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THE ROLE OF EARLYWOOD AND LATEWOOD PROPERTIES ON DIMENSIONAL STABILITY OF LOBLOLLY PINE

Abstract. The role of tree ring location and height within tree has a very significant impact on the properties of earlywood and latewood. This paper explores the role of earlywood and latewood properties on the dimensional stability of loblolly pine. Test results from isolated 1 mm by 1 mm by 30 mm pieces of earlywood and latewood show the differences in earlywood and latewood make different contributions to the stability of timber. Latewood is more sensitive to changes in moisture and shrinks longitudinally differently than earlywood. Influencing the proportion and properties of latewood can have a significant impact on the dimensional stability of wood. Determining hemicellulose chemistry may be a tool to identify material that is susceptible to high longitudinal shrinkage.

1. INTRODUCTION

One of the major contributors to loss of quality in dimension lumber is excessive longitudinal shrinkage. Intensive plantation forestry can greatly affect the growth rate and percent latewood that is present in trees being managed. This difference in growth rate directly impacts the structural performance of the lumber produced from the trees. Rapid growth means that the juvenile wood core of a tree and its associated inferior properties becomes a much larger proportion of the merchantable log (Fig. 1). This increase in juvenile wood core causes an increase in the frequency of excessive shrinkage in dimension lumber (Larson et al. 2001). Longitudinal shrinkage in juvenile wood can be 10 or more times greater than longitudinal shrinkage in mature wood (Ying et al. 1994). This paper investigates earlywood and latewood properties and their impact on the dimensional stability of loblolly pine.

2. BACKGROUND

An obvious feature of wood structure in many coniferous species, and especially pines, is the presence of annual growth rings. The growing conditions a tree experiences directly affects the formation and width of earlywood and latewood layers (Larson 1969). Climate and localized soil conditions result in non-uniform amounts of woody material in growth rings from year to year within a tree as well as from tree to tree.

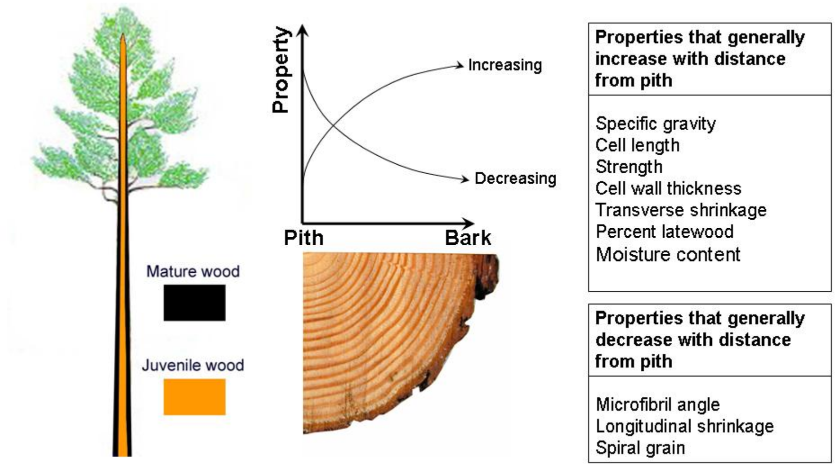


Figure 1. Effects of juvenile wood on physical and mechanical properties (Hernandez and others 2006)

Wood can be considered a complex hierarchical structure ranging in scale from tree to board to growth ring (macro scale), to multi layered cells walls, composite cellulose micro-fibril structure (micro scale), and down to the structure of the three main polymer components, cellulose, hemicellulose, and lignin (nanoscale) (Fig. 2).

The driving force behind our work is a concern with the detrimental effects that increases in juvenile wood content will have on the dimensional stability of lumber. It has been well proven that the juvenile core material in a tree shrinks longitudinally much more than does mature material (Benson 1957, Cockrell 1949, Foulger 1966, Hann 1969, Harris & Meylan 1965, Meylan 1968, Bendtsen & Senft 1986). This can affect the dimensional stability of wood-based products. Groundbreaking work has been done on theoretically modelling relationships between microfibril angle (MFA) and longitudinal shrinkage (Barber & Meylan 1964, Barret et al. 1972). According to these models, the primary cause of shrinkage anisotropy can be explained by modelling wood as if it consisted of reinforcing microfibrils in a weak matrix. These studies suggested that observed deviations for the theory could be explained by the effect of the components of the cell wall other than the S2 layer or by changes in the ratio between the elastic moduli of the amorphous matrix of the S2 layer and of the reinforcing microfibrils. Others have built on these earlier works by looking at different species and methods for determining the important factors controlling longitudinal shrinkage (Espenas 1974, Meylan 1972, Tang & Smith 1975, Voorhies & Groman 1982).

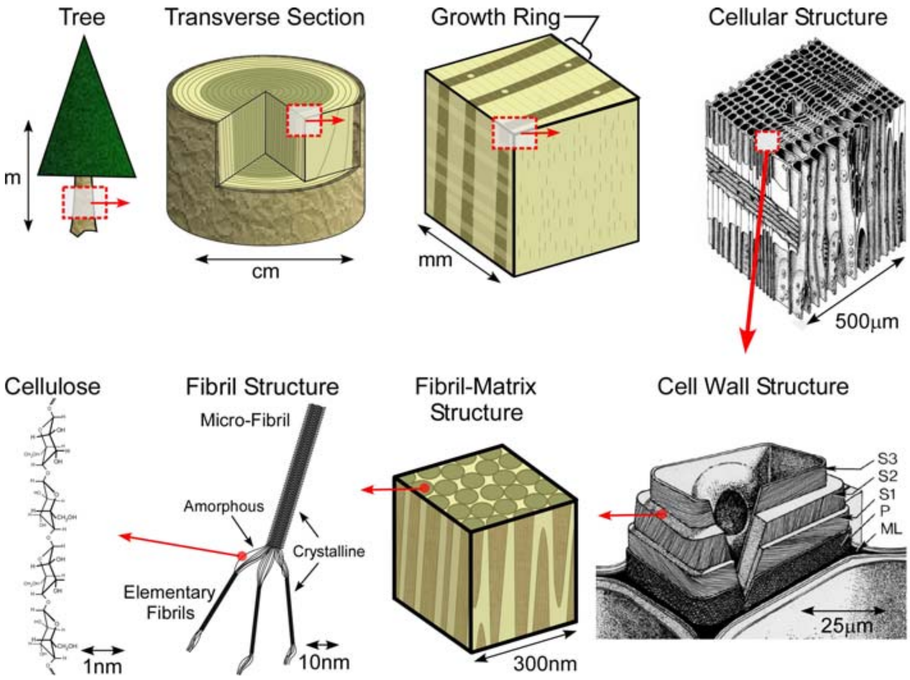


Figure 2. The Hierarchical nature of wood showing the size scale of each structural feature within wood. (adapted from Moon and others 2006)

Based on earlier experimental and theoretical work, abnormal longitudinal shrinkage is associated with age-related factors, compression wood, MFA, and specific gravity. Of these factors, MFA appears to be the most significant. Apparently, whatever the species, longitudinal shrinkage is a highly variable property, the variability decreases with age.

