AIR PERMEABILITY, SHRINKAGE, AND MOISTURE SORPTION OF LODGEPOLE PINE STEMWOOD

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ABSTRACT

The longitudinal air permeabilities, shrinkage (from fully swollen to oven-dry), and moisture sorption characteristics of two varieties (*latifolia* and *murrayana*) of lodgepole pine (*Pinus contorta*) were measured, based on wood samples taken from ten latitudes (37.5° to to 60°N) in western North America, from 279 trees of three diameter classes (76, 152, 228 mm DBH).

The mean permeabilities of the sapwood and heartwood were 0.13 and 0.014 darcy, respectively. Geographical latitude and elevation of trees did not affect permeability. The mean calculated radius of pit pores in the sapwood was 1.5 μm, with median values between 12–13 pit pores per mm². There was a fair correlation between water retention in an empirical water-soaking test and axial gas permeability.

The volumetric and radial shrinkages, as well as the ratio of radial to tangential shrinkage, all increased with increasing specific gravity for both varieties. Tree size and latitude also affected shrinkage somewhat, primarily through their effects on specific gravity. The mean ratio of percent volumetric shrinkage to specific gravity was 30.7 ± 2.9% for the two varieties combined.

The moisture sorption study gave adsorption and desorption equilibrium moisture content (EMC) values at 30 C at relative humidities of 34.4, 65.0, and 83.2% for both varieties, on each of 62 test samples, representing the three different tree sizes and nine different latitudes. The mean adsorption–desorption (A/D) ratio was 0.79. The EMCs generally decreased with increasing latitude, with no significant difference between varieties at corresponding latitudes.

Keywords: Permeability, lodgepole pine, latitude, elevation, specific gravity, sapwood, heartwood, shrinkage, moisture, sorption.

INTRODUCTION

This study is part of a decade-long research program by the Intermountain Research Station of the USDA Forest Service to improve the utilization of lodgepole pine (*Pinus contorta*) by providing data on its distribution and on the anatomical, physical, mechanical, and chemical properties of its wood. Details of the field material collected during the summers of 1983–1984 are given in Koch (1987) and in Kim et al. (1989).

The first portion of the study relates to the longitudinal or axial air permeabilities of the heartwood and sapwood of two varieties of *Pinus contorta*, var. *latifolia* and var. *murrayana,* sampled from over most of their geographical ranges. The permeability of wood is a good indicator of its treatability with preservatives and

other chemicals used to improve its properties, as well as to convert it into pulp. It was decided to measure axial rather than transverse permeabilities because they are more reliable. Also gas rather than liquid permeabilities were measured for reasons of convenience and consistency, particularly in view of the large number (over 1,000) of individual specimens measured. The specific objectives (Hofmann 1986) were to determine the effects on longitudinal air permeability of tree diameter, latitude, elevation, and botanical variety for both sapwood and heartwood, to estimate the mean diameters and numbers of pores connecting the tracheids where practicable, and to determine if the air permeabilities are related to the rate of penetration of liquid water into the wood.

The second portion is concerned with shrinkage from the fully water-soaked (after having been air-dried) to the oven-dry condition. Shrinkages in the tangential, radial, and longitudinal or axial directions were measured. The research (Wiedenbeck 1988) was designed to detect the effect of tree latitude, elevation, and diameter on shrinkage in these three orthotropic directions. Certain relationships between these shrinkages and individual wood parameters such as specific gravity and radial location in the tree stem were also explored.

In the third portion, adsorption and desorption EMCs at 30 C were measured on groups of the same specimens used for shrinkage studies, at each of three different relative humidities, 34.4, 65.0, and 83.2%. This study was more limited in scope, in that specimens from individual trees were not measured, but were pooled such that there was a single pooled test specimen for all trees of a given latitude and diameter. Heartwood and sapwood were also pooled.

LITERATURE REVIEW

Air permeability

Darcy's law for the flow of compressible fluids (i.e., gases) through a permeable porous material, such as wood, may be expressed as

$$K_g = QPL(A\bar{P}\Delta P) \tag{1}$$

where K_g is the superficial gaseous permeability, Q the volume of air per unit time measured at the pressure P at which Q is measured through the wood specimen under steady-state conditions, L and A are the length and cross-sectional area of the specimen, and $\bar{P}$ and ΔP are the mean pressure in, and the pressure drop across, the specimen, respectively. The magnitude of K_g varies with the viscosity η of the gas used. The specific gaseous permeability K_{gd} in darcys is obtained by multiplying K_g and η (Siau 1984). Thus

$$K_{gd} = K_g(\eta) \tag{2}$$

Equations (1) and (2) are derived from the assumption that gas flow is viscous or laminar. Such is not the case for gas flow through pores sufficiently small that they are in the same order of magnitude as the mean free path or mean distance between collisions of individual gas molecules. In this case the measured or superficial permeability K_g consists of two components, the true permeability K, and a second pressure-dependent component known as slip flow. These are related by the equation (Siau 1984)

$$K_{gd} = K(1 + b/\bar{P}) \tag{3}$$

where K_{gd} is the measured gas permeability, K is the true permeability, b a constant and $\bar{P}$ the mean gas pressure in the sample. Thus Eq. (3) predicts a linear relationship between the measured gas permeability and $1/\bar{P}$, the intercept of which gives the true permeability K. The mean or effective radius r (micrometers) of the pores can be obtained from the slope bK, using the relation

$$r = 4(10^4)(K/bK) \tag{4}$$

when air at 20 C is used as the gas, and P is the mean gas pressure in Pa.

An estimate of n, the number of pit pores per unit cross-sectional area of the wood, can also be calculated from air permeability measurements, by the use of the equation

$$n = 8\eta K_p/\pi r^4) \tag{5}$$

where K_p is obtained by multiplying K by a number related to the pit-pore membrane thickness, the amount of tracheid overlap and tracheid length (Siau 1984).

A number of factors have been shown to affect the permeability of softwoods (Comstock 1970). These include: sapwood-heartwood differences, moisture content, growth rate, geographic factors, specific gravity, and variations among trees.

A number of different experimental techniques have been used to measure the permeability of wood. These fall into two general categories, liquid permeability techniques and gaseous techniques. Gas permeability measurements are more convenient than liquid measurements, provided they are adjusted for the factors given in Eqs. (1) to (3). A modification of a method proposed by Petty and Preston (1969) was used in this study.

