ASSESSMENT OF LONGITUDINAL SHRINKAGE AND SWELLING USING THE APA AND ASTM METHODS

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Abstract. The APA and ASTM methods of measuring longitudinal shrinkage and swelling were evaluated and compared using radiata pine coupons with a wide range of wood properties and different operators. The two methods gave different measurements of longitudinal shrinkage and swelling as a result of differences in the location of the measurement points, and the ability to correct for out-of-plane distortion. The APA method gave more precise measurements from the use of inserted brass eyelets and the correction of out-of-plane distortion with a vacuum table. The measurements were not affected by wood type or operator. The ASTM method was found to be sensitive to the condition of the transverse surface at the measurement point and to the presence of drying distortion. The measurements varied in response to wood type and operator. The results indicate the APA method is more precise for measuring longitudinal shrinkage and swelling when measurements are made in series along boards and cants.

Keywords: APA, ASTM, longitudinal shrinkage, radiata pine, swelling.

INTRODUCTION

The American Plywood Association (APA) and American Society for Testing Materials (ASTM) methods provide alternative approaches to the measurement of longitudinal shrinkage and swelling that differ in the location of the measurement points and the correction of out-of-plane distortion. In the APA method (APA test method 2001), the measurement points are brass eyelets inserted in prebored holes a set distance from the coupon ends, and out-of-plane distortion is corrected using a vacuum table. The distance between the centers of the brass eyelets is measured using a trammel gauge. In the ASTM method (ASTM standard 1999), the measurement point is the cut transverse surface of the coupon end, and there is no correction for out-of-plane distortion. The distance between the two ends of the coupon is measured by placing one end of the coupon against a stationary metal stop, and the other end against a sliding metal stop connected to a dial gauge. The differences between the APA and ASTM methods could cause different values of longitudinal shrinkage and swelling, depending on the operator using the method and the properties of the coupons.

The APA and ASTM methods were compared in this study using radiata pine (*Pinus radiata* D. Don) coupons with a wide range of wood properties and different operators. The sources of coupon length variation were evaluated, and the differences in longitudinal shrinkage and swelling were compared for the APA and ASTM

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methods, on the basis of the coupon wood properties and operators using a paired comparison design.

MATERIALS AND METHODS

Repeatability and reproducibility

The sources of variation in coupon length include:

- Repeatability of the measurement equipment,
- Reproducibility of the operators making the measurements,
- Differences in the cut length of the coupons being measured,
- Interaction of the operators and coupons.

The variance components for these sources of variation are given in the following equation:

$$\sigma_{total} = \sqrt{\sigma^2_{equipment} + \sigma^2_{operator} + \sigma^2_{coupon} + \sigma^2_{operator...\times...coupon}}. \quad (1)$$

The repeatability of the measurement equipment ($\sigma^2_{equipment}$) is obtained from repeated measurements of coupon length. The reproducibility of the operator measurements ($\sigma^2_{Operator}$ + $\sigma^2_{Operator...\times...Coupon}$) is obtained from length measurements of the same coupons by different operators.

Other sources of variation can include changes in environmental conditions, such as the air temperature and relative humidity. The environmental effect was minimized in the study by measuring the coupon lengths in a controlled environment room at 23°C and 50% RH.

Materials and preparation

Wood samples. The green radiata pine coupons were sourced from three sapwood boards, one heartwood board, and one board containing pronounced compression wood. The dry radiata pine coupons were obtained from two kiln-dried sapwood boards.

Coupon preparation. The green and dry coupons were cut to radial, tangential, and length dimensions: 15 × 15 × 300 mm, using a circular saw with a fine-tooth tungsten–carbide-tipped blade.

Two holes were drilled in one radial or tangential surface of each coupon at a distance of 10 mm from the coupon ends using a dual drill press. Stimpson GS 4-11 brass eyelets, with 3.07-mm outside diameter, 5.08-mm flange diameter, 8.74-mm length under flange, and 0.241-mm metal thickness, were inserted in the holes. The length of the eyelets ensured they were oriented correctly in the coupons, and provided a large surface area of contact with the wood.

Coupon drying. The green coupons were oven-dried at 60°C to constant weight.