Adding to the complexity of the response of wood is the fact that there is a continuous transition of cell characteristics that occurs between the start of one growing season and the start of the next. Cell radial diameter and secondary wall thickness are the main characteristics distinguishing earlywood from latewood (Fig. 3). Large diameter cells with thin walls characterize the beginning of spring growth. When the dry high temperature part of the growing season begins the material transitions to the small diameter thick cell wall material that characterizes summer growth. However these characteristics can be altered independently by different factors (Larson 1969).

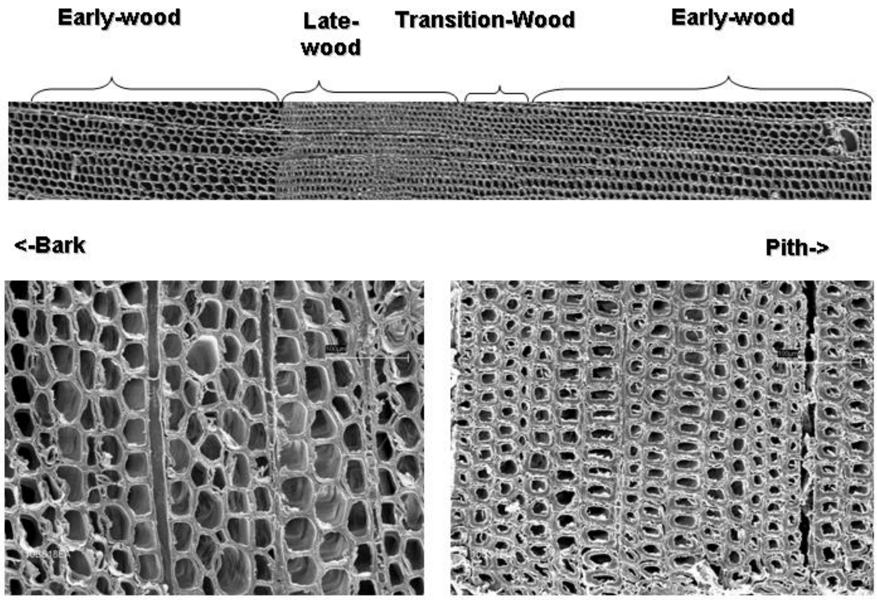


Figure 3. Cellular structure of earlywood and latewood. (micrographs courtesy of Beecher, USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 2004)

This complex structure must be understood at several different scales to allow an understanding of macroscale behavior. While tests of macroscale samples combining earlywood and latewood are widely reported and while some have investigated the performance of individual cells, we have chosen to concentrate our attention on characterizing individual earlywood and latewood properties for small specimens of loblolly pine which are assumed to be homogeneous pieces of earlywood or latewood. We chose to study loblolly pine because it is by far the most commonly available pine species in the southeast United States (ASTM D2555).

Others have studied the differences between earlywood and latewood by looking at specific gravity and the cell wall differences that account for specific gravity differences. McMillan (1968) sampled 40 loblolly pine trees and found the radial tracheid diameter of earlywood cells to be approximately twice that of latewood cells and the cell wall thickness of earlywood tracheids to be about ½ that of latewood tracheids. Megraw (1985) showed that the specific gravity of latewood loblolly pine could be over three times that of earlywood for a given ring, with a maximum specific gravity attained in the middle of the latewood band. Others investigating loblolly pine include Paul (1958) who found the average specific gravities of earlywood and latewood were 0.310 and 0.625, respectively.

Goggans (1964), Hodge & Purnell (1993), and Pew & Knechtges (1939) obtained similar results.

Megraw (1985) and Ying et al. (1994) found that specific gravity varied with ring number within a tree, but that earlywood and latewood followed different trends. The specific gravity of latewood increased drastically going from the pith until approximately the tenth ring and then was relatively constant. Earlywood had less variation with age. The specific gravity of earlywood declined during the first few growth rings, and then it remained relatively constant.

Biblis (1969) studied the variations in the specific gravity and MOE within the earlywood and latewood zones. Adjacent latewood specimens positioned less than 1 mm apart had MOE values that differed by 50 percent. Biblis and Megraw both indicated that a transitional zone exists between the earlywood and latewood zones. In the transitional zone the material properties gradually change from typical earlywood values to typical latewood values.

Megraw et al. (1999) studied individual earlywood and latewood bands of loblolly pine by conducting 4-point bend tests on small specimens. They examined 6 heights, 6 rings and 24 trees and found MOE varied greatly but systematically with ring height and location. For their data they determined that approximately 93% of the variation in MOE was explained by specific gravity and MFA. Prior work, including that by Booker et al. (1998) on radiata pine established the strong relationship between MOE and the combination of specific gravity and MFA. Booker's earlier work did not, however, separate the earlywood and latewood properties.

Groom, Mott, and Shaler (Groom et. al., 2002a, 2002b, Mott et. al. 2002) went one step further down the hierarchical structure of wood and measured the specific gravity and MOE of individual earlywood and latewood fibers. Specimens were obtained by macerating samples from a 48-year-old loblolly pine tree harvested from an Arkansas plantation. Latewood slivers were removed from 6 growth rings at 3-m intervals over the height of the tree and then were macerated in a solution of hydrogen peroxide, distilled water and glacial acetic acid. The average latewood MOE values showed an increase of 40 percent going from pith to bark. Similarly, earlywood MOE showed an increase of 35 percent from pith to bark. The difference in the MOE values of the earlywood and latewood fibers were attributed to differences in MFA.

