Wood material behaviour during drying: moisture dependent tensile stiffness and strength of radiata pine at 70-150°C

Chris Lenth *Wood Processing Unit, Ensis – the joint forces of CSIRO & Scion, Private Bag 3020, Rotorua, New Zealand*

Rosie Sargent *Wood Processing Unit, Ensis – the joint forces of CSIRO & Scion, Private Bag 3020, Rotorua, New Zealand*

ABSTRACT

Improvements in kiln-drying process efficiency and dried-timber product quality are difficult to realise given the current lack of knowledge as to how in-kiln conditions impact basic properties such as strength and stiffness. A significant effort has been invested in an initiative to evaluate the instantaneous stress-strain, time dependent creep, and mechano-sorptive behaviour of radiata pine. The strength and stiffness of longitudinal specimens of radiata pine wood from the inner and outer portions of the stem have been evaluated across a range of low to high moisture contents at temperatures from 70 – 150°C drying. Results show expected decreases in both Yield Stress and MOE with increasing temperature and increasing moisture. Inner-wood is generally less rigid and strong than outer-wood. This paper will review methodology and experimental results in addition to discussing trends in MOE and Yield Strength with temperature, moisture content and sample type.

INTRODUCTION

Wood is a viscoelastic material: a substance that will exhibit characteristics of both a solid and a fluid, dependent on the time domain, the temperature and the moisture concentration. Wood's viscoelastic character is manipulated in many aspects of timber processing: from lumber drying to mechanical pulping. However, the nature of wood's viscoelastic response is still poorly understood and inadequately documented. Significant gains in utilization and process efficiency will be made with increased knowledge of the interacting influence of time, temperature and moisture on the physical and mechanical properties of wood. The kiln drying of lumber is one application where a limited knowledge of fundamental wood behaviour in the processing environment restricts progress towards improved methodology and increased material recovery.

A major factor contributing to this void in material knowledge is the difficulty of generating experimental data over the range of environments common to wood processing. Complex instrumentation and testing methodologies are required to maintain uniform moisture contents in wood samples at high temperatures. For example, an environmental pressure of 5 bar is required to maintain fibre saturation in wood at 150°C. An elevated pressure, high temperature testing system (EPHT) has been constructed at Ensis that provides for material property data collection on wood samples in severe environments.

The total deformation occurring upon drying a piece of wood is comprised of strains from: shrinkage, instantaneous stress (elastic and plastic), creep, mechano-sorptive deformation and thermal expansion. Total deformation can thus be represented as in Equation. 1:

$$\varepsilon_{\text{total}} = \varepsilon_w + \varepsilon_i + \varepsilon_c + \varepsilon_{ms} + \varepsilon_{th} \qquad [1$$

where ε_w is shrinkage strain, ε_i is instantaneous strain, ε_c is creep strain, ε_{ms} is mechano-sorptive strain and ε_{th} is thermal expansion strain. This representation of strain in drying has been introduced and employed by several authors in various forms (Salin 1992; Ormarsson and Dahlblom 1994; Wu and Milota 1995; Muszynski and Olejniczak 1996; Ormarsson 1999; Keep and Keey 2000; Lenth et al. 2000; Pang 2001). Thermal strain is often neglected due to low magnitude. To predict the total deformation, and thus estimate the drying stresses and subsequent distortion, each one of these strain components must be characterized across the range of conditions encountered in drying, specific to the species and type material of interest. This particular study was focused on the characterising the longitudinal instantaneous stress-strain behaviour of radiata pine as a function of temperature and moisture content. Experiments are currently being conducted to evaluate the stiffness and strength in the radial and tangential directions. The time dependent components of total drying deformation, namely: shrinkage, creep and mechano-sorptive strains, are also being characterised in the wood material behaviour program at Ensis.

The instantaneous stress-strain behaviour (commonly referenced as strength and stiffness) of a piece of wood is extremely dependent on its temperature and moisture content. There is very little available data characterizing this relationship for commercial species, which spans the range of temperatures encountered in commercial timber drying. Two of the three primary wood constituents, namely the hemicelluloses and lignin, undergo significant conformational changes across the range of temperatures and moisture encountered. These changes express the glass transition behaviour of constituent polymers and are associated with wood softening.

The observed softening behaviour of wood consists of one or more of rather broad transitions and is most often characterised by dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC), or dielectric thermal analysis (DETA), (Hillis and Rosa 1978; Salmen 1984; Wert et al. 1984; Kelley et al. 1987), however static experiments are sometimes used (Uhmeier et al. 1998). Reported softening temperatures in the temperature range common for commercial timber drying are generally attributed to the glass transition of in situ lignin (Becker, H. and Noack, D. 1968, Chow and Pickles 1971; Funakoshi et al. 1979; Atack 1981; Irvine 1984; Östberg et al. 1990; Takahashi et al. 1998). In addition to observing thermally activated dielectric relaxations in wood as a function of moisture content, Lenth and Kamke (2001) provide a summary of reported softening temperatures. In the range of –20 to 192°C, two separate softening temperatures have been observed for various species of solid wood with moisture contents from green to dry.

