Wood Sci Technol (2017) 51:771–784
DOI 10.1007/s00226-017-0895-8

ORIGINAL

Effect of supercritical CO_2 dewatering followed by oven-drying of softwood and hardwood timbers

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Received: 8 August 2016 / Published online: 25 February 2017

Abstract Supercritical CO_2 dewatering of green wood creates timber with unique properties due to the removal of sap directly from cell lumens as a result of cycling between supercritical and gas phases. The susceptibility of 22 softwoods and hardwoods to shrinkage, collapse and checking during dewatering and oven-drying was investigated. The results were compared to green control specimens that were directly oven-dried. Dewatering efficiency was highly variable amongst species and was highest (93–94%) for the permeable sapwood of four softwoods and lowest for the impermeable heartwood of two hardwoods and two softwoods (4–27%). In general, there was less collapse after dewatering followed by oven-drying than after oven-drying alone, more so in hardwoods than softwoods. Six species (a softwood and five hardwoods) displayed strong collapse. Checking was more prevalent after CO_2 dewatering and oven-drying than after oven-drying alone. The supercritical dewatering treatment alone did not induce collapse or internal checking; however, for collapse-prone timber either collapse or internal checking, or a combination of both, was induced on subsequent oven-drying.

Introduction

Wood can distort, in the form of shrinkage, collapse and checking, as a result of increased drying stresses after moisture change. Collapse-prone Australian eucalypt species in particular are difficult to process into timber products with kiln-drying methods and usually require a lengthy pre-drying phase (Blakemore and Northway 2009; Chafe et al. 1992; Ilic 1999).

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There is potential to greatly reduce overall drying time in the pre-drying phase of some difficult-to-dry species with a concomitant reduction in shrinkage, collapse and checking. The current approach is based on temperatures less than 30 °C in the early drying stage to restrict collapse and internal checking, followed by kiln-drying at temperatures up to 115 °C and finally steam reconditioning of the dried timber at 100 °C and 100% relative humidity to relieve drying stresses and reverse collapse (Haslett 1988; Kauman 1964).

A solution to shorten drying time and reduce unwanted distortion is proposed for difficult-to-dry species. This involves a high-pressure supercritical CO_2 dewatering process which cycles between the supercritical and gas phases producing dewatered wood by extracting free lumen water (sap) and leaving the bound water in the wood cell wall (Dawson et al. 2015; Franich et al. 2014; Newman et al. 2016). Kiln-drying after lumen dewatering theoretically avoids water tension-related collapse and could lead to less distortion (Chafe et al. 1992).

A range of wood species was screened to test the hypothesis of whether less distortion of green wood would occur on oven-drying after dewatering compared to oven-drying alone.

Materials and methods

Timber

Twenty-two New Zealand grown hardwoods (dicotyledonous angiosperms) and softwoods (conifers) were selected for the trial (Table 1) and were sourced in most cases from Scion's trial plots in Rotorua, New Zealand (S 38°7′ E 176°15′). One–metre-long log sections were cut at breast height from the butt log of trees. Their ends were sealed with wax before storage under tarpaulins in the shade for up to 2 weeks prior to being prepared for dewatering. Before dewatering, they were reduced in size, wrapped in plastic and stored at 4 °C for no more than two days before further treatment.

Pinus radiata D.Don and *Nothofagus menziesii* (Hook.f) Oerst. were supplied as freshly sawn boards from local sawmills. The boards were delivered to Scion the day they were sawn and were wrapped in plastic and stored at 4 °C for no more than two days before dewatering. The *Nothofagus fusca* (Hook.f) Oerst. trees were felled and immediately reduced in size before being wrapped in plastic and transported to Scion. They were reduced to final specimen size the day they arrived at Scion and dewatered the following day.

Two inner and two outer boards ($37 \times 37 \times 600\ mm^3$; $R \times T \times L$) were prepared from each log section (Fig. 1). If logs had very narrow sapwood bands, no sapwood was sampled and four heartwood boards were cut (two inner and two outer). Conversely, no inner heartwood specimens could be prepared from sawn *Nothofagus menziesii* and *Nothofagus fusca* boards since the four boards supplied for each species were from the outer position of the tree. Sawn *Pinus radiata* sapwood boards for replicated weekly treatments were also only from the outer position in the log.