There has also been extensive work conducted by the Wood Quality Consortium in the southeast United States on the effect of fertilization and controlling herbaceous and woody competing vegetation on wood quality and the juvenile/mature wood transition in loblolly pine as defined by annual ring specific gravity, proportion of latewood, and MFA (Jordan et al. 2006, Clark et al. 2006a, Clark et al. 2006b). This work has all been done by extensively analysing 12 mm thick cores from four physiographic regions the south-eastern United States (Lower Coastal Plain, Upper Coastal Plain, Hilly Coastal Plain, and Piedmont).

The studies discussed above did not investigate the relationship between longitudinal shrinkage and specific gravity, MOE, and MFA with distance from the pith for individual earlywood and latewood bands. It is the objective of this paper to present the interactions of these properties for earlywood and latewood and discuss how they relate to the observed longitudinal shrinkage patterns in full size lumber.

3. EARLYWOOD AND LATEWOOD PROPERTIES TESTS

The information and test results discussed are limited to material gathered from 10 trees collected from two different loblolly pine plantations in the Hilly Coastal Physiographic region of the south-eastern United States.

3.1 Test Procedures

Earlywood and latewood samples were collected from the 10 trees using the following procedure. Disks were taken from up to four different heights. For seven of the trees disks were take from two heights (1 and 7 m) and for three trees disks were taken from four heights (1, 2.5, 7, and 10m) (Fig. 4). Earlywood samples were taken from the thin walled initial growth for a season. Latewood samples were taken from the darker material for a given ring, contained in the last 1 mm of growth for that years growing season. Complete details of the sample preparation and testing methods can be found in Schmidt (2003), Cramer et al. (2005), Mertz (2005), and Pheil (2006).

The smaller earlywood and latewood and shrinkage specimens produced from the disks were 1 mm by 1 mm by 30 mm specimens cut from the four cardinal directions and different heights in the tree (Fig. 4a). MFA was measured on the small specimens by X-ray diffraction (Verrill et al. 2006). Chemical analysis of the earlywood and latewood samples was conducted to determine the sugar contents of the hydrolysates by anion exchange high performance liquid chromatography using pulsed amperometric detection (Davis 1998). A light microscope with a digital stage with an accuracy of 0.0001mm was used to track shrinkage of specimens over time and a balance accurate to 0.00001g was used to measure weights. For a complete description of the shrinkage measurement technique see Pheil (2006). Compression wood was determined using light transmission through thin cross sectional wafers produced from the disks (Pillow 1941).

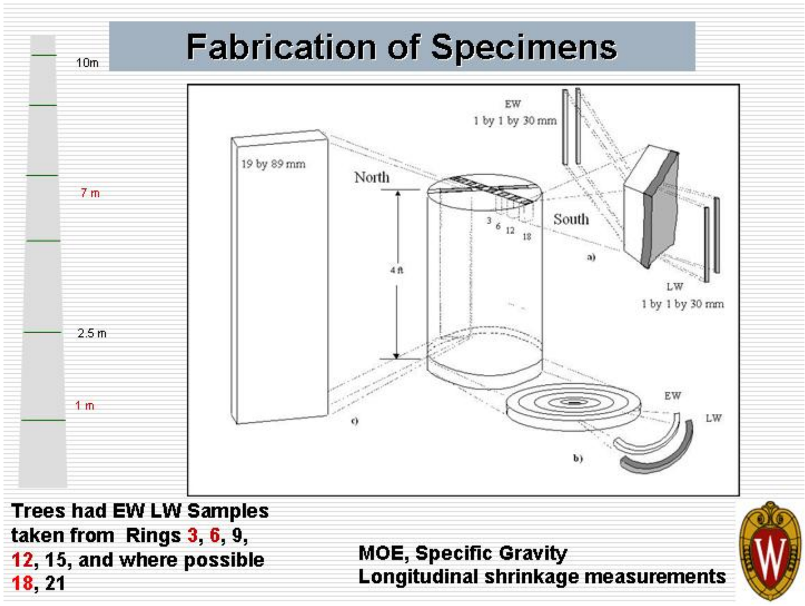


Figure 4. The cut out pattern of specimens from trees. a) 1 by 1 by 30 mm specimens b) chemical analysis specimens, c) full size board specimens .

The weighted averages of our results were compared against complete ring tests conducted by Clark and others for the hilly coastal plane region. The distribution of individual test results and average for all of our tests follow closely the trend observed by Clark for the Hilly Coastal Physiographic region (Clark III et al. 2006b) (Figure 5).

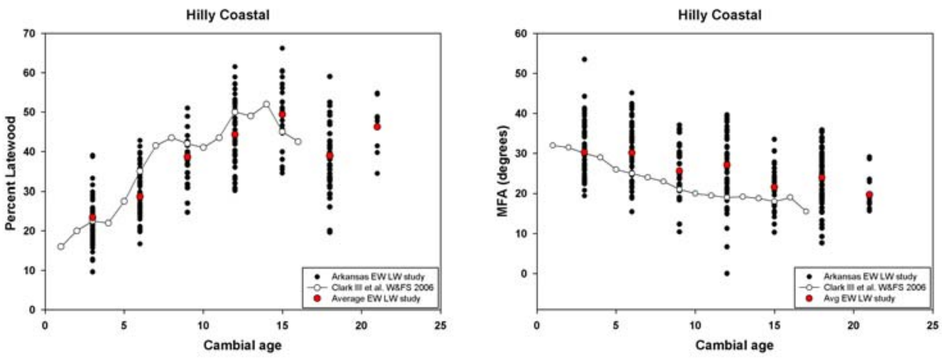


Figure 5. Weighted average percent latewood and MFA specimens of this study compared to findings of Clark et al. (2006).

3.2 Results

The test results for specific gravity, MFA, and MOE were investigated to see what similarities and differences there are in earlywood and latewood and how these characteristics related to longitudinal shrinkage. This required looking at the effect of cardinal direction, ring position, and height.

3.2.1 Cardinal direction

Differences in properties for the four cardinal directions of the trees were examined. Figure 6 illustrates a typical example of the variability of earlywood and latewood properties varied around the tree. For cardinal direction there was no consistent pattern detectable visually for a given ring. Latewood properties were much more variable, however, with increased distance from the pith. There was no statistically significant effect of cardinal direction on any of the properties investigated. Therefore the remaining discussion is based on pooled cardinal direction data for each ring.

