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Relations between various extracted basic densities and wood chemical components in *Eucalyptus globulus*

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Abstract Relations between various extracted basic densities and wood chemical components were investigated by their within-tree variations in *Eucalyptus globulus* for assistance in the prediction of the properties of wood or wood-derived products. Extraneous compounds affect the relations between various basic densities and wood chemical components such as holocellulose and the lignin syringyl/guaiacyl ratio. We also discuss the relation of various densities, the molar composition of neutral sugars constituting hemicellulose, and fiber morphology.

Key words Relations · Extracted basic densities · Wood chemical components · Within-tree variation · *Eucalyptus globulus*

Introduction

Wood density is one of the key properties for wood end-usage.[1,2] Extracted wood density has been examined for trees,[3,4] as the estimation of wood mechanical and pulp properties are sometimes mislead by wood density because of the presence of extraneous compounds.[3,5] However, lumber is manufactured from one individual, and such an investigation should be performed within trees. We reported previously on the effect of extraneous compounds on the basic density in *Eucalyptus camaldulensis* trees.[6] Although *E. globulus* has a lower content of extraneous compounds than *E. camaldulensis*,[7] the effect of the small amount of these components on the relations between various extracted basic densities and wood components should be investigated.

In this paper, we examine the effect of extraneous compounds on the relations between various basic densities and wood chemical components by their within-tree variations in *Eucalyptus globulus*.

Materials and methods

Materials

Two 14-year-old *E. globulus* (numbered 1 and 2) trees grown in Western Australia were utilized for this study.[8] All trees were planted and grown under an annual average temperature of 15°–16°C and annual average rainfall of 1000 mm. The estimated whole-tree height and the diameter at breast height after debarking, for each tree, were as follows: no. 1: 19.9 m, 24.4 cm, no. 2: 30.0 m, 23.8 cm. Debarked disks of 6 cm thickness were obtained; they were cut 0.3 m above the ground with a 1-m interval up to the height with a 8 cm diameter. Two 2 cm bars were sawn out from the center of the disks (Fig. 1). The bars were then divided into 2 cm each from the pith, and 2 × 2 × 6 cm blocks were prepared to include at least 2 years growth, as false rings instead of annual rings were observed with random intervals. Two blocks at the same distance from the pith were combined and utilized for the wood property analysis. The trend of within-tree variations at 0.3 m height was different from those at other heights,[7–11] so the data from specimens obtained at 0.3 m height were omitted in the analysis of the relations between various extracted basic densities and wood properties. Blocks possibly containing incompletely lignified parts adjacent to cambium or rotted parts or two piths were also omitted from this study. As a result, 50 blocks from individual no. 1 and 70 from no. 2 were utilized.

Various basic densities

Basic density was determined by the water immersion method[12] combined with freeze-fracture and freeze-drying; it was expressed as dry weight/green volume (kg/m^3).[8] Extractives-free basic density (EF-BD), alkali-extractives-free basic density (AF-BD), total-extractives-free basic

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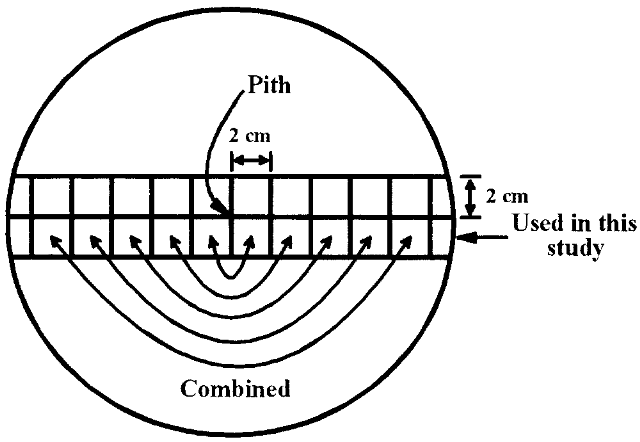

Fig. 1. Sampling method

density (TF-BD), and extraneous-compounds-free basic density (ECF-BD) were defined, respectively, as basic density × [100 – extractives content (%)]/100; basic density × [100 – alkali-extractives content (%)]/100; basic density × [100 – total-extractives content (%)]/100; and basic density × [original wood basis holocellulose (%) + original wood basis lignin (%)]/100.

