COMPRESSION DRYING OF SAPWOOD

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(Received April 1985)

ABSTRACT

A compression drying experiment carried out on small blocks of sapwood from *Pinus radiata, Araucaria cunninghamii, Eucalyptus regnans,* and *E. obliqua* is described. Effects of initial moisture content, speed of compression, specimen thickness and orientation on moisture loss and energy input were studied. All specimens were compressed perpendicular to the grain to the same stress in either a radial or tangential direction in a jig that prevented lateral expansion. Force and deformation changes of the specimens were recorded during compression, and water loss at the end of the process was measured. From these data, volumetric compressions, moisture losses, energy inputs, and energy efficiencies of water removal were calculated.

The analyses of variance confirmed that initial moisture content, species and wood specific gravity, amount of volumetric strain, rate of compression, and specimen orientation all affected unit water removal; specimen thickness did not. The lower density softwoods deformed to a greater extent than the hardwoods and lost more water. More water was removed from wetter specimens than drier ones at the same stress, and a slow compression rate caused a greater water loss than a more rapid rate. Specimens compressed tangentially lost more water than those compressed radially. Energy efficiency of water removal was greatest in the relatively low specific gravity *Pinus radiata* specimens with high moisture contents which were compressed tangentially at a slow rate.

Keywords: Pinus radiata, Araucaria cunninghamii, Eucalyptus regnans, E. obliqua, sapwood, compression, drying, moisture loss, energy input, moisture content, compression rate, orientation, specimen thickness.

INTRODUCTION

During recent years, the energy crisis has caused increased interest in the use of wood as a fuel. Within the developed countries, there is a trend to use wood as a substitute fuel where it can supply energy more cheaply than the nonrenewable alternatives such as oil. In less developed countries, where fuelwood is often the most important source of energy for domestic cooking and heating, it is simply the dwindling accessible supplies that are causing the crisis. Dried fuelwood, compared with the freshly cut green material, has a higher energy density, is lighter to transport, and can be burned more efficiently. A rapid, energy-efficient process for drying fuelwood would therefore be advantageous.

Compression drying is much more energy efficient than evaporative drying (Haygreen 1981, 1982; Liu and Haygreen, 1985) but, compared with other drying procedures, little research has been carried out into the process (Wingate-Hill 1983a). Wingate-Hill and Cunningham (1984b) report a study of compression

Wood and Fiber Science, 18(2), 1986, pp. 315–326

drying in small blocks of sapwood from four Australian species compressed to the same level of volumetric strain. This paper describes a similar experiment in which maximum compressive stress applied to the test specimens, as opposed to maximum strain, was held constant. These regimes represent two alternative methods that could be used in practice for water removal, that is, pressing a constant volumetric charge to a fixed stop or to a constant load in a platen press. The object of the experiment was to provide additional information on water losses, moisture content changes, and energy inputs and identify the factors, or combinations of factors, that have the major influence on these variables. This information could then be used for a preliminary assessment of the potential value of compression drying and an indication of where further research is required.

MATERIALS AND METHODS

Five factors likely to influence water removal per unit volume of wood were studied. These were species (4), initial degree of saturation (60 and 100%), specimen orientation (radial and tangential), rate of deformation (0.4, 8.0, 15.0 mm min^{-1}) and specimen thickness (5, 10 and 15 mm).

The species of wood used were two softwoods, radiata pine (*Pinus radiata,* PR), and hoop pine (*Araucaria cunninghamii,* AC); and two hardwoods, mountain ash (*Eucalyptus regnans,* ER) and messmate stringybark (*E. obliqua,* EO). This choice of species was made so that the influence of wood structure on moisture removal could be studied. The hardwoods and softwoods represented two different types of structure, the latter more permeable than the former. Both hardwoods have similar anatomies (Dadswell 1972), but the two softwoods are somewhat different. PR has bordered pits with tori, whereas the pits in AC have no tori and the pit membranes should be more permeable than those in PR. The wood samples were compressed perpendicular to the grain to remove moisture. Green wood from the four species shows a fairly uniform increase in its resistance to this type of compression in the order PR, least resistant, AC, ER, and EO (Bolza and Kloot 1963).