Table 1 Classification and sampling of all species in the dewatering trial

Family	Genus	Species	Authority	Heart\sap	Inner\outer
Hardwoods					
Myrtaceae	*Eucalyptus*	*delegatensis*	R.T.Baker	H	I
				H	O
Lauraceae	*Beilschmiedia*	*tawa*	(A.Cunn.) Kirk	H	I
				H	O
Myrtaceae	*Eucalyptus*	*fastigata*	(J.B.Armstr.) H.Deane & Maiden	H	I
				H	O
Myrtaceae	*Eucalyptus*	*nitens*	(H.Deane & Maiden) Maiden	H	I
				H	O
Myrtaceae	*Eucalyptus*	*regnans*	F.Muell.	H	I
				H	O
Nothofagaceae	*Nothofagus*	*fusca*	(Hook.f.) Oerst.	H	O
				H	O
Nothofagaceae	*Nothofagus*	*menziesii*	(Hook.f.) Oerst.	H	O
				H	O
Proteaceae	*Knightia*	*excelsa*	(Müll.Hal.) R.Br.	H	I
				H	O
Softwoods					
Cupressaceae	*Cryptomeria*	*japonica*	(L.f.) D.Don	H	I
				H	O
Cupressaceae	*Cupressus*	*lusitanica*	Mill.	H	I
				S	O
Cupressaceae	*Cupressus*	*macrocarpa*	Gordon	H	I
				H	O
Cupressaceae	*Thuja*	*plicata*	D.Don	H	I
				H	O
Cupressaceae	*Sequoia*	*sempervirens*	(D.Don) Endl.	H	I
				H	O
Pinaceae	*Abies*	*grandis*	(D.Don) Lindl.	H	I
				S	O
Pinaceae	*Picea*	*abies*	(L.) H.Karst.	H	I
				S	O
Pinaceae	*Picea*	*sitchensis*	(Bong.) Carrière	H	I
				H	O
Pinaceae	*Pinus*	*lambertiana*	Douglas	H	I
				S	O
Pinaceae	*Pinus*	*patula*	Schltdl. & Cham.	H	I
				S	O
Pinaceae	*Pinus*	*radiata*	D.Don	H	I
				S	O
Pinaceae	*Tsuga*	*heterophylla*	(Raf.) Sarg.	H	I
				S	O

Table 1 continued

Family	Genus	Species	Authority	Heart\sap	Inner\outer
Pinaceae	*Pseudotsuga*	*menziesii*	(Mirb.) Franco	H	I
				S	O
Podocarpaceae	*Podocarpus*	*totara*	D.Don	H	I
				S	O

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$n = 2$ for all inner and outer specimens

Three end-matched specimens were cut from each board and labelled as series A, B or C sets of specimens as follows:

Series A—37 × 37 × 200 mm^3 ($R \times T \times L$); for dewatering followed by oven-drying.
Series B—37 × 37 × 100 mm^3; for wood properties including moisture content and density.
Series C—37 × 37 × 200 mm^3; for oven-drying only.

Holes, 3 mm in diameter × 100 mm deep, were drilled in the middle of one end of each series A specimen to snugly fit a thermocouple for internal temperature measurements during supercritical CO_2 treatments. All specimens were weighed, and their dimensions recorded with digital callipers. Specimens were sealed in plastic bags and stored at 4 °C prior to treatment. They were equilibrated overnight to 20 °C in the laboratory before dewatering.

Wood volumes for assessment of density were measured by water displacement for all series B specimens. Weights and dimensions were measured, and green moisture content, basic density, maximum moisture content and % saturation were calculated following Kininmonth and Whitehouse (1991). The weights and dimensions of all series C specimens were recorded before and after oven-drying to a constant weight at 105 °C.

Dewatering experiments

The series A specimens were dewatered over a six-week period with the four specimens per species dewatered on the same day. All plant pipework was dismantled and cleaned with acetone and ethanol between each species.

The supercritical dewatering plant and operation has been described previously (Dawson et al. 2015). In summary, for seven cycles the CO_2 pressure was cycled between 4 MPa (gas) and 20 MPa (supercritical) with 2 min each for pressurisation, decompression and hold times with a dewatering vessel jacket temperature of 50 °C.

Dewatering efficiency

The fibre saturation point (FSP) is relevant in defining a measure of dewatering efficiency as it is a natural endpoint in the dewatering process (at the FSP, lumen

