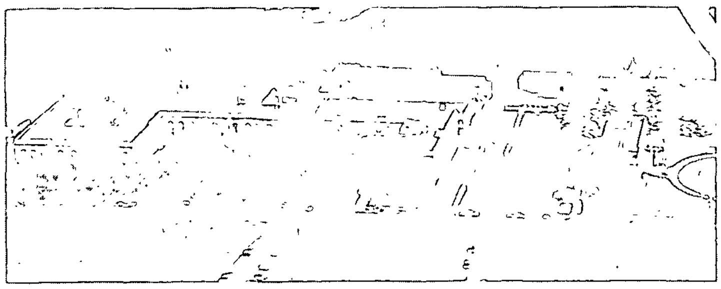

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CORRELATION OF FIBER MORPHOLOGICAL VARIATION AND FILTRATION RESISTANCE, SPECIFIC VOLUME AND SPECIFIC SURFACE

A. P. BINOTTO AND G. A. NICHOLLS

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Correlation of fiber morphological variation and filtration resistance, specific volume and specific surface

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Foreword

This is the second paper on studies in the area of fiber morphology and processes.

The results show that fiber morphology which relates to growth within a tree significantly influences the filtration resistance of unbeaten, bleached loblolly pine pulp fractions. Most of the influence on filtration resistance is through change in hydrodynamic and geometric specific surface arising from change in fiber diameter, fiber length and the number of fibers per g. The results imply, with stated assumptions, that including more juvenile wood would tend to increase filtration resistance and, for example, either decrease liquor flow rate in existing displacement bleaching and washing equipment or increase required drainage area and capital cost in new equipment designed for constant liquor flow rate. With greater amounts of mature wood included in a chip supply, the converse would tend to apply.

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Correlation of fiber morphological variation and filtration resistance, specific volume and specific surface

A. P. Binotto and G. A. Nicholls

Abstract

Unbeaten, bleached loblolly pine pulp fractions, differing in wall fraction and mean fiber lenfth ($\underline{L}_{\underline{f}}$), have a threefold change in number of fibers/g (η) with overall change in $\underline{L}_{\underline{f}}$. Two bases for obtaining η confirm that allied experimentally determined values are relatively correct, except for shortest earlywood fibers. Average specific filtration resistance ($\langle \underline{R} \rangle$), determined by constant-rate filtration shows significant differences. At constant mat density, $\underline{c}$ = 1.00 g/cc, $\langle \underline{R} \rangle$ for shortest earlywood is four times that for longest latewood fibers. This implies, with stated assumptions, that including more juvenile wood would tend to increase $\langle \underline{R} \rangle$ and either decrease liquor flow rate in existing displacement bleaching and washing equipment or increase required drainage area and capital cost in new equipment designed for constant liquor flow rate. With greater amounts of mature wood, the converse would tend to apply. Average specific volume ($\langle \underline{v} \rangle$) shows apparently twice as much water is immobilized in interstitial regions of fiber mats of smallest earlywood compared with largest latewood fibers. However, $\langle \underline{R} \rangle$ is essentially proportional to the square of average hydrodynamic specific surface ($\langle \underline{S}_{\underline{W}} \rangle^2$) and relatively insensitive to changes in $\underline{c}$ and $\langle \underline{v} \rangle$. Reasonable agreement exists between $\langle \underline{S}_{\underline{W}} \rangle$ and geometric specific surface ($\underline{S}_{\underline{WG}}$), calculated for a cylindrical model using fiber diameter ($\underline{d}_{\underline{f}}$), $\underline{L}_{\underline{f}}$ and η measurements. Hence, $\langle \underline{R} \rangle$ is mainly influenced by fiber morphological variation, through change in hydrodynamic and geometric specific surface arising from change in $\underline{d}_{\underline{f}}$, $\underline{L}_{\underline{f}}$ and η.

A. P. Binotto, graduate student, and G. A. Nicholls, Prof. Pulp and Paper Technology, The Institute of Paper Chemistry, Appleton, WI 54911.

INTRODUCTION

An earlier paper by Ingmanson and Whitney covered specific filtration resistance as an important property of papermaking fibers (1). Since then various aspects of filtration resistance that have been considered include the use of the Kozeny-Carman equation (2), the effects of synthetic fiber cross-sectional shape (3), and the effect of beating (4). The specific volume and specific surface components of filtration resistance were also considered in the study on the effect of beating, and the influence of high-yield on filtration resistance, specific volume and specific surface of kraft pulps was reported later (5).

