POLYCHROMATIC X-RAY ATTENUATION CHARACTERISTICS AND WOOD DENSITOMETRY APPLICATIONS[1]

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ABSTRACT

The use of polychromatic X-ray energy in wood densitometry complicates the mathematical relationship between the material and X-ray attenuation. Attenuation of polychromatic X-ray energy through cellulose acetate was investigated and characterized. Under polychromatic radiation with 30 keV maximum photon energy, an attenuation coefficient of 0.638 cm^2/g was determined for samples of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) from two trees at 9% equilibrium moisture content. X-ray energy was sensitive to wood moisture content within a 2% range.

Keywords: Polychromatic X-ray, attenuation, cellulose acetate, wood density, moisture content.

INTRODUCTION

Direct scanning X-ray densitometry is the technique of passing X-rays through a wood sample onto a detection device. Though wood is easily penetrated by X-rays, some energy is attenuated in relation to the kind and amount of material that the X-rays must pass through. When a wood sample of uniform thickness is scanned beneath an X-ray source, the intensity of X-rays striking the detector, and thus the output of the detector, is related to the wood density.

Phillips (1960) was one of the first to use direct scanning techniques for measuring wood density. Beta rays from a $Strontium_{90}$ source were passed through wood sections 100 micrometers thick onto a scintillation detector, and attenuation data were recorded by a strip-chart recorder. Ring-by-ring densities of earlywood and latewood were determined from the strip-chart records. Wood of higher density absorbed more energy; thus the relationship of density to attenuation was documented. Scanning speeds were slow, 2.5 cm/h, and the resolving power of

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the beta-ray densitometer used by Phillips was limited by the relatively large aperture needed to obtain satisfactory detector count rates.

X-ray energy

X-ray sources produce either monochromatic or polychromatic energy. Monochromatic sources typically consist of an X-ray emitting isotope such as Fe_{55} (Cown and Clement 1983; Moschler and Dougal 1988), and the characteristics of the energy are specific to the isotope selected. Polychromatic sources are generally X-ray tubes in which a target material is bombarded with high-energy electrons. The characteristics of polychromatic energy are described by both the target material and the potential of the electrons striking the target.

Monochromatic X-rays consist of radiation of a single wavelength. Attenuation of monochromatic X-ray energy through a homogeneous material is exponential and of the form:

$$I = I_0 \exp(-\mu_l t) \quad (1)$$

where: I = intensity of the attenuated X-ray, I_0 = intensity of the unattenuated X-ray, μ_l = the linear attenuation coefficient, and t = the thickness of the material. The attenuation coefficient is specific to the attenuating material and the X-ray energy level (Kaelbel 1967).

Olson et al. (1988) calculated that for measurements of conifer wood density, the ideal X-ray photon energy is between 5.13 and 5.69 keV (mean: 5.41 keV for 1-mm-thick wood samples). X-ray energy falling within this range provides the maximum attenuation differential between low-density earlywood and high-density latewood with the least error due to ash content, and therefore with greater accuracy.

Polychromatic X-rays consist of a spectrum of radiation wavelengths. X-ray quality is defined not only by the maximum photon energy of the continuous spectrum, which identifies the minimum radiation wavelength, but also by the spectral distribution of wavelengths. Polychromatic X-ray attenuation is not described by a simple linear attenuation coefficient. However, Kaelbel (1967) suggests that a polychromatic X-ray source is a simple, reliable, absorption-type tool. It is typically lower in cost than monochromatic X-ray equipment, yet approximates the fundamental exponential relationship expressed by Eq. (1).

Attenuation

At any energy level, X-ray attenuation is dependent on the chemical nature of the attenuating material. Each element has an attenuation coefficient specific to a given level. Laufenberg (1986) describes the calculation of an attenuation coefficient for wood as a summation of the coefficients for each of the elemental components, proportional to their fraction of the mass.

Olson and Arganbright (1981) presented a model based on the elemental composition of wood, and Liu et al. (1988) further refined it for a lower energy X-ray. Attenuation coefficients are determined empirically from substances of known composition that can be related to wood density. Phillips et al. (1962) used step wedges of cellulose acetate for calibration, Heger et al. (1974) wedges made from Douglas-fir pulp, Jozsa et al. (1987) Delrin® acetal, and Cown and Clement (1983) woods of known, uniform density. Generally, the calibration material is scanned

and attenuation data are related to the known density of the calibration material by application of Eq. (1), or by other regression techniques.