Coupon resaturation. The dry coupons were resaturated by placing them in water and applying a vacuum of −85 kPa for 20 min, and then a pressure of 1400 kPa for 1 h in a single cycle.

Coupon measurements

Green coupons.

- Weight–green and oven-dried to constant weight at 60°C;
- Radial and tangential dimensions–green;
- Length–green and oven-dried to constant weight at 60°C;
- Basic density–oven-dried weight/green volume

Dry coupons.

- Weight–dry, resaturated with water, and oven-dried to constant weight at 60°C;
- Radial and tangential dimensions–dry and resaturated with water;
- Length–dry and resaturated with water;
- Dry density oven-dried weight/oven-dried volume

Coupon radial and tangential dimensions. The radial and tangential dimensions were measured at the coupon midpoint using a Sylvac dial gauge vertically mounted in a dial gauge stand with the coupon placed on a metal cylinder. The Sylvac dial gauge was calibrated at 20 mm using a Mitutoyo gauge block, and the radial and tangential dimensions were measured to a resolution of 10 μm.

Coupon length. The APA method involved placing the coupon on a vacuum table, sealing with plastic film, applying a vacuum to correct out-of-plane distortion, and then measuring the distance between the centers of the two brass eyelets, using a trammel gauge fitted with a Sylvac P25 measuring probe, to a resolution of 1 μm (Fig 1a). The pins of the trammel gauge were placed in the brass eyelets and centered. The length measurement was taken by pressing a foot pedal connected to the Sylvac P25 measuring probe via a D50S control unit. The Sylvac measuring probe was calibrated with a stainless steel calibration bar that had two holes drilled at a distance of 280.0 mm between centers.

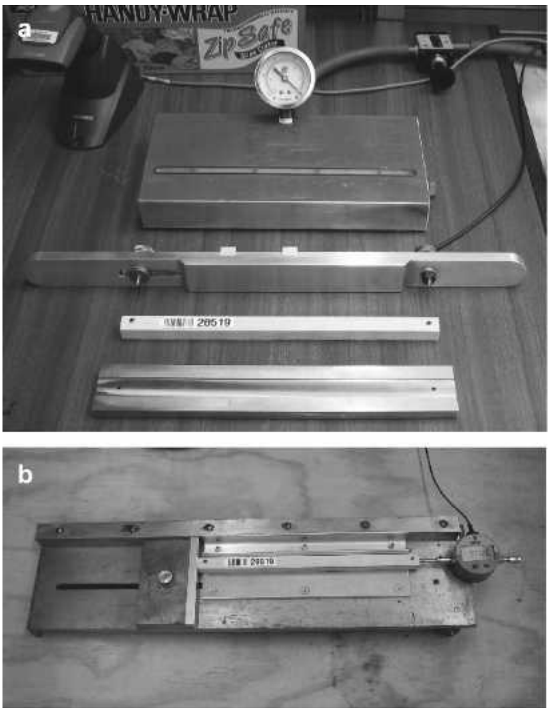

FIGURE 1. Longitudinal shrinkage and swelling measurement equipment (a) APA method, from back to front: the vacuum table, trammel gauge, coupon, and calibration bar; (b) ASTM method.

The ASTM method involved placing one end of the coupon against the stationary aluminium stop on a brass table and the other end of the coupon against the Sylvac dial gauge and measuring the distance between the two ends of the coupon to a resolution of 10 μm (Fig 1b). This adaptation of the ASTM method was used because of the small cross-sectional area of the coupons. The Sylvac dial gauge was calibrated at 300 mm using Mitutoyo gauge blocks.

Three operators measured the green and oven-dried, and dry and resaturated coupon lengths twice in random order (Table 1). There were a total of 16 length measurements for each initially green and dry coupon.

Data analysis

The APA and ASTM methods were compared using analysis of variance (ANOVA) with a paired-comparison design. Because of the large coupon-to-coupon variation in longitudinal shrinkage and swelling, a paired-comparison design is more effective in evaluating differences between the APA and ASTM methods, and the operators, based on paired-measurements of length for each coupon.