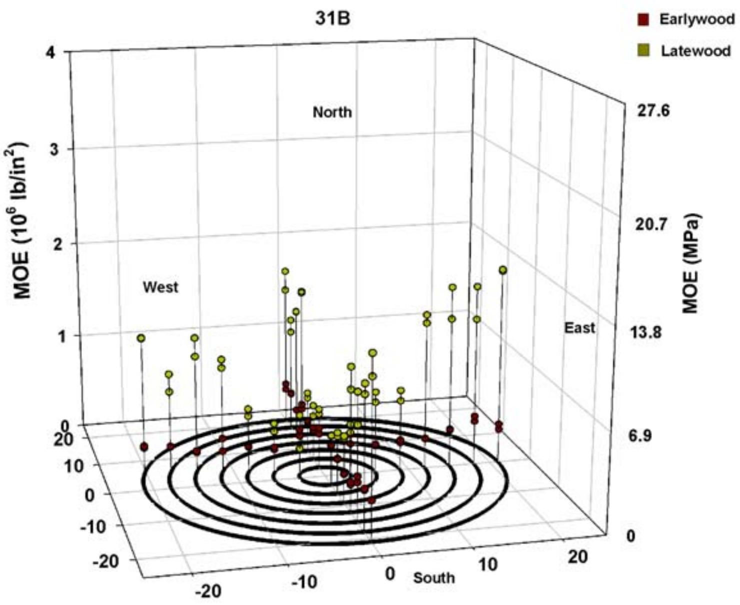


Figure 6. Distribution of modulus of elasticity (MOE) at different cardinal directions.

3.2.2 Specific Gravity

The change in average specific gravity at various rings and heights for earlywood and latewood are shown in Figure 7. The specific gravities of the 2.5 m, 7 m, and 10 m height earlywood remains relatively constant regardless of height or ring number. The 1 m earlywood was consistently denser then the earlywood samples from other heights but was not sensitive to ring position. Latewood specific gravity did not show a consistent trend with height. Latewood specific gravity increased rapidly between rings 3 and 6, and then increased more gradually with increasing distance from the pith. The 1 m height latewood was the least sensitive to increasing distance from the pith.

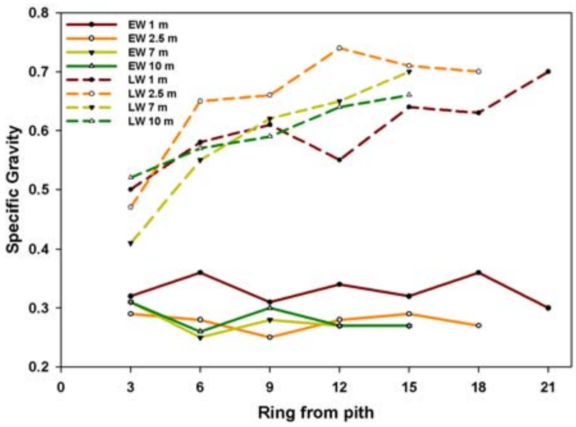


Figure 7. The change in average specific gravity at various rings and heights for earlywood and latewood.

3.2.3 Microfibril Angle

The change in average MFA at various rings and heights for earlywood and latewood are shown in Figure 8. MFA for both earlywood and latewood decreased with increasing height and distance from pith. We expected that the earlywood and latewood MFA would be discernibly different, but this was not the case. There was not a consistent difference between the MFA for earlywood and latewood for a given ring. It appears that the angle of fibril that is set at the start of the growing season is maintained, to a great extent, as that particular growing season progresses.

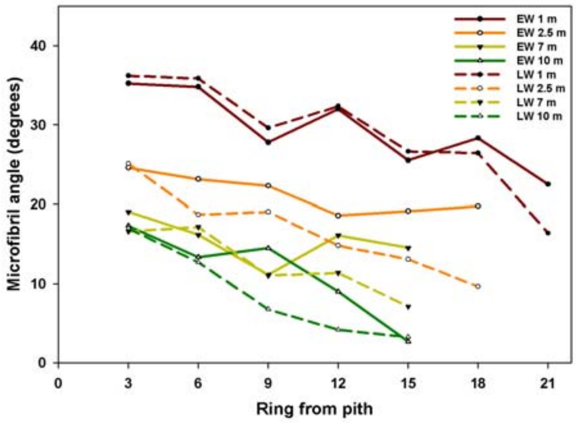


Figure 8. The change in average microfibril angle at various rings and heights for earlywood and latewood.

3.2.4 Modulus of Elasticity

The change in average MOE at various rings and heights for earlywood and latewood are shown in Figure 9. MOE for earlywood was relatively constant with increasing distance from pith but increased slightly with increasing height. Latewood MOE for 2.5, 7, and 10 m heights increased substantially with distance from pith, but latewood MOE for the 1 m height responded differently. The response of the 1m latewood is more similar to the pattern found in earlywood close to the pith, before the material starts to mature at about ring 12.

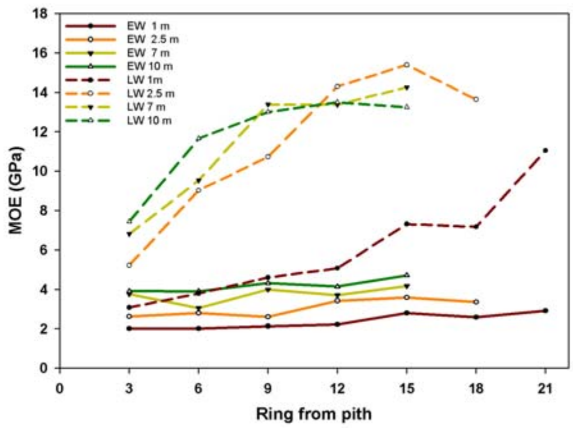


Figure 9. The change in average Modulus of elasticity (MOE) at various rings and heights for earlywood and latewood.

3.2.5 Green to Oven-dry Longitudinal Shrinkage

The change in average green to oven-dry longitudinal shrinkage at various rings and heights for earlywood and latewood are shown in Figure 10. Earlywood green-oven dry longitudinal shrinkage was generally about twice that of latewood for a given height and ring, except for ring 3. Earlywood and latewood shrinkages for ring 3 were very similar. Both earlywood and latewood shrinkages decrease with distance from pith. The variability of longitudinal shrinkage was highest at lower heights and inner rings for both earlywood and latewood.