Shrinkage

Normal shrinkage, associated with loss of bound or hygroscopic water from the cell wall, is often a linear function of the moisture loss over most of the moisture range below M_f. Several primary factors have been shown to affect shrinkage in normal wood. These include wood density or specific gravity, extractive content, differences between heartwood and sapwood, earlywood and latewood, and juvenile and mature wood. Other factors, including growth rate or ring width, radial position in the tree and tracheid length, are generally interrelated with the primary factors noted above. Detailed discussions of these factors are given in Choong (1969a), Koch (1972), Boyd (1977), and Skaar (1988).

Sorption isotherms

The mechanisms of moisture sorption and moisture isotherms are discussed in Stamm (1964), Siau (1984), and Skaar (1988). Specific isotherms related to this study are given under results and discussion.

MATERIAL AND PROCEDURES

All of the material came from short (150–200-mm) bolts taken from a height about 10% of the distance from the stump to the top of the tree. One air-dry bolt from each of the 279 trees of lodgepole pine, *Pinus contorta* (243 from var. *latifolia* and 36 from var. *murrayana*) was supplied by the Intermountain Research Station of the USDA Forest Service (Koch 1987).

The trees of var. *latifolia* had been sampled from nine different northern lati-
tudes throughout its range as follows, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, and
60 degrees. At each latitude, trees were sampled from each of three elevations,
designated as low, medium, and high. Three different trees were sampled for each
of the three nominal diameters, 3, 6, and 9 inches, or 76, 152, and 228 mm, for
a total of 243 trees.

The trees of var. *murrayana* were sampled from only four northern latitudes,
37.5, 40, 42.5, and 45 degrees, for a single elevation only, and with 3 replicates
of each of the three diameters, for a total of 36 trees.

Air permeability

One end of each bolt was first trimmed to remove the end-coating applied to
reduce the rate of moisture change after initial air drying. A single round disk,
each of the bolt-diameter, and of thickness ranging from 9 to 17 mm, was cut
from the trimmed end of each bolt. Four dowels were removed from each disk,
using a 9.5-mm plugcutter, two from opposite sides of the sapwood, and two from
opposite sides of the heartwood, sapwood and heartwood distinguished by color
differences. Thus there was a total of 972 permeability samples of var. *latifolia*
and 144 of var. *murrayana*.

For the 76-mm disks, the sapwood dowels were removed from the outermost
portion of the disk and the heartwood dowels from as close as practicable to the
pith. It was not possible to completely exclude heartwood from sapwood dowels
in some cases for these disks, nor sapwood from heartwood, because of the small
size and variable widths of sapwood. For the 152-mm disks, sapwood dowels
were taken 10 mm from the outer edge and heartwood dowels 10 mm from the
pith. The 228-mm disks were sampled similarly except that the respective dis-
tances were 20 rather than 10 mm. Each dowel specimen was microtomed on
both ends to free it from loose fibers so as to reduce blockage of the lumens on
the dowel ends (Choong et al. 1975).

Two different variations of the gas permeability apparatus described by Petty
and Preston (1969) were used in this study, one (sapwood apparatus) for specimens
with permeabilities above 0.01 darcy, generally sapwood, and the second (heart-
wood apparatus) for specimens with lower permeability, generally heartwood.

Both sets of apparatus were similar (Fig. 1) in that a microflowmeter (A) was
used to measure the air flow rate through the test specimen (G). The air filter (I)
removed particulate matter from the air which then passed through the specimen
at a rate controlled manually by a needle valve (D). The air next passed through
a Cartesian manostat (F) which regulated the low pressure provided by the vacuum
pump (E).

The essential difference in the two measurement systems was in the magnitude
and method of measuring the pressure differential ΔP. For the permeable sapwood
specimens, ΔP was measured directly with a differential mercury manometer (C),
whereas for the typical impermeable heartwood specimens, it was calculated from
the difference between the absolute pressure measured by the mercury manometers
on the high (B) and low (C') ends of the specimen (G).

The specimen holder (G) consisted of thick-walled rubber tubing of 9.5-mm
inside diameter. The sample was inserted into the center of the tubing and securely
clamped so as to prevent air leaks around the edge. Trial measurements were
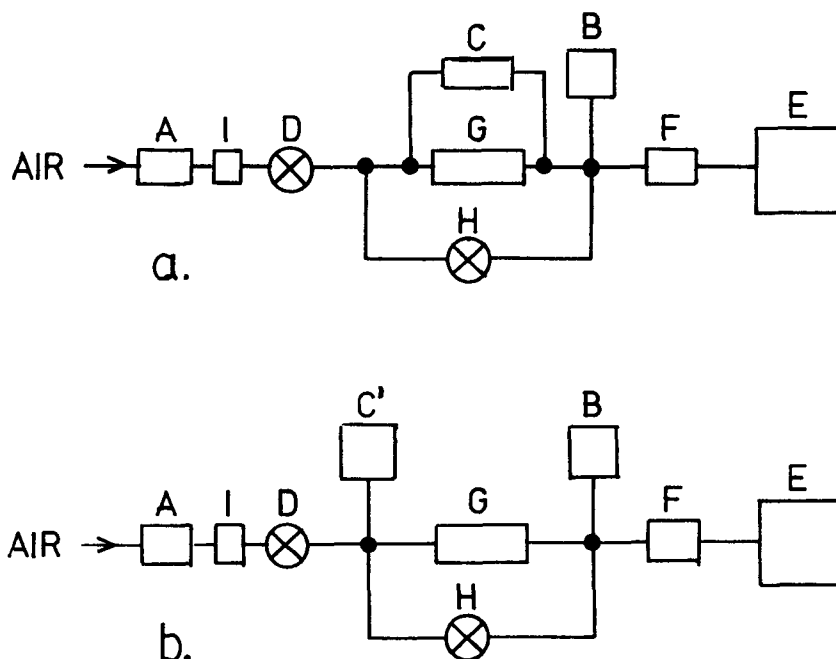
FIG. 1. Functional diagram of air permeability apparatus used for: a. High permeability (sapwood) specimens. b. Low permeability (heartwood) specimens. (See text for details.)

made on impermeable specimens to assure that this technique excluded measurable air leaks.