The sources of coupon length measurement variation for the APA and ASTM methods were analyzed using SAS Proc Mixed (Littell et al 1996) with a two-way random effects ANOVA model of the form:

$$Y_{ijk} = \mu + Operator_i + Coupon_j + (Operator \times Coupon)_{ij} + Equipment_{k(ij)}, \qquad (2)$$

where Y_{ijk} is the coupon length for the ith operator ($i = 1,2$); jth coupon ($j = 1, \ldots, 199$); and kth measurement ($k = 1, 2$).

TABLE 1. *Operator allocation for the coupon length measurements, using the APA and ASTM methods.*

Coupon measurements	Operators	Operators
Longitudinal shrinkage	Green coupon length	Oven-dried coupon length
APA method	Operator 1 + Operator 2	Operator 2 + Operator 3
ASTM method	Operator 1 + Operator 2	Operator 2 + Operator 3
Longitudinal swelling	Dry coupon length	Resaturated coupon length
APA method	Operator 1 + Operator 2	Operator 1 + Operator 3
ASTM method	Operator 1 + Operator 2	Operator 1 + Operator 3

The operators and coupons were considered to be random factors in the model.

The variance components were represented by the equation:

$$\sigma_y^2 = \sigma_{Operator}^2 + \sigma_{Coupon}^2 + \sigma_{Operator\ldots\times\ldots Coupon}^2 + \sigma_{Equipment}^2. \quad (3)$$

The variance components for the equipment repeatability ($\sigma_{Equipment}^2$), the operator reproducibility ($\sigma_{Operator}^2 + \sigma_{Operator\ldots\times\ldots Coupon}^2$), and the coupon-to-coupon variability (σ_{Coupon}^2) were calculated for the green and oven-dried, dry and resaturated coupon lengths, for each wood type and measurement method.

The longitudinal shrinkage or swelling of each coupon was calculated using the equation:

$$LS = \frac{G_{Length} - D_{Length}}{G_{Length}} \times 100 \quad (4)$$

where: *LS* is the longitudinal shrinkage or swelling, G_{Length} is the green or dry coupon length, and D_{Length} is the oven-dried or resaturated coupon length.

The average values of longitudinal shrinkage and swelling were calculated for each combination of wood type, operator, and measurement method.

An approximation of the variance of longitudinal shrinkage and swelling was calculated using the delta method (Oehlert 1992). This approximation produces the following equation for the variance:

$$Variance\,(LS) = \frac{1}{G_{Length}} \times Variance\,(D_{Length}) + \frac{D_{Length}^2}{G_{Length}^4} + Variance\,(G_{Length}) \quad (5)$$

The variances of longitudinal shrinkage and swelling were calculated for the different wood types and measurement methods, using the average values of green and oven-dried, and dry and resaturated coupon lengths, and the variances of the repeated measurements ($\sigma_{Equipment}^2$) in the equation.

The green or dry, and resaturated moisture content of each coupon was calculated using the equation:

$$MC = \frac{G_{Weight} - D_{Weight}}{D_{Weight}} \times 100 \quad (6)$$

where: *MC* is the moisture content, G_{Weight} is the green, dry or resaturated coupon weight, D_{Weight} is the oven-dried coupon weight.

The basic density of each green coupon and the dry density of each dry coupon were calculated using the equation:

$$Density = \frac{D_{Weight}}{G_{Volume}} \quad (7)$$

where: *Density* is the basic or dry density, D_{Weight} is the oven-dried weight of the green coupon or the dry weight of the dry coupon, G_{Volume} is the green volume of the green coupon or dry volume of the dry coupon.

The longitudinal shrinkage and swelling, and the green moisture content and basic density for the different wood types were compared using SAS

Proc GLM (SAS Institute Inc. 2000) with pairwise t-tests, equivalent to Fisher's LSD test in the case of equal cell sizes.

RESULTS AND DISCUSSION

Coupon wood properties

The green radiata pine coupons provided a wide range of green moisture content and basic density (Table 2, Fig 2) with significant differences between the sapwood, heartwood, and compression wood coupons. The heartwood coupons had lower green moisture content and lower basic density (indicating the presence of juvenile wood). The sapwood and compression wood coupons had higher green moisture content, and the compression wood coupons had higher basic density.