Calculation of specific volume and specific surface makes use of wet mat compressibility. Recent results correlating the compressibility of loblolly pine bleached kraft pulp and fiber morphological variation have been reported (6). The aim of the present study is to correlate the same morphological fractions and filtration resistance, specific volume and specific surface.

RESULTS AND DISCUSSION

Morphological Fractions and Related Data

The preparation and fractionation of a bleached loblolly pine pulp, as described previously (6), provided seven morphological fractions. These consisted of earlywood and latewood fibers with a range of mean lengths as in Table I. In this table earlywood and latewood fibers are clearly differentiated by their difference in wall fraction. Their increase in mean fiber length (L_f) is accompanied by an increase in mean fiber width (d_f) and wall thickness (WT) but these joint trends generally will be referred to in terms of fiber length which can be determined most accurately.

[Table I here]

In Table I the numbers of fibers per gram are presented on two bases: One basis is the experimentally determined numbers ($\eta_{\underline{f}}$) for which counted fibers were weighed, and these data are essentially in accord with other values for southern pine (7). The other case ($\eta_{\underline{fG}}$) is for numbers calculated on a geometric basis, first assuming a cylindrical model to obtain the volume of the fiber wall ($\underline{V}_{\underline{W}}$) from experimentally determined values of $\underline{L}_{\underline{f}}$, $\underline{d}_{\underline{f}}$ and $\underline{WT}$ (6). Then, $\eta_{\underline{fG}}$ is calculated from $\underline{V}_{\underline{W}}$ and assuming fiber wall densities of 0.27 and 0.36 g/cc for earlywood and latewood, respectively. These densities are essentially in the range expected on the basis of other work (8). Comparison of the listed values for $\eta_{\underline{f}}$ and $\eta_{\underline{fG}}$ confirms that, with the exception of the shortest earlywood fiber fraction, the allied experimentally determined values are relatively correct.

For the fiber fractions in Table I it has been shown (6) that the shortest earlywood and longest latewood fibers essentially gave the highest and lowest wet mat density, respectively. In addition, as static pressure was increased, the greatest compressibility of the shortest earlywood fibers, or those with the thinnest walls, resulted in a relatively greater increase in wet mat density. A corollary is that a constant mat density of 0.100 g/cc, which is equivalent to about a 10% consistency, is achieved at lowest pressure for the shortest earlywood fibers, as shown in Table I.

Filtration Resistance and Implications

Average specific filtration resistance values were calculated using the following equation, which is a form of the Darcy equation:

$$\langle R \rangle = \frac{A^2}{(dV/dt)^2 \; \mu C} \frac{\Delta P_f}{t} = B \frac{\Delta P_f}{t} \tag{1}$$

where

- $\langle R \rangle$ = average specific filtration resistance, cm/g
- A = cross-sectional area of bed perpendicular to direction flow, sq cm (49.5 sq cm)
- ΔP_f = overall frictional pressure drop across the filter bed, dynes/sq cm
- dV/dt = volumetric rate of flow, cc/sec
- μ = filtrate viscosity, poises
- C = mass of fibers in the filter bed per unit volume of filtrate, g/cc
- t = time of filtration, sec
- B = constant in a constant-rate filtration, c.g.s. units

and using constant-rate filtration data as described previously (1,2,4). Values are based on at least triplicate runs for each of the fiber fractions and the 95% confidence limits were ±2.0 to 8.5% of the means which were 4.4 to 40.6 × 10^6 cm/g. This range reflects the effect of fiber morphological variation and pressure drop on average specific filtration resistance of the unbeaten pulps as shown in Fig. 1. In this figure there are significant differences in filtration resistance at constant pressure drop related to wall fraction and fiber length. Filtration resistance also varies with pressure drop with the greatest change observed in the smallest earlywood fibers.

[Fig. 1 here]

The trends in filtration resistance with increase in pressure drop tend to parallel those seen for wet mat density. However, the percentage change in filtration resistance with fiber length is much greater than the change found for wet mat density with fiber length (6). So, in Table I, for the shortest earlywood fiber fraction a mat density equivalent to about a 10% consistency is achieved at lowest pressure whereas the corresponding filtration resistance is actually at a maximum compared with the other fiber fractions. The converse holds for the longest latewood fiber fraction.

