FREE SHRINKAGE OF *PINUS RADIATA* AT AN ELEVATED TEMPERATURE

A. M. CARRINGTON, R. B. KEEY,

Department of Chemical and Process Engineering,
University of Canterbury, Christchurch, New Zealand

and J. C. F. WALKER,

School of Forestry,
University of Canterbury, Christchurch, New Zealand

(Received for publication 29 November 1995; revision 18 April 1996)

ABSTRACT

Preliminary tests to measure free shrinkage strain on *Pinus radiata* D.Don at elevated temperatures (dry-bulb 70°C, wet-bulb 43–68°C) were conducted on disks taken from an internodal portion of the stem of an 8-year-old tree. Radial, tangential, and sectional shrinkage strains were determined against the moisture content. These tests showed unexpected scatter due to large and variable amounts of compression wood in the disks. There was little correlation between the measured strains and the percentage of latewood or the density of the samples.

The tests were therefore repeated using wood slats 10 mm thick from a tree grown in an environment which reduced the amount of compression wood, i.e., in Southland which is less windy than the area in Canterbury where the test disks originated. These tests indicated that a very small strain appeared at high volume-averaged moisture contents (greater than the fibre saturation point). This may have been due to contraction of the surface layers which had dried below the fibre saturation point. However, significant strains began at a volume-averaged moisture content of 33% (dry basis). Of particular significance is the development of a new technique to measure strain continuously at higher temperatures which should be useful for kiln-drying studies.

Keywords: free shrinkage; radial shrinkage strain; slats; disks; *Pinus radiata*.

INTRODUCTION

Free (or unconfined) shrinkage strain is that which is produced as the wood decreases in moisture content during drying in the absence of any load or constraint. A method for measuring free shrinkage strain at kiln temperatures was required to provide data for a model of the stress-strain behaviour of wood during drying. Initial tests used measurements on disks cut from stem wood, but the young wood contained some compression wood. A further requirement for the new tests was that these should be monitored continuously, without removal from the kiln. These slats were dried under different conditions using various methods to measure the induced free shrinkage strain. Only free shrinkage strain in the radial direction was measured as the boards were quartersawn.

EXPERIMENTAL

Disks

For an initial set of experiments complete disks of wood were cut from a stem to measure the free shrinkage strains both radially and tangentially. Disks were used as they required very little additional preparation after being cut from the stem.

In a plantation at Rolleston, south-east of Christchurch, an 8-year-old tree with long internodal intervals and minimal eccentricity was felled. Disks approximately 30 mm thick were cut from the mid-length of the stem, and any containing knots were discarded, leaving eight defect-free disks for testing. *Pinus radiata* in Canterbury is noted for the presence of some compression wood due to persistent windy conditions and compression wood was a feature of the young wood samples examined, despite efforts to select material with minimal amounts. This feature is reflected in an eccentric cross-section of stems that lean.

These tests involved drying the disks at a constant dry-bulb temperature of 70°C in a small kiln. The desired equilibrium moisture content (emc) values under kiln conditions were estimated from the tabulated data of Bramhall & Wellwood (1976). The emc was varied by decreasing the wet-bulb temperature from 60°C to 48°C and measurements were made at each setting. The disks were held in the kiln until they attained a steady mass, at which point they were removed and finally weighed.

One side of the disks was dressed to a smooth surface on which small dots were made with Devshield paint (an epoxy paint which adheres to green wood). Three pairs of dots were painted on either side of a radial line, at the centre, middle, and edge. The distances between these marks, in both the radial and tangential directions, were measured using an electronic travelling microscope. A kerf was made through the disk along this line which allowed the relief of internal growth stresses (Fig. 1) and the distances between marks were remeasured. The distances between the dots were measured again after each conditioning treatment in the kiln, and after oven drying. The percentage of latewood was noted for each sample.

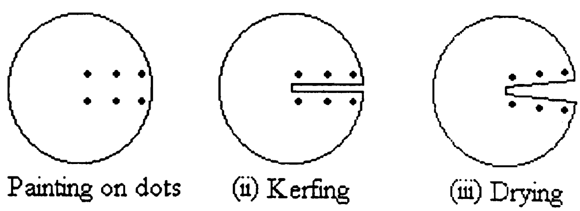

FIG. 1–The kerf cut in the tree disk opens up during drying.