The dry radiata pine coupons had a narrow range of dry moisture content and a wide range of dry density (Table 2). The dry coupons were resaturated in water to high moisture contents, indicating the boards from which they were cut were sapwood.

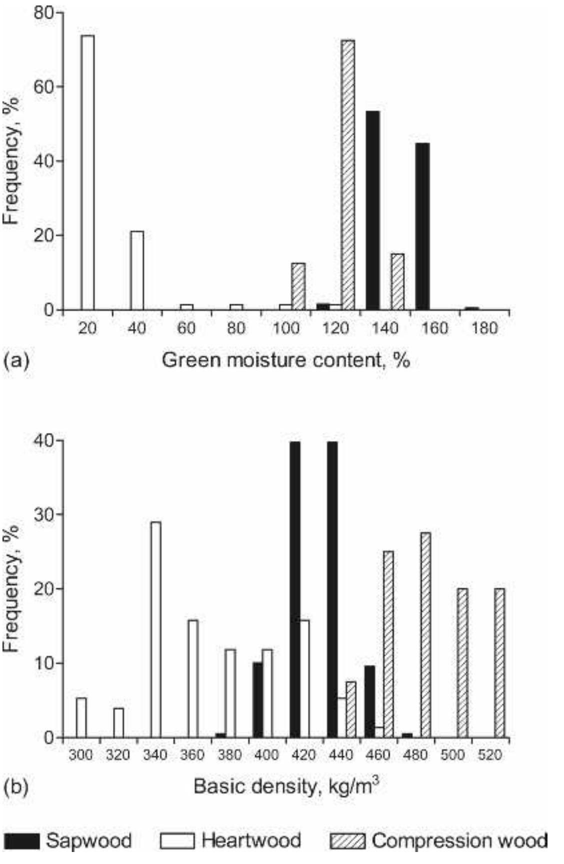

FIGURE 2. Wood property distributions for the sapwood, heartwood and compression wood coupons (a) green moisture content; (b) basic density.

Coupon length variation

The difference in the cut-length of the coupons was the largest source of coupon length variation, with the length measurements being a small source of coupon length variation (Tables 3 and 4, Figs 3 and 4). The measurement variation included the repeatability of the equipment and the reproducibility of the operators. The APA method had good equipment repeatability and operator reproducibility with both being very small sources of length variation. For the ASTM method, the equipment repeatability and operator reproducibility varied with wood type, and the green and oven-dried, and dry and resaturated coupon lengths.

The equipment repeatability for the ASTM method green and dry coupon lengths was a sig-

TABLE 2. *Coupon wood properties. Average and range in brackets, with different letter following the average value indicating a significant difference at $p < 0.01$.*

Coupon	Wood type	No.	Moisture content (%)	Density[1] (kg/m³)
Green	Sapwood	199	148 c (126–171)	429 b (387–473)
Green	Heartwood	76	32 a (26–120)	371 a (300–462)
Green	Compression wood	40	119 b (102–137)	484 c (433–524)
Dry	Sapwood	68	14 (12–16)	412 (341–460)
Resaturated[2]	Sapwood	68	186 (157–236)	

[1] Basic density for the green coupons, dry density for the dry coupons.
[2] The dry coupons were resaturated in water under vacuum and pressure.

TABLE 3. *Variance components for the sources of coupon length variation for green and dry wood using the APA and ASTM methods.*

	Variance components (%)			
Sources of variation	Green sapwood	Green heartwood	Green compression wood	Dry wood
APA method				
Repeatability	0.5	1.1	0.6	1.4
Reproducibility	0.0	0.1	0.0	0.0
Operator	0.0	0.1	0.0	0.0
Operator × coupon	0.0	0.0	0.0	0.0
Coupon	99.5	98.8	99.4	98.6
ASTM method				
Repeatability	2.2	3.9	5.7	4.6
Reproducibility	0.7	1.3	0.0	13.0
Operator	0.7	0.6	0.0	9.6
Operator × coupon	0.0	0.7	0.0	3.4
Coupon	97.1	94.8	94.3	82.4

TABLE 4. *Variance components for the sources of coupon length variation for oven-dried and resaturated wood using the APA and ASTM methods.*