Consideration of the chemical composition of wood and its effect on X-ray attenuation must take into account wood moisture content. Chemical composition of wood at various moisture contents can be calculated on the basis of the 8:1 oxygen-to-hydrogen molecular-weight ratio of water. As moisture content increases, the percentage of the carbon component decreases, while that of the oxygen and hydrogen components increases. Phillips (1960) reported only a slight effect of wood moisture content on monochromatic energy attenuation; a 10% change in sample moisture content resulted in only 0.37% change in the attenuation measured by a detector.

Study objectives

The objective of this study was specifically to identify a polychromatic X-ray source (X-ray tube) as a reliable device for wood densitometry applications. Relationships between attenuation and both energy and density were evaluated to characterize polychromatic X-ray attenuation. An empirical calibration procedure was devised and an attenuation coefficient determined for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Finally, wood moisture content as it affected the attenuation relationship was evaluated.

MATERIALS AND METHODS

The X-ray densitometer

The work flow of a densitometer system can be summarized as sample preparation, calibration, scanning for data acquisition, and data analysis. Increment cores or disk samples are first prepared for scanning. Calibration determines and verifies predicting coefficients for the density calculations. A sample is then moved between the X-ray sources and the sensor and scanned for attenuation data. Data analysis includes density calculation and processing of the growth-ring components from the linear density record.

The densitometer in the Department of Forest Products at Oregon State University represents an evolution of the system described by Hoag and McKimmy (1988). The system has four interconnected operating components: a signal-source component (system hardware consisting of a high voltage power supply, an X-ray tube, and a sample stage), an X-ray sensing component (the X-ray sensor, electrometer and sensor aperture), a system-control component (a desktop computer with input/output capabilities and software), and a data-analysis component (computer software for calculating and evaluating density).

The X-ray tube is a constant-power device designed to operate at a peak applied energy of 50 kilovolts (kV). Typical operating conditions for wood applications are between 20 to 30 kV, with a tube current of 2 milliamps. The target material, which is the X-ray generating source in the tube, is tungsten.

The X-ray sensor is a scintillation detector consisting of a cesium iodide crystal encased with a photo diode in a small aluminum canister. X-rays passing through the canister impinge upon the crystal, emitting photons that are sensed by the photo diode. This generates electric current in proportion to the X-ray energy reaching the sensor.

There is no filtering or shaping of the X-ray energy before or after reaching the sensor. The 0.12- × 2-mm slit aperture mounted on the sensor collimates the X-ray energy, minimizing X-ray signal noise.

Resolution and accuracy

The X-ray densitometer is described by its resolution and accuracy. Resolution is the minimum sample area that may be discretely identified, a measure that is particularly important when evaluating maximum latewood density and the latewood-to-earlywood transition zone. Accuracy or precision of the X-ray density measurement may be described by an error band around the gravimetric density.

The aperture of the X-ray sensor and the step-increment of the sample stage determine system resolution. As the step-increment or the aperture decrease in size, resolution improves. However, as resolution improves, system accuracy decreases. Electronic noise, consisting primarily of diode shot noise from the X-ray sensor, limits accuracy. The magnitude of the shot noise is constant; thus anything that reduces the X-ray sensor output, such as decreased aperture width, will decrease the signal-to-noise ratio and therefore measurement accuracy (Hoag and McKimmy 1988).

Techniques of sample preparation also affect resolution and accuracy. Poor vertical alignment of the longitudinal tracheids blurs the resolution of maximum and minimum values and the latewood-to-earlywood transition zones. Blurring is minimized by use of thinner samples but is best prevented by careful sample preparation. Variations in sample thickness directly affect measurement accuracy.

Because of these system limitations, the Department of Forest Products densitometer operates with a 0.12- × 2-mm rectangular aperture and a 0.053-mm step-increment between discrete sample measurements. At these settings, the resolving power of this densitometer represents approximately four rows of tracheids in a Douglas-fir sample. Measurement accuracy depends on thickness. At 0.15 cm, measurements such as average ring density or core density varied within ± 0.01 g/cm^3 of the gravimetric density. However, individual measurements, such as maximum density, varied ± 0.02 g/cm^3.

Sample preparation

Samples from two trees were used in calibrating and testing the densitometer. One tree came from the Cascade Mountains near Sweet Home, Oregon, at an elevation of approximately 3,000 feet and the other from the Coast Range near Corvallis, Oregon, at an elevation of approximately 600 feet.

Two sample disks 4 inches thick were cut every 4 feet beginning at the butt of the stem and progressing to a 5-inch top. Disks without branch whorls were selected wherever possible. The first tree provided 22 pairs of sample disks, and the second 26 pairs.