The research described in this report is component project of a large-scale research initiative. The broad program has been designed to build our basic knowledge of the material behaviour of radiata pine during lumber drying in terms of moisture distribution, drying stress development and board deformation. It is the goal of this effort to establish a database of the instantaneous and time dependent mechanical properties of radiata pine in tension and compression as a function of temperature, moisture content, loading direction and wood type. This knowledge will be augmented by computer modelling, and applied to the tasks of reducing drying degrade, optimizing drying schedules and developing new drying technologies. This paper reviews the equipment and techniques employed to evaluate the instantaneous stress-strain behaviour of radiata pine. Experimental results in tension are presented and discussed, as is ongoing research and implications for commercial drying.

EXPERIMENTAL

Instantaneous tensile stress-strain behaviour was evaluated for radiata pine in the longitudinal direction. Samples of "inner-wood" were obtained from inside the 9th growth ring, while "outer-wood" specimens came from outside the 14th growth ring. Three moisture conditions (nominally 7, 14 and 21% MC) were evaluated at three test temperatures (70, 110 and 150 °C. Six replications were tested for each condition. Table 1 illustrates the design of the experiments.

Table 1. Design of experiments: number of replications tested for each environmental condition.

Temp	70°C		110°C		150°C	
Type	inner	outer	inner	outer	inner	outer
MC[1]						
7 %		6	6	6		6
14 %	6	6	6	6	6	6
21 %		6	6	6		6

[1] Nominal moisture content.

Raw Material

A 26-year-old radiata pine tree was felled from a plantation forest located in the central North Island of New Zealand and a 3.5 meter log (excluding the bottom most 1.5m) was extracted to Rotorua for testing. The stem was cut into 600 mm long sections, which were further broken down into flitches approximately 600mm x 300mm x 50mm. The cutting plan was based on experimental requirements for longitudinal, radial and tangentially oriented tensile coupons, employing a sample matching strategy to associate subsequent time dependent tests with the stress-strain experiments reported here. The flitches were further broken down into sample blanks 10 mm thick and left to equilibrate for 3 months at ambient temperature in an environmental conditioning room at 40, 65, or 95% RH. Prior to testing, the equilibrated sample blanks were machined to the final dimensions of 260 mm x 40 mm x 10 mm, with the 60 mm central "gauge area" having a reduced cross section to control failure location. Samples were machined such that they were made up of clear inner- or outer-wood.

Experimental Apparatus

The test equipment used has been specially designed for the task of wood material property evaluation in severe environments is referred to as the Elevated Pressure - High Temperature (EPHT), testing system (Lenth et al. 2000). The EPHT system is designed to maintain the environmental conditions necessary to achieve wood specimen moisture contents from fibre saturation down to 5% at temperatures from 20 to 160°C. The system operates under conditions of humid air and superheated or saturated steam, to generate relative humidities from 15 to 100% across the temperature range. The entire system is sealed and can be operated at internal pressures as high as 10 bar. The EPHT system consists of two parts: an environment control unit for generating the experimental atmospheric conditions, and a test chamber for physically evaluating specimen behaviour. This device is schematically displayed in Figure 1. The image in Figure 2 displays the EPHT testing system as fitted to an Instron^{TM} testing machine.

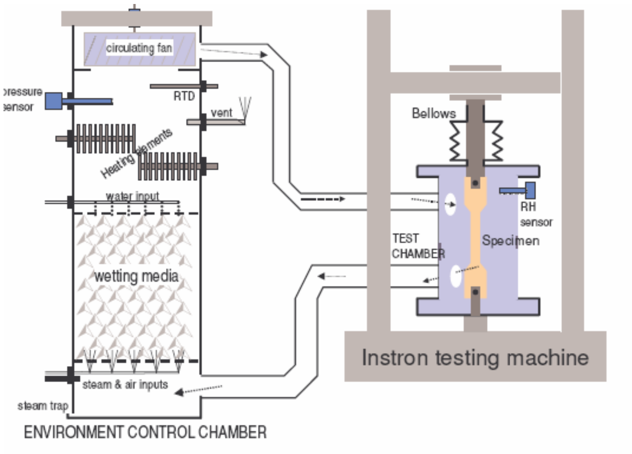

Figure 1. Schematic of EPHT testing system in tensile configuration**.**

The environment control unit is an instrumented device for conditioning the water vapour atmosphere. It is connected to the test chamber via flexible, insulated tubing and a fan provides circulation of the controlled environment between the chambers. Environmental moisture is maintained by metering a mixture of saturated steam and dry, compressed air. Temperature and dew point in the immediate vicinity of the sample are monitored and as environmental control parameters. Eight electrical resistance heating elements function to heat the circulating environment to the desired temperature, and cooling is achieved by mixing dry air at 20°C into the circulating media.