Slats

Later, slats rather than disks were used for measuring shrinkage strain as they could be cut from timber which was essentially free of compression wood. Green wood samples of *P. radiata* were obtained from an old sheltered stand in Tapanui Forest in Southland.

Material from the outerwood was quarter-sawn to give boards 1.8 m long, 150 mm wide, and 10 mm thick. Specimens 50 mm long in the longitudinal direction were taken randomly from each sawn board.

The distance between the dots on the slats was approximately 40 mm, yielding an accuracy of ±0.2% strain. Separate information about earlywood and latewood behaviour was not possible as the dot interval spanned several growth rings (and the extent of growth had precluded cutting flat-sawn samples of only earlywood or latewood).

Air-dried samples were immersed in water and held under a vacuum of 90 kPa to remove the air from the wood. The wood was kept submerged to allow water to replace the air. This continued until the wood was denser than water. Thus, a sample air-dried to 12% moisture content would be "vacuum re-wetted" for 18 hours, with the moisture content of the wood increasing to over 120%. The sample swelled again and the distances between points were very close to the original spacing on the green wood: the difference between the re-wetted wood and the green wood was ±0.3% strain, compared with a total strain of 1.7%. This difference was partly measurement error and partly the irrecoverable strain of the drying process.

The ability of the wood to be dried out and re-wetted, while recovering most of the original shrinkage movement, led to the possibility of using strain gauges on the wood. The strain gauges were glued on to the air-dried wood and the adhesive allowed to cure. A two-part epoxy adhesive, Loctite® 3801, was used which the manufacturers claim to be able to stick to both metal and wood and, when cured, withstand immersion and temperatures up to 120°C. Single 5-mm strain gauges, RS 632-180, were used which would function over a temperature range from –30°C to 180°C. They consisted of a copper-nickel alloy foil on a polyimide (a high-temperature dielectric) backing.

The change in resistance of the strain gauge is proportional to the development strain. Absolute measurements are not possible with strain gauges stuck to wood because of the unknown amplification of the signal. The strain gauge data were used in conjunction with a continuous measurement of the weight of the slat.

An open-circuit drying tunnel was used for testing samples above ambient temperature. The advantage of using the tunnel was that a balance was already in place to measure the weight loss during the test without the need to remove the sample from the drying environment. The tunnel could operate at a maximum wet-bulb temperature of 55°C, and so tests were performed at 80°C dry-bulb / 54.5°C wet-bulb temperatures, 70°C/46°C, and 60°C/38°C, combinations corresponding to an equilibrium moisture content of 4.1% (dry basis). However, the boards tended to bend during drying which would require a strain gauge to be placed on either side of the board. Uncertainties in signal amplification and problems with adhesion and tolerance to the expected wood movement led to the consideration of an alternative method. A simpler technique was devised in which a rod was fitted against a linear position sensor and passed through a 5-mm-diameter hole in the centre of the board (Fig. 2).

RESULTS

Disks

The moisture content was calculated for each disk after each conditioning treatment. The moisture content at end of each stage slightly exceeded the equilibrium moisture content,