Each permeable sample (K_g = 0.01 darcy or higher) was measured at each of four different mean pressures P within the test specimen (ca. 7, 14, 20, 34 kPa), corresponding to reciprocal mean pressures $1/\bar{P}$ of approximately 140, 70, 50, and 30 reciprocal MPa. The superficial specific gas permeability K_g (darcys) was calculated in each case using Eq. (1), and plotted against $1/\bar{P}$, giving a typical Klinkenberg curve (Fig. 2). The regression curve of K_g against $1/\bar{P}$ was calculated from which the intercept permeability K and slope bK were obtained for each specimen. These values were then used to estimate both the mean pore radius r and the effective number n of pores per unit area, based on Eqs. (4) and (5).

It was impractical to obtain Klinkenberg plots on the low permeability heartwood specimens, primarily because of limitations in the capability of the flowmeter to measure low flow rates. For these specimens a larger pressure differential ΔP was required to obtain measurable flow rates, in most cases almost one atmosphere. The mean pressure, $\bar{P}$ at which measurements were taken for these specimens was 47 kPa, giving a value for $1/\bar{P}$ of 21 reciprocal MPa. This is a superficial gas permeability K_g, but at a sufficiently low value of $1/\bar{P}$ as to be nearly comparable to the intercept for the typical sapwood specimens. Therefore, it was used in the analyses of results.

After completion of all permeability measurements, the samples were subjected to empirical tests to determine their retention of liquid water in simple soak tests. Preliminary tests had indicated that weighing specimens both before and after a simple soaking in water under a vacuum (pressure of one kPa) for five minutes
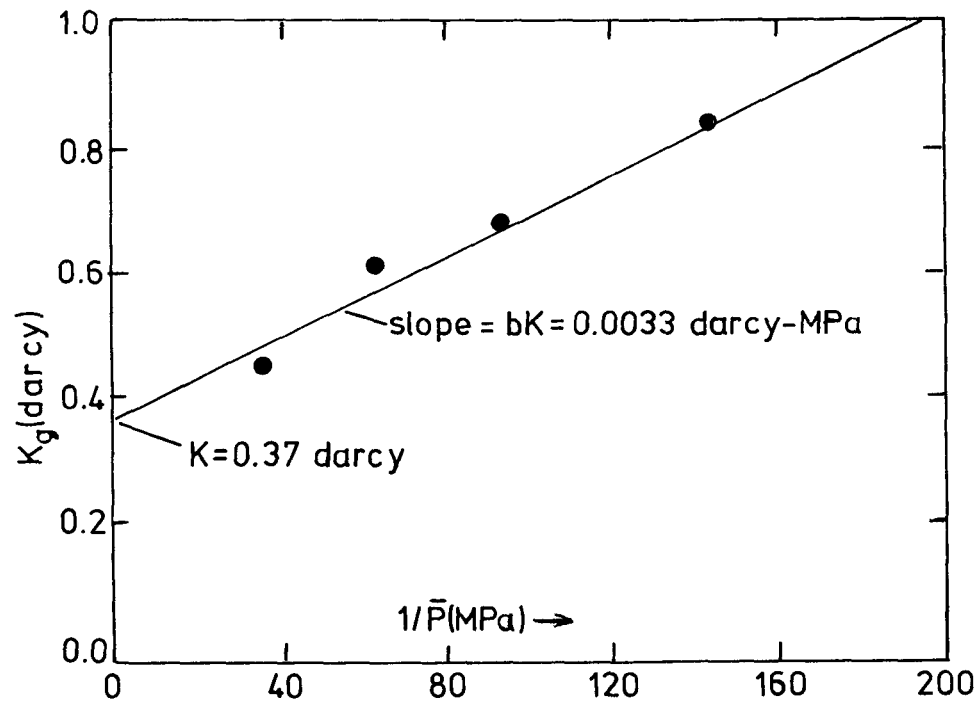
FIG. 2. Typical Klinkenberg plot of apparent permeability K_g (darcy) against reciprocal of mean pressure $\bar{P}$ (MPa).

(followed by exposure to atmospheric pressure (100 kPa) and subsequent blotting of specimens to remove excess surface water) would give a wide distribution of water retentions among individual samples. This empirical test was then adopted for the water retention tests.

After soaking, blotting, and reweighing, the fraction of void volume filled with water was calculated for each specimen using the equation of Siau (1984) to calculate the porosity or void fraction V_a,

$$V_a = 1 - G(0.667 + 0.01M)$$ (6)

where G is the specific gravity of the specimen and M its moisture content before immersion. The water retention Ret, or fraction of void volume filled with water, was calculated from

$$Ret = [w_s - w_a - w_o(M/100)]/(VV_a)$$ (7)

where w_s, w_a and w_o are the soaked, initial and oven-dry weights (g) of the specimen, and V is its volume (ml).

Shrinkage measurements

The transverse shrinkage specimens were cut from cross-sectional discs, which ranged in thickness from 10 to 20 mm.

Pie-shaped pieces extending from the pith to the outermost edge of the wood were cut from sections of the discs that were free of compression wood and knots (Fig. 3). These samples were used for combined (sapwood and heartwood) radial
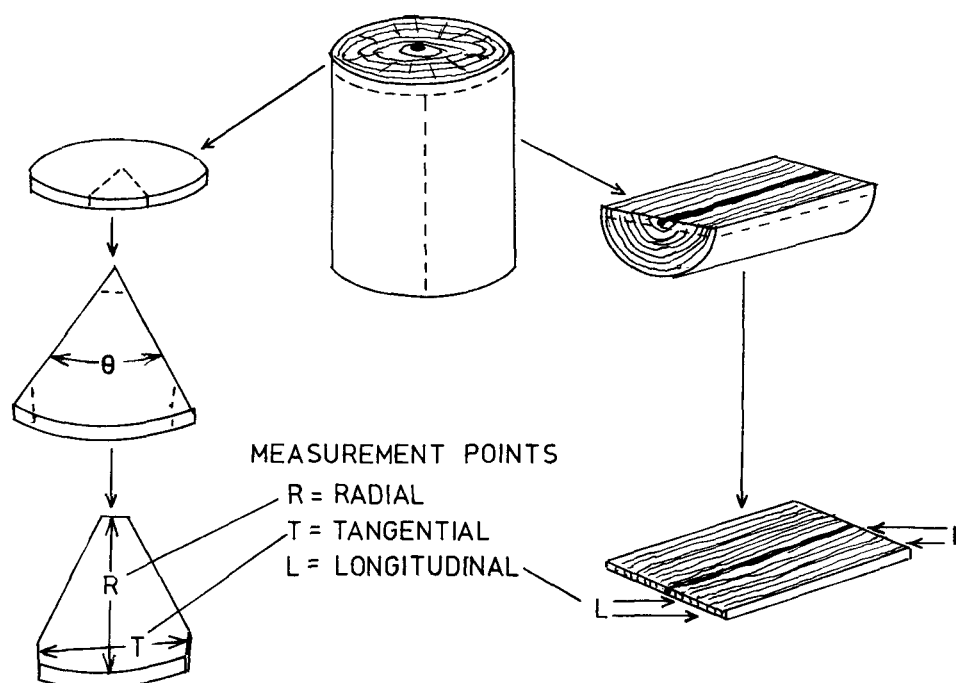
FIG. 3. Schematic diagram showing origin of shrinkage measurements specimens and points of measurement.