Figure 2. EPHT testing system.

The test chamber was constructed to facilitate mechanical testing with an universal testing machine. The test chamber itself consists of three components. Top and bottom fixtures function as end caps to the chamber and fix the ends of the specimens to the loading frame. A removable, cylindrical centre section surrounding the test specimen and its environment is sealed between the top and bottom fixtures, through which the circulating water vapour environment and all electrical and plumbing connections enter and exit the chamber. A flexible stainless steel bellows at the top of the chamber provides an interface allowing displacements to be applied to the specimens while they are contained within the prescribed environment. Two LVDTs (linear variable displacement transducers) are affixed to the tensile sample to record displacement under load over the gauge area of the specimen**.**

Instantaneous Stress-Strain Tests

For test conditions above ambient temperature, samples were preheated in a conditioning chamber adjacent to the environment generating unit and maintained at similar conditions to the test chamber.

Displacement was applied at a constant rate of 1mm of cross head movement per minute, while load and strain in the gauge region were observed. Specimens were weighed before and after testing to assess any moisture content changes during the experiments. To achieve the nominal moisture content conditions of 7, 14 and 21%, the dew point control parameters were, at dry bulb = 70°C: 56, 65 and 70°C, at dry bulb = 110°C: 100, 106 and 110°C and at dry bulb = 150°C: 145, 148 and 150°C respectively.

RESULTS AND DISCUSSION

The average air-dry densities for the inner-wood and outer-wood samples were respectively 369 and 432 kg/m3, with respective COV's of 4.7 and 2.9%.

In this analysis, what is reported as Yield Strength is the stress level at the point of deviation from linearity on the stress versus strain curve, the initial linear slope of which is taken as MOE. Results for Tensile Yield Strength are listed in Table 2 and illustrated in Figure 3. Unfortunately, considerable variability obscures obvious trends in the results. Observed yield strength values do show moderate agreement with values of 35 and 80 MPa reported by Walford (1985) for 30-year-old low density radiata pine (green and 12% MC, respectively), however direct comparison of Yield Strength results from our tensile extension experiments to results for MOR (from bending tests) should be done mindfully.

Table 2. Tensile Yield Strength (MPa) as a function of temperature and moisture content (COV% in parentheses).

Temp	70°C		110°C		150°C	
Type	inner	outer	inner	outer	inner	outer
MC[1]						
		39.3	19.1	31.8		19.3
7 %		(25.5)	(15.4)	(21.2)		(22.4)
	22.7	35.5	17.4	18.8	16.9	20.5
14 %	(27.1)	(16.5)	(17.9)	(22.3)	(17.2)	(19.5)
		28.0	10.4	12.0		9.7
21 %		(30.7)	(9.0)	(14.4)		(36.6)

[1] Nominal moisture content.

It is evident that for both outer and inner-wood, Yield Strength decreases expectedly as temperature and moisture content increase. In all cases inner-wood samples have lower strength than outer-wood at the same nominal moisture content. At 110°C, it appears that the difference between inner-wood is greatest at the lowest moisture contents Also, at a nominal moisture content of 14%, the difference between inner and outer-wood is greatest at lower temperature. This suggests that there is an interaction between moisture and temperature, whereby differences between inner-wood and outer-wood decrease as wood softens. However the large scatter in the observed data, likely due to material variability resultant from small sample dimensions and the limited number of replications tested, undermines the validity and limits the predictive capability of this data set. In addition, variability in actual sample moisture content while testing from the reported "nominal" moisture content values will certainly influence the results. In attempt to mitigate this problem, The strength values are plotted as a function of moisture content.

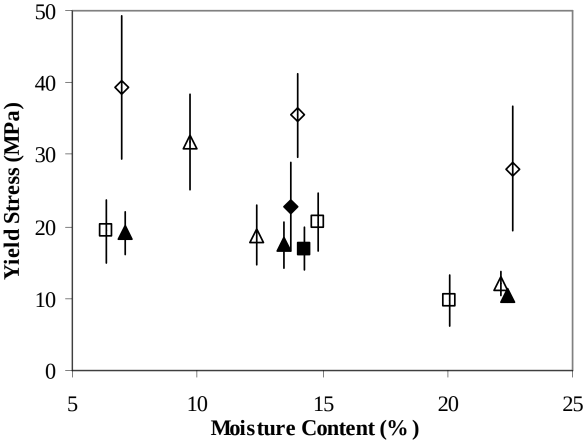

Figure 3. Yield Stress as a function of moisture content for three temperatures. Diamonds: 70°C, Triangles: 110°C and Squares 150°C. Empty symbols: outer-wood and filled symbols: inner-wood.