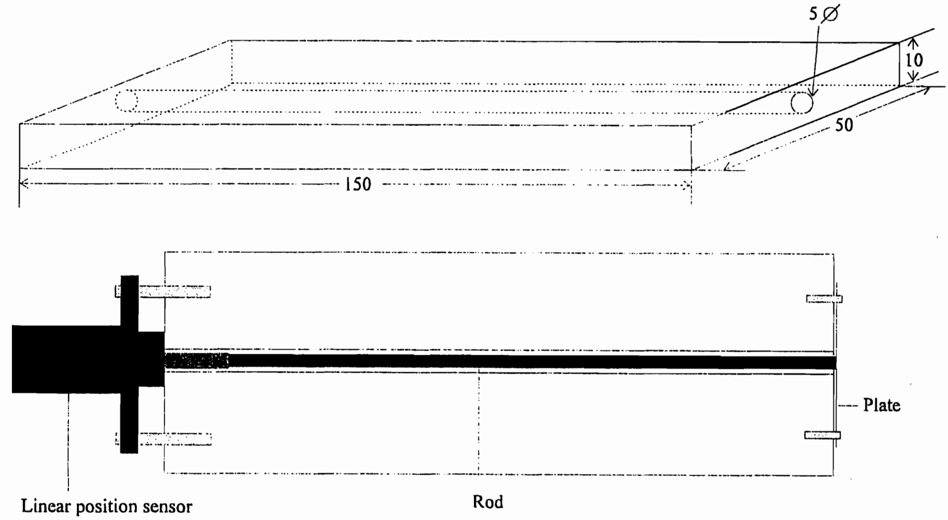

FIG. 2–Sample slat with linear position sensor (all dimensions in millimetres).

indicating that a very small moisture-content gradient remained. Under these near-equilibrium conditions, both radial and tangential shrinkage strains were measured at the various end moisture contents. Strains could be measured to within 0.25% (5% of the total strain).

Measured radial and tangential shrinkage strains are plotted against moisture content on a dry basis in Fig. 3 and 4. If a linear relationship between shrinkage strain and moisture content is assumed, these lines intersect the moisture content axis (corresponding to zero strain) at just above the fibre saturation point, at about 32–34% moisture content.

Slats

Four slats, 150 mm in the radial direction with a cross-section of 50 × 10 mm each with three dots 40 mm apart for measuring radial shrinkage strain, were used in this experiment. Measurements under various conditions were taken once equilibrium was achieved (Fig. 5).

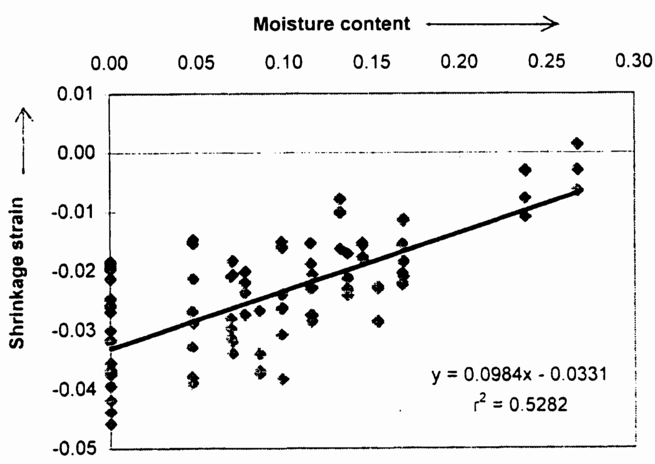

FIG. 3–Correlation between radial shrinkage strain and moisture content (dry basis).

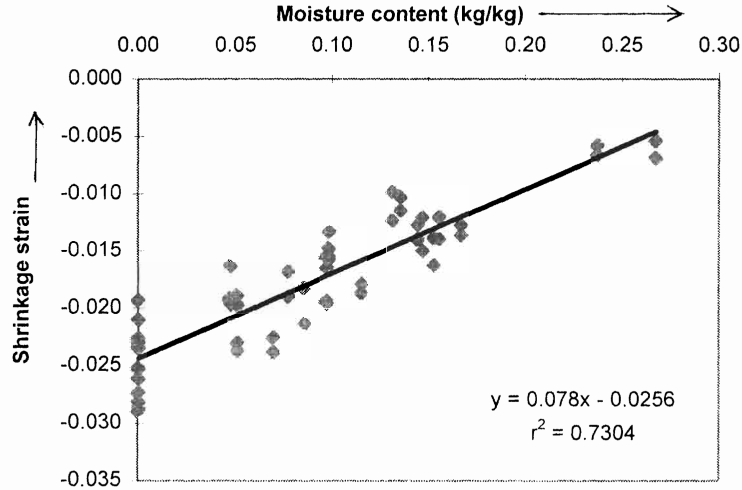

FIG. 4–Correlation between tangential shrinkage strain and moisture content (dry basis).