shrinkage measurements and for tangential shrinkage measurements of the sapwood. The radial measurement points were located near the pith (at a point one to two annual rings in from the pith; 3.5 mm from the pith on average), and at a position on the outer edge of the wood. Thus, the radial dimension was just slightly less than the tree's radius. The tangential measurement points were located on either side of the pie-shaped piece, near its periphery, in the most recently formed sapwood (Fig. 3). The sample sizes in the tangential direction were approximately 25, 38, and 50 mm for the 76-, 152-, and 228-mm diameter trees, respectively.

In addition to the transverse shrinkage samples described above, samples were cut from all (27) of the medium-elevation, 228-mm trees of var. *latifolia,* and from all (12) of the 228-mm trees of var. *murrayana,* for use in a study of isolated heartwood and sapwood shrinkages. The boundary between heartwood and sapwood was located based on color variation. Pie-shaped pieces were again cut. A bandsaw was then used to separate the heartwood and sapwood. The tangential measurement points for the sapwood samples were located in the most recently formed sapwood, for the heartwood in the most recently formed heartwood, close to the heartwood-sapwood boundary. Radial shrinkage measurements for the heartwood included the entire heartwood radius except for the 3.5 mm sanded off next to the pith. Radial shrinkage for the sapwood was calculated based on the difference between the radial shrinkage of the combined heartwood-sapwood sample and the heartwood-only sample.

Longitudinal shrinkage measurements were made on clear, straight-grained,

quarter-sawn samples that averaged approximately 100 mm along the grain and included the entire diameter of the tree (Fig. 3). They were sawn as thin as possible (3 mm) so as to minimize drying stresses. Two longitudinal shrinkage measurements, one 6 mm from the pith (referred to as the corewood measurement), and the other 6 mm from the outer wood surface (designated as the maturewood measurement), were made on the 76, 152, and 228 mm specimens. In addition to these measurements, a third measurement, located approximately 57 mm from the pith (midway between the other two), was made on the 228-mm specimens. A total of 1,326 shrinkage values were obtained.

The shrinkage samples were measured with a stand-mounted dial-gauge to the nearest 0.025 mm. Measurement precision, determined by taking repeat measurements on 20% of the samples, averaged ±0.038 mm.

Specific gravity was computed on the oven-dry weight, swollen volume basis, and linear shrinkages as the percent dimensional change from the fully swollen condition. Volumetric shrinkage S_v was estimated from the radial and tangential shrinkages, as follows:

$$S_v = S_r + S_t - 0.01(S_r)(S_t) \tag{8}$$

The oven-dry samples were used to determine the central angle θ (Fig. 3) of the transverse samples. This angle was used to correct the tangential shrinkage measurements for growth ring curvature based on the equation of Kelsey and Kingston (1953),

$$S_t = [T/(R\theta)](S_T - S_r) + S_r \tag{9}$$

where S_t and S_T are the true and measured tangential shrinkages, T, R and θ are tangential dimension, radius of curvature, and "central angle," respectively, of the oven-dry sample, and S_r is the radial shrinkage.

A three-factor, random effects, model ANOVA was used in testing var. *latifolia* for differences in shrinkage as affected by variations in latitude, elevation, and diameter. For var. *murrayana* a two-factor, model ANOVA was used since elevation was not a variable. In testing for differences in shrinkage between the two varieties paired sample t-tests were conducted. Simple regression analysis provided information on the functional dependency of shrinkage on specific gravity.

Sorption isotherm

The sorption isotherm measurements were made on the same specimens used for transverse shrinkage, after these were completed. Some of the thicker specimens were resawn so that the axial thickness was 10 mm or less in all cases, in order to minimize the time required to attain equilibrium. All of the specimens included both sapwood and heartwood.

Different specimens were used for adsorption than for desorption experiments. Furthermore, all specimens in a given diameter class and latitude were pooled to give a single test sample, each sample normally consisting of 9 specimens for var. *latifolia* and 3 for var. *murrayana*. There were no desorption samples for the 76-mm diameter trees. Thus there was a total of 62 test samples, 45 for var. *latifolia* and 17 for var. *murrayana*. The 45 var. *latifolia* samples contained 27 adsorption samples, three from each of the nine latitudes, representing 76-mm, 152-mm, and 228-mm diameter trees; and 18 desorption samples, from the same nine

latitudes, but only from 152- and 228-mm diameter trees. The 17 var. *murrayana* samples had the same distribution of tree sizes for adsorption and desorption samples, but only from four latitudes. Furthermore, there was only a single adsorption sample (consisting of 12 pooled specimens) and no desorption sample for the 76-mm trees for this variety.

All samples had previously been oven-dried at least once during the shrinkage measurement experiments. The desorption samples were each remoistened with liquid water to a minimum of 35 to 40% moisture content. They were then wrapped overnight to permit moisture equilibration without loss of moisture, prior to placement in the controlled environment chamber. The adsorption samples were oven-dried overnight at 103 C and then placed into the controlled environment chamber, together with the desorption samples. This procedure was repeated on the same samples for each of three different humidity conditions, nominally 34.4%, 65.0%, and 83.2%, all at 30 C.

Environmental conditions were maintained in an insulated chamber supplied by a PGC Climate-Lab-AA conditioned air generator, designed to maintain relative humidity control of ±0.5%.