Results for Tensile MOE are listed in Table 3 and illustrated in Figure 4. Similar to the strength results, values reported by Walford (1985) for green and dry (12%) MOE of 5.47 and 8.23 GPa respectively for 30-year-old medium density radiata pine are in reasonable agreement with our findings.

Table 3. Tensile MOE (GPa) as a function of temperature and moisture content (COV% in parentheses).

Temp	70°C		110°C		150°C	
Type	inner	outer	inner	outer	inner	outer
MC[1]						
7 %		8.8	4.9	8.5		6.0
		(10.0)	(21.6)	(30.7)		(9.5)
14 %	4.7	8.0	5.2	6.4	4.1	6.2
	(17.8)	(18.1)	(26.2)	(17.2)	(15.6)	(24.6)
21 %		7.6	3.6	6.3		4.7
		(31.0)	(22.9)	(29.6)		(36.0)

[1] Nominal moisture content.

As with the results for Yield Strength, the measured MOE tends to decrease with increasing temperature and moisture content. It is interesting to note that in one case the environmental conditions where an anomaly in this trend occurs, happen to be the same temperature and moisture condition for both strength and stiffness results, namely at 150°C and nominally 14% moisture content. There is also, as before, a uniform trend of higher MOE for outer-wood samples when compared to inner-wood, and a reoccurrence of the phenomenon of this difference being larger at lower temperatures given fixed moisture content and at lower moisture contents given a fixed temperature. Once more this suggests that softening, activated by either moisture or temperature, could be reducing stiffness differences between inner and outer-wood. However again as with the strength results, the large variability observed undermines the robustness of these MOE results.

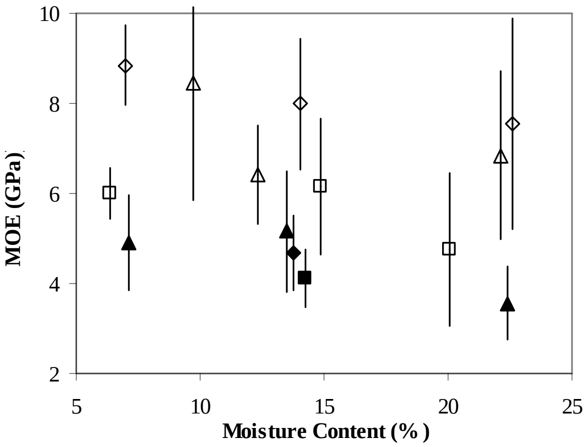

Figure 4. MOE as a function of moisture content for three temperatures. Diamonds: 70°C, Triangles: 110°C and Squares 150°C. Empty symbols: outer-wood and filled symbols: inner-wood.

In a previous study, looking also at low density radiata pine, the authors found similar results for longitudinal tensile MOE (Lenth and Sargent 2004) of radiata pine. These results are reproduced in Figure 5.

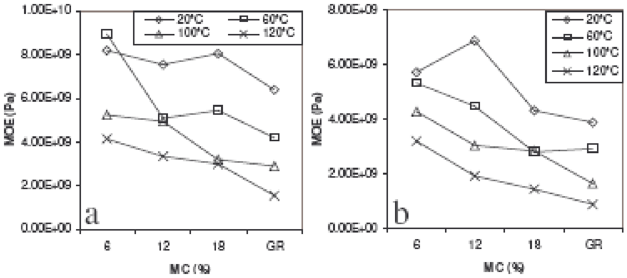

Figure 5. MOE for radiata pine as a function of temperature and moisture content: a) longitudinal sapwood, b) longitudinal heartwood (Lenth and Sargent 1984).

While scatter in the data and anomalous results was also problematic for this previous study, trends here are similar, and a wider range of conditions was covered.

CONCLUDING REMARKS

While it is good to at last be getting results with this novel testing equipment and to begin to see data for mechanical properties in severe environments which are relevant to commercial timber processing, scatter in the data prevents any significant new conclusions being made from this study. There is much future work to do in repetitive testing such that a robust data set can be created, which can extend our understanding of wood behaviour during drying and serve as a resource for modelling stress development and relaxation.

ACKNOWLEDGEMENT

This effort has been funded through by support from the Australian Forest and Wood Products Research and Development Corporation (FWPRDC) and by the New Zealand government through the Foundation for Research Science and Technology. The efforts of Ensis staff, namely those of Hamish Pearson, Ian McElroy and Steve Riley, have been essential in developing the novel material testing equipment and protocols employed herein.

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