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THE BEHAVIOUR OF FIVE WOOD SPECIES IN COMPRESSION[1]

by

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SUMMARY

Five wood species, Oregon ash (*Fraxinus latifolia* Benth.), Balau (*Shorea* spp.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Western red cedar (*Thuja plicata* Donn ex D. Don), and Trembling aspen (*Populus tremuloides* Michx.) were loaded in compression longitudinally, radially and tangentially. The wood cubes were conditioned to one of four moisture contents prior to loading. Small cubes were loaded until no void space remained after which samples were released and soaked in water. Stress/strain curves were recorded over the whole range of strain and cube thicknesses were recorded at the end of the compression, after release from the testing apparatus, and after soaking in water. Denser woods resulted in a greater Young's modulus, higher levels of stress and shorter time to densification than did less dense woods. Higher initial moisture contents apparently increased the plasticity of the wood leading to a lower Young's modulus and lower levels of stress during compression, greater springback after release of stress and greater recovery after swelling in water. Differences observed in the radial and tangential behaviours were believed to be due to the supporting action of the rays when the wood was compressed in the radial direction in balau and trembling aspen and to the relative difference between the lower density earlywood and higher density latewood regions in ash, Douglas-fir and western red cedar.

Key words: Wood anatomy, compression, springback, swelling.

INTRODUCTION

In the formation of flakeboard it has been recognized that in the plane of the mat the compression experienced by the wood flakes is not uniform due to the random nature of the mat formation. Certain areas will contain greater numbers of flakes in the thickness of the mat and thus when the mat is pressed the flakes in those regions will experience greater crushing stresses than will those flakes in regions containing fewer flakes. This phenomenon leads to a horizontal density distribution within the pressed

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2) Deceased.

mat (Suchsland 1962, 1967). As a result of the compaction occurring during formation the average density of the finished flakeboard may be twice that of the wood raw material. Thus the strain experienced by some of the wood flakes will be well above the elastic limit in compression perpendicular to the grain. As part of this laboratory's continuing investigations of the behaviour of wood during the formation of wood flake composites a study of the compression behaviour of five different wood species was conducted. The objective of this study was to characterize the behaviour of the wood species in compression longitudinally, radially and tangentially in terms of their stress/strain relationships and the recovery of the wood after release of the compression stresses and soaking in water.

PREVIOUS WORK

Bodig (1965) studied four wood species at a moisture content of 10% and related their anatomy to their observed behaviour in compression up to a strain level of 0.20. Theories of weak layers occurring in compression radially and of spaced column behaviour in compression tangentially were discussed. Kennedy (1968) investigated the behaviour of nine wood species in compression perpendicular to the grain at moisture contents of 4.0–5.5%. Ring orientation and wood specific gravity strongly influenced the strength and stiffness of the samples tested. The radial : tangential ratio of mechanical properties increased with higher ray volumes and decreased with greater latewood percentage and differential density between earlywood and latewood within a growth increment. Gibson and Ashby (1988) studied the compression behaviour of five wood species ranging in relative density from 0.05 to 0.50 at a moisture content of 12%. They used scanning electron microscopy to observe the mechanism of deformation of balsa wood in the longitudinal and transverse directions. In transverse compression the collapse of the cells started at the surface of the loading plate and then proceeded inwards as the compression continued. In compression longitudinally the cells collapsed by yielding and fracture of planes of material where the ends of adjacent layers of cells joined together. In woods of higher density localized plastic buckling of the cells wall can also occur. Wolcott (1989) compressed small blocks and flakes of yellow poplar conditioned to different moisture contents and temperatures. The cell wall modulus decreased with increasing temperature and moisture content. The effective cell wall modulus of the flakes compressed radially was approximately twice that of the flakes compressed tangentially due to the reinforcing action of the rays. Bariska (1996) studied the relationships between wood anatomy and fracture mechanics when small wood specimens were stressed to failure under compression and under tension. Four wood species were selected for their macroscopically distinct textures in the radial and tangential directions. Video recordings of the specimens being tested in a scanning electron microscope were obtained. Under radial compression, when rows of tracheids or rings of pores were present, these regular structures collapsed together in a tangential row. The build-up was slow but failure propagation was sudden. At the failure front the damage progressed one cell row at a time.