The defining equation for average specific filtration resistance (1) can be written in the form:

$$\frac{dV}{dt} = \frac{A^2}{\mu W} \frac{\Delta P_f}{\langle R \rangle} \qquad (2)$$

where W is the total mass of fibers in the bed. For displacement diffusion bleaching or washing equipment operating at essentially constant consistency and with assumptions as noted below, μ, W and A^2 are constant so that in Table I the sixfold change, for $\Delta P_f/\langle R \rangle$ arising from morphological variation, results in a proportional change in (dV/dt) which is the volumetric rate of flow. Similarly, a constant flow rate can be maintained by changing the drainage area (A) in which case, since the square of this is inversely proportional to $\Delta P_f/\langle R \rangle$, there is a two to threefold change in A arising from morphological variation.

This morphological variation relates to growth within a tree in such a way (9) that more juvenile or mature wood in a chip supply would result in relatively more shorter or longer fibers, respectively. Thus, assuming essentially constant consistency conditions are maintained in displacement bleaching and washing, if more juvenile wood is utilized it would tend to be necessary to use a lower maximum pressure between the washer head and screen. In existing equipment a trend to increased filtration resistance, even at lower pressure (Table I), would be expected to result in a slower flow of liquor through the pulp mat so that efficiencies and/or production capacity could be lower. For new equipment, assuming a constant flow rate is maintained, a trend to increased filtration resistance would imply a need for more drainage area with increase in capital cost. These implications also assume a constant dilution factor and that any changes in diffusion, dispersion, etc., are relatively insignificant on an overall basis. When utilizing a greater amount of mature wood, the converse would apply to these implications.

Specific Volume and Specific Surface

The Kozeny-Carman equation (1) recognizes that at a given pressure drop filtration resistance is a function of mat density, porosity ($1-vc$) where v is the effective specific volume of fibers, and fiber hydrodynamic specific surface area (S_W). For determining volume and surface area Ingmanson and Andrews (10) used an equation which can be expressed as follows:

$$\langle R\rangle = \langle S_W\rangle^2 \left\{ \frac{3.5\,(1-N/2)\,c^{1/2}}{\langle v\rangle^{1/2}} \left[1 + 57\,\langle v\rangle^3\,(1-N/2)^6\,c^3\right] \right\} \qquad (3)$$

where

N = 0.373 for the fiber fractions under study (6)

$\langle S_W\rangle$ = average specific surface per unit mass

$\langle v\rangle$ = average specific volume

This equation is based on Eq. 1, the Kozeny-Carman equation, and an empirical value assigned to the Kozeny factor (11).

On the above bases, c, <v> and $\langle S_W \rangle$ would be the main factors that could influence filtration resistance. Also, in arriving at Eq. 3 specific volume and specific surface have been assumed constant with respect to pressure in an integration step (10). Hence, without further information it is invalid to calculate them at different pressures as was done for filtration resistance in Fig. 1.

The effective specific volume of fiber fractions, as in Table II, is in essence the volume of dry fibers plus the relative amount of associated immobilized water per g dry fiber (1). Assuming a constant pycnometric specific volume of 0.62 cc/g for dry fibers (12), the increase in specific volume in Table II corresponds to an apparent increase in immobilized water from 1.04-1.97 cc water per g fiber. Further assuming no increase in fiber swelling as found in beating (4), then most of this increase arises from more water being immobilized in the interstitial regions of the fiber mat as a reflection of changes in fiber morphology.

[Table II here]

For specific volumes of 1.66-2.59 cc/g, the apparent fiber consistency is 49-33%. About a 33% consistency would be a more plausible maximum and this discrepancy probably is a reflection of the limitations of the assumptions made in deriving Eq. 3. Nevertheless, a relatively high consistency suggests that most of the immobile water is within the fibers, and not outside them.