One disk of each pair from each tree was used for basic-density measurements (green-disk volumes measured by water submersion, followed by measurement of oven-dry weight). The second disk of each pair was equilibrated to 10–12% moisture content in a standard conditioning room, then cut into two X-ray samples 0.25 cm thick × 1.5 cm wide × disk-radius length, one from the north and one from the south orientation of the standing tree. Because of breakage, the 48 disks provided just 90 samples for scanning. Prepared samples were stored at the X-ray

site, where room conditions maintained wood equilibrium moisture content (EMC) at approximately 9%.

Attenuation and X-ray density measurements

Characteristics of X-ray attenuation by cellulose-acetate were evaluated with polychromatic energy and the exponential model

$$I = I_0 \exp(-\mu_m x) \tag{2}$$

where I = the attenuated X-ray intensity, I_0 = the unattenuated X-ray intensity, μ_m = the mass attenuation coefficient (cm^2/g), and x = density times thickness (p × t). The attenuation coefficient is calculated

$$\mu_m = -\ln(I/I_0)/(p \times t). \tag{3}$$

Attenuation ratios, $\ln(I/I_0)$, were determined by measuring the unattenuated signal intensity through air (I_0) and the attenuated signal (I) through a five-step cellulose-acetate wedge 0.036 to 0.178 cm thick for five energy levels between maximum photon energy 20 and 30 keV. The attenuation coefficient of cellulose-acetate (density 1.35 g/cm^3) was determined for each of the five energy levels with Eq. (3).

Wood samples were scanned at maximum photon energy 30 keV, and data were acquired at a rate of four sampling points per second, allowing sample translation at a rate of 2.4 cm/min for 100 sampling points per centimeter. X-ray data for the wood samples were converted to density values by manipulating Eq. (3) to become $p = \ln(I/I_0)/(-\mu_m \times t)$ and applying the attenuation coefficient determined for cellulose-acetate for that specific scan.

Just before being scanned, density of each X-ray specimen was determined from weight and dimension measurements. These gravimetric densities were compared with density values determined by X-ray and were used to ascertain a more precise energy-specific attenuation coefficient for Douglas-fir.

Reliable density calculations depend on the stability of the X-ray source. Variations in the energy level will alter the attenuation characteristics of the cellulose-acetate and cause the attenuation coefficient to vary, which subsequently introduces error into the wood-density calculation. The calibration wedge was scanned before all wood-density measurements to verify the system stability and thus the reliability of the calculation.

The influence of moisture content on X-ray attenuation was investigated in a series of 24 scans on a single Douglas-fir sample at moisture contents between 1% and 35%. The sample was first cut to approximately 6 mm by 6 mm by 100 mm in longitudinal, tangential, and radial directions, respectively. Oven-dry mass was estimated on the basis of the known 9% EMC of the storage room. The sample was vacuum-pressure soaked in water until it sank, and then allowed to air-dry to 35% moisture content. It was scanned alternately on radial and transverse surfaces every 15 minutes (total: 14 scans) to examine the attenuation relationship as the sample desorbed. Next it was oven-dried, and a second series of 10 scans was made to examine the attenuation relationship as the sample adsorbed moisture. The sample was weighed and measured with calipers before and after each scan. Moisture contents and dimensions were calculated by averaging these measurements. Average attenuation values for each scan were used to calculate the

TABLE 1. *X-ray attenuation ratios for five thicknesses of cellulose-acetate and calculated mass attenuation coefficients at each of five energy levels (keV).*

Cellulose-acetate thickness (cm)	Maximum photon energy				
	20 keV	24 keV	25 keV	28 keV	30 keV
			Attenuation ratio[a]		
0.036	0.051	0.041	0.040	0.034	0.033
0.071	0.107	0.081	0.080	0.069	0.064
0.107	0.163	0.122	0.120	0.103	0.094
0.142	0.219	0.163	0.159	0.137	0.127
0.178	0.271	0.203	0.196	0.170	0.158
			Mass attenuation coefficient[b]		
μ_m	1.152	0.847	0.816	0.709	0.653

[a] $\ln(I/I_0)$ determined for thicknesses 0.036 to 0.178 cm with X-ray densitometer.
[b] $\mu_m = -\ln(I/I_0)/(1.35 \times \text{thickness})$.

linear attenuation coefficients at each moisture content, which were regressed against sample moisture contents.