Table 1. Air-dry densities and number of growth rings per inch for wood species studied.

Species	Air-dry density (g/cm^3)	Growth rings per inch
Ash	0.710	11.0
Balau	0.979	indistinct growth rings
Western red cedar	0.323	28.7
Douglas-fir	0.503	24.4
Aspen	0.400	17.5

Air-dry density is based on the weight and volume measured in the air-dry condition.
All values shown are the averages of ten measurements.

MATERIALS AND METHODS

Five species with different densities (see Table 1) and distinct anatomies were studied: Oregon ash (*Fraxinus latifolia* Benth.), a ring-porous hardwood; balau (*Shorea* spp.), a diffuse-porous hardwood; Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), an abrupt transition softwood; western red cedar (*Thuja plicata* Donn ex D. Don), a softwood which is described as having an abrupt early–latewood transition (Panshin & De Zeeuw 1980) but the relative proportion of latewood is so low that the nature of the transition from earlywood to latewood is not of any great importance; and trembling aspen (*Populus tremuloides* Michx.), a diffuse-porous hardwood (see Figure 1). The density of each wood was determined according to ASTM D2395 (Anonymous 1983). Ten samples of each wood were measured. The number of growth rings per inch was determined from ten samples of each wood.

Cubes of wood 25.4 mm in dimension were cut from carefully selected air dry wood with the growth rings running as parallel as possible to one face of the cube. The cubes were marked in five evenly spaced locations on the surface to be loaded and the thickness of the cubes was measured at those locations. The cubes were weighed and then were conditioned in different environments to attain moisture contents of 5, 10 or 20%. Five samples of each wood were measured at each environment to determine the moisture content. Some cubes were also aspirated and soaked in cold water to attain a moisture content greater than that of the fiber saturation point. Each block was remeasured prior to testing. The cubes were loaded in compression, using a Materials Testing System 810 Universal Testing Machine, longitudinally, radially or tangentially to the grain. Radial loading refers to loading applied in the radial direction (i.e., loading applied to the tangential face) and tangential loading refers to loading applied in the tangential direction (i.e., loading applied to the radial face). The loading speed of the compression head was 0.50 mm/min. The samples were contained within a steel frame either 26.0 or 28.0 mm square in order to minimize out of plane deformation during testing. Three replications were performed for each set of testing and conditioning variables. The stress/strain data were recorded automati-