Degree of saturation was used in preference to moisture content because it refers to the proportion of the total void space within the wood occupied by water and it is this "free" water that is removed during compression drying. Sixty and 100% saturation were chosen to represent the extremes. Sixty percent is a little below the mean value measured in some preliminary sampling of EO, the driest species which, in common with the rest of the samples, were cut near the end of a very severe drought. Sapwood is probably never 100% saturated in practice, but data on water losses caused by compression from saturated sapwood represent an upper datum for a given species and compressive strain.

The rate of deformation of 0.4 mm min^{-1} was as close as it was possible to get with the equipment available to the standard rate of 0.3 mm min^{-1} for testing the strength of wood in compression perpendicular to the grain (Mack 1979). Fifteen mm min^{-1} was the highest rate available on the testing machine. Faces of the specimens subject to compression were the small standard size for specimens compressed perpendicular to the grain, 20 mm wide × 60 mm long (Mack 1979) so that adequate compressive strain could be achieved with the 20 kN capacity testing machine available. The thinnest specimens were intended to approximate to wood chips and 5 mm was the minimum thickness that could be machined conveniently and accurately without the specimens breaking.

The sources of sample material and some details of the trees are given in

Wingate-Hill and Cunningham (1984b). A randomized split plot design was used for the experiment. Three trees were selected at random from each species at each site to provide the replication. Lengths of stem close to breast height were cut from the selected trees. These samples were wrapped immediately in polyethylene sheeting to minimize moisture loss and were stored in a refrigerator until required. Two discs, a little thicker than 60 mm, were cut from each sample, and twelve test specimens were cut from around the periphery of each disc just inside the bark. Each test specimen was machined accurately to 20 × 20 × 60 mm, using a method described by Wingate-Hill and Cunningham (1984a). Six each of the 5-, 10-, and 15-mm-thick specimens were then cut from these 12 specimens in pairs so that each member of a pair came, as far as possible, from adjacent locations in the original sample disc. One specimen from each pair was compressed tangentially, the other radially. All specimens from one sample disc of each pair were conditioned as close as possible to 100% saturation; those from the other disc were conditioned to approximately 60% saturation.

Test specimens requiring almost complete saturation were submerged in a beaker of water within a desiccator, which was evacuated for at least six hours. Air was then admitted and water entered the previously air-filled voids in the wood. A procedure had to be devised for conditioning specimens to 60% saturation to reduce the initial unacceptably wide range in specimen degree of saturation values caused by the relatively large variations in sapwood specific gravity and moisture content from tree to tree. The procedure adopted was to test all the almost 100% saturated samples in each batch, then oven-dry them. The mean oven-dry mass (M) for each batch was substituted into Eq. (1) with specimen volume (V) and required degree of saturation (S) to calculate the target mass (TM) down to which the samples selected for 60% saturation had to be dried.

$$TM = S(V - 0.95M) + 1.30M \tag{1}$$

The derivation of Eq. (1) is given in Wingate-Hill and Cunningham (1984b).

Prior to compression, specimens were weighed and measured, then inserted into a jig that confined the vertical side faces so that lateral expansion could not occur during compression. The advantage of this type of compression was that specimen size at the end of each test could be measured easily and accurately and macroscopic cracking was eliminated. Compression was carried out in a small universal testing machine. A record of the forces applied to each specimen and the resulting deformation were taken by using an X-Y recorder. When the required load was reached, all water was quickly wiped from the ends of each specimen to prevent re-absorption, and the load was removed. Each specimen was then taken out of the jig, weighed, oven-dried, and re-weighed.

RESULTS

Table 1 contains the species means for initial degree of saturation, moisture content, and specific gravity. The aim was to condition all specimens within the "lower" and "upper" groups to the same degree of saturation so that there would be a uniform basis for comparing moisture loss from the different species, specimen thicknesses, etc. Moisture contents of the specimens were more variable than their degrees of saturation because of the differences in specific gravity both within and between species.