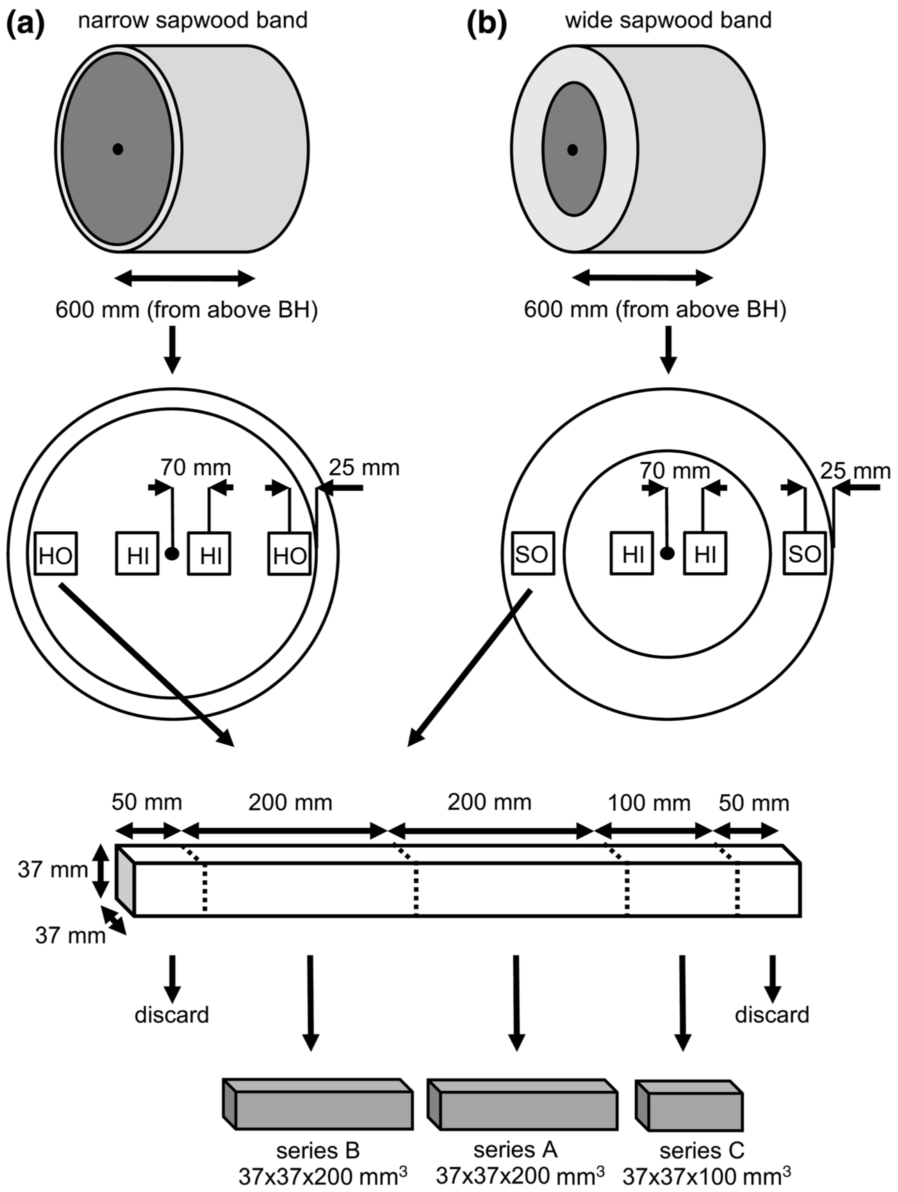

Fig. 1 Wood sampling regime for **a** narrow sapwood bands and **b** wide sapwood bands. *BH* breast height, *HI* inner heartwood, *HO* outer heartwood, *SO* outer sapwood

water has been removed but wood cell walls are still saturated). The FSP for wood at ambient temperature and pressure is about 30% (Berry and Roderick 2005; Kininmonth and Whitehouse 1991; Kollmann and Cote 1968; Simpson and TenWolde 1999). The dewatering efficiency (DW_{eff}) of wood (Eq. 1) was defined as:

$$DW_{eff}\,(\%) = 100\left(\frac{MC_{green} - MCDW}{MC_{green} - FSP}\right) \tag{1}$$

where MC_{green} and MCDW are the moisture contents of green and dewatered wood, respectively, and the FSP is assumed to be 30% for all species. Siau (1984) considered that although 30% is an average, the FSP can vary from between 24 and 32% depending on species. This means that dewatering efficiency results could vary by ±3.5% if MCgreen is 100% and ±7% if MCgreen is 40%. Characterisation of FSP for each species would lead to a refinement of the results but was considered to be outside the accuracy required for this screening study.

Shrinkage, collapse and checking measurements

The volumetric shrinkage, checking and collapse of all species were measured on the end-matched series A, B and C specimen sets after:

- Dewatering only.
- Dewatering and oven-drying.
- Oven-drying only.

Specimen dimensions were measured using digital callipers, and the position of cross sectional measurements was marked on the specimens to ensure consistency of readings of green, dewatered and oven-dried wood.