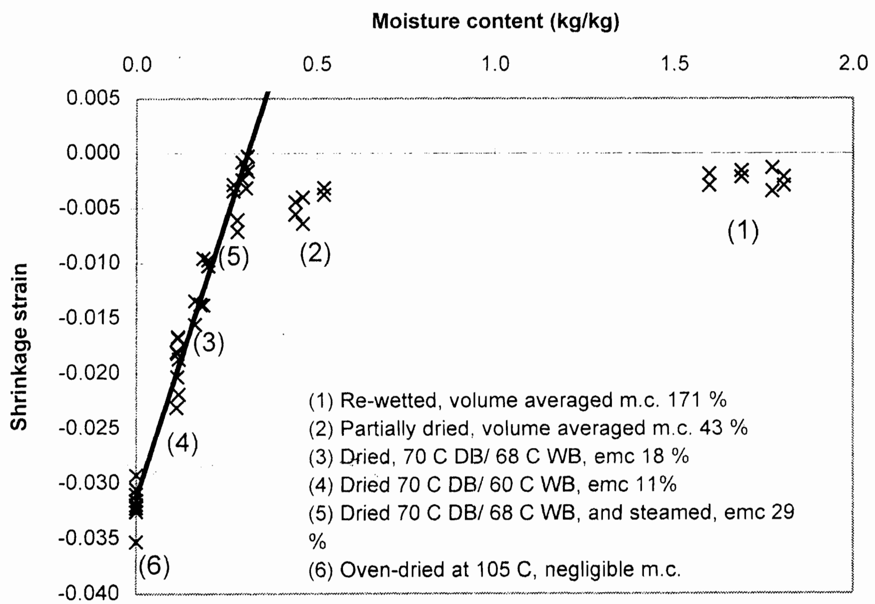

FIG. 5–Radial strain at various moisture contents.

Samples of wood were either air-dried in the laboratory at 20°C or oven-dried at 105°C. Strain was measured optically. The results of these tests showed that some shrinkage occurred when the average moisture content of the sample was above the fibre saturation point. The shrinkage strain did, however, increase rapidly after the volume-averaged moisture content of the board fell below the fibre saturation point. These results for both sets of data are given in Fig. 6.

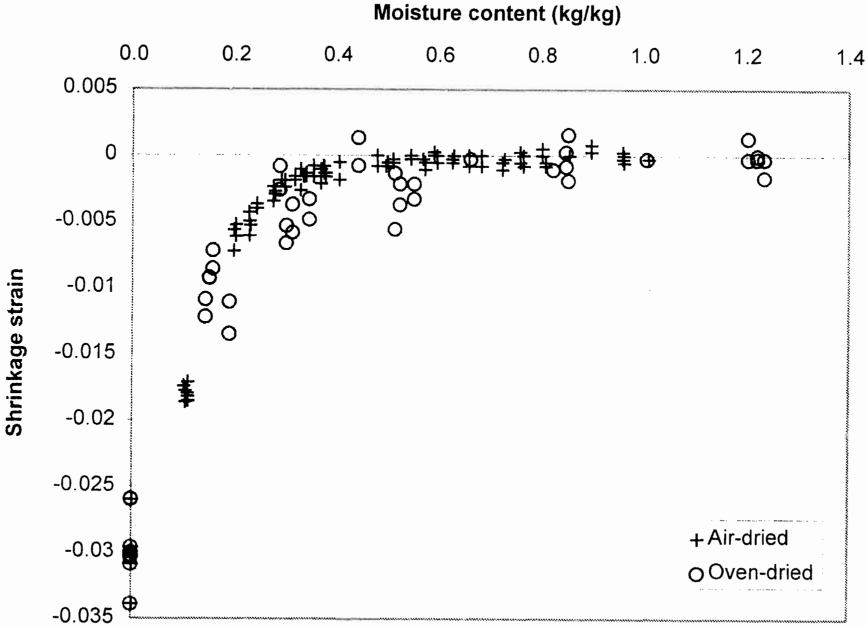

FIG. 6–Radial shrinkage strain on drying measured optically for a 10-mm-thick slat.