When detectable weight changes could not be measured, usually after 8 to 10 days, all 62 test samples were weighed to determine their final equilibrium weights. These weights, together with the oven-dry weights, were used to determine equilibrium moisture contents for the exposure conditions.

RESULTS AND DISCUSSION

Air permeability

As is generally found (Siau 1984), the permeabilities were considerably greater (ca. 10 times) for sapwood than for heartwood of both varieties (Table 1). Also the mean permeabilities of var. *latifolia* were substantially greater for both sapwood (ca. 1.5 times) and heartwood (ca. 1.75 times) than those of var. *murrayana*. There were also significant differences among trees, although geographical factors such as latitude and elevation had no consistent effect.

Table 1 also includes the results of "*t*-tests," which indicate that the permeability of var. *latifolia* is significantly greater than that of var. *murrayana*, for both sapwood and heartwood. Figure 4 shows the mean sapwood and heartwood permeabilities of both varieties, plotted against latitude.

A statistical analysis for the effects of wood variables such as moisture content, ring width, specific gravity, and sample length indicated that very little of the variation in permeability was due to these factors.

For the sapwood examples, the permeabilities were sufficiently high that the effective pit pore size and number per square centimeter could be calculated for each specimen. The mean pore radius in micrometers, and the median number of pores per square mm were 1.29 and 13, for var. *latifolia*, and 1.52 and 12 for var. *murrayana*, respectively. These values approximate the values of 0.95 micrometers and 6 per square mm reported for *Pinus koraensis* by Bao et al. (1986), who did not distinguish between sapwood and heartwood.

Comparisons of the results of the empirical water retention tests with those for permeability indicated a fair correlation ($R^2 = 0.64$) between them (Fig. 5). Since the water-soaking tests were entirely empirical, there were no quantitative studies

TABLE 1.   *Summary of results including mean moisture contents (MC), ring widths (RW), and permeabilities (K). Standard deviations are shown in parentheses.*

Factor	Heartwood				Sapwood			
	Latifolia		Murrayana		Latifolia		Murrayana	
No. samples	464		69		479		72	
MC (%)	14.0	(2.8)	15.9	(2.5)	13.8	(2.7)	15.9	(2.9)
RW (mm)	2.1	(1.3)	2.2	(1.2)	1.8	(1.1)	1.1	(0.7)
K (darcy)	0.014 (0.023)*		0.008 (0.011)*		0.133 (0.095)***		0.088 (0.077)***	

* Varieties significantly different at 95% level.
*** Varieties significantly different at 99.9% level.

in the literature with which to compare these results. However, Siau and Shaw (1971), and Tesoro et al. (1966), found positive relationships between the amount of non-aqueous liquid retention and gaseous permeability in wood.

It is of interest to compare the permeability results of this study on lodgepole pine with those reported by Fogg (1969), who measured the axial air permeability of the four most important southern hard pines (*P. taeda, P. palustris, P. elliottii, P. echinata*). The mean sapwood permeability of these four woods was 0.45 darcy, somewhat more than three times the mean value (0.133 darcy) of var. *latifolia*, and about five times that (0.088 darcy) of var. *murrayana*, as reported here. The mean heartwood value he reported, of 0.013 darcy, was close to the values found in this study (0.014 darcy for var. *latifolia* and 0.008 darcy for var. *murrayana*).
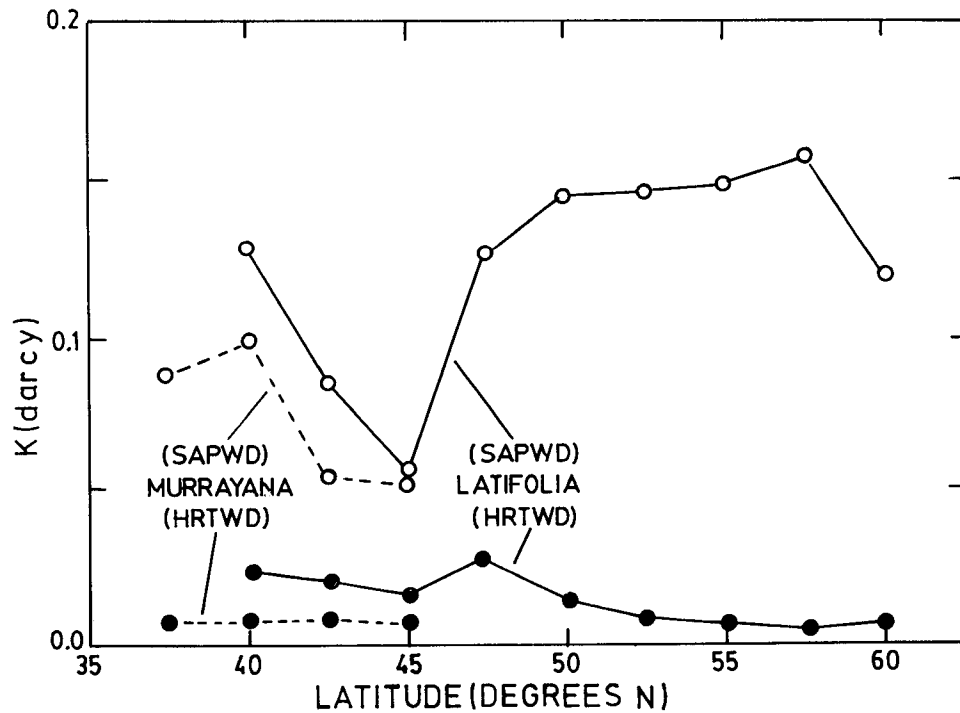