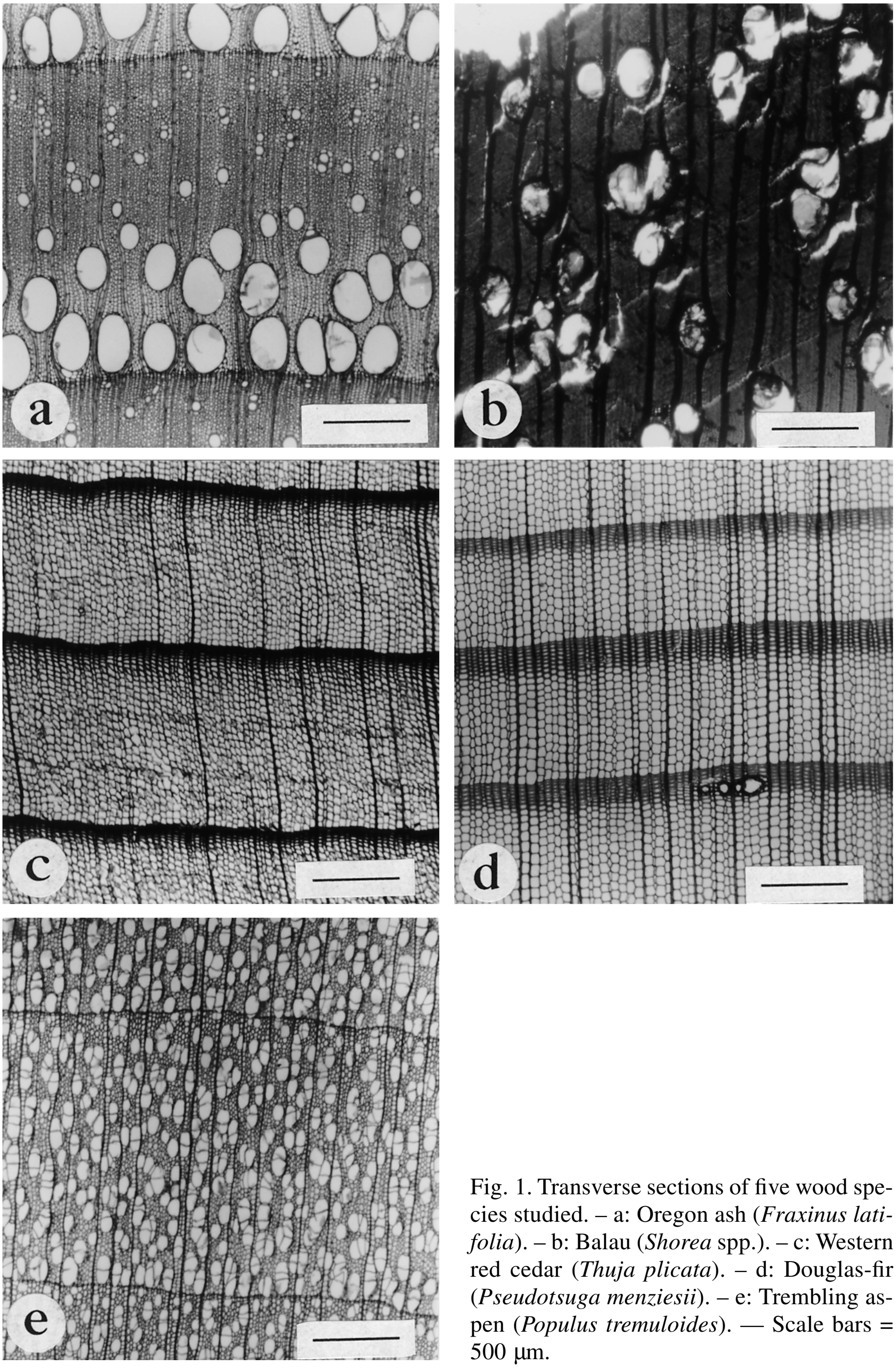

Fig. 1. Transverse sections of five wood species studied. – a: Oregon ash (*Fraxinus latifolia*). – b: Balau (*Shorea* spp.). – c: Western red cedar (*Thuja plicata*). – d: Douglas-fir (*Pseudotsuga menziesii*). – e: Trembling aspen (*Populus tremuloides*). — Scale bars = 500 µm.