Collapse was measured on the two radial faces as the sum of the largest cross sectional depressions from the original green surface (Standards Australia and Standards New Zealand Standards Australia and Standards New Zealand 2001). This method traditionally determines the depth of collapse degrade to be removed from each board to maximise timber recovery. Volumetric shrinkage was measured as volume change, calculated from dimensional changes, before and after treatments.

Visible checks on the *two ends* of each specimen were characterised by the number of checks and their total width, and on the *four faces* by the number of checks and their total length. Checking data were normalised to a per dm^2 area density.

Quality control

Every third day, four *Pinus radiata* sapwood quality control specimens were dewatered to assess the consistency of both plant operation and the repeatability of shrinkage, collapse and checking measurements. Both the moisture content after dewatering and the dewatering efficiency showed no significant difference ($p > 0.05$) over the six-week period, confirming consistency of plant operation. The shrinkage, collapse and checking of the quality control specimens were each tightly grouped with small variation, compared with the hardwood and softwood groups, confirming the repeatability of the distortion measurement procedures.

Statistical analyses

A general linear model for analysis of variance using pooled variance was used to test differences between dewatering and oven-drying, and oven-drying alone treatments for shrinkage, collapse and checking of individual species.

Results and discussion

Dewatering efficiency

In both softwoods and hardwoods, there were species that dewatered to a greater extent than others. Dewatering efficiencies ranged from 4% (*Nothofagus fusca* outer heartwood) to 93–94% for a group of softwood sapwoods (*Pinus radiata*, *Pinus patula*, *Pinus lambertiana* and *Pseudotsuga menziesii*). Species have been grouped into low-, medium- and high-dewatering-efficiency groups (Fig. 2a, b; Table 2).

Penetration of CO_2 into specimens manifested itself as internal temperature changes over time and is presented for representatives of each species group (Fig. 2a, b). During each of the seven high-pressure dewatering cycles, the internal temperature of specimens changed as a consequence of firstly, heating of the vessel jacket to maintain a temperature at 50 °C, secondly, heat of compression from CO_2 pressure increase and finally, decompression cooling. For specimens that dewatered well (softwoods *Pseudotsuga menziesii* sapwood and *Sequoia sempervirens* inner heartwood; hardwoods *E. nitens* and *E. regnans* inner heartwood, highlighted in Fig. 2a, b), as water removal from lumens occurred during a cycle, more CO_2 could be pressurised into the specimen during the following cycle and the increased heat of compression led to a concomitant rise in internal temperature (Dawson et al. 2015). Similarly, in these situations the mass of CO_2 exiting the specimen on decompression increased, leading to a further reduction in the internal specimen temperature. As dewatering proceeded, the moisture content in the specimens, calculated following the method of Dawson et al. (2015), fell continually (Fig. 2a, b). Conversely, the internal temperature of low-dewatering-efficiency species (hardwood *Nothofagus fusca* and softwood *Thuja plicata*) increased from ambient temperature to 50 °C and reached a constant moisture content, as dewatering and CO_2 penetration occurred at low levels. The very low moisture content of green *Pseudotsuga menziesii* inner heartwood corresponded to the FSP with no lumen water, and hence, further dewatering could not occur and CO_2 fully penetrated into and was removed from the wood structure resulting in the same magnitude of internal temperature changes observed across each cycle (29–48 °C; not shown). Half of all softwood specimens were not suitable for dewatering since their green % saturation values were less than 40%, whereas all hardwood specimens had values greater than 60%.