Table 1. Various basic densities and wood chemical components

Wood properties	Nos. 1 + 2 (n = 128)	No. 1 (n = 50)	No. 2 (n = 78)
BD (kg/m^3)	609 ± 76	599 ± 70	615 ± 79
EF-BD (kg/m^3)	579 ± 74	563 ± 67	589 ± 77
AF-BD (kg/m^3)	525 ± 83	523 ± 101	527 ± 70
TF-BD (kg/m^3)	495 ± 80	487 ± 98	500 ± 66
ECF-BD (kg/m^3)	614 ± 77	604 ± 70	621 ± 82
Holocellulose (%)	84.0 ± 3.4	82.6 ± 2.2	84.9 ± 3.7
α-Cellulose (%)	47.8 ± 3.7	46.8 ± 3.6	48.4 ± 3.7
Hemicellulose (%)	36.2 ± 2.8	35.7 ± 3.1	36.5 ± 2.5
Lignin (%)	16.9 ± 1.6	18.3 ± 0.9	16.0 ± 1.3
Extractives (%)	5.0 ± 2.0	6.0 ± 1.1	4.3 ± 2.2
Alkali extractives (%)	13.7 ± 8.6	12.8 ± 13.5	14.3 ± 2.3
Total-extractives (%)	18.7 ± 8.6	18.8 ± 13.4	18.7 ± 2.5
Lignin S/G ratio	3.54 ± 0.38	3.24 ± 0.26	3.74 ± 0.33
Glucose (mol%)	9.3 ± 2.4	10.5 ± 2.3	8.6 ± 2.1
Xylose (mol%)	71.5 ± 9.5	61.6 ± 7.2	77.8 ± 3.6
Galactose (mol%)	10.8 ± 8.1	18.3 ± 8.3	6.0 ± 2.2
Rhamnose (mol%)	1.0 ± 0.1	0.9 ± 0.1	1.0 ± 0.1
Arabinose (mol%)	3.0 ± 0.7	3.3 ± 0.7	2.8 ± 0.6
Mannose (mol%)	4.4 ± 1.5	5.4 ± 1.7	3.8 ± 1.0

Results are the average ± SD.
Contents of wood chemical components are expressed as original wood basis.
No. 1, *No. 2*, the individual; *EF*, *AF*, *TF*, *ECF*, mean extractives-free, alkali-extractives-free, total-extractives-free, and extraneous-compounds-free, respectively; *Lignin S/G ratio*, lignin syringyl/guaiacyl molar ratio.
Each sugar mol% is for the hemicellulose fraction.

Determination of wood chemical components

The contents of holocellulose, α-cellulose, hemicellulose, lignin, and extractives (extraneous compounds soluble by Soxhlet apparatus with a sequence of toluene/ethanol, ethanol, and water), alkali extractives (extraneous compounds soluble by 0.1 N NaOH, 100°C, 1 h), and total extractives (extractives + alkali extractives) were determined using the small-scale method[13]; they were expressed as original wood basis.[14] The lignin syringyl/guaiacyl (S/G) ratio was determined by a modified thioacidolysis method[10] and expressed as the molar ratio.[14] The molar composition of neutral sugars constituting hemicellulose (i.e., glucose, xylose, galactose, rhamnose, arabinose, and mannose) was determined by hydrolysis of holocellulose with trifluoroacetic acid using high-performance liquid chromatography.[11,14]

Correlation coefficients between wood properties were calculated by statistical computer software, SPSS (SPSS, Chicago, IL, USA).