	Variance components (%)			
Sources of variation	Oven-dried sapwood	Oven-dried heartwood	Oven-dried compression wood	Resaturated wood
APA method				
Repeatability	0.6	0.4	0.4	0.5
Reproducibility	0.1	0.1	0.0	0.4
Operator	0.1	0.1	0.0	0.4
Operator × coupon	0.0	0.0	0.0	0.0
Coupon	99.3	99.5	99.6	99.1
ASTM method				
Repeatability	0.7	0.5	4.4	0.8
Reproducibility	0.2	0.1	0.0	0.0
Operator	0.1	0.1	0.0	0.0
Operator × coupon	0.1	0.0	0.0	0.0
Coupon	99.1	99.4	95.6	99.2

nificant source of measurement variation (Table 3, Fig 3b). The surface roughness of the green- and dry-sawn coupon ends, and the small surface contact area of the Sylvac dial gauge measuring pin, are thought to have contributed to this variation. Changes in the position of the Sylvac dial gauge measuring pin with repeated measurements often resulted in changes in coupon length. The APA method was not affected by this problem because the two inserted brass eyelets provided precise positioning of the trammel gauge pins with repeated measurements.

The ASTM-method oven-dried compression wood coupon lengths showed significant variation with repeated measurements (Table 4, Fig 4b). Interestingly, this variation was not observed for the oven-dried sapwood and heartwood, and resaturated wood coupons. This observation suggests surface roughness may not have been a major factor, but instead drying distortion may have contributed to this variation. Many of the compression wood coupons distorted during oven-drying, and with the ASTM method there was no correction for out-of-plane distortion. Since the distorted coupon end surface was at an angle to the axis of the Sylvac dial gauge measuring pin, changes in the position of the measuring pin with repeated measurements would cause apparent changes in coupon length. The APA method did not appear to be affected by drying distortion, with the use of a vacuum table reducing the out-of-plane distortion.

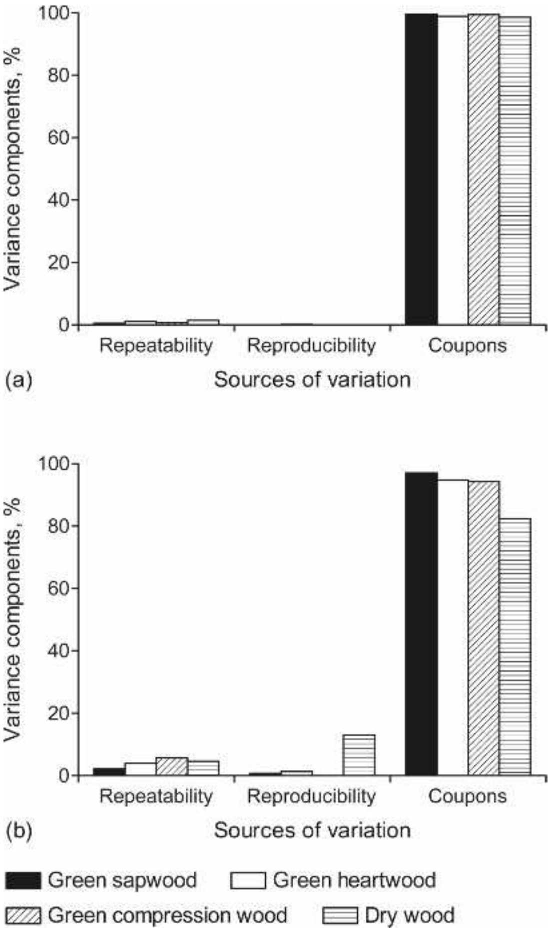

FIGURE 3. Variance components for the sources of green and dry coupon length variation (a) APA method; (b) ASTM method.