RESULTS AND DISCUSSION

The X-ray attenuation ratios measured for cellulose-acetate and listed in Table 1 represent a single scan of the wedge at each of the five energy levels. As the X-ray energy increased from a maximum photon energy of 20 keV to 30 keV, the attenuation coefficient decreased; as the wedge thickness increased, the natural log of the attenuation ratios increased linearly with respect to the increased cross-section of cellulose-acetate. Attenuation coefficients were calculated for each of the five energy levels. With Eq. (3) as the model, correlations were high (R^2 = 1.00, 4 df) at each energy level. Cellulose-acetate thickness did not appear to affect attenuation. The attenuation coefficient calculated for cellulose-acetate at the 30 keV setting was 0.653 cm^2/g; the average of 62 cellulose-acetate attenuation coefficients, each obtained in a similar manner during scanning of wood samples, was 0.655 cm^2/g, with a standard error of 0.002 cm^2/g.

Calculations of wood density were made with the acetate attenuation coefficient determined for each scan. The relationship between the gravimetric density of an X-ray sample and its density determined by X-ray is illustrated in Fig. 1. There is high correlation (R^2 = 0.94, 46 df) between the two determinations; however, the X-ray densities were an average 2.4% lower than gravimetric densities. The small variation in the attenuation coefficients of the cellulose acetate from the 62 scans would not account for this difference; therefore, it is assumed to be the result of calculating Douglas-fir wood density with the attenuation coefficient derived from cellulose acetate. As such, 2.4% is a measure of the difference in the coefficients. Assuming that Beer's law (Weast 1968) applied to the attenuation of polychromatic X-rays, as it does to monochromatic X-rays, a more precise Douglas-fir attenuation coefficient (μ_m) can be determined from the average X-ray density of all samples (0.504 g/cm^3), the average gravimetric density of these X-ray specimens (0.516 g/cm^3), and the average cellulose-acetate attenuation coefficient (0.655 cm^2/g). Then,

$$\mu_m = \frac{0.504 \times 0.655}{0.516} = 0.638 cm^2/g \quad (4)$$

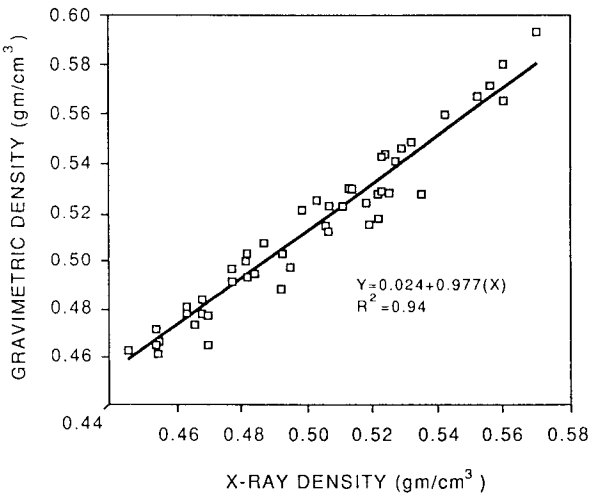

FIG. 1. Relationship to gravimetric densities of Douglas-fir density calculated from X-ray data with the cellulose acetate attenuation coefficient.

This attenuation coefficient is specific to the x-ray source and energy level in this part of the study.

Basic densities of the disks were compared with the average weighted densities of the X-ray samples from the Cascade Mountain tree (Fig. 2). X-ray densities were weighted ring-by-ring on the basis of their radial distance from the pith by the equation

$$\rho_w = \frac{\Sigma\pi(r_i^2 - r_{i-1}^2)\rho_i}{\pi r_n^2} \tag{5}$$

where ρ_w = the weighted density of the X-ray specimen, r_i = the outer radius of the ith ring, and ρ_i = the density of the ith ring (i = 1 to n rings). Weighted

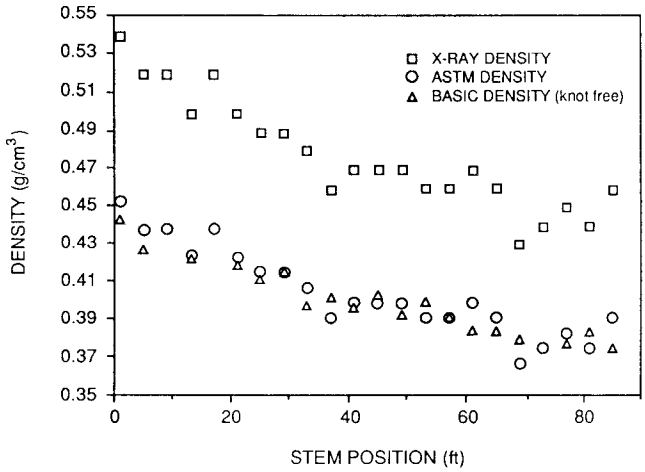

FIG. 2. Basic densities of Douglas-fir disks, densities calculated with the ASTM formula and X-ray data, and average weighted densities from the X-ray data.