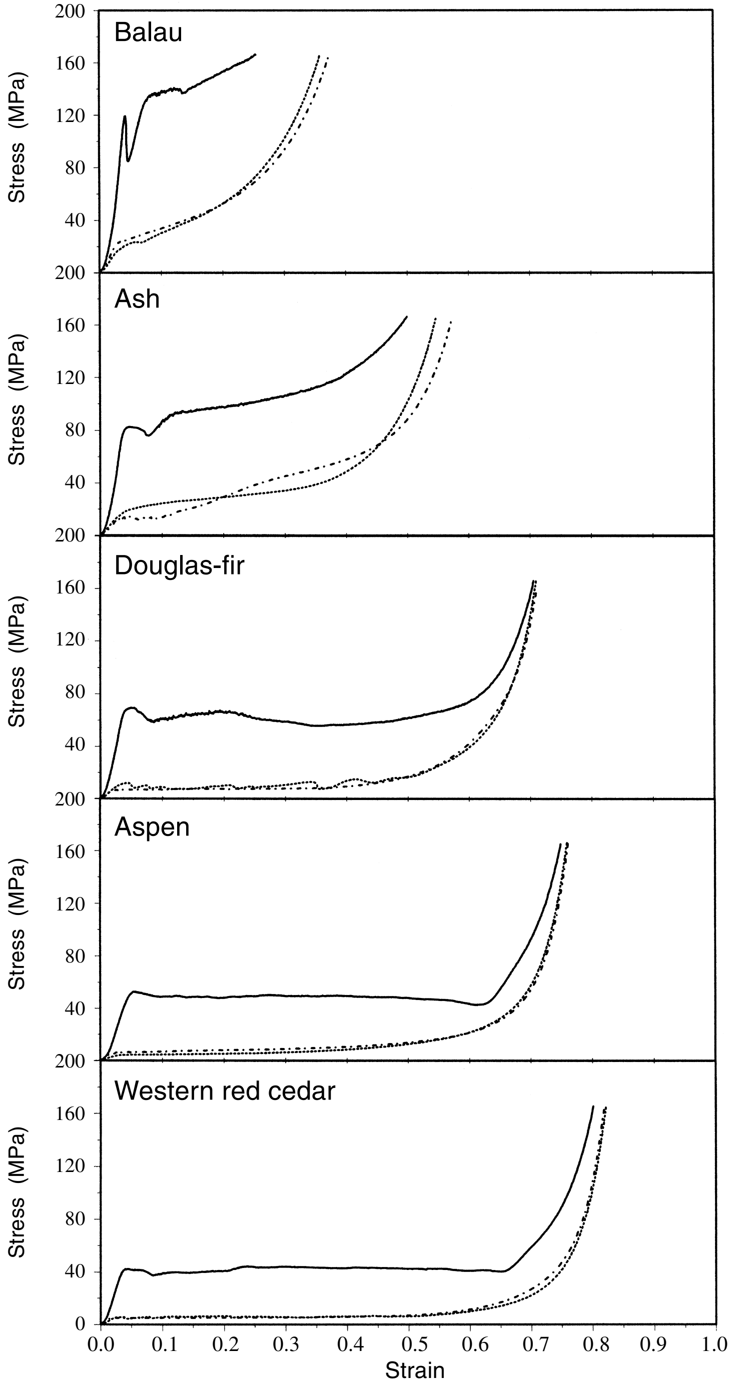

Fig. 2. Stress/strain relationships for five wood species loaded in compression up to a strain level of 1.00 (———— longitudinal, ---------- radial, ·············· tangential).