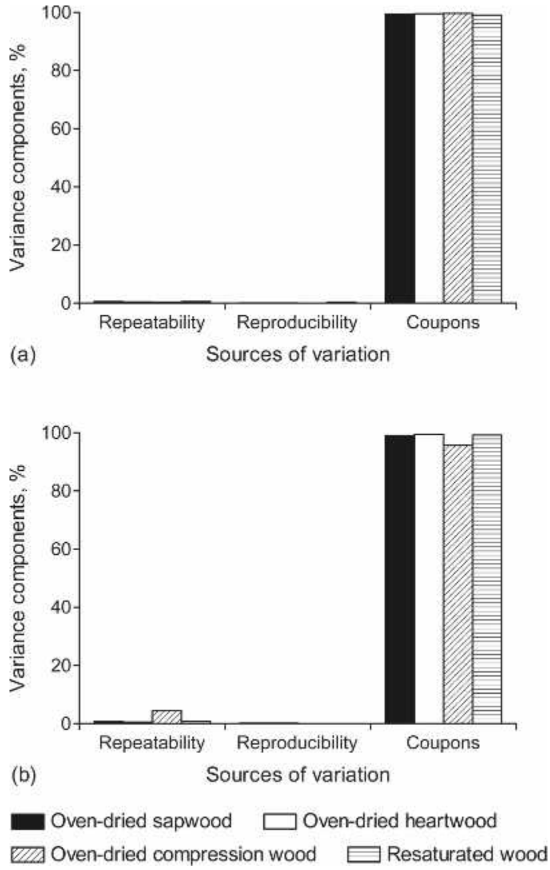

FIGURE 4. Variance components for the sources of oven-dried and resaturated coupon length variation (a) APA method; (b) ASTM method.

The ASTM-method dry-coupon lengths showed significant measurement variation due to operator reproducibility (Table 3, Fig 3b). The dry coupon length measurements were different for the two operators when using the ASTM method. Although the Sylvac dial gauge was calibrated with gauge blocks, it appears that with the ASTM method some measurement bias can be introduced by different operators.

Longitudinal shrinkage and swelling

The APA and ASTM methods differed in their measured values of longitudinal shrinkage and swelling (Table 5, Fig 5). The APA method gave higher values of longitudinal shrinkage, and lower values of longitudinal swelling, compared with the ASTM method. The results suggest there was less surface shrinkage at the coupon ends with oven-drying and greater surface swell-

TABLE 5. *Longitudinal shrinkage for sapwood, heartwood and compression wood, and longitudinal swelling for resaturated wood, measured using the APA and ASTM methods. A different letter following the values indicates a significant difference at $p < 0.01$.*

	Longitudinal shrinkage (%)			
Methods	Sapwood	Heartwood	Compression wood	Resaturated wood
APA	0.24 b	0.31 a	0.62 b	0.05 a
ASTM	0.21 a	0.27 a	0.52 a	0.08 b

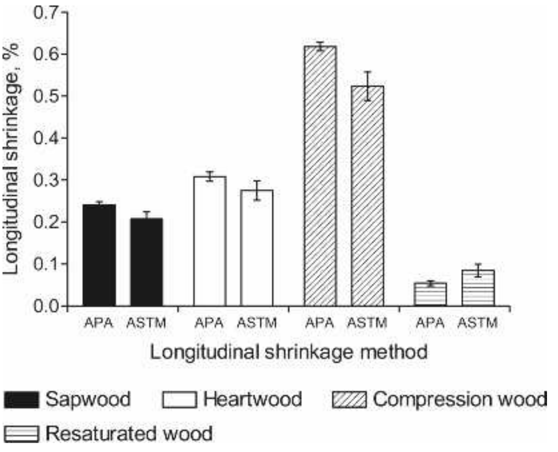

FIGURE 5. Longitudinal shrinkage for sapwood, heartwood and compression wood, and longitudinal swelling for resaturated wood, measured using the APA and ASTM methods. The error bars are the standard deviation of repeated coupon length measurements.