Analyses of variance were carried out on the data derived from the dimensional

TABLE 1. *Initial mean values for degree of saturation, moisture content and specific gravity of the test specimens.*

Species	Degree of saturation (%)		Moisture content (%)[a]		Specific gravity[b]
	Lower[c]	Upper[c]	Lower	Upper	
Pinus radiata	62.1	99.8	108.2	154.8	0.46
Araucaria cunninghamii	59.6	99.9	98.1	148.3	0.48
Eucalyptus regnans	61.8	99.0	101.1	140.8	0.48
Eucalyptus obliqua	64.1	97.6	90.0	116.2	0.54
Coefficient of variation[d]	1.9		4.9		2.9

[a] Gravimetric, oven-dry basis.
[b] (Oven-dry mass of wood sample/mass of a volume of water equal to the green volume of the sample.)
[c] "Lower" and "upper," refer to the target degrees of saturation of 60% and 100% respectively, and to the corresponding wood moisture contents.
[d] For all specimens.

and weight measurements taken on the specimens and from the recorder charts. All the data sets met the requirements for homogeneity and additivity except the energy input per unit water loss set, which was transformed by $\log_e$ prior to analysis. A summary of these analyses is given in Table 2. All specimens were subjected to approximately the same force, i.e., close to the maximum that the testing machine could apply and, since the area of the horizontal faces in all specimens was the same, they were all subjected to similar maximum stresses. The mean maximum stress was 17.4 MPa, range 16.6 to 18.6 MPa.

Maximum volumetric strains caused by the imposed stresses changed very significantly with all the primary variables except initial degree of saturation (Table 2). Some illustrative mean values are given in Table 3. The softwoods, PR and AC, were deformed more than the hardwoods, in some cases by up to twice as much. PR was compressed more than AC in every thickness, orientation combination, but the differences between ER and EO were less consistent. Volumetric strains changed very significantly with specimen orientation; they were always greater in the tangential orientation except in 5-mm-thick EO specimens. The amount of compression decreased with an increase in the rate of compression (Table 3) in all species.

These changes in volumetric strain were reflected in the reductions in moisture content and mass caused by compression, with the initial degree of saturation as a major additional variable influencing the values (see Tables 4–7). Mass reductions are listed (in Table 5) in addition to moisture content reductions because some of the high values, especially in the softwoods, may have important implications in relation to lowering transport costs of green timber (Wingate-Hill, 1983b). The order of moisture content and mass loss was always PR, AC, ER, EO (the lowest), and for comparable samples those with the highest initial degree of saturation lost the most water. Samples compressed in the tangential direction generally lost more water than those compressed radially, and moisture loss decreased as the rate of compression increased.

Some mean values of energy inputs during compression are listed in Table 6. The energy inputs were obtained by expressing the area beneath each force deformation curve, drawn on graph paper by the X-Y recorder, as a proportion of the initial mass of the specimen. General trends were for energy input to decrease in the order AC, PR, EO, and ER with tangentially compressed specimens ab-

TABLE 2. *Summarized analyses of variance.*

Source of variation	Degrees of freedom	Variance ratios: Maximum volumetric strain	Moisture content reduction	Mass reduction	Energy input/unit initial wood mass	Energy input/unit water loss	Energy increase/energy input ratio
Species (S)	3	24.2***	13.3**	31.5***	99.1***	14.0**	17.9**
Residual	6						
Degree of saturation (DS)	1		278***	767***	221***	290***	820***
S × DS	3				15.8***	9.94**	10.9**
Residual	8						
Compression rate (SR)	2	159***	36.9***	80.1***	65.7***	16.0***	8.54***
Thickness (T)	2	17.9***					
S × SR	6	14.6***	7.52***	15.1***	45.1***	2.74*	
DS × SR	2					15.9***	9.03***
S × T	6	2.53*					
S × DS × SR	6					5.21***	3.21**
Residual	128						
Orientation (O)	1	39.8***	40.5***	59.1***	36.7***	15.6***	4.78*
S × O	3	7.38***	7.72***	10.3***	103***	23.6***	35.7***
SR × O	2				7.36***		
S × DS × O	3				3.07*		9.46***
S × SR × O	6	2.51*			3.36*		
S × T × O	6	2.42*					
Residual	144						