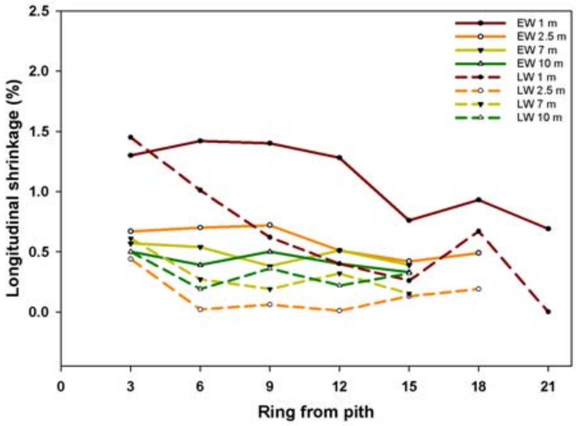
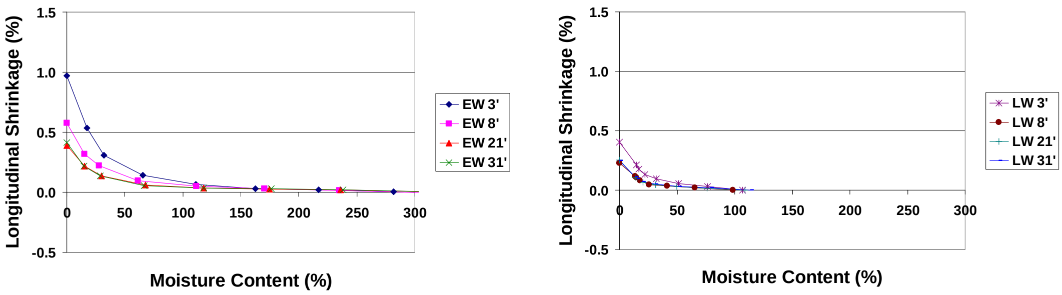


Figure 10. The change in average longitudinal shrinkage at various rings and heights for earlywood and latewood.



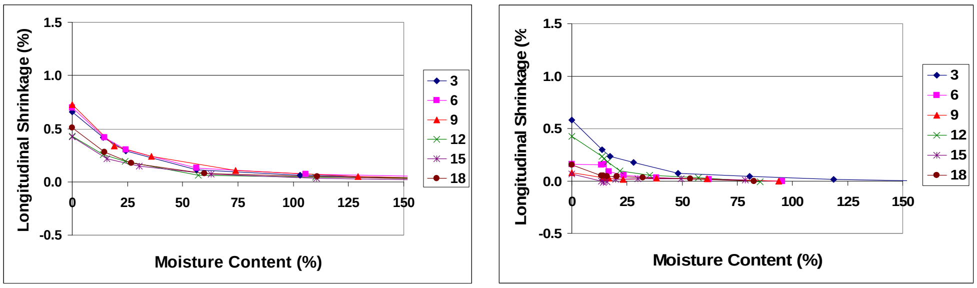
a) Earlywood b) Latewood

Figure 11. The change in longitudinal shrinkage at various heights1 m (3'), 2,5 m (8'), 7 m (21'), and 10 m (31') for a) earlywood and b) latewood. (Pheil, 2006)

3.2.6 Longitudinal Shrinkage Change with Changes in Moisture Content

Shrinkage was measured every 10 minutes for 70 minutes. The rates of drying for earlywood for 7 and 10 m heights were statistically similar but were statistically different from the 1, and 2.5 m heights (Fig. 11a). The drying rate of latewood for 2.5, 7, and 10m heights were statistically similar but statistically different from the 1 m height (Fig. 11b). For both earlywood and latewood, rate of longitudinal shrinkage increased more rapidly with decreasing moisture content as height in tree decreased (Figure 11).

Inner rings for both earlywood and latewood had distinctly different longitudinal shrinkage - moisture content relationships when compared to outer rings (Fig. 12). Earlywood and latewood longitudinal shrinkages both increased more rapidly with decreasing moisture content for the rings closest to pith.



a) Earlywood b) Latewood

Figure 12. The change in longitudinal shrinkage at various rings (3, 6, 9, 12, and 18) for a) earlywood and b) latewood. (Pheil, 2006)

3.2.7 Relationship among properties.

The relationships between specific gravity, MFA, MOE and longitudinal shrinkage for the test material are illustrated in Figures 13-15. The highlighted points are outliers with excessive longitudinal shrinkage in the test data and they will be discussed in more detail in section 4.

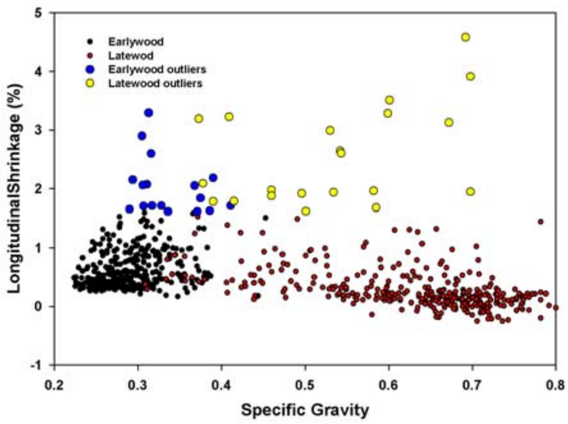


Figure 13. Plot showing the relationship between specific gravity and longitudinal shrinkage. Outliers are shown in blue (earlywood) and yellow (latewood).

Earlywood longitudinal shrinkage did not show a clear trend with specific gravity while latewood longitudinal shrinkage decreased with increasing specific gravity (Fig. 13).

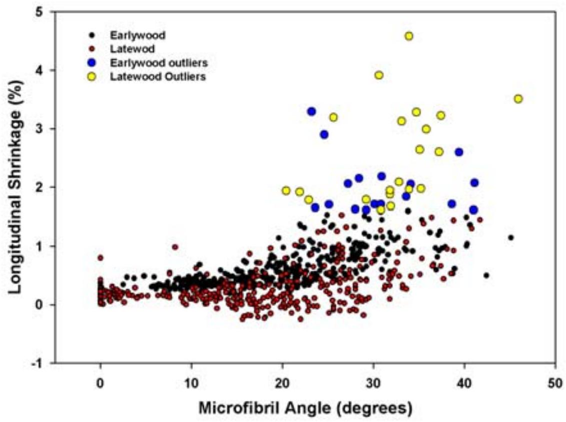


Figure 14. Plot showing the relationship between microfibril angle and longitudinal shrinkage. Outliers are shown in blue (earlywood) and yellow (latewood)

The relationship between MFA and longitudinal shrinkage for earlywood or latewood are not distinct from each other. Earlywood and latewood longitudinal shrinkage increased in a similar nonlinear fashion with increasing MFA (Fig. 14). For a given MFA however, longitudinal shrinkage of earlywood was generally greater than that of latewood.