Air-drying experiments at room temperature (20°C) were carried out on slats, both 5 mm and 10 mm thick, using a strain gauge and a balance. The strain and the weight were measured continuously. The strain gauge yielded the relative shrinkage, while the total strain was measured optically. The shrinkage strain of wood was measured continuously in a drying tunnel under three sets of conditions with the rod-test equipment. The results of these tests are plotted in Fig. 7 and compared with data obtained under air-drying conditions. These results were distorted by bending of the slat.

DISCUSSION

The shrinkage of the disks to the oven-dry conditions was 3.1% in the radial direction and 2.6% in the tangential direction, whereas Cown & McConchie (1980) found a tangential shrinkage of around 7% and radial shrinkage about half this value at 3.4%. The relatively low tangential shrinkage is suggestive of the presence of compression wood as tangential shrinkage decreases with increasing microfibril angle, being about 2.5% at an angle of 45° (Harris & Meylan 1965). The modified S2 layer in compression wood has a microfibril angle of this magnitude (Panshin & De Zeeuw 1980).

The shrinkage, as measured, appears to commence before the fibre saturation point is reached. This may be the result of a moisture content gradient within the disk, with surface layers significantly drier than the volume-averaged value, or it may be due to deformation of tracheids still partially saturated.

The measurements of shrinkage strain of quarter-sawn slats at various equilibrium moisture contents (Fig. 5) that relate to equilibrium condition (runs (3) to (6) inclusive) can

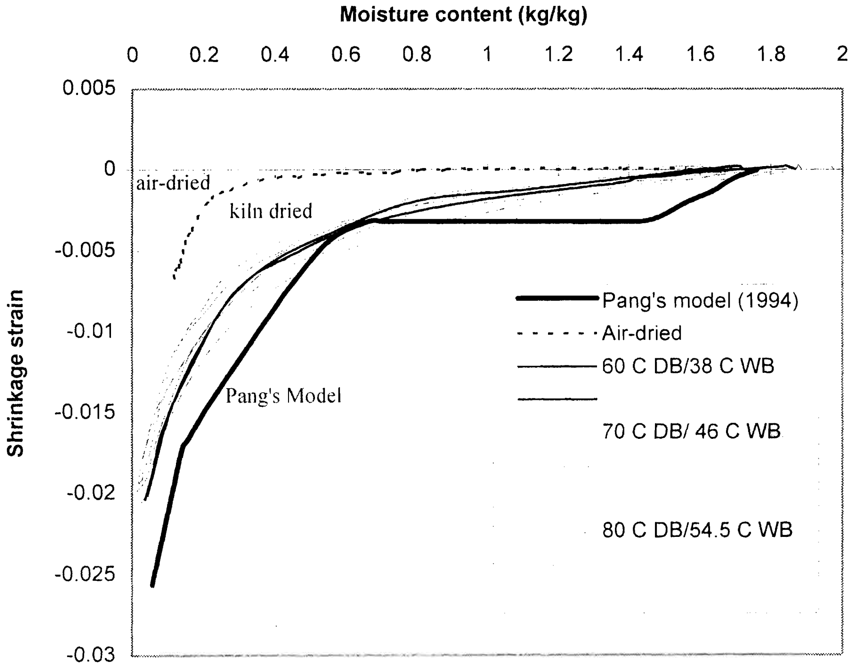

FIG. 7–Radial shrinkage strain measured with a linear position sensor under various conditions in the drying tunnel compared with data obtained by air drying (Pang's model from Pang *et al.* 1994).

be extrapolated to determine the fibre intersection point (FIP) at zero strain, an estimation of the fibre saturation point (FSP), which gives a value of 35% (dry basis) at 70°C.

The data from test (2), which show a shrinkage of –0.5% at a volume-averaged moisture content of 43%, suggest that wood begins to shrink above the fibre saturation point. However, this observed contraction may have been due to the shrinkage of a surface layer, while the bulk was being restrained by an inner wet core of wood.