NB: The thick horizontal lines mark divisions between strata in the analyses of variance. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

TABLE 3. *Mean values of maximum volumetric strain (%).*[a]

Species	Orientation[b]			Orientation[b]			Orientation[b]		
	Radial	Tangential	Means	Radial	Tangential	Means	Radial	Tangential	Means
	Thickness (mm)								
	5			10			15		
Pinus radiata	40.1[b]	43.0	41.6	43.3	45.2	44.3	44.6	47.4	46.0
Araucaria cunninghamii	37.9	38.4	38.1	40.1	40.9	40.5	39.2	42.3	40.7
Eucalyptus regnans	19.4	20.5	20.0	21.8	22.8	22.3	23.8	24.2	24.0
Eucalyptus obliqua	23.7	22.6	23.1	21.7	22.9	22.3	23.3	23.4	23.3
Means	30.3	31.1		31.7	33.0		32.7	34.3	
	Compression rate (mm min^{-1})								
	0.4			8.0			15.0		
Pinus radiata	45.2	46.9	46.0	41.8	44.5	43.1	40.9	44.2	42.5
Araucaria cunninghamii	42.8	44.1	43.4	37.8	40.2	39.0	36.7	37.4	37.1
Eucalyptus regnans	31.5	30.5	31.0	16.9	18.9	17.9	16.6	18.1	17.3
Eucalyptus obliqua	27.1	27.9	27.5	21.5	21.3	21.4	20.2	19.6	19.9
Means	36.6	37.4		29.5	31.2		28.6	29.8	

Approximate standard errors of differences of means for the species × thickness × orientation interactions were:

	Maximum volumetric strain
For any pairwise comparison across species	3.4
For any pairwise comparison within species	1.1

Approximate standard errors of differences of means for the species × compression × orientation interactions were:

	Maximum volumetric strain
For any pairwise comparison across species	3.3
For any pairwise comparison within species	1.0

[a] Volumetric strain defined as: ((initial volume − volume at end of compression)/initial volume) × 100%.
[b] Samples were compressed in the radial and tangential directions, respectively.

sorbing more energy than radially compressed specimens of the two softwoods, but the reverse was true in the hardwoods. The two groups also behaved differently with respect to the effects of strain rate variation. The largest difference is between the compression rates of 0.4 and 8.0 mm min^{-1} in the hardwoods; the other differences are relatively small.

The energy efficiency of water removal was expressed as energy input per unit of water lost during compression and a selection of mean values are listed in Table 7. In the case of PR the high energy input values were matched by large water losses so that the efficiency of water removal was relatively high. Generally the descending order of efficiency was AC next then ER and EO. Less energy was required per unit of water removal from the fully saturated specimens compared with the drier ones, and the efficiency of water removal decreased as compression rate increased in the specimens with the lower degree of saturation but not in the fully saturated specimens. Radial compression was less efficient than tangential in the hardwoods, ER and EO, and in AC, but the reverse was the case for the softwood PR.

When water is removed from wood, there is an increase in net heating value of the wood because less water has to be heated and vaporized when it is burned. This increased energy value can be used as an alternative means of measuring efficiency in compression drying, particularly appropriate in the case of fuelwood. The increase in net heating value is expressed as a proportion of the energy input required to remove the water. Representative values of this energy ratio are given

TABLE 4. *Mean values of moisture content reduction (%)*[a] *and initial moisture content (%).*[b]

Species	Initial degree of saturation		Orientation		Compression rate (mm min⁻¹)			
	Lower	Upper	Radial	Tangential	0.4	8.0	15.0	Means
Pinus radiata	61.9[a]	106.1	80.4	87.5	85.4 (130.6)[b]	83.8 (131.8)	82.8 (132.2)	84.0 (131.5)
Araucaria cunninghamii	51.2	96.7	72.1	75.8	77.1 (122.8)	74.0 (124.1)	70.7 (122.6)	73.9 (123.1)
Eucalyptus regnans	21.0	54.0	36.3	38.7	50.7 (121.2)	31.3 (119.5)	30.5 (122.2)	37.5 (121.0)
Eucalyptus obliqua	18.9	48.3	33.5	33.7	38.7 (103.2)	31.6 (101.7)	30.4 (104.5)	33.5 (103.1)
Means	38.2	76.2	55.5	58.9	63.0 (119.4)	55.1 (119.3)	53.6 (120.4)	