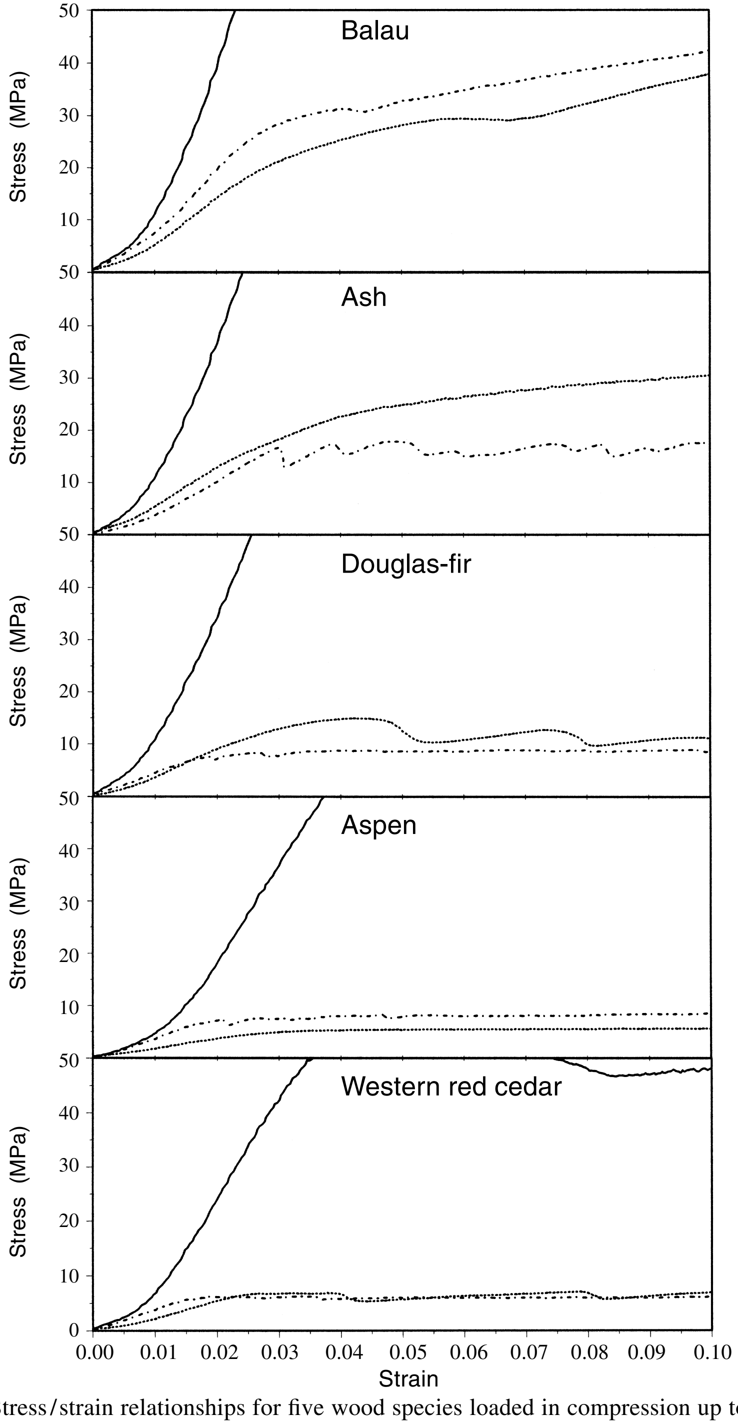

Fig. 3. Stress/strain relationships for five wood species loaded in compression up to a strain level of 0.10 (———— longitudinal, - · - · - · - · - radial, ·············· tangential).

cally. Each compression test was halted when the measured stress started to rise very rapidly indicating that there was no longer any void space remaining in the cube. The thickness of the sample at this point was recorded from the data file generated by the testing equipment. After removing the sample from the testing frame the thickness was remeasured at the five locations. The samples were then aspirated and soaked in cold water for 48 hours after which time they were again remeasured.

RESULTS AND DISCUSSION

The stress/strain relationships for the five different species pressed at 10% moisture content over the whole strain range studied are shown in Figure 2 and over the lowest 0.10 strain range are shown in Figure 3. At small strain levels (less than 0.03 to 0.04) the behaviour of the woods was approximately linear-elastic in all three directions. Young's modulus was much larger in the longitudinal direction than in the radial or tangential directions as indicated by the steepness of the stress/strain curve. Young's modulus was also greater for the higher density woods.

An initial increase in stress (after a strain level of about 0.05) was typically followed by a plateau in the level of stress, the level of which depended on the wood density and represented cellular collapse. As expected, the lower density woods required a greater level of strain to be applied to reach the point at which the stress started to rise very rapidly signifying that no more void space existed within the wood cube. From the strain value at which each test was stopped and the initial density found for each species (Table 1) a density that was reached when the compression test was halted could be calculated for each species (Eqn. 1).

$$\text{final density} = \frac{\text{initial density}}{(1 - \text{strain})} \qquad \text{(Equation 1)}$$

The values calculated averaged 1.61 g/cm^3, which is very close to that of the air-dry density of solid cell wall material (approximately 1.60 g/cm^3) confirming that no void space remained in the cubes at this point.

Over most of the strain range, for all five species the stress parallel to the grain was 5–8 times greater than that perpendicular to the grain. In balau, over the strain range up to 0.20 the radial stress was slightly greater than the tangential, presumably due to the supporting action of the rays. In aspen, there was a slightly higher resistance to compression when stressed radially compared to tangentially, also presumably as a result of the supporting action of the rays. In ash, in radial compression up to a strain level of about 0.10 there were some sporadic drops in the stress level due to the observed collapse of the successive layers of earlywood regions dominated by relatively large-diameter thin-walled vessel elements. After this strain level, the stress rose gradually and passed that of the tangentially loaded samples at a strain level of about 0.20. In the Douglas-fir in the tangential direction there was a series of small drops in the load supported from strain levels of 0.05 to 0.45, presumably due to successive buckling actions of the columns of latewood. In western red cedar, there