FIG. 4.   Plotted points of mean permeability *K* (darcy) against latitude, for sapwood and heartwood of both varieties.
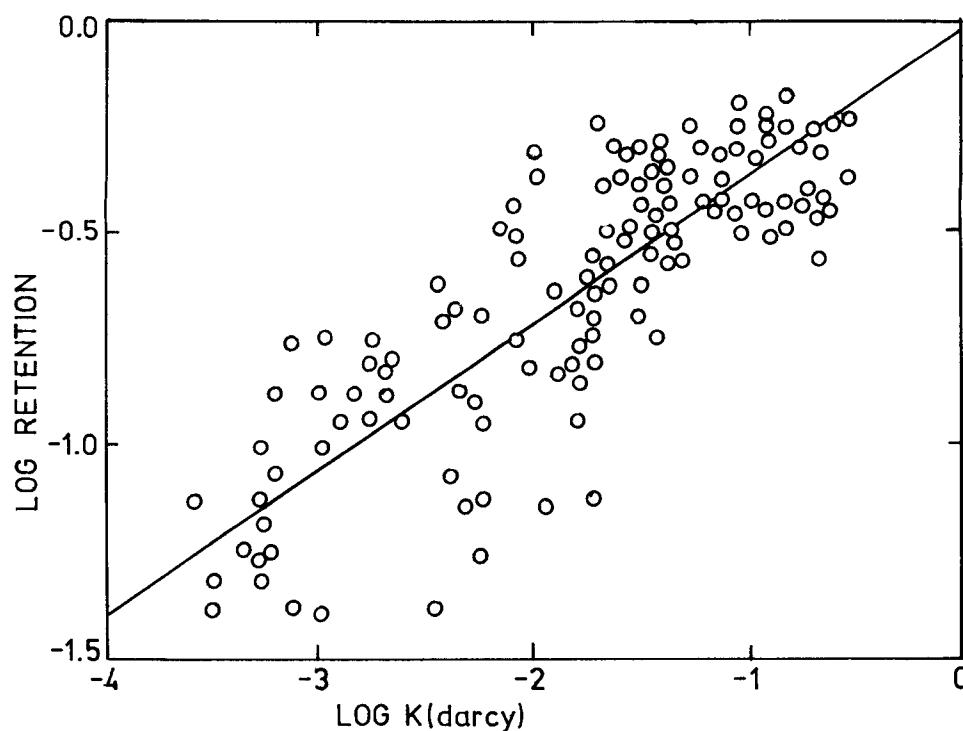
FIG. 5.   Plotted points and calculated regression curve of the logarithm of water retention (fraction of void volume filled) against the logarithm of permeability K (darcy), for var. *murrayana*.

From these comparative values, sapwood of lodgepole pine should be more resistant to treatment with fluids than that of the southern pines. However, the more refractory heartwood should have similar fluid treatment characteristics as those of the southern pines.

Shrinkage

The summary shrinkage statistics for both varieties, including sample size, mean and standard deviation, are shown in Table 2. The mean radial, tangential and volumetric shrinkages for var. *latifolia* were significantly lower ($P < 0.01$) than those for var. *murrayana*, based on t-test results. The mean values compare well with the corresponding values of 4.8, 7.4, and 12.3% given for lodgepole pine in the USDA Wood Handbook (1974). Longitudinal shrinkage for corewood of both

TABLE 2.   *Summary statistics on shrinkage.*

Factor*	Latifolia			Murrayana		
	Sample size	Mean (%)	(SD) (%)	Sample size	Mean (%)	(SD) (%)
S_r (mixed wood)	239	4.674	(0.693)	36	4.845	(0.905)
S_t (sapwood)	239	7.638	(0.892)	36	7.801	(1.070)
S_{lc}	197	0.472	(0.321)	23	1.109	(1.298)
S_{lm}	233	0.145	(0.103)	32	0.243	(0.303)
S_v	239	11.954	(1.181)	36	12.266	(1.462)

* S_r = radial shrinkage; S_t = tangential shrinkage; S_{lc} = longitudinal, corewood shrinkage; S_{lm} = longitudinal, maturewood shrinkage; S_v = volumetric shrinkage (calculated from S_r and S_t).

varieties was three to five times greater than that of maturewood, presumably because of the presence of juvenile wood in the corewood.

The mean basic specific gravities (G) were 0.402 for var. *latifolia* and 0.419 for var. *murrayana*, a highly significant difference ($P < 0.01$). These are lower than the respective mean values of 0.418 and 0.451 given by Koch (1987), but higher than the value of 0.38 reported in the USDA Wood Handbook (1974). The specific gravity values given by Koch were mean values for entire trees, and were based on green volumes. Those reported here are for one location in the tree and were based on volume of the water-soaked wood, previously air-dried.

A series of analysis of variance (ANOVA) tests was carried out on the shrinkage data for both varieties, to determine the effect on shrinkage of the primary factors of tree diameter, latitude, elevation (var. *latifolia* only), and specific gravity.

According to the analysis, tree diameter had no effect on the shrink-properties of either variety, except for radial shrinkage (S_r) in var. *murrayana*, for which a highly significant ($P < 0.01$) inverse relationship was detected. Latitude also had no effect on shrinkage of var. *latifolia*, but was significant ($0.01 < P < 0.05$) for S_r, S_t, and S_v in var. *murrayana*, shrinkage generally increasing with increasing latitude.

Specific gravity, as a dependent variable, was highly correlated with increasing diameter in var. *murrayana*, in agreement with the results of a full tree study by Koch (1987). For var. *latifolia*, however, the effect was not significant ($0.10 < P < 0.20$), although the same trend was evident. Specific gravity increased significantly ($P < 0.01$) with latitude for var. *latifolia* but not for var. *murrayana*.

Specific gravity, as an independent variable, had a highly significant ($P < 0.01$) positive effect on both the radial (S_r) and calculated volumetric (S_v) shrinkages of both varieties. It also had a smaller but significant positive effect ($0.01 < P < 0.05$) on tangential (S_t) shrinkage of var. *latifolia*, but not of *murrayana*. Tree-to-tree variation may account for the small observed effect of specific gravity on tangential shrinkage.

Boutelje (1973), Choong (1969b), and Yao (1969, 1972) all concluded that radial shrinkage is more strongly correlated with specific gravity than is tangential shrinkage, in agreement with the findings of this study. Since volumetric shrinkage is nearly equal to the sum of the radial and tangential shrinkages, volumetric shrinkage should also be dependent on specific gravity. Regression equations of measured radial (S_r), of calculated volumetric (S_v) shrinkages, and of the radial/tangential shrinkage ratio (S_r/S_t), each against specific gravity, were calculated for each variety (Table 3). Figures 6 and 7 show plots of the individual points, and the regression equations for S_v, and for S_r/S_t, against G, for var. *murrayana*.