Approximate standard errors of differences of means were:

	Moisture content reduction			
	Initial degree of saturation	Orientation	Compression rate	Initial moisture content
For any pairwise comparison across species	10.4	9.9	10.1	12.3
For any pairwise comparison *within* species	4.6	1.0	2.3	2.3

[a] (Initial MC (%) − final MC (%).)
[b] Initial MC (%), gravimetric, oven-dry basis.

in Table 8. The percentage increase in net heating value was calculated by using Eqs. (2) and (3), viz.,

$$\Delta NHV = 100R(MC_g + 1)/(y - MC_g) \tag{2}$$

Where,

$$\text{Mass reduction ratio, } R = (M_g - M_f)/M_g \tag{3}$$

and,

M_f = mass of specimen after compression de-watering
M_g = initial mass of specimen
MC_g = initial moisture content of specimen, oven-dry basis
y = a constant equal to 7.1

The derivation of Eq. (2) is given in Wingate-Hill and Cunningham (1984b).

Mean values of the energy ratio showed a similar pattern of variation to the values for energy efficiency of water removal (Table 7). Generally the ratio decreased in the order PR, AC, ER, EO, except in the fully saturated specimens of AC and ER, where the order was reversed. Efficiency fell as compression rate was increased in the specimens with the lower initial degree of saturation but did not change much in the fully saturated specimens as compression rate was increased. Tangential compression was more efficient than radial in AC, ER, and EO but not in PR.

DISCUSSION

Changes that occurred within the specimens during compression were very complex because the specimen volume and mass, the external forces acting upon

TABLE 5. *Mean values of mass reduction (%).*[a]

Species	Initial degree of saturation		Orientation		Compression rate (mm min^{-1})			
	Lower	Upper	Radial	Tangential	0.4	8.0	15.0	Means
Pinus radiata	29.6	41.5	34.1	37.0	36.3	35.4	35.0	35.5
Araucaria cunninghamii	27.7	38.9	32.3	34.3	34.8	33.3	31.8	33.3
Eucalyptus regnans	10.3	22.2	15.8	16.7	22.1	13.5	13.1	16.2
Eucalyptus obliqua	9.8	22.2	15.9	16.0	18.4	15.3	14.3	16.0
Means	19.4	31.2	24.5	26.0	27.9	24.4	23.5	

Approximate standard errors of differences of means were:

	Initial degree of saturation	Orientation	Compression rate
For any pairwise comparison across species	2.74	2.69	2.74
For any pairwise comparison within species	0.85	0.38	0.72

[a] (Reduction in mass due to moisture loss/initial mass) × 100%.

it, and the forces on its constituents were all changing throughout the compression process. The external compressive force was supported initially by the wood structure, water and air in the wood and, as a small amount of lateral expansion occurred, by frictional forces on the vertical faces in contact with the jig. The air and wood structures were compressible, but the water was not. Nevertheless air (in the nonsaturated specimens) and water vapor were forced out of the specimens first as the wood structure was deformed. Near the region on the force/deformation curve corresponding to the limit of proportionality, water began to appear on the ends of the specimens initially conditioned to 60% saturation. Water flow increased rapidly to a maximum then slowed down, but did not stop completely until the load was removed. Water losses caused by compression would therefore have been slightly greater if specimens had been left under load for a longer period.