The relationship between MOE and longitudinal shrinkage also shows a rather consistent nonlinear pattern (Fig. 15). As the MOE increases the longitudinal shrinkage decreases nonlinearly. It is worth noting that the majority of the outliers for all properties are from latewood.

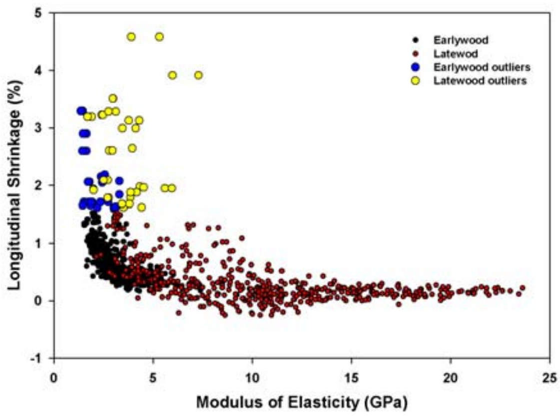


Figure 15. Plot showing the relationship between modulus of elasticity (MOE) and longitudinal shrinkage. Outliers are shown in blue (earlywood) and yellow (latewood).

4.OUTLIERS

The longitudinal shrinkage outliers highlighted above, from a producer's point of view, are of most interest, because they cause trouble for consumers. The excessive longitudinal shrinkage, which may result from these outliers, would shake a consumer's confidence in the product being bought and therefore make studying outliers very important.

4.1 Characteristics of outliers

The outliers in our data were defined by calculating the averages for each wood type at each ring and height and then adding or subtracting 2 times the standard deviation at the same location; the outliers fell outside of that range. There were 41 statistical outliers identified in this way. Compilation of corresponding "normal" specimens allowed comparisons of properties of the outliers with the properties of the "normal" specimens. Earlywood outliers tended to have twice the longitudinal shrinkage, similar specific gravities, and MFAs that were 1.2 to 2.1 times those of normal specimens. Latewood outliers tended to have 4 to 6 times the longitudinal shrinkage, similar specific gravities, and MFAs that were 1.1 to 2.1 times those of normal specimens. Of the 41 statistical outliers, 60 percent were from ring 3 or the 1m height, slightly more than 60 percent were latewood specimens, and fewer than half were classified as compression wood.

It was somewhat surprising to have fewer than half of the pieces that were classified as statistical outliers to be compression wood. We had expected a much larger portion of the outliers to be compression wood. We postulate that the basic chemical composition of the earlywood and latewood outliers causes them to exhibit excessive longitudinal shrinkage. This led us to investigate the chemistry of the samples.

4.2 Chemistry of samples

The chemical analysis was conducted at the USDA Forest Products Laboratory analytic chemistry lab. A sub sample of our test specimens was examined to determine their chemical makeup. Chemical analyses were conducted on earlywood and latewood samples from three different rings at three different heights in three different trees.

4.2.1 Method of chemical analysis

Samples were milled to pass a 20-mesh screen, then were vacuum dried at 45^o C. Approximately 100 mg of each sample was hydrolyzed with 1.00 ml 72% (w/w) H_2SO_4 for 1 hr at 30^o C. Samples were then diluted to 4% (w/w) H_2SO_4 with distilled H_2O, fucose was added as an internal standard, and a secondary hydrolysis performed for 1 hr at 121^o C. To control for sugar degradation during secondary hydrolysis, a standard mixture of sugars was hydrolyzed in parallel with each batch of samples. Losses during primary hydrolysis were minimal and were ignored. Following secondary hydrolysis samples were immediately filtered through tared Gooch porcelain crucibles containing Whatman 934-AH glass fiber filters. The filtrate and three washes with 5 ml distilled H_2O were collected in 100 ml volumetric flasks and brought to volume with H_2O. Acid-soluble lignin was estimated from the absorbance of the hydrolysate at 205 nm, using the formula: Dilution factor x Absorbance/110 = Acid-soluble lignin.

The acid-insoluble residue (Klason lignin) was washed an additional six times with 10 ml hot distilled H_2O and quantified gravimetrically. Klason lignin values were corrected for ash content gravimetrically following incubation of the lignin at 575^o C for at least 3 hr. Positive interferences in acid soluble and Klason lignin values in samples other than woods and pulps were likely, due to protein, tannins, etc.

Sugar contents of the hydrolysates were determined by anion exchange high performance liquid chromatography using pulsed amperometric detection. After filtration through 0.45 μm PTFE membranes, acid hydrolysates (1-4% sulfuric acid, w/w) were injected into the chronograph with no further treatment. The chromatographic system consists of an AS50 autosampler, a GS50 quaternary gradient high pressure pump, and an ED50 pulsed amperometric detector. Sugar separation is achieved with Carbo-Pac PA1 guard and analytical columns connected in series. Sugars were eluted with distilled H_2O at a flow rate of 1.1 ml/min at a temperature of 18^oC. For detection, 300 mM NaOH was added as a post-column reagent at a flow rate of approximately 0.3 ml/min. Prior to each injection, the anion exchange columns were conditioned with 240 mM $NaC_2H_3O_2$ in 400 mM NaOH, thenequilibrated with distilled H2O. Sugars were quantified using an internal standard method. Results are reported in terms of percent of the original sample mass. The process used to conduct the Chemical Analysis is described in detail in Davis (1998).

4.2.2 Chemical Analysis Results

The summary of the chemical analyses are shown in Table 1. The most noticeable changes in chemistry with height or ring are highlighted. lignin content and glucan in latewood are factors that are noticeably affected by height and ring position. Also, galactan has significant but not always consistent shifts in percentages with changes in height and ring position in latewood. The other sugar contents remain relatively stable.