The log-log plot of filtration resistance *vs*. specific surface in Fig. 2 shows that there is an essentially linear relationship between log $\langle \underline{R} \rangle$ and log $\langle \underline{S}_W \rangle$ with slope = 2, as also observed in connection with refining studies (13). This implies that in Eq. 3 the sum of the terms containing $\underline{c}$ and $\langle \underline{v} \rangle$ does not vary significantly for the various fiber fractions. The values for each term, τ_1 and τ_2, are shown in Table II. Although the second term has a clear trend, its value is significantly less than that of the other term, which varies relatively little. Consequently, whatever trend there may be in the sum of the terms, τ, it is insufficient to cause the slope in Fig. 2 to vary significantly from a value of 2. Hence, in Eq. 3 $\langle \underline{R} \rangle$ is essentially a reflection of $\langle \underline{S}_W \rangle^2$ and is relatively insensitive to changes in mat density and specific volume in the other terms, at least for the fiber fractions under study.

[Fig. 2 here]

Geometric specific surface ($\underline{S}_{WG}$) of the fiber fractions, as in Table II, is based on a cylindrical fiber model for which:

$$\underline{S}_{WG} = \pi\, \underline{d}_f\, \underline{L}_f\, \eta_f \tag{4}$$

Since fiber length is 50-100 times the diameter, tapered end effects were ignored. There is reasonable agreement between the data for average hydrodynamic specific surface and the values calculated on this geometric basis from fiber dimensions. Hence, a major factor in the observed changes in filtration resistance is fiber morphological variation which relates to change in geometric and hydrodynamic specific surface arising from change in $\underline{d}_f$, $\underline{L}_f$ and η_f.

EXPERIMENTAL

Average specific filtration resistance was calculated on the basis of Eq. 1 using plots of pressure drop *vs.* time from an established constant rate filtration procedure (*4*). Mean data from the strip-chart recording of ΔP_f vs. t are included in Table III. Mean $\langle R \rangle$ values, as plotted in Fig. 1, were calculated from mean ΔP_f and t data.

[Table III here]

Average specific surface and average specific volume were determined graphically from data in Table III and corresponding c values using an equation similar to Eq. 3 (*4*). The graphical procedure involved linear regression of a plot of $\Delta P_f/(c^{1/2}\ t)$ vs. c^3 from ΔP_f = 50 to 90 cm H_2O. Interpolated mat density, c, from compressibility data (*6*), has been related to average mat density, $\langle c \rangle$, in constant rate filtration by defining average porosity, $\langle \varepsilon \rangle$, as equal to $1-(1-N/2)^2 \langle v \rangle M \Delta P_f^{\,N}$ (*10*) so that $\langle c \rangle = (1-N/2)^2 c$, as discussed more fully elsewhere (*14*). The 95% confidence limits in Table II represent variation for the set of constant rate filtration data obtained from individual runs for a particular fiber fraction.

Number of fibers/g was determined by weighing samples of 100-300 fibers on a quartz balance accurate to 0.5×10^{-6} g.

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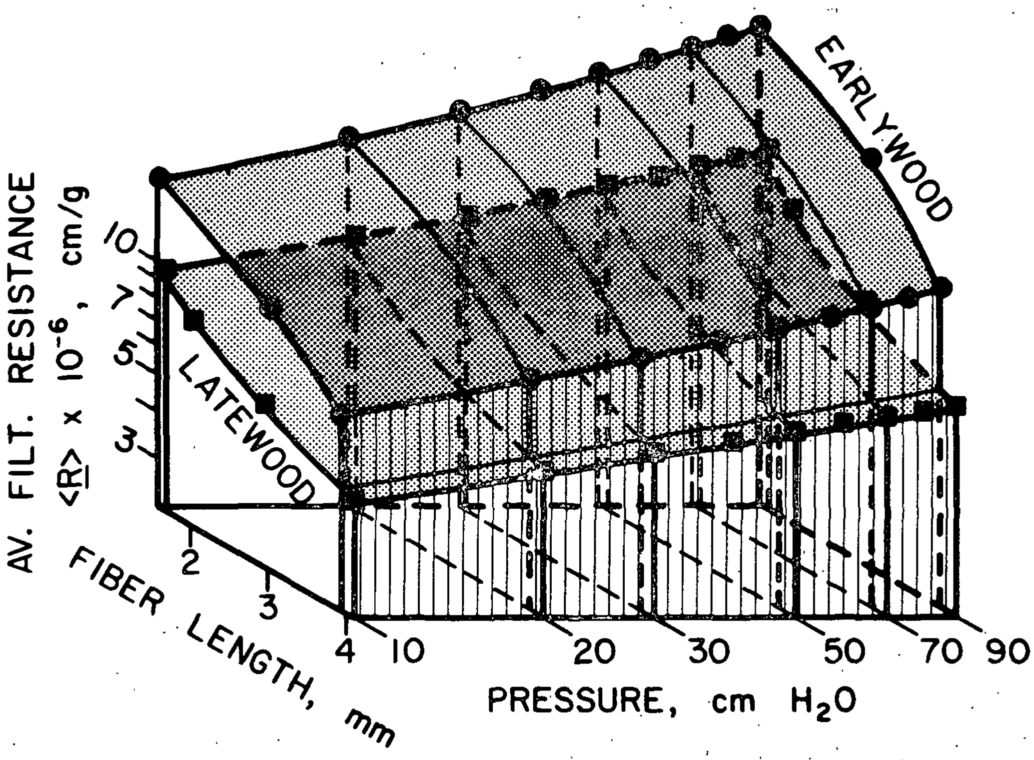