Initial degree of saturation was one of the most important factors influencing moisture loss (Tables 2 and 4). The greater water loss from the two softwoods was expected in view of their lower specific gravities, lower compressive strengths and greater volumetric strains, and initial moisture contents compared with the

TABLE 6. *Mean values of energy input per unit initial wood mass during compression (Jg^{-1}).*

Species	Initial degree of saturation		Compression rate (mm min^{-1}) 0.4 Orientation		8.0 Orientation		15.0 Orientation		
	Lower	Upper	Radial	Tangential	Radial	Tangential	Radial	Tangential	Means
Pinus radiata	3.5	2.9	2.9	3.4	2.9	3.5	3.0	3.6	3.2
Araucaria cunninghamii	4.5	3.6	3.8	4.0	4.0	4.2	4.0	4.2	4.0
Eucalyptus regnans	2.4	1.8	2.9	2.4	1.9	1.8	1.8	1.8	2.1
Eucalyptus obliqua	2.5	2.3	2.8	2.7	2.4	2.2	2.2	2.0	2.3
Means	3.2	2.6	3.1	3.1	2.8	2.9	2.7	2.9	

Approximate standard errors of differences of means were:

	Initial degree of saturation	Compression rate
For any pairwise comparison across species	0.14	0.13
For any pairwise comparison within species	0.08	0.06

TABLE 7. *Mean values of energy input per unit water lost during compression.*[b]

Species	Orientation		Initial degree of saturation							
			Lower				Upper			
			Compression rate (mm min^{-1})				Compression rate (mm min^{-1})			
	Radial	Tangential	0.4	8.0	15.0	Means	0.4	8.0	15.0	Means
Pinus radiata	2.17[a]	2.25	2.46	2.47	2.52	2.48	1.91	1.93	1.97	1.94
	(9.2)[b]	(9.9)	(11.8)	(12.0)	(12.6)	(12.1)	(6.8)	(6.9)	(7.2)	(7.0)
Araucaria cunninghamii	2.51	2.50	2.68	2.80	2.85	2.78	2.17	2.20	2.24	2.20
	(13.0)	(12.7)	(14.8)	(16.8)	(17.9)	(16.5)	(8.8)	(9.3)	(9.5)	(9.2)
Eucalyptus regnans	2.80	2.61	2.98	3.43	3.43	3.28	2.13	2.10	2.08	2.10
	(20.9)	(16.6)	(20.4)	(35.0)	(32.3)	(29.2)	(8.5)	(8.2)	(8.1)	(8.3)
Eucalyptus obliqua	2.85	2.76	3.20	3.24	3.39	3.28	2.37	2.36	2.28	2.34
	(20.1)	(18.2)	(25.5)	(26.9)	(31.1)	(27.8)	(10.8)	(10.7)	(9.8)	(10.4)
Means	2.58	2.53	2.83	2.98	3.05		2.15	2.15	2.14	
	(15.8)	(14.4)	(18.1)	(22.7)	(23.5)		(8.7)	(8.8)	(8.7)	

Approximate standard errors of differences of means were:

	Orientation	Initial degree of saturation
For any pairwise comparison across species	0.10	0.13
For any pairwise comparison within species	0.02	0.11

[a] A $\log_e$ transformation was carried out on the data prior to statistical analysis.
[b] Numbers in brackets are the original, untransformed means (J g^{-1}).

TABLE 8. *Mean values of energy ratio.*[a]

			Initial degree of saturation							
	Orientation		Lower				Upper			
			Compression rate (mm min⁻¹)				Compression rate (mm min⁻¹)			
Species	Radial	Tangential	0.4	8.0	15.0	Means	0.4	8.0	15.0	Means
Pinus radiata	336	305	242	239	226	235	413	407	396	405
Araucaria cunninghamii	239	242	192	171	161	174	320	303	297	307
Eucalyptus regnans	212	244	146	104	93	114	334	343	348	342
Eucalyptus obliqua	182	197	117	115	97	110	257	265	287	270
Means	242	247	174	157	144		331	330	332	

Approximate standard errors of differences of means were:

	Orientation	Initial degree of saturation
For any pairwise comparison across species	18.6	21.9
For any pairwise comparison within species	4.4	14.6

[a] (Increase in net heating value of wood due to compression de-watering/energy input during compression.)