The relationships between S_v and G, and S_r/S_t and G, were not significantly different for the two varieties; the corresponding data could thus be pooled. Analysis of the ratio S_v/G in the present study yielded an overall mean for the two varieties of 30.66% (±2.94). This is somewhat higher than the value of 29.2%, obtained using the values for S_v (11.1%) and G (0.38), given for lodgepole pine in the USDA Wood Handbook (1974).

Equilibrium moisture content

The sorption study produced three equilibrium moisture contents for each of the 62 moisture sorption samples, one at each relative humidity, 34.4, 65.0, and

TABLE 3.   *Regression equations of shrinkage vs. specific gravity G.**

Factor	Var. *latifolia* regression eq.	R^2	Var. *murrayana* regression eq.	R^2
Radial	$S_r = 11.952G - 0.140$	0.466	$S_r = 12.525G - 0.407$	0.567
Volumetric	$S_v = 15.442G + 5.883$	0.256	$S_v = 17.897G + 5.195$	0.389
Rad/Tang	$S_r/S_t = 1.242G + 0.118$	0.222	$S_r/S_t = 1.539G - 0.016$	0.442

* G = specific gravity (oven-dry weight/swollen-volume basis).

83.2%, all at 30 C. The mean A/D ratio was 0.791 (±0.019), at corresponding relative humidities, close to the mean A/D ratios reported by Choong (1969b) for the woods of several hard pines, most of which ranged between 0.77 and 0.82. Salamon et al. (1975) reported a mean A/D ratio for lodgepole pine of 0.84, with individual values varying between 0.74 and 0.94, over the humidity range from 40 to 80%.

Equilibrium moisture contents were measured at only three relative humidities (34.4, 65.0, 83.2%). In order to estimate the EMC at other humidities the data were fitted to an isotherm of the form,

$$M = A + B \ln[\ln(100/H)] \tag{10}$$

where M (%) is the estimated EMC at a given relative humidity H (%), and A and B are constants. The values of A and B are 5.929 and -4.210 with an R^2 of 0.996 for the pooled adsorption data, and 7.673 and -4.927 with an R^2 of 0.995, for desorption.
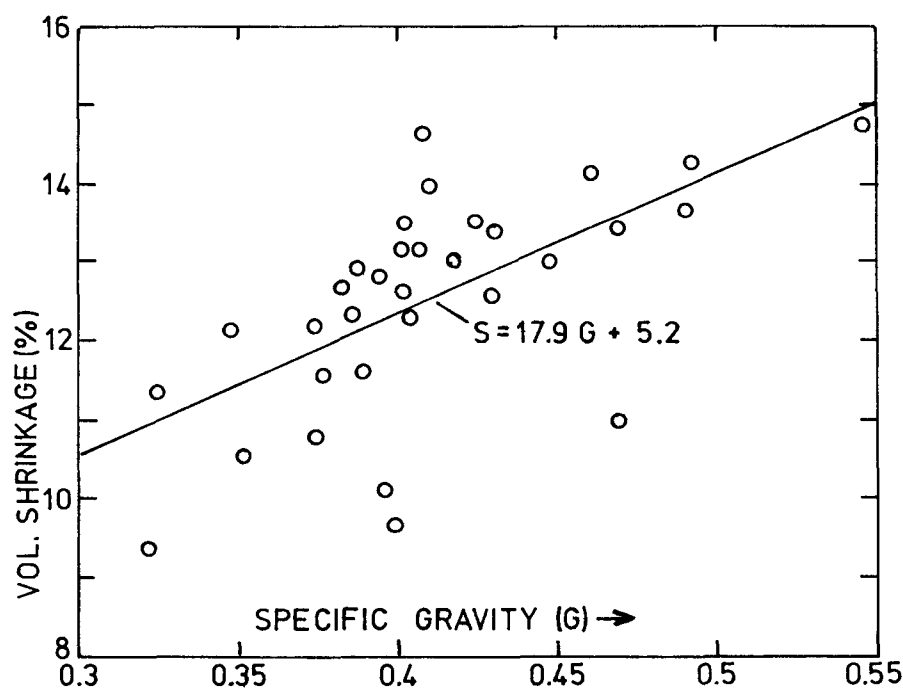

FIG. 6.   Plotted points and calculated regression of volumetric shrinkage against specific gravity for var. *murrayana.*
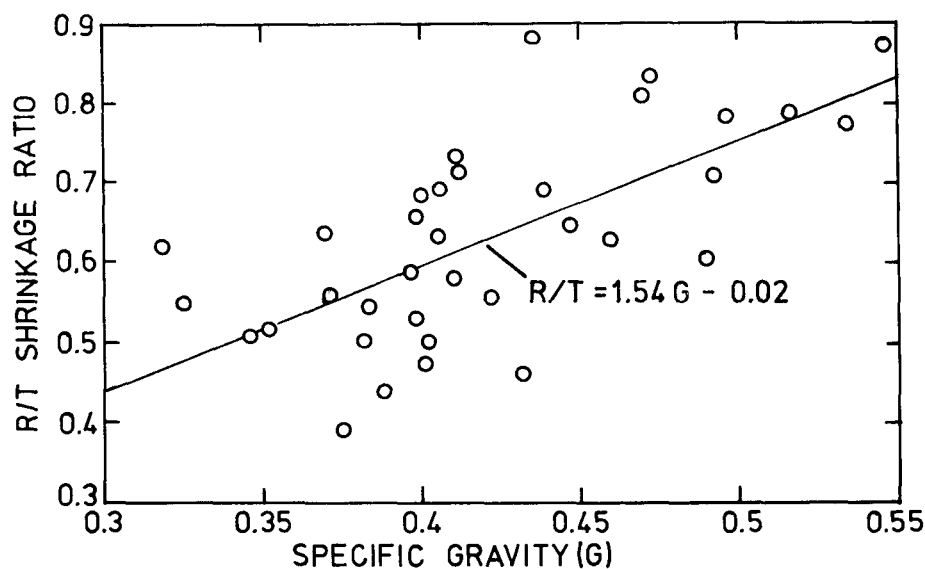
FIG. 7.   Plotted points and calculated regression curve of the radial/tangential shrinkage ratio against specific gravity for var. *murrayana*.