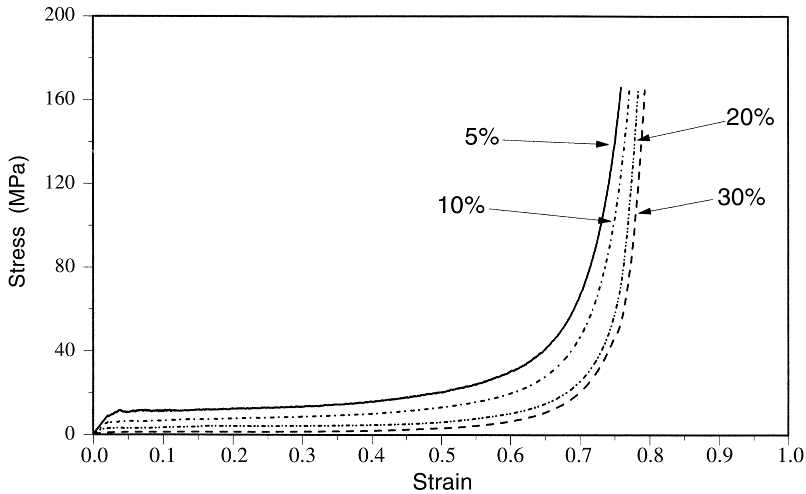

Fig. 4. Stress/strain relationships in radial compression for aspen (*Populus tremuloides*) conditioned at four moisture contents up to a strain level of 1.00.

was very little difference between the radial and tangential behaviours although small sporadic drops in the tangential stress, similar to but smaller than those noticed in Douglas-fir were observed.

The stress/strain relationships for aspen compressed in the radial direction at the four different moisture contents over the whole strain range studied are shown in Figure 4 and over the lowest 0.10 strain range are shown in Figure 5. Wood cubes

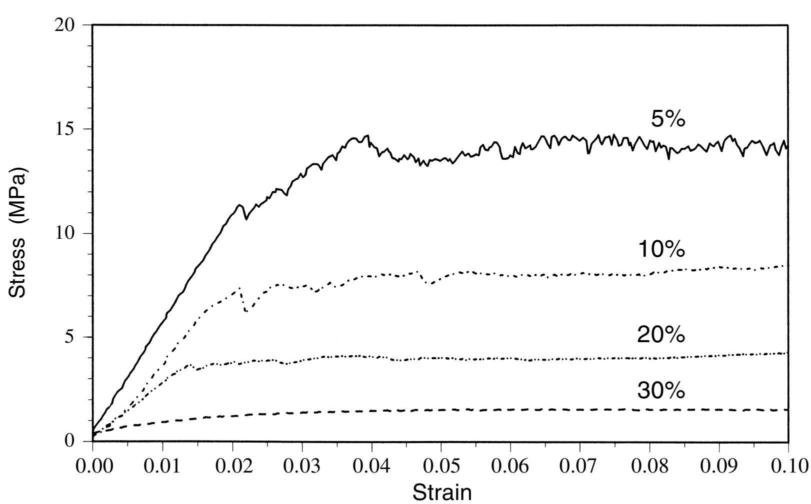

Fig. 5. Stress/strain relationships in radial compression for aspen (*Populus tremuloides*) conditioned at four moisture contents up to a strain level of 0.10.