The correlation matrixes for earlywood and latewood for all test variables are shown in Tables 2 and 3 respectively. Note that, as reported by Floyd (2005), lignin and galactan are positively correlated with longitudinal shrinkage while the other hemicelluloses, with the exception of arabinan, are negatively correlated. Earlywood galactan is also inversely related to the concentration of the other hemicelluloses. glucan has a negative correlation with longitudinal shrinkage (r = -0.59 EW, -0.71 LW), whereas lignin content has a positive correlation with longitudinal shrinkage (r = 0.56 EW, 0.70 LW). For both earlywood and latewood galactan has a slightly weaker but significant positive correlation with lignin (r = 0.41 EW, 0.59 LW). The latewood correlations to lignin are weaker for xylan while the correlation improves for arabinan.

Tables 4 and 5 summarize multiple regression results for the loblolly pine earlywood and latewood data. MOE has a big influence on earlywood shrinkage but is less of a factor in latewood. Latewood's most significant factors were specific gravity and galactan content. These regression results indicate that galactan has a big influence on latewood longitudinal shrinkage but is not as important to the longitudinal shrinkage of earlywood.

Table 1—Summary of the chemical analysis. The results are reported in terms of percent of the original sample mass.

		Rings							
		3		9		12		15	
	Height	EW	LW	EW	LW	EW	LW	EW	LW
Lignin (%)	1 m	34.2	32.3	30.8	28.8	--	--	30.5	28.7
	7 m	30.2	30.3	30.2	28.0	--	--	30.2	27.5
	10 m	30.2	28.9	30.0	27.6	30.0	27.7	--	--
	Overall	31.6	30.5	29.9	28.1	30.0	27.7	30.4	28.1
Galactan (%)	1 m	3.1	2.9	2.5	2.9	--	--	2.3	2.1
	7 m	2.5	3.3	1.6	1.6	--	--	1.6	1.7
	10 m	2.3	2.3	1.9	1.4	1.8	2.3	--	--
	Overall	2.6	2.8	1.8	2.0	1.8	2.3	2.0	1.9
Glucan (%)	1 m	35.0	34.8	39.6	40.2	--	--	40.5	42.4
	7 m	38.3	38.0	41.5	42.9	--	--	41.5	43.7
	10 m	38.4	39.3	40.7	43.6	42.2	42.6	--	--
	Overall	37.3	37.4	40.6	42.2	42.2	42.6	41.0	43.1
Xylan (%)	1 m	6.6	8.0	6.8	6.6	--	--	6.4	6.3
	7 m	8.3	8.2	6.7	6.7	--	--	6.9	6.1
	10 m	8.2	8.3	7.0	6.4	6.4	6.0	--	--
	Overall	7.7	8.2	6.8	6.6	6.4	6.0	6.6	6.2
Mannan (%)	1 m	8.5	10.0	10.0	11.9	--	--	10.2	12.0
	7 m	9.6	10.0	9.9	11.7	--	--	9.7	12.3
	10 m	9.8	10.4	10.3	12.0	10.4	11.9	--	--
	Overall	9.3	10.1	10.1	11.9	10.4	11.9	9.9	12.1

4.2.3 Longitudinal Shrinkage Predictive Modelling

Floyd (2005) argues that "If specific hemicellulose components are providing the driving force behind longitudinal shrinkage and the microfibril network is providing the resistance, we would expect a variable representing the ratio of these properties might be a useful predictor".

Figure 17 shows the trends for the average longitudinal shrinkage, and lignin, galactan, and glucan contents for earlywood and latewood at various heights. Tables 2 and 3 indicate that as longitudinal shrinkage decreases lignin and galactan content decreases, while as longitudinal shrinkage decreases glucan content increases. The similar response of lignin, glucan and longitudinal shrinkage along with glucan's opposite response as height varies are visually presented in Figure 17.

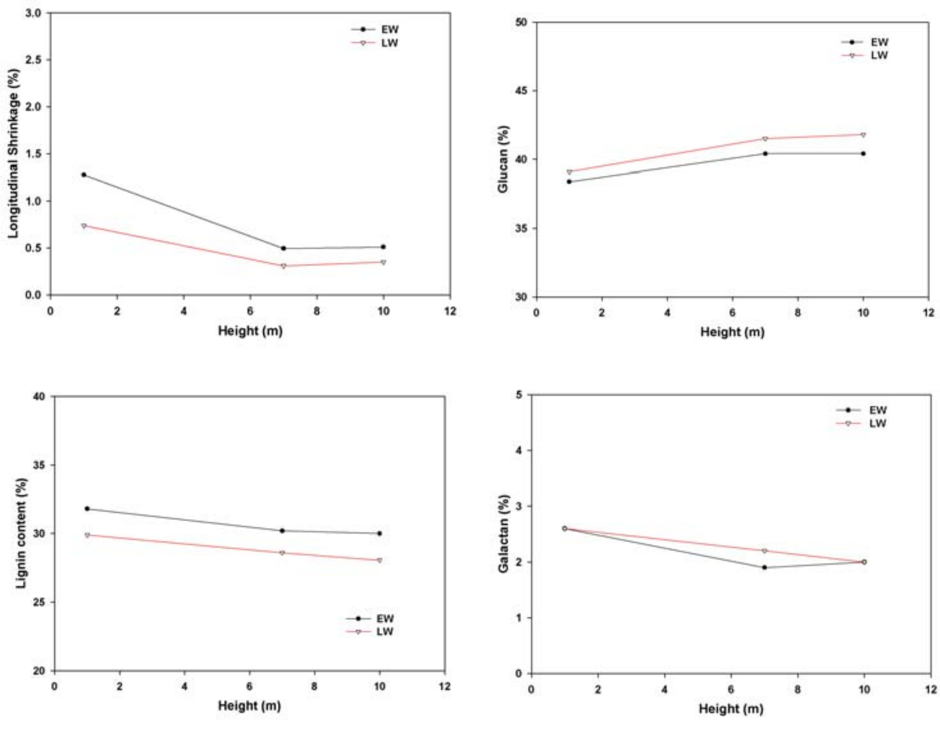


Figure 17. Illustration of earlywood and latewood normal vs. Shrinkage, Lignin, Galactan, and Glucan results by height.