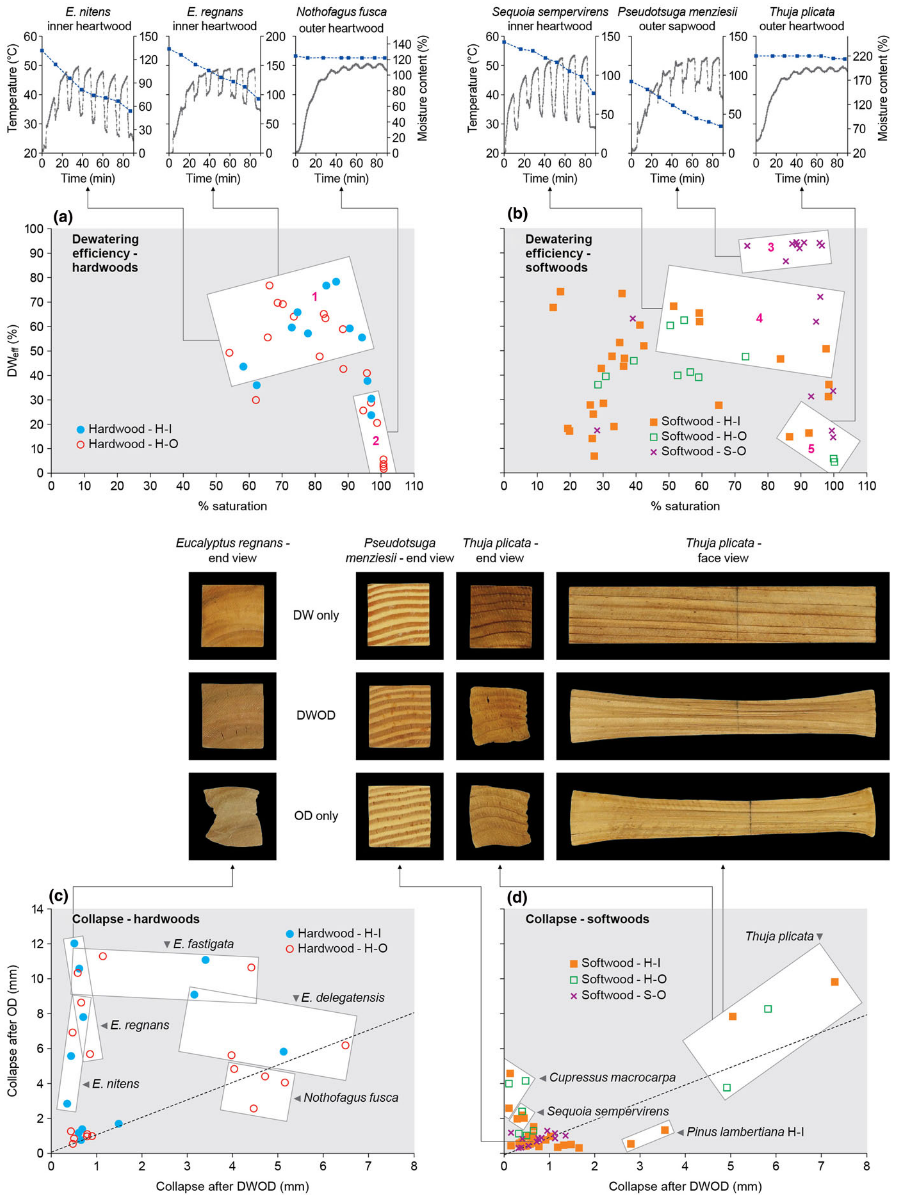

Fig. 2 Dewatering efficiency as a function of % saturation for **a** hardwood species and **b** softwood species (see Table 2 for species in each group). Changes in specimen internal temperature (*left vertical* axis) and moisture content (*right vertical* axis) during dewatering are highlighted for representative species from each group. Collapse after dewatering and oven-drying, and after oven-drying alone of **c** hardwoods and **d** softwoods. The *dashed straight line* shows equal effect of dewatering and oven-drying, and oven-drying alone. Highlighted photographs: End view of *Eucalyptus regnans*, *Pseudotsuga menziesii* and *Thuja plicata* after dewatering alone, dewatering and oven-drying, and after oven-drying alone and face view of *Thuja plicata* after the same treatments. *Note* this figure displays the complete set of raw data

Table 2 Dewatering efficiency[a] groups[b] for softwoods and hardwoods[c]

	Heart/sap	Inner/outer	High $DW_{eff} > 90\%$	Medium DW_{eff} 50–90%	Low DW_{eff} < 30%
				Group 1	Group 2
Hardwood	H	I	–	*Eucalyptus nitens* (78: 77, 78) *Knightia excelsa* (63: 60, 66) *Eucalyptus regnans* (58: 57, 59)	*Eucalyptus delegatensis* (27: 24, 31)
Hardwood	H	O	–	*Nothofagus menziesii* (66: 49, 77) *Knightia excelsa* (64: 64, 65) *Eucalyptus regnans* (56: 48, 64) *Eucalyptus nitens* (51: 43,59)	*Eucalyptus delegatensis* (25: 21, 29) *Nothofagus fusca* (4: 3, 5)
				Group 4	Group 5
Softwood	H	I	–	*Cupressus lusitanica* (67: 61, 73) *Sequoia sempervirens* (66: 63, 69)	*Thuja plicata* (16: 16, 16)
Softwood	H	O	–	*Sequoia sempervirens* (53: 46, 60)	*Thuja plicata* (4: 4, 5)
			Group 3		
Softwood	S	O	*Pinus radiata* (94: 94, 94) *Pinus patula* (94: 93, 94) *Pinus lambertiana* (93: 93, 94) *Pseudotsuga menziesii* (93: 92, 93)	*Picea abies* (83: 72, 94) *Cupressus lusitanica* (74: 62, 86)	*Abies grandis* (16: 15, 18)