Fig. 1. Log-log plots of average specific filtration resistance vs. pressure with mean fiber length of earlywood and latewood plotted linearly on the z-axis.

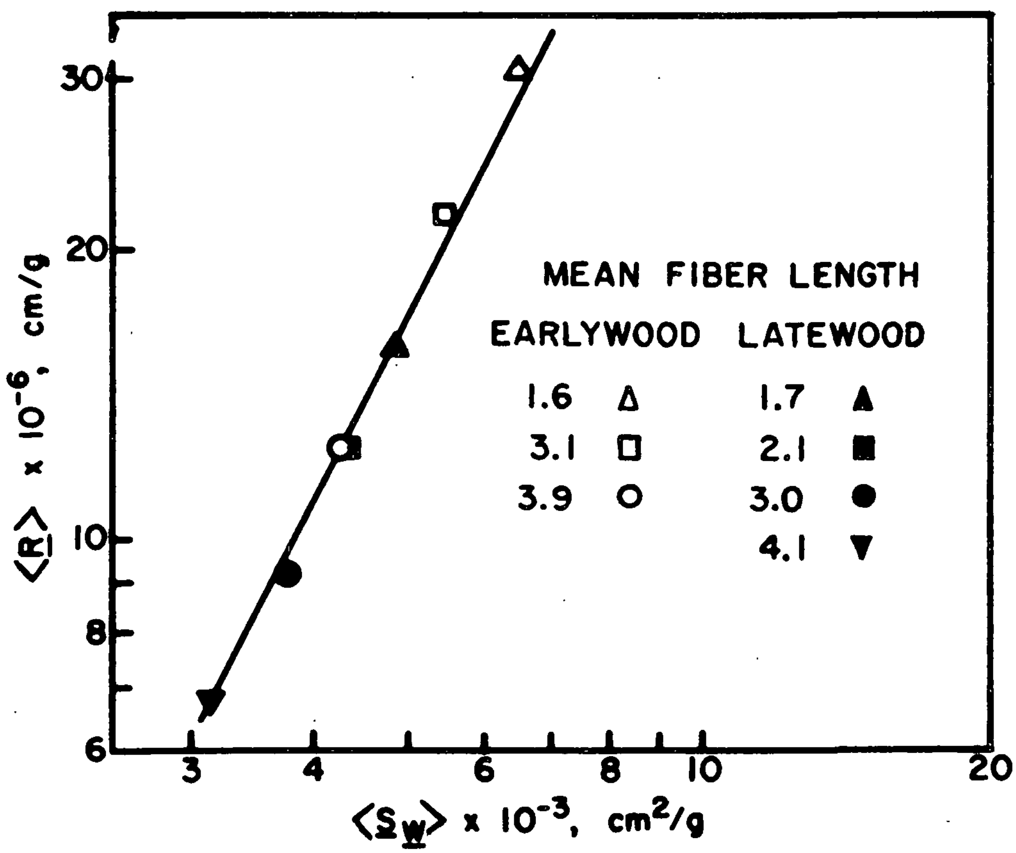

Fig. 2. Correlation between average specific filtration resistance, $\langle \underline{R} \rangle$ at $\Delta \underline{P}_f$ = 50 cm and average specific surface, $\langle \underline{S}_W \rangle$ for $\Delta \underline{P}_f$ = 50-90 cm for the earlywood and latewood fiber fractions.

