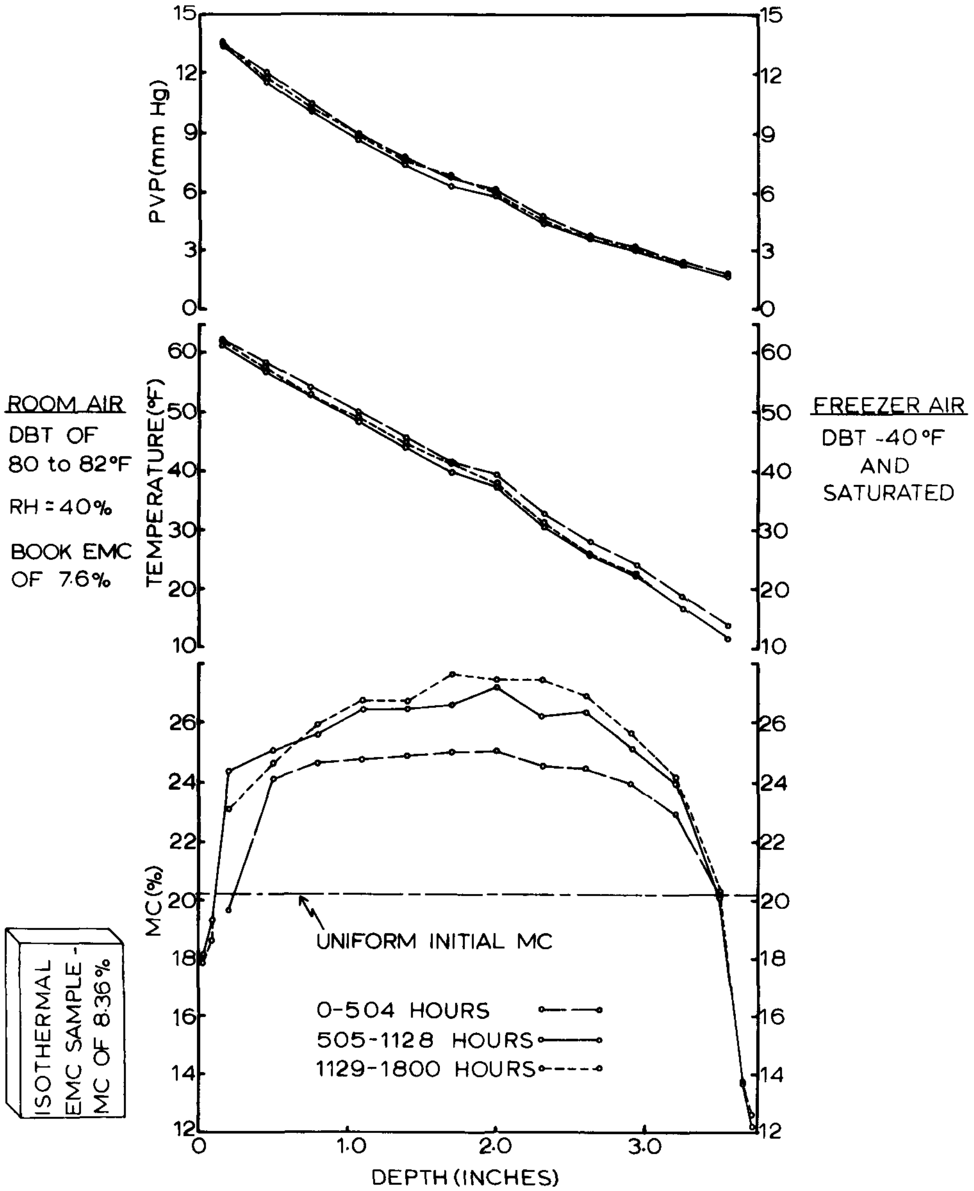

FIG. 5. Summary of the moisture content, temperature and partial vapor pressure profile data that were obtained with the AshII set of samples.

spectively, for the 0–504, 505–1,128, and 1,129–1,800 hour AshI profiles. The average increases in MC relative to the initial MC for the AshII profiles were 28.2%, 54.3%, and 57.3%. The near surface MCs on the warm face of the non-isothermal samples were well above the average MC of the isothermal samples, and the cold surface MC was well below the predicted MC for isothermal samples held in the freezer. (There were no freezer isothermal samples for the ash samples, but presumably if there had been they would have given MCs similar to those obtained from the SYP samples.)

The MC profiles were not noticeably skewed toward the warm face as was the case for the SYP samples. However, the fact that the RH of the warm air in the green ash experiment was 40%, compared to 70% for the SYP experiment, should have a significant effect on the moisture flux through the warm face. Also, differences in specific gravity, thermal conductivity, and wood structure between ash and SYP would be influential.

Figures 2, 4, and 5 showed that moisture did not accumulate at the cold surface to such a degree that one could reasonably expect to observe significant crook caused by a shrinkage gradient. In fact, as shown in Fig. 2, accumulation was greatest near the warm surface. This would cause a dimensional change in a direction which was opposite to that necessary for it to influence the truss arching phenomenon.

CONCLUSIONS

Water vapor moved into and through wood that was used as a thermal barrier between constant warm and cold air environments. The average moisture content of the wood was higher at the conclusion of the test. The moisture content at the warm surface of the nonisothermal samples exceeded the equilibrium moisture content of isothermal samples maintained in the warm environment. Conversely, the moisture content at the cold surface of the nonisothermal samples was less than the equilibrium moisture content of the isothermal samples held in the freezer air.

This constitutes further experimental evidence that under certain environmental conditions the temperature gradient can influence moisture content distribution. However, moisture flux was not measured and consequently it was not possible to determine if the experimentally observed moisture build up could be predicted.

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