Table 2 continued

Species not included in groups 1–5[d]				Comment on DW_{eff} values	% Saturation (<40%)
Hardwood	H	I	*Eucalyptus fastigata* (47: 38, 55)	Did not fit a DW_{eff} group	
			Beilschmieda tawa (40: 36, 44)	Did not fit a DW_{eff} group	
Hardwood	H	O	*Beilschmieda tawa* (43: 30, 56)	Did not fit a DW_{eff} group	
			Eucalyptus fastigata (33: 26, 41)	Did not fit a DW_{eff} group	
Softwood	H	I	*Pinus radiata* (71: 68, 74)		16
			Abies grandis (51: 48, 54)		34
			Cryptomeria japonica (49: 47, 52)		39
			Podocarpus totara (45: 44, 46)	Did not fit a DW_{eff} group	Large variation
			Cupressus macrocarpa (40: 28, 51)	Did not fit a DW_{eff} group	
			Picea abies (39: 28, 50)	Did not fit a DW_{eff} group	
			Picea sitchensis (35: 28, 42)		28
			Pinus lambertiana (34: 32, 36)	Did not fit a DW_{eff} group	
			Tsuga heterophylla (19: 14, 25)		27
			Pinus patula (18: 18, 18)		19
			Pseudotsuga menziesii (13: 7, 19)		30
Softwood	H	O	*Cupressus macrocarpa* (51: 39, 63)	Large variation	
			Cryptomeria japonica (44: 41, 47)	Did not fit a DW_{eff} group	
			Picea sitchensis (38: 36, 40)		30
Softwood	S	O	*Tsuga heterophylla* (40: 18, 63)	Large variation	34
			Podocarpus totara (32: 31, 33)	Did not fit a DW_{eff} group	

[a] % DW_{eff} values in brackets are mean: min, max and have been rounded to two significant figures

[b] For *Nothofagus fusca* and *Nothofagus menziesii*, four outer board specimens were used

[c] Group numbers (1–5) of species are shown in Fig. 1a, b

[d] Species not included in a group (1–5) if $30 < \text{mean } DW_{eff} < 50$

Table 3 Mean and standard error of collapse of various softwood and hardwood groups following treatment

Hard/soft wood	Heart/ sap	Inner/ outer	*n*	Collapse on DW[a] (mm)	Collapse on DWOD[b] (mm)	Collapse on OD[c] (mm)
Hardwood	H	I	12	0.0 ± 0.0	1.5 ± 0.5	5.8 ± 1.2
Hardwood	H	O	20	0.0 ± 0.0	2.1 ± 0.5	4.4 ± 0.8
Softwood	H	I	28	0.1 ± 0.0	1.2 ± 0.3	1.6 ± 0.4
Softwood	H	O	10	0.0 ± 0.0	1.4 ± 0.7	2.8 ± 0.8
Softwood	S	O	18	0.0 ± 0.0	0.7 ± 0.7	0.8 ± 0.1

[a] Dewatering alone

[b] Dewatering followed by oven-drying

[c] Oven-drying alone

Collapse

Collapse is a form of shrinkage which occurs during timber drying above the FSP, expressed as a buckling of cell walls and squashing of lumens. In both softwoods and hardwoods, there was no collapse after dewatering green wood (Table 3). Collapse after oven-drying was striking for the softwood *Thuja plicata* and for the hardwoods (*E. nitens*, *E. regnans*, *E. fastigata*, *E. delegatensis*, *Nothofagus fusca*), resulting in severe distortion in end grains (Fig. 2c, d). *Thuja plicata* timber in particular also exhibited an 'hour-glass' appearance after both dewatering and oven-drying and oven-drying alone, in which the ends of specimens retained their shape and size to a greater degree than the middle of the specimens.

The collapse of cells after dewatering and oven-drying was significantly less than after oven-drying alone ($p < 0.05$). Collapse of cell walls that is perpendicular to the grain is thought to occur as a result of water tension forces, expressed through liquid columns within saturated timber, exceeding the wood cell wall strength. Collapse may be more prevalent in low-density eucalypts (Blakemore and Northway 2009; Hansmann et al. 2002; Kauman 1964). Water tension forces, within the water-filled wood cells, increase with a decrease in both the capillary radii of ultra-structure pathways and pores and in the permeability of the timber (Chafe et al. 1992). The size of pore diameters defines both the permeability and water tension. Pores are smaller in hardwoods (5–170 nm) than in softwoods (20–4000 nm) (Hansmann et al. 2002; Siau 1995). This results in higher capillary tensions in hardwoods than softwoods during kiln-drying and can lead to collapse. Collapse occurs on oven-drying after dewatering, when the free lumen water has to a considerable extent been removed, but it is reduced compared to collapse after oven-drying alone. The mechanism for this process is not fully understood. Furthermore, all hardwood specimens used in this study were heartwood which exhibits a decrease in effective pore radii as a result of extractives synthesis and pit encrustation.