Results and discussion

Wood properties are summarized in Table 1, and the correlations of various extracted basic densities and wood chemical components sought by their within-tree variations are summarized in Table 2. Within-tree variation of each wood property was observed as in Table 1, and the correlation coefficients were obtained from the combined data of two individuals because the relation of wood properties did not depend on between-tree variation but depended on only the values of the wood properties.[14]

Basic density did not relate to holocellulose, although it significantly related to α-cellulose (positive, +), hemicellulose (negative, −), and lignin (−). When the fiber wall becomes thick, holocellulose or cellulose content increases and lignin content decreases.[15] Basic density in this study reflects the fiber morphology from these results on cellulose and lignin. On the other hand, the correlation between holocellulose and α-cellulose was high (+), although basic density has no correlation to holocellulose. Two hypothesis are proposed from these results, as follows: One is that the relation between holocellulose, which is the sum of cellulose and hemicellulose, and the basic density was compensated between cellulose and hemicellulose, as basic density correlated to α-cellulose positively and to hemicellulose negatively. The other is that the basic density variation was partly generated by extractives and the compensation between holocellulose and extractives masked the relation between basic density and holocellulose since holocellulose correlated to extractives negatively. To figure this out, relations between extracted basic densities and wood chemical components were examined. Four kinds of extracted basic densities were examined: EF-BD, AF-BD, TF-BD, and ECF-BD. Alkali extraction was nominated, as all extraneous compounds cannot be removed from *E. globulus* by solvent extraction.[7] Furthermore, ECF-BD was considered to be the theoretically complete removal of extraneous compounds.

Correlations between EF-BD or ECF-BD and holocellulose were significantly positive at at least the 5% level, and EF-BD and ECF-BD correlated to α-cellulose

Table 2. Correlation coefficients between various basic densities and wood chemical components

	Holocellulose (%)	α-Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Alkali extractives (%)	Total extractives (%)	Lignin S/G ratio	Glucose (mol%)	Xylose (mol%)	Galactose (mol%)	Rhamnose (mol%)	Arabinose (mol%)	Mannose (mol%)
BD (kg/m³)	0.058	0.285***	−0.314***	−0.193**	−0.070	−0.015	−0.032	0.141	0.096	−0.102	0.180**	−0.140	−0.142	−0.399***
EF-BD (kg/m³)	0.198**	0.356***	−0.238***	−0.271***	−0.243***	0.010	−0.048	0.211**	0.111	−0.055	0.125	−0.119	−0.179**	−0.407***
AF-BD (kg/m³)	0.037	0.308***	−0.371***	−0.099	0.036	−0.606***	−0.601***	0.084	0.095	−0.089	0.140	−0.089	−0.096	−0.283***
TF-BD (kg/m³)	0.165*	0.376***	−0.306***	−0.167*	−0.119	−0.603***	−0.635***	0.147*	0.110	−0.048	0.090	−0.070	−0.129	−0.289***
ECF-BD (kg/m³)	0.259***	0.407***	−0.231***	−0.213**	−0.233***	−0.021	−0.077	0.184**	0.142	−0.102	0.165*	−0.136	−0.168*	−0.377***
Holocellulose (%)	–	0.704***	0.277***	−0.546***	−0.805***	0.004	−0.185**	0.439***	0.149*	0.279***	−0.342***	0.192**	−0.213**	−0.063
α-Cellulose (%)		–	−0.487***	−0.510***	−0.439***	−0.138	−0.242***	0.196**	0.261***	0.091	−0.153*	0.102	−0.203**	−0.075
Hemicellulose (%)			–	0.018	−0.396***	0.191	0.099	0.274***	−0.170*	0.220**	−0.214**	0.098	0.013	0.024
Lignin (%)				–	0.465***	−0.080	0.028	−0.572***	0.075	−0.616***	0.639***	−0.417***	0.228***	0.253***
Extractives (%)					–	−0.142	0.092	−0.426***	−0.091	−0.256***	0.283***	−0.086	0.244***	0.127
Alkali extractives (%)						–	0.972***	0.034	−0.026	−0.002	0.023	−0.051	−0.032	−0.057
Total extractives (%)							–	−0.065	−0.049	−0.060	0.088	−0.069	0.024	−0.028
Lignin S/G								–	−0.247***	0.618***	−0.560***	0.419***	−0.290***	−0.398***
Glucose (mol%)									–	−0.538***	0.255***	−0.338***	0.373***	0.308***
Xylose (mol%)										–	−0.931***	0.754***	−0.304***	−0.368***
Galactose (mol%)											–	−0.746***	0.070	0.115
Rhamnose (mol%)												–	−0.237***	−0.174**
Arabinose (mol%)													–	0.509***
Mannose (mol%)														–