Table I. Morphological Fractions with Correlated Mat Density and Filtration Data

Wall fraction, %[a]	Mean fiber length, mm[b]	No. fibers, $\times 10^{-5}$/g[c] n_f	No. fibers, $\times 10^{-5}$/g[c] n_{fG}	c = 0.100 g/cc[d] ΔP_f, cm H_2O	c = 0.100 g/cc[d] $\langle R \rangle \times 10^{-6}$, cm/g	$\Delta P_f/\langle R \rangle \times 10^3$, (g-dynes)/cm^3
			Earlywood			
30	1.63 ± 0.02	21.5	36.0	49.1	30.2	1.59
32	3.05 ± 0.03	13.7	14.0	56.2	21.4	2.58
32	3.95 ± 0.04	9.4	9.0	60.2	13.1	4.51
			Latewood			
62	1.74 ± 0.03	22.7	22.8	61.5	17.1	3.53
66	2.07 ± 0.04	17.0	16.5	66.3	13.5	4.82
66	2.98 ± 0.03	11.1	10.5	70.7	10.3	6.73
68	4.13 ± 0.06	6.9	7.0	70.1	7.4	9.29

[a] Calculated from fiber width and cell wall thickness (6).

[b] Arithmetic mean ± 95% confidence limits.

[c] The two bases for no. fibers/g are covered in text.

[d] G o.d. fiber/cc wet mat.

Table II. Average Specific Volume, $\langle \underline{v} \rangle$, Average Specific Surface, $\langle S_{\underline{W}} \rangle$, Geometric Specific Surface, $S_{\underline{WG}}$, and Other Data for Morphological Fractions

Mean fiber length, mm	$\langle \underline{v} \rangle$, cm^3/g	τ_1[b]	τ_2	τ	$\langle S_{\underline{W}} \rangle \times 10^{-3}$, cm^2/g	$S_{\underline{WG}} \times 10^{-3}$, cm^2/g
			Earlywood			
1.63	2.50 ± 0.03[a]	0.57	0.15	0.72	6.50 ± 0.09	4.39(7.35)[c]
3.05	2.59 ± 0.02	0.55	0.13	0.68	5.44 ± 0.13	5.89
3.94	2.30 ± 0.04	0.57	0.09	0.67	4.28 ± 0.13	5.71
			Latewood			
1.74	2.27 ± 0.05	0.57	0.09	0.68	4.89 ± 0.21	4.03
2.07	2.19 ± 0.06	0.58	0.07	0.65	4.34 ± 0.11	3.77
2.98	2.11 ± 0.19	0.58	0.06	0.64	3.78 ± 0.04	3.72
4.13	1.66 ± 0.25	0.66	0.03	0.69	3.14 ± 0.09	3.29

[a] 95% Confidence limits.

[b] $$\frac{3.5(1-\underline{N}/2)\,\underline{c}^{1/2}}{\langle \underline{v} \rangle^{1/2}}\,[1 + 57\,\langle \underline{v} \rangle^3\,(1-\underline{N}/2)^6\,\underline{c}^3] = \tau_1 + \tau_2 = \tau.$$

[c] Value in parenthesis calculated using $\eta_{\underline{fG}}$.

Table III. Constant Rate Filtration Data.

L_f,	dV/dt,			V, $\times 10^{-1}$,	Filtration time, t, sec at respective pressure drops, ΔP_f, cm H_2O								
mm	cm^3/sec	μ, cp.	W, g	cm^3	10	20	30	40	50	60	70	80	90
					Earlywood								
1.63	78.6	0.8705	6.80	6513	223.9	350.5	447.3	526.5	594.0	656.0	710.9	758.7	802.9
3.05	78.2	0.9299	9.70	6238	214.4	333.5	423.8	500.2	568.1	624.3	677.3	726.2	770.5
3.94	81.1	0.9028	16.85	9774	278.1	447.0	585.2	704.4	813.3	912.7	1001	1084	1160
					Latewood								
1.74	84.9	0.9979	11.22	7583	200.3	325.9	430.8	523.2	602.2	675.7	743.0	805.9	864.8
2.07	87.4	0.9218	15.37	7496	183.8	305.9	406.8	494.4	573.9	647.1	715.1	780.1	837.2
2.98	87.6	0.9175	20.83	11066	259.1	434.7	581.2	713.8	834.3	946.6	1053	1150	1235
4.13	90.0	0.8551	30.38	11144	243.3	405.3	544.3	675.4	791.6	905.1	1014	1119	1221