At temperatures below 105°C it is postulated that the ultimate shrinkage strain depends only on the equilibrium moisture content. This is shown by the data for air drying the slats at room temperature, drying at 70°C dry-bulb temperature, and oven drying at 105°C, where all samples reached the same final shrinkage (Fig. 6). These strains developed with a very small change in moisture content during the later period of drying, just below the fibre saturation point, and so it is this period which is crucial in the development of drying shrinkage stresses. Any apparent shrinkage above fibre saturation is a reflection of the shrinkage of the surface layers which are below fibre saturation when the volume-averaged moisture content of the sample is greater than the fibre saturation value. Strains estimated from the calculated moisture content profiles form an envelope to the measured strain data under kiln conditions.

The shrinkage strain tests that were performed at temperatures above ambient had a greater shrinkage strain at higher volume-averaged moisture contents than those conducted at room temperature. This is believed to be due to the presence of a drier surface layer below fibre saturation predicted by Pang *et al.* (1994). The surface layer has been calculated to occur initially in the outer 1 mm of the wood. With kiln conditions of 70°C dry-bulb temperature and 46°C wet-bulb temperature, this layer consists of an average of 14% of the slat thickness in the first tenth of the drying period.

The different methods of measuring strain under air drying conditions can be compared (Fig. 8). The optical and rod-test readings were very similar over the whole range in moisture content although the latter method was less influenced than strain gauges by surface effects. The strain gauge measurement compared very well with the predicted behaviour for high volume-averaged moisture contents, based upon the estimated moisture-content profiles in the slat using a physiological model of moisture movement through the wood (Pang *et al.* 1994).

The results of the experiments on the disks and those for the slats can also be compared (Fig. 9). The optical tests on the disks yielded essentially the same data as those on the slats. The disk results were more highly scattered owing to varying amounts of compression wood present in the samples and the inherently greater experimental error.

Extrapolation of the shrinkage from low to higher moisture contents to estimate the fibre intersection point should be treated with caution because the data were determined from drying experiments where moisture gradients were present within the timber.

CONCLUSION

Free shrinkage occurs below a volume-averaged moisture content of 33–34% at a dry-bulb temperature of 70°C. The presence of compression wood was probably responsible for the reduced strain in the tangential direction measured with disks.

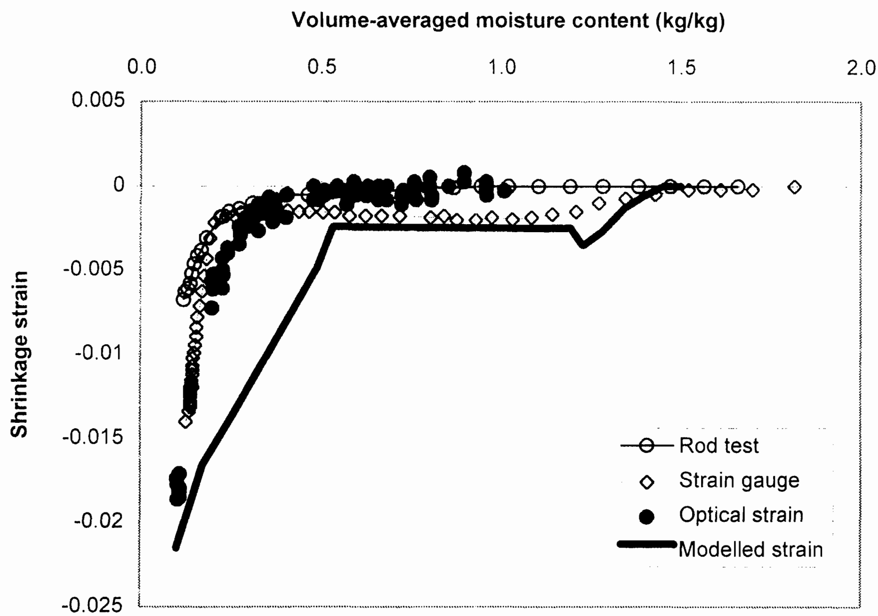

FIG. 8—Comparison between slat methods of measuring shrinkage strain with estimated strain at 20°C.