See footnotes to Table 1.
*** Significant at 1% level; ** significant at 5% level; * significant at 10% level.

(+), hemicellulose (−), and lignin (−) in the same way as basic density does. However, AF-BD had no correlation to holocellulose, and alkali extractives in *E. globulus* would not play an important role to mask the relation between basic density and holocellulose as that in *E. camaldulensis* would do.[6] From these results, only the extractives appear to mask the relation between basic density and holocellulose. In other words, extractives among extraneous compounds certainly affect the within-tree variation of basic density, but at much smaller magnitude in *E. globulus* than in *E. camaldulensis*.

Holocellulose is sometimes a more important wood property than cellulose for wood utilization and conversion.[16] In this case, from the character of each extracted basic density, ECF-BD is the best wood property to predict the property of end-use materials, but it has the disadvantage of requiring further efforts to determine. EF-BD may satisfy the same requirements with minimal experimental efforts.

Hardwoods cells with a large diameter and thick wall have a high lignin S/G ratio, as noted by a spectroscopic study.[17] In our study, the lignin S/G ratio significantly correlated to α-cellulose (+), hemicellulose (+), and lignin (−). As reported before, the cellulose content increases and lignin content decreases when the fiber wall thickens.[15] Consequently, the lignin S/G ratio represents fiber morphology. However, the basic density correlated to the lignin S/G ratio at a medium level only. In contrast, EF-BD, TF-BD, and ECF-BD were highly correlated with the lignin S/G ratio, significant at the 5% level. From these results, extraneous compounds, especially extractives, are believed to mask the relation between basic density and the lignin S/G ratio, both of which represent fiber morphology.

Good relations were observed between various basic densities, but AF-BD, TF-BD, and the neutral sugar composition constituting hemicellulose as the basic densities increased when galactose increased and arabinose and mannose decreased. These results are similar to previously determined relations for *E. camaldulensis*.[6] Accordingly, this may be caused by the difference in the cell wall layers between the high-density parts, which have thick cell walls, and the low-density parts, which have thin cell walls, as hemicellulose polysaccharide composition is known to differ in early and late woods, at least in softwoods[18,19]; or it may be due to the cell wall thickening, having a higher density, resembling that in tension wood except the gelatinous layer as speculated for *E. camaldulensis*.[6] As a matter of fact, extracted basic densities in both *E. camaldulensis* and *E. globulus* varied with an increase in galactose and a decrease in arabinose and mannose; these relations, perhaps caused by the difference in the constituent ratio of cell wall layers, may be consistent in *Eucalyptus*, although more investigation of the relation is required from an anatomical aspect.

Conclusions

Even a small amount of extractives among various extraneous compounds can mask the relation between basic density and the holocellulose or lignin S/G ratio; it was proven certainly to affect basic density.

Extracted basic densities in both *E. camaldulensis* and *E. globulus* varied with an increase in galactose and a decrease in arabinose and mannose. These relations, perhaps caused by the difference in the constituent ratio of the cell wall layers, may be consistent in *Eucalyptus*.

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