hardwoods. The trend of differences in specific gravity between species (Table 1) paralleled, in an inverse manner, moisture loss differences and was probably a major causative factor. Moisture content reductions in PR and AC were similar to those reported by Haygreen (1981) for 25- × 25- × 12-mm-thick blocks of Loblolly pine (SG 0.40) and yellow poplar (SG 0.38) at similar initial moisture contents and volumetric strains. Specimen orientation had a highly significant influence on volumetric strain and water loss (Tables 2 and 3). The authors are unable to explain why thicker specimens generally had greater volumetric strains than thinner specimens and those compressed tangentially deformed to a greater extent and lost more water than those compressed radially. Indeed, according to the theory put forward by Bodig (1965), in which weaker earlywood layers account for most of the deformation in radial compression and in tangential compression the latewood layers act as columns supported laterally by the earlywood layers, one would expect greater strain in thinner specimens and higher strains and water losses in the radial rather than the tangential orientation. Differences due to orientation were quite small in the hardwood specimens but larger in the softwoods, especially PR (Table 3). However, since compression is most likely to be carried out in practice in the radial direction, it is doubtful whether advantage can be taken of the apparent benefits of tangential compression.

Volumetric strain, moisture content, and mass reductions all decreased as compression rate was increased (Tables 3, 4, and 5). The decrease in water loss with increase in compression rate was to be expected if one assumes that the vessels and tracheids in the specimens approximate to long thin tubes. Mean rate of water loss increased with strain rate and according to the Hagen-Poiseuille theory of flow in long tubes pressure drop is directly proportional to mean velocity or (mean velocity)$^{7/4}$ for laminar or turbulent flow, respectively (Kay 1968; Siau 1984). Haygreen (1982) also noted these time-dependent effects in compression drying but in a different type of experiment. He compressed 25-mm cubes of birch (SG 0.54) and aspen (SG 0.40) as rapidly as possible to given volumetric strains and measured the water loss after maintaining the compression for varying time periods. The increase in water removal with time under compression was quite small in birch but much greater in the lower density species aspen.

In a commercial compression drying process one problem would be to balance the greater moisture loss per unit initial mass of wood at low deformation rates against the increased total water loss per unit time, that is, greater throughput rate of processed wood, at the higher compression rates.

At the maximum stress used in this experiment, the hardwoods were compressed less than the softwoods and the actual energy input was lower (Tables 2, 3, and 6). However, the hardwoods lost much less water than the softwoods (Table 4) so that the energy inputs per unit of water lost (Table 7) were generally higher and their energy ratio values lower (Table 8) than corresponding values for the softwoods. Haygreen (1982) found the same thing in comparing compression drying of red oak (SG 0.48) with balsam fir (SG 0.35).

Data in Tables 7 and 8 emphasize the factors that were important in affecting the energy efficiency of compression drying, i.e., efficiency was highest in the lowest density wood, PR, with a high initial moisture content compressed slowly. The work of Haygreen (1981, 1982), Wingate-Hill and Cunningham (1984b) and data in this paper all lead to the conclusion that compression drying is likely to show its greatest value when applied to freshly cut softwoods with high moisture content intended for use as a fuel.

CONCLUSIONS

Compression to a constant stress, perpendicular to the grain caused moisture losses and moisture content changes in specimens from the four species tested. These changes increased with initial moisture content but decreased with wood specific gravity and rate of compression. Tangential compression quite consistently resulted in a greater moisture loss than radial compression, but no reason for the differences could be found. Volumetric strain was greater in the thicker specimens; otherwise specimen thickness had no significant effect in the compression drying process.

There were generally small differences in maximum volumetric strain and water loss between the two softwoods, which lost the most water, and between the two hardwoods but greater differences between the two groups.

Energy efficiency of water removal was highest in the low density specimens with high initial moisture content compressed slowly. Tangential compression resulted in greater efficiency in the hardwoods but a small or reverse effect in the two softwoods.

The greatest potential value of compression drying probably lies in removing water from softwoods with high initial moisture content that are to be used as a fuel.

ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance provided by Messrs. P. O. Carden, K. W. Groves, D. M. Stodart, J. Hartley and H. C. Wheeler; and thank the University of New South Wales, Faculty of Military Studies for use of a universal testing machine. Wood samples were kindly supplied by A. C. T. Forests; Department of Forestry, Queensland, and the Forestry Commission of New South Wales.

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