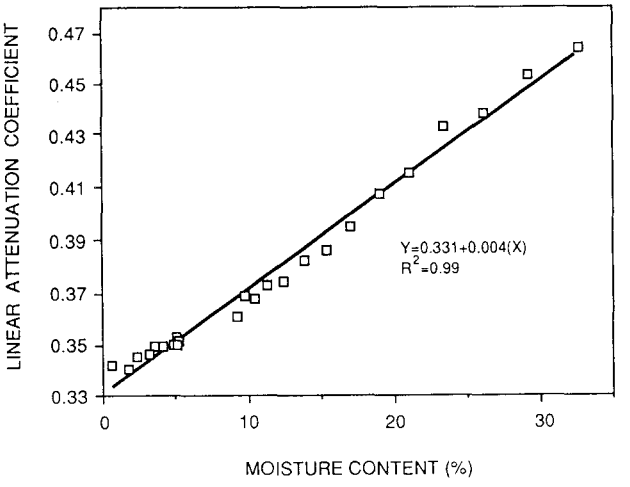

FIG. 3. Linear attenuation coefficient (μ_l) of a single Douglas-fir sample at different moisture contents. Sample was 5.96 mm in the longitudinal direction, and 6.0 to 6.33 mm at 0% to 35% moisture content in the transverse direction.

densities of the north and south X-ray samples from each disk were averaged to obtain a single X-ray density.

Average basic density of the disks from the first tree was 0.408 g/cm^3, and average density of the X-ray samples 0.477 g/cm^3; values for the second tree were 0.460 g/cm^3, for disks and 0.529 g/cm^3 for X-ray samples. The difference between basic densities and those determined by X-ray is explained by the fact that mass and volume were measured on X-ray samples at 9% moisture content, while mass of disks was based on oven-dry weight, and volume on green moisture content. Eq. (6), from the American Society for Testing and Materials (ASTM 1985), was used to adjust X-ray density to the same mass and volume basis as basic density.

$$S_b = \frac{S_a/(M_1 + 1)}{1 + [S_a/(M_1 + 1)](0.9)(M_2 - M_1)} \quad (6)$$

where S_b = density of the X-ray sample calculated on the basis of oven-dry weight and green volume; S_a = the density measured by X-ray scanning; M_1 = the average EMC of the X-ray samples (9%); and M_2 = the fiber saturation point of wood (30% moisture content).

When Eq. (6) is applied to the X-ray densities for each tree, the average density is 0.404 g/cm^3 for the first tree and 0.445 g/cm^3 for the second. The adjusted X-ray density for each disk from the first tree was within $\pm$0.01 g/cm^3 of the gravimetric density of all but one disk, which agrees well with the expected error of the densitometer and shows that polychromatic X-ray measurements may be used to estimate the basic density of wood. The adjusted X-ray densities for each disk from the second tree varied considerably more, $\pm$0.05 of the gravimetric density. Greater variability was judged to be associated with more knotting in the second tree.

The effect of moisture content on the linear attenuation coefficient, and therefore on density measurements, is shown in Fig. 3. As moisture content increased, the

attenuation coefficient of Douglas-fir ($\mu_l = -\ln(I/I_0)/t$) increased, resulting in a high positive correlation ($R^2 = 0.99$, 22 df). These results indicate an error in density of 0.006 g/cm^3 if the moisture content of the X-ray samples was 1% different from the moisture content at which the attenuation coefficient was determined. Given the ± 0.002 g/cm^3 standard error of X-ray density predictions from the densitometer, sample moisture content should be maintained within $\pm 2\%$ of the average EMC to ensure wood density measurements within ± 0.02 g/cm^3. Variations outside this range would require separate calibration at the new moisture content for accurate results.

SUMMARY

Attenuation of polychromatic X-ray energy in the range of 20 to 30 keV was accurately modeled by Eq. (1) as an exponential decay relationship. Although polychromatic X-ray attenuation is known to be dependent on thickness of the attenuating material, in this study, sample thickness did not affect the attenuation relationship. Application with 30 keV X-ray energy yielded an attenuation coefficient of 0.638 cm^2/g for Douglas-fir 2.5 mm thick at 9% EMC. Use of the coefficient for estimating basic densities of disks from matched X-ray samples produced reliable results. X-ray energy was sensitive to variations in wood moisture content; therefore the EMC of wood samples for X-ray scanning should be maintained within a 2% range.

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