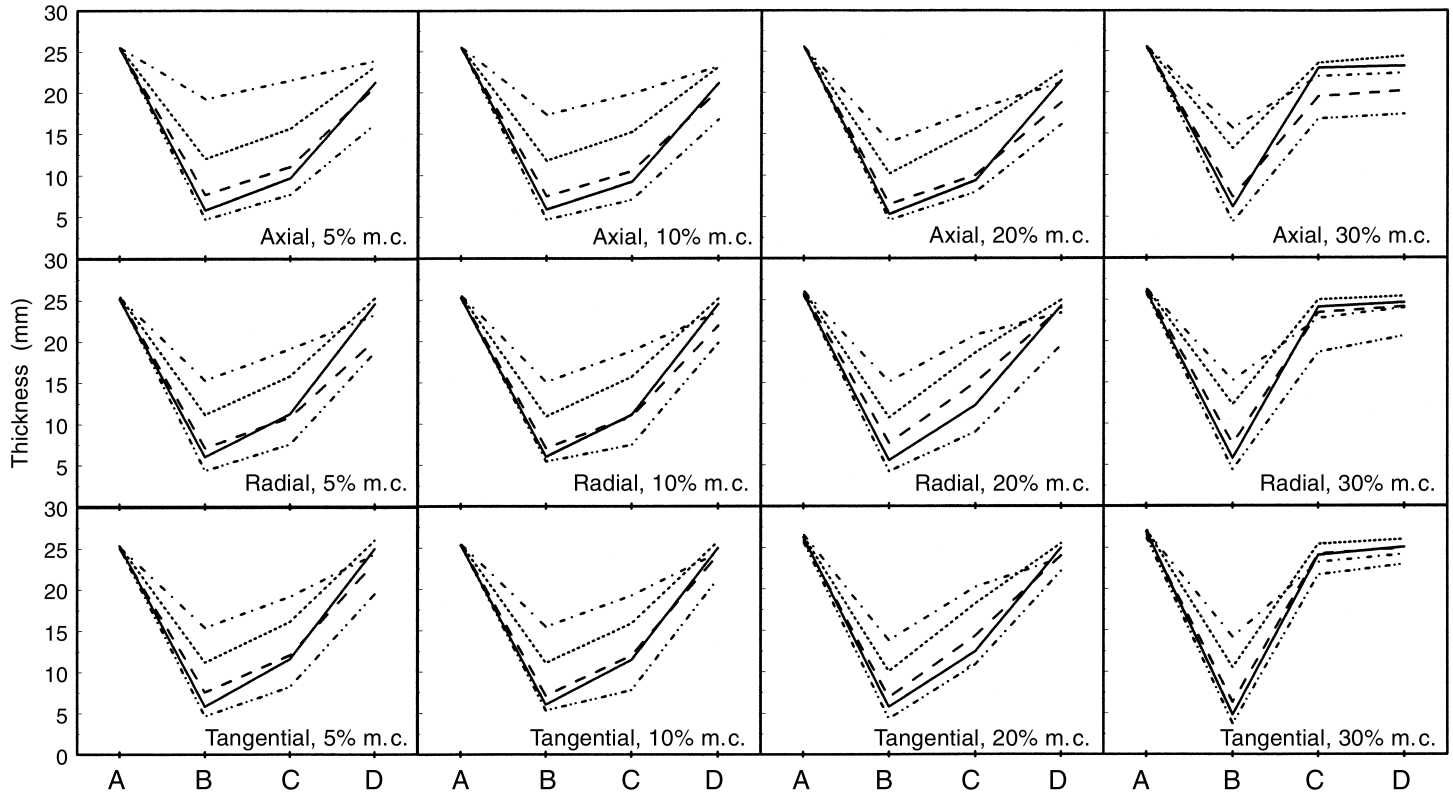

Fig. 6. Thickness of cubes measured: A: prior to pressing; B: at the end of the application of load; C: after removal from the pressing jig; D: after soaking in water [-·-·-·-·-·- balau (*Shorea* spp.); ·············· ash (*Fraxinus latifolia*); – – – – – Douglas-fir (*Pseudotsuga menziesii*); ———— aspen (*Populus tremuloides*); -··-··-··-··- western red cedar (*Thuja plicata*)].

conditioned to the lower moisture contents exhibited a greater Young's modulus, greater resistance to the crushing stress and approached the point at which the test had to be terminated sooner than did those cubes conditioned to higher moisture contents. At the higher moisture contents the stress/strain curve after the elastic limit had been reached was smoother than at the lower moisture contents (Fig. 5). The higher moisture content thus increased the plasticity of the wood. Only the data gathered for aspen are reported here but this trend was also observed for the other four species studied.