Table 2—Earlywood Correlation Matrix

	Shrinkage	MOE	Sp. Gr.	Lignin (%)	Arabinan (%)	Glucan (%)	Xylan (%)	Mannan (%)	Galactan (%)
Shrinkage	1.00								
MOE	-0.73	1.00							
Sp. Gr.	0.31	-0.08	1.00						
Lignin	0.56	-0.38	0.36	1.00					
Arabinan	0.34	-0.36	0.30	0.05	1.00				
Glucan	-0.59	0.43	-0.46	-0.90	-0.30	1.00			
Xylan	-0.27	0.24	-0.04	-0.45	0.37	0.12	1.00		
Mannan	-0.23	0.00	-0.28	-0.63	-0.05	0.64	-0.12	1.00	
Galactan	0.41	-0.26	0.50	0.61	0.11	-0.66	-0.19	-0.57	1.00

Table 3.—Latewood Correlation Matrix

	Shrinkage	MOE	Sp. Gr.	Lignin (%)	Arabinan (%)	Glucan (%)	Xylan (%)	Mannan (%)	Galactan (%)
Shrinkage	1.00								
MOE	-0.54	1.00							
Sp. Gr.	-0.55	0.47	1.00						
Lignin	0.70	-0.49	-0.45	1.00					
Arabinan	0.26	-0.36	-0.40	0.20	1.00				
Glucan	-0.71	0.26	0.52	-0.91	-0.50	1.00			
Xylan	-0.07	-0.26	-0.23	-0.09	0.78	-0.22	1.00		
Mannan	-0.48	0.46	0.47	-0.75	-0.53	0.81	-0.44	1.00	
Galactan	0.59	-0.40	-0.29	0.67	0.25	-0.69	0.05	-0.78	1.00

Table 4.—Earlywood Multiple Regression to Predict Longitudinal Shrinkage

	All variables included adjusted r^2=0.63		
Mean Square Error=0.125	Coefficients	Standard Error	t-value
Intercept	1.073	4.352	0.25
MOE	-0.305	0.036	-8.46
Sp. Gr.	1.627	0.813	2.00
Arabinan	0.373	0.286	1.30
Galactan	0.00028	0.047	0.01
Glucan	-0.0143	0.042	-0.34
Xylan	-0.053	0.071	-0.75
Mannan	-0.039	0.071	-0.55
Lignin	0.033	0.059	0.56
Mean Square Error=0.135	Reduced Variable Set adjusted r^2=0.60		
Intercept	1.068	0.227	4.71
MOE	-0.358	0.029	-12.25
Sp. Gr.	2.29	0.770	2.98
Galactan	0.083	0.037	2.26

Table 5—Latewood Multiple Regression to Predict Longitudinal Shrinkage

	All variables included adjusted r^2=0.69		
Mean Square Error=0.125	Coefficients	Standard Error	t-value
Intercept	-9.73	4.85	-2.01
MOE	-0.138	0.009	-1.52
Sp. Gr.	-1.652	0.322	-5.13
Arabinan	0.685	0.391	1.75
Galactan	0.276	0.053	5.17
Glucan	0.0022	0.044	0.05
Xylan	0.069	0.09	0.77
Mannan	0.382	0.087	4.38
Lignin	0.171	0.63	2.71
Mean Square Error=0.191	Reduced Variable Set adjusted r^2=0.53		
Intercept	1.366	0.226	6.05
MOE	-0.0297	0.0096	-3.10
Sp. Gr.	-1.785	0.361	-4.94
Galactan	0.186	0.0295	6.30

The model suggested by Floyd using MOE, SG, galactan and glucan content was applied to the earlywood and latewood chemical data. The results are given in Table 6 and Figure 18. The model to predict longitudinal shrinkage for earlywood has a higher r^2 value than the latewood model. We did not achieve as large of a correlation as Floyd achieved with his larger-size wood samples. Much of this difference is most likely the result of the increased variability associated with measuring shrinkage on such small specimens. However, Figure 18 illustrates that measured versus predicted longitudinal shrinkage values for the earlywood and latewood models combined are highly correlated (r^2 = 0.66) and could give a very useful indication of potential longitudinal shrinkage. Since our compression wood samples were included in this analysis our data also agrees with Floyd's assertion that the predictive ability of this model appears to be independent of compression wood content. This suggests that lignin, galactan, and glucan content could potentially be used as indicators of longitudinal shrinkage.

Table 6.—Simplified Lengthwise Shrinkage Model

	Earlywood	adjusted r^2=0.70	
Mean Square Error=0.086	Coefficients	Standard Error	t Stat
Intercept	-0.325	0.0614	-5.29
SG*Glucan/MOE(GPa)	0.219	0.020	10.87
SG*Galactan/MOE(GPa)	0.885	0.148	5.98
	Latewood	adjusted r^2=0.61	
Mean Square Error=0.152	Coefficients	Standard Error	t Stat
Intercept	-0.0536	0.064	-0.89
SG*Glucan/MOE(GPa)	0.0312	0.021	1.49
SG*Galactan/MOE(GPa)	2.086	0.161	12.94

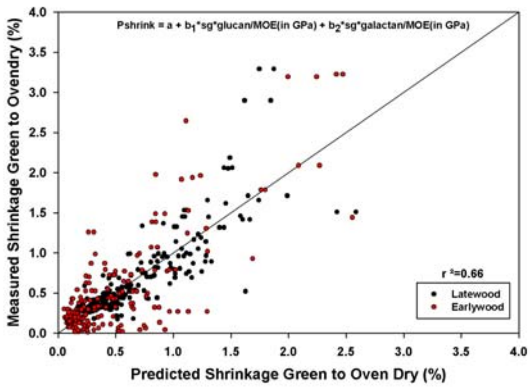


Figure X.18. The simplified longitudinal shrinkage model predicted shrinkage vs. measured shrinkage (Green to Oven-dry).

5. SUMMARY

Tree ring location and height within a tree have significant impacts on the properties of earlywood and latewood. Test results from isolated 1 mm by 1 mm by 30 mm pieces of earlywood and latewood show that latewood is much more sensitive to location within tree stem than earlywood. From our work the following observations can be made.

- The longitudinal shrinkage behavior of wood is controlled by a complex interaction of:
  - MFA
  - Specific Gravity
  - Proportions of lignin, and hemicelluloses such as galactan, and glucan.
- Earlywood properties seem to be relatively constant within a tree, changing slightly with height. The variability in earlywood properties from tree to tree may be utilized to select for improved longitudinal shrinkages.
- On average longitudinal shrinkage of earlywood was about twice as great as latewood.
- The proportion and properties of latewood have significant roles in the dimensional stability of wood.
- Lignin, galactan, and glucan content could potentially be used and an indicator of potential longitudinal shrinkage.

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