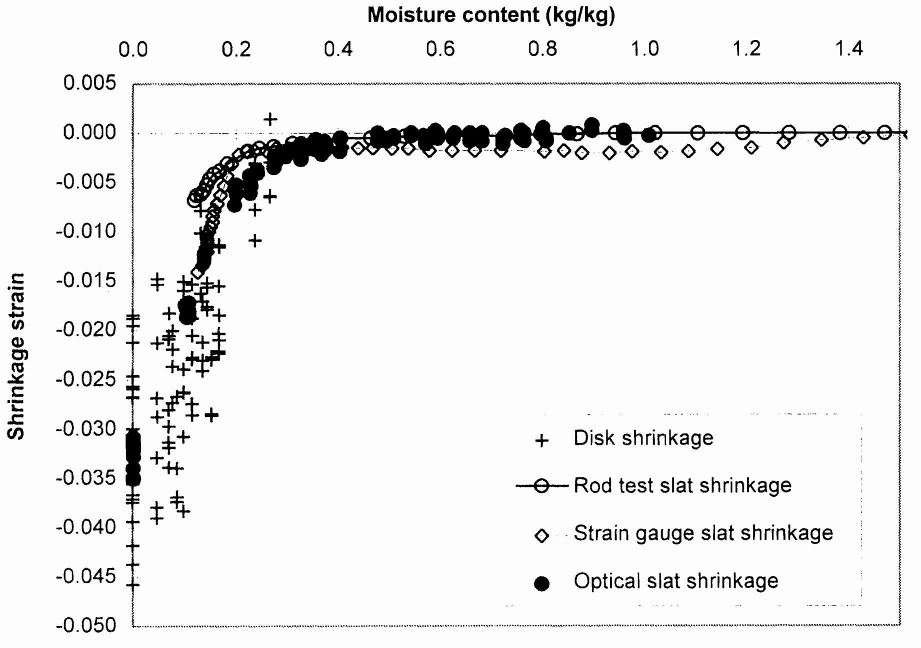

FIG. 9—Comparison between measurements on disks and 10-mm-thick slats at 20°C.

Any free shrinkage strain above the fibre saturation point (fsp) may be due to the presence of moisture content gradients in test samples. Below the fsp the strain was linear with moisture content over most of the tested range. At a moisture content of around 10% (dry basis) the free shrinkage was 2% in the radial direction.

These experiments showed that the simplest and most accurate method for measuring free shrinkage strain is the rod-test using a linear position sensor. The results given by this method have an uncertainty of ±0.1% strain. This method should be adaptable for any timber and to tangential or longitudinal shrinkage measurements. The linear position sensor described here can operate at temperatures to 130°C. This technique to measure strain continuously at high temperature should be useful more generally for kiln-drying studies.

ACKNOWLEDGMENTS

This work was supported by the New Zealand Foundation for Research, Science and Technology (UOC Contract 406). Dr Guangnam Chen is thanked for calculations of the moisture content profiles. The timber was supplied by Blue Mountain Lumber.

REFERENCES

BRAMHALL, G.; WELLWOOD, R.W. 1976: Kiln drying of western Canadian lumber. *Canadian Forestry Service, Western Forest Products Laboratory, Information Report VP-X-159.*

COWN, D.J.; McCONCHIE, D.L. 1980: Wood property variations in an old-crop stand of radiata pine. *New Zealand Journal of Forestry Science 10(3)*: 508–20.

HARRIS, J.M. 1977: Shrinkage and density of radiata pine compression wood in relation to its anatomy and mode of formation. *New Zealand Journal of Forestry Science 7(1)*: 91–106.

HARRIS, J.M.; MEYLAN, B.A. 1965: The influence of microfibril angle on longitudinal and tangential shrinkage of *Pinus radiata*. *Holzforschung 19(5)*: 144–53.

PANG, S.; LANGRISH, T.A.D.; KEEY, R.B. 1994: Moisture movement in softwood timber at elevated temperatures. *Drying Technology 12(8)*: 1897–914.

PANSHIN, A.J.; DE ZEEUW, C. 1980: "Textbook of Wood Technology Structure, Identification, Properties, and Uses of the Commercial Woods of the United States and Canada", 4th ed. McGraw-Hill Book Company.

PETONEY, R.E. 1953: Mechanisms affecting tangential *v.* radial shrinkage. *Forest Products Journal 3(2)*: 27–33.