Figure 6 shows the average thicknesses of the cubes prior to pressing (A - initial), at the point at which the loading was stopped (B - compressed), after the cubes were removed from the pressing jig (C - springback) and after soaking in water (D - swollen). The values shown are the average of three measurements. As already noted, the lower density woods were compressed to a smaller thickness than the higher density woods. This was true for all moisture contents and loading directions. At 20% moisture content, there was slightly more, but not significantly greater, springback than at 5 and 10% moisture content and at 30% moisture content there was significantly greater springback than at the other three moisture contents. The cubes loaded longitudinally exhibited less springback than those loaded radially or tangentially. The nature of the failure axially was such that the full original dimensions of the cells could not be reattained.

Both Douglas-fir and western red cedar exhibited slightly more springback when loaded tangentially than when loaded radially, especially at 20 and 30% moisture content. This phenomenon is presumably due to the columns of denser latewood being able to dominate the behaviour of the less dense earlywood in the tangential direction. In the radial direction the earlywood and latewood act in series rather than in parallel and the same recovery was not attained. For explaining any differences between the radial and tangential directions in the diffuse-porous hardwoods there are two effects due to the rays which must be considered. First, the rays will make the wood more resistant to crushing in the radial direction but, second, when the wood is swollen in water the rays act to restrain the wood from swelling in the radial direction. Ray cell thickness must also be considered that at the extent of crushing to which the cubes were subjected the thin-walled ray cells would retain little structural integrity.

From the swollen thicknesses it might appear that the denser woods generally recovered more when soaked than did the less dense woods. This observation may be true but there is the confounding effect that denser woods will naturally swell more anyway due to the presence of more cell wall material. Therefore, it cannot be distinguished whether the observed greater swollen thickness in the denser wood was due to an ability to recover better or simply due to more inherent swelling. In this context it was noted that the cubes of balau did not swell to the thicknesses that might have been expected based on their high density (in fact they swelled to a lesser extent than the lower density ash and Douglas-fir samples).

CONCLUSIONS

A greater Young's modulus, higher level of stress and shorter time to densification were observed for denser woods. Longitudinally loaded cubes exhibited a greater Young's modulus and higher levels of stress than did those cubes loaded transversely. These results agree with general knowledge of the effects of density on mechanical properties and across the grain vs. parallel to the grain behaviour (Panshin & De Zeeuw 1980). Wood cubes loaded transversely exhibited more springback and recovery when soaked in water than did those cubes loaded longitudinally. Wood cubes conditioned at higher moisture contents exhibited more springback and recovery after soaking in water than those cubes conditioned at lower moisture contents. Differences in radial and tangential behaviours were believed to be due to the supporting actions of the rays in balau and trembling aspen and to the relative difference between the lower density earlywood and higher density latewood regions in ash, Douglas-fir and western red cedar.

REFERENCES

Anonymous. 1983. Standard test methods for specific gravity of wood and wood-base materials. American Society for Testing and Materials. D2395-83.

Bariska, M. 1996. Fracture mechanics and wood anatomy. In: L. Donaldson et al. (eds.), Recent advance in wood anatomy: 261–272, New Zealand Forest Research Institute, Rotorua, New Zealand.

Bodig, J. 1965. The effects of anatomy on the initial stress-strain relationship. For. Prod. J. 15: 197–202.

Gibson, L.J. & M.F. Ashby. 1988. Cellular solids; structures and properties. Pergamon Press, New York, NY.

Kennedy, R.W. 1968. Wood in transverse compression; influence of some anatomical variables and density on behavior. For. Prod. J. 18: 36–40.

Panshin, A.J. & C. De Zeeuw. 1980. Textbook of wood technology. McGraw-Hill, New York, NY.

Suchsland, O. 1962. The density distribution in flakeboard. Michigan Quart. Bull. 45: 104–121.

Suchsland, O. 1967. Behavior of a particleboard mat during the press cycle. For. Prod. J. 17: 51–57.

Wolcott, M.P. 1989. Modeling viscoelastic cellular materials for the pressing of wood composites. PhD Dissertation, Virginia Polytechnic Institute and State University. 182 pp.