Water tension is highly related to the permeability of timber. Permeability is a measure of how well a gas or liquid fluid travels through a porous material under the influence of a pressure gradient. Pore size and the distribution and interconnectivity of pathways determine the permeability characteristics of various timbers (Lehringer et al. 2009). Chafe et al. (1992) considered that the lower the permeability of hardwoods, the greater the tendency for collapse to occur. Permeability measurements have been taken previously with a variety of techniques (Hansmann et al. 2002). In the current work, a direct link is made between CO_2 permeability and internal temperature of each specimen during dewatering. The higher the penetration of gaseous CO_2, the greater the heating effect from compression and the greater the rise in internal temperature. From the internal temperature plots (Fig. 2a, b highlights), *Nothofagus fusca* and *Thuja plicata* both appear to be impermeable to supercritical CO_2 and are susceptible to collapse. *Nothofagus fusca* impermeability is due to polyphenol (Hillis and Inoue 1967) encrustation of pit membranes (Kininmonth 1972), while the impermeability of New Zealand grown *Thuja plicata* is due to a high extractives content (Cown and Bigwood 1979). This compares with *E. delegatensis* which exhibited the lowest dewatering efficiency, and therefore, lowest permeability of the four eucalypts, and *E. regnans* and *E. nitens* which both displayed a level of dewatering efficiency and CO_2 penetration in between that of *Nothofagus fusca and Pseudotsuga menziesii* (Table 2).

For collapse to occur, lumens should not contain air as any tension forces would be dissipated as a result of air expansion (Chafe et al. 1992). Saturated specimens that underwent oven-drying alone could have collapsed at high moisture contents as a consequence of high liquid tension and high stress moisture gradients across the drying front. The reduced collapse on dewatering alone and on dewatering followed by oven-drying implies that the dewatering process induces some form of stress relief in the same way that prolonged air-drying reduces moisture content to just above the FSP without collapse, due to the slow dissipation of stresses through creep relaxation. Furthermore, dewatering of *Pinus radiata* sapwood results in uniform moisture contents within the specimens over successive dewatering cycles (Meder et al. 2015) with greatly reduced stress moisture gradients. The dewatering process mechanism operates over a shorter time frame than kiln-drying and involves several possible factors that are thought to play parts in the process; creep, dewatering time, wood softening and meniscus disruption through bubble formation.

Volumetric shrinkage and checking

Shrinkage and collapse of hardwoods and softwood outer heartwoods were highly correlated ($r^2 = 71–84\%$) after dewatering followed by oven-drying. Sapwoods did not show differences in shrinkage and checking between dewatered then oven-dried and oven-dried only wood. For many heartwoods, shrinkage was significantly less ($p < 0.05$) after dewatering and oven-drying than after oven-drying alone, but checking was significantly higher ($p < 0.05$) particularly the width of end checks and length of face checks of *Pseudotsuga menziesii, Pinus lambertiana* and *Cupressus lusitanica* heartwood.

The width of *end* checking per square decimetre was an order of magnitude more prevalent than *face* checking in the sapwoods. The hardwood *Nothofagus fusca* checked the most. Unlike collapse and shrinkage, these results are clearly not attributable to permeability since sapwoods had the highest permeabilities and *Nothofagus fusca* the least. Haslett (1988) found that low-density eucalypt timber checked internally more than higher density material.

Dewatering and drying

According to Clifton (1994), *E. regnans, E. nitens*, *Knightia excelsia*, *Cupressus lusitanica* and *Sequoia sempervirens* heartwood and *Cupressus lusitanica* sapwood should all be air-dried to FSP to avoid collapse. These species had dewatering efficiencies of 50–70%. From dewatering, shrinkage and collapse viewpoints, some medium-permeability collapse-prone species could be promising candidates for dewatering prior to drying. This suggests that there is potential to greatly reduce time in the pre- or air-drying phase of some difficult-to-dry species with a reduction in shrinkage and collapse.

Conclusion

The hypothesis has been tested of whether less distortion of wood would occur on oven-drying green wood after dewatering compared to oven-drying alone. Results showed that distortion-prone timber from hardwood heartwoods would benefit most from this drying approach. For all the hardwoods, heartwood moisture contents were suitable for dewatering and dewatered to varying degrees. Since impermeability is a key indicator for collapse on drying, species with medium to high dewatering efficiency would also be candidates for reducing both the long pre- or air-drying phases of difficult-to-dry species and their collapse. The sapwood of some softwoods dewatered very efficiently, however, about half of softwood specimens had moisture content and % saturation values too low to be suitable for dewatering.