The analysis of variance indicated no difference between the sorption data for the two varieties at corresponding northern latitudes, of which there were only three, 40, 42.5 and 45 degrees. However, the EMC decreased with increasing latitude for both adsorption and desorption, at all three relative humidities (Fig. 8). Simple linear regression equations were calculated, relating A and B to latitude L over the total latitude range from 37.5 to 60 degrees, pooling the data for the two varieties where the latitudes overlapped. For adsorption the equations were A = 6.65 − 0.0152 (L), (R^2 = 0.85), and B = −4.60 + 0.0082 (L), (R^2 = 0.72). For desorption they were A = 8.16 − 0.0103 (L), (R^2 = 0.46), and B = −5.31 + 0.0081 (L), (R^2 = 0.69).

The general decrease in EMC associated with increasing latitude noted above may be related to the changes in the chemical constituents of lodgepole pine with latitude. Kim et al. (1989), who characterized the chemical constituents of lodgepole pine wood from the same trees used in the present study, reported that the overall holocellulose content decreased, while the alpha-cellulose and extractive contents generally increased, all with increasing latitude. Since the holocellulose is generally considered to consist primarily of hemicellulose and alpha-cellulose, this indicates that the most hygroscopic major component of wood, the hemicellulose, generally decreased with increasing latitude. Both a decrease in hemicellulose content and increase in extractive content with increasing latitude would account for the observed decrease in hygroscopicity.

SUMMARY AND CONCLUSIONS

This study on the physical properties of stemwood from the base of 279 lodgepole pine (*Pinus contorta*) trees (vars. *latifolia, murrayana*) consists of three parts. These are, air permeability, shrinkage, and moisture sorption.

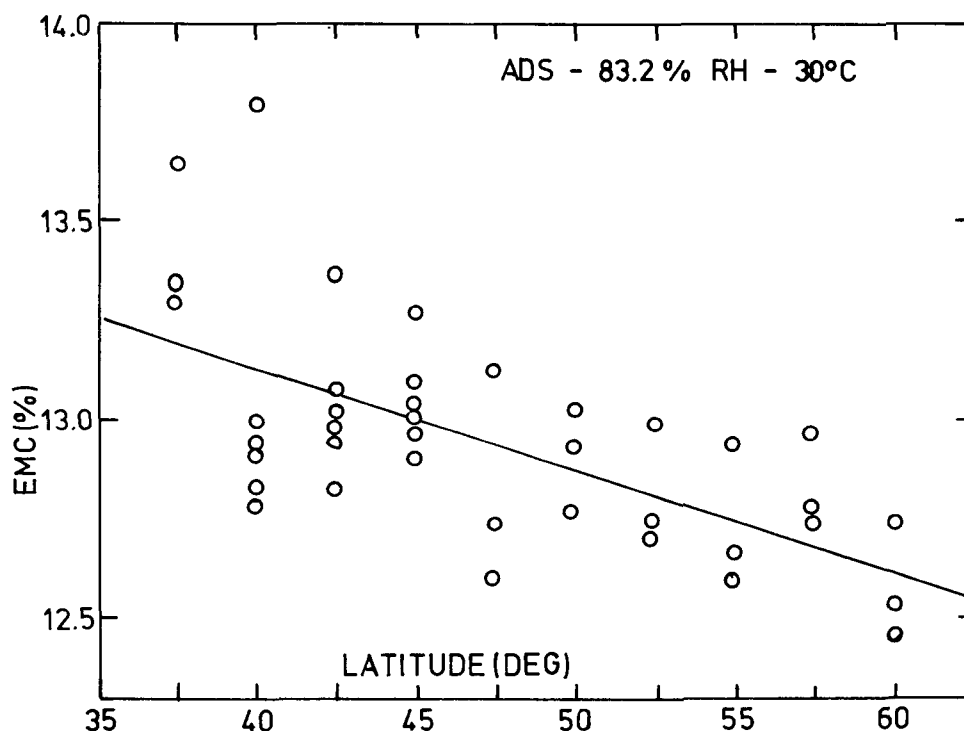1. In the permeability study, the longitudinal air permeabilities of the sapwood

FIG. 8.   Plotted points and calculated regression curve of EMC against latitude for both varieties, for adsorption at 83.2% RH, and 30 C.

and heartwood of lodgepole pine were measured with a steady-state apparatus. It was found that:

a. The mean sapwood permeability was about 10 times greater than that of heartwood. The mean permeabilities of var. *latifolia* were 1.5 times (sapwood) to 1.75 times (heartwood) greater than those of var. *murrayana*.

b. The most important source of variation following the difference between heartwood and sapwood was that among trees. Geographical locations, such as latitude and elevation, had no significant effect; and tree size had only a minor effect.

c. Mean pit pore radii of 1.5 μm and 1.3 μm were calculated for sapwood of vars. *latifolia* and *murrayana*, respectively, together with median values between 12–13 pit pores per mm^2 of wood cross-section.

d. Empirical water retention measurements, in terms of the amount of water absorbed after soaking for a prescribed period, correlated fairly well with air permeabilities measured on the same specimens.

2. In the shrinkage study the radial, tangential, and longitudinal (corewood from near the pith, and maturewood from near the circumference) shrinkage of 243 trees of var. *latifolia* and 36 trees of var. *murrayana* were measured. Volumetric shrinkages were calculated from the linear shrinkages in each case. Specific gravities, based on oven-dry weights and water-soaked volumes, were also calculated. Analysis of the data showed that:

a. Specific gravity was the most important single factor affecting shrinkage.

Radial and volumetric shrinkages as well as the ratio of radial to tangential shrinkage all increased with increase of specific gravity.

   b. Both mean specific gravity and volumetric shrinkage were 1.15 times greater for var. *murrayana* than for *latifolia*. The radial and tangential shrinkages were also greater for var. *murrayana*.

   c. The mean ratio of volumetric shrinkage to specific gravity (30.7 ± 2.9%) was essentially the same for both varieties.

   d. Tree size, latitude, and elevation had no effect on the shrinkage of var. *latifolia*, but for var. *murrayana* shrinkage was affected by both latitude and tree size.

3. In the moisture sorption study both adsorption and desorption EMCs were measured on 45 pooled samples of var. *latifolia* and 17 pooled samples of var. *murrayana* at 30 C and relative humidities of 34.4, 65.0 and 83.2%. The results indicated that:

   a. There was no difference in the sorption isotherms of the two varieties at corresponding latitudes.

   b. The EMCs generally decreased with increasing latitude.

   c. The mean adsorption/desorption ratio was 0.79 ± 0.02.

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