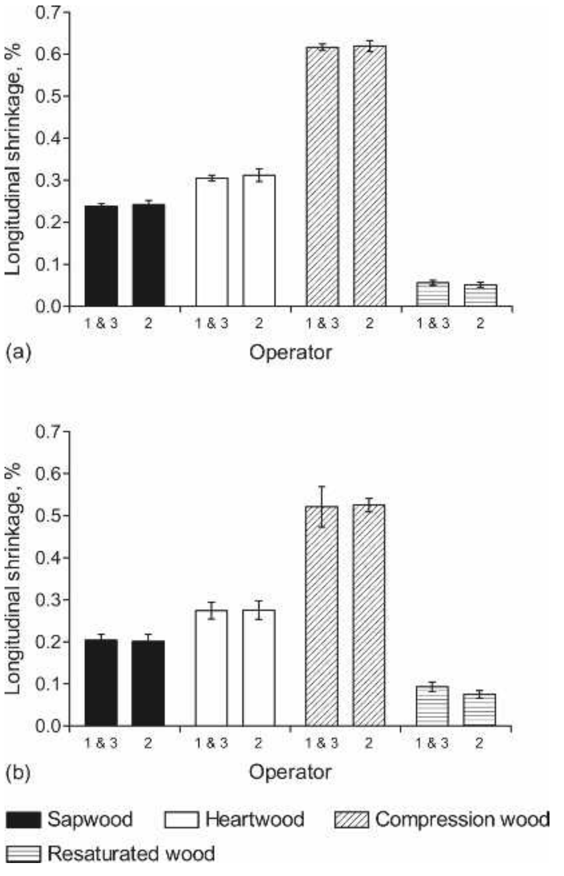

FIGURE 6. Longitudinal shrinkage for sapwood, heartwood and compression wood, and longitudinal swelling for resaturated wood, measured using different operators with (a) APA method; (b) ASTM method. The error bars are the standard deviation of repeated coupon length measurements.

ing with resaturation, compared with the internal shrinkage and swelling. The earlywood and latewood fibers on the circular saw-cut surfaces of the coupon ends will be damaged and very deformed (Nordström and Johansson 1995), and subject to less drying stress or swelling restraint compared with the fibers within the coupons. The response of these fibers to oven-drying varied with wood type, with the sapwood and heartwood showing similar shrinkage differences, and the compression wood a much larger shrinkage difference, between the APA and ASTM methods.

The operator measurements of longitudinal shrinkage and swelling were similar for the APA and ASTM methods (Table 6, Fig 6). The only exception was the measurement of longitudinal swelling with the ASTM method, where there was a significant difference between the opera-

TABLE 6. *Longitudinal shrinkage for sapwood, heartwood and compression wood, and longitudinal swelling for resaturated wood, measured using different operators and the APA and ASTM methods. A different letter following the values indicates a significant difference at* $p < 0.01$.

	Longitudinal shrinkage (%)			
Operators	Sapwood	Heartwood	Compression wood	Resaturated wood
APA method				
Operators 1 & 3	0.24 a	0.30 a	0.62 a	0.06 a
Operator 2	0.24 a	0.31 a	0.62 a	0.05 a
ASTM method				
Operators 1 & 3	0.20 a	0.27 a	0.52 a	0.09 b
Operator 2	0.21 a	0.28 a	0.53 a	0.08 a

tors ($p < 0.05$). This difference can be attributed to the operator difference in the dry-coupon length measurements (Table 3, Fig 3b). The APA method provides very consistent operator reproducibility for longitudinal shrinkage and swelling. The difference in swelling with the ASTM method suggests some caution is required with this method.

The precision of the measured values of longitudinal shrinkage and swelling differed for the APA and ASTM methods. The standard deviation for repeated measurements of longitudinal shrinkage and swelling with the APA method was one-half that of the ASTM method (Fig 5). This occurred as a result of the consistently smaller standard deviations of the APA method for the repeated measurements of green and oven-dried, and dry and resaturated coupon length. The operators were generally consistent in the precision with which they measured longitudinal shrinkage and swelling with the APA and ASTM methods (Fig 6) which suggests the precision was largely a function of the measurement method.

CONCLUSIONS

The APA method gave higher values of longitudinal shrinkage, and lower values of longitudinal swelling, compared with the ASTM method. The APA method measured internal shrinkage and swelling using inserted brass eyelets, while the ASTM method measured both internal and surface shrinkage and swelling from measurements on the coupon ends. The results suggest less surface longitudinal shrinkage and greater surface longitudinal swelling occurred on the coupon ends, compared with internal longitudinal shrinkage and swelling.

The differences in longitudinal shrinkage between the APA and ASTM methods were larger for compression wood than sapwood and heartwood. The values of longitudinal shrinkage, and the standard deviation of repeated measurements for each wood type, were generally consistent for the different operators. This suggests the differences between the APA and ASTM methods were largely a function of the measurement methods.

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