Supercritical CO_2 dewatering of wood offers a new window with which to look at wood processing properties of various timber species with ideally a material close to the FSP. The observation of an hour-glass shape on drying of *Thuja plicata* (after both dewatering and oven-drying and after oven-drying alone) shows uneven drying forces at work on the ends and middle of specimens of a very challenging species. For both the dewatering and oven-drying and oven-drying alone schedules used, checking is one route for stress dissipation along with collapse or normal shrinkage. The increased internal checking on dewatering and oven-drying suggests that collapse, shrinkage and checking operate simultaneously. There may be potential to control their expression.

Acknowledgements The following Scion staff are thanked for their assistance: Hank Kroese and Ian Simpson for technical contributions, Mark Kimberley for statistical analysis and Gareth Lloyd-Jones for editorial guidance.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Berry SL, Roderick ML (2005) Plant-water relations and the fibre saturation point. New Phytol 168:25–37

Blakemore P, Northway R (2009) Review of, and recommendations for, research into preventing or ameliorating drying related internal and surface checking in commercially important hardwood species in south-eastern Australia. For Wood Prod Aust, Melbourne

Chafe SC, Barnacle JE, Hunter AJ, Ilic J, Northway RL, Rozsa AN (1992) Collapse: an introduction. CSIRO Division of Forest Products, Melbourne

Clifton NC (1994) New Zealand timbers: the complete guide to exotic and indigenous woods. GP Publications, Wellington

Cown DJ, Bigwood SR (1979) Some wood characteristics of New Zealand-grown western red cedar (*Thuja plicata* D. Don). N Z J For 24:125–132

Dawson BSW, Pearson H, Kroese HW, Sargent R (2015) Effect of specimen dimension and pre-heating temperature on supercritical CO_2 dewatering of radiata pine sapwood. Holzforschung 69:421–430

Franich RA, Gallagher S, Kroese H (2014) Dewatering green sapwood using carbon dioxide cycled between supercritical fluid and gas phase. J Supercrit Fluid 89:113–118

Hansmann C, Gindl W, Wimmer R, Teischinger A (2002) Permeability of wood—a review. Drev Vysk 47:1–16

Haslett A (1988) Properties and utilisation of exotic speciality timbers grown in New Zealand. Part V: ash eucalypts and *Eucalyptus nitens* (FRI Bulletin No. 119). Ministry of Forestry and Forest Research Institute, Rotorua

Hillis WE, Inoue T (1967) The polyphenols of *Nothofagus* species-II. The heartwood of Nothofagus fusca. Phytochemistry 6:59–67

Ilic J (1999) Shrinkage-related degrade and its association with some physical properties in *Eucalyptus regnans* F. Muell. Wood Sci Technol 33:425–437

Kauman WG (1964) Cell collapse in wood. CSIRO Division of Forest Products, Melbourne

Kininmonth JA (1972) Permeability and fine structure of certain hardwoods and effects on drying: II. Differences in fine structure of *Nothofagus fusca* sapwood and heartwood. Holzforschung 26:32–38

Kininmonth JA, Whitehouse LJ (1991) Properties and uses of New Zealand radiata pine. Volume one—wood properties. Ministry of Forestry and Forest Research Institute, Rotorua

Kollmann FFP, Cote WA (1968) Principles of wood science and technology. I: Solid wood. Springer, Berlin

Lehringer C, Richter K, Schwarze FWMR, Militz H (2009) A review on promising approaches for liquid permeability improvement in softwoods. Wood Fiber Sci 41:373–385

Meder R, Franich RA, Callaghan PT, Behr VC (2015) A comparative study of dewatering of Pinus radiata sapwood using supercritical CO_2 and conventional forced air-drying via in situ magnetic resonance microimaging (MRI). Holzforschung 69:1137–1142

Newman RH, Franich RA, Meder R et al (2016) Proton magnetic resonance imaging used to investigate dewatering of green sapwood by cycling carbon dioxide between supercritical fluid and gas phase. J Supercrit Fluid 111:36–42

Siau JF (1984) Transport processes in wood. Springer, Berlin

Siau JF (1995) Wood: influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, New York

Simpson W, TenWolde A (1999) Physical properties and moisture relations of wood. In: Wood handbook: wood as an engineering material (Gen. Tech. Rep. FPL-GTR-113). Forest Products Laboratory, Madison, Chapter 3, 1–24

Standards Australia, Standards New Zealand (2001) Timber-assessment of drying quality AS/NZS4787. Wellington, Sydney