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Modeling Relaxation Length and Half-Thickness of Wood by Method of Gamma Radiation

Louis E. AKPABIO[*], **Sunday E. ETUK**, **Samuel D. EKPE**
Department of Physics, University of Uyo, P.M.B 1017, Uyo, Akwa Ibom State-NIGERIA
e-mail: leabio2002@yahoo.com

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Abstract

Relaxation lengths and half-thickness values of different types of wood were determined using gamma radiation from ^{60}C0 source. Results show that oxystigma (*Oxystima spp*) has the highest relaxation length of 23.810cm, while mangrove (*Rhizoohora spp*) has the least relaxation length of 1.247 cm. Results also show that Oxystima (*Oxystima spp*) has the highest half thickness value of 16.500 cm and Mangrove (*Rhizophora spp*) has the least half-thickness value of 0.864 cm. Two mathematical models have been developed for the prediction or determination of density ρ, variation with relaxation length and half thickness value of wood. A good agreement (greater than 80% in most cases) was observed between the measured values and the predicted ones (models 1 and 2).

Key Words: Relaxation Length, Half-Thickness Value, Gamma Radiation.

1. Introduction

Wood from all conifers is classified as soft wood, while the wood from all other trees which have broad leaves is termed hard wood. Woods have a variety of uses: they can be used as packaging materials and as an efficient heat insulator in various interior spaces and furniture works. They can also be used to shield radiation from nuclear sources.

In its many applications, wood maybe used as it is or after suitable chemical modification intended to tailor the material properties to those desired in the end-product. Besides the use of wood and new wood composite materials in building and furniture, wood is also extensively used as a source of fiber for pulp and paper and as a source of chemicals for new materials and applications [1]. In order to fully understand wood properties and its behavior when subjected to physical, chemical or biological processes, there is need for further research on wood. This information is very important for the development of new applications of wood and wood derived materials. Gamma radiation technique has proved to be a useful method for achieving this [2].

All around us there are many possible mechanisms for one to be exposed to radioactive effects, one classical example being the effects resulting from volcanic eruptions, often causing worldwide radionuclides fallout [3–8]. As a result of such releases to the environment, there may be greater risk of one coming into contact with ionizing radiation. Such ionizing radiation, combined with the industrial use of gamma

[*]Corresponding author

irradiation (such as food preservation, sterilization of medical devices, etc.), could increase the sources and frequency of exposure to gamma irradiation in our environment [8, 9].

For this investigation, gamma radiation from cobalt 60 [11, 12] was used to determine the relaxation length and half-thickness values of different types of wood.

2. Theory

The attenuation of gamma radiation is due to the effect of all the energy exchange mechanisms (Photoelectric attenuation, pair production and Compton effect) as it interacts with the atoms contained in a material, thus reducing the transmitted intensity. The transmitted intensity depends on the density, thickness of the absorbing layer and the cross-sectional properties of the material [13, 14]. When gamma radiation of intensity $I_\circ$ is incident on a material of thickness x, the attenuation of the gamma radiation by the material is given by the relationship [15, 16]

$$I = I_\circ e^{-x/L}, \tag{1}$$

where $I_\circ$ is the intensity of the incident radiation, x is the thickness of the material, I is the intensity after passage and L is the relaxation length.

The attenuation of gamma radiation may also be expressed in terms of a quantity called the half-thickness length $x_{1/2}$, defined such that $I(x_{1/2}) = 1/2I_\circ$. Equation (1) may also be written as

$$ln\,(I_\circ/I_\circ) = \alpha x, \tag{2}$$

where α is the attenuation coefficient. Thus from Equation (2), we have it that

$$x_{1/2} = \frac{0.693}{\alpha}. \tag{3}$$

The attenuation coefficient α and the relaxation length L are determined by plotting $ln\,(I_\circ/I)$ against x for each wood sample.

2.1. Materials and Experimental Method

In this investigation, twelve different wood samples were used. Eleven of the wood samples were: camwood (*Pterocarous spp.),* Black afara (*Terminalia ivorensis)*, Owen (*Mitragyna ciliate)*, achi (*Brachystegia eurycoma)*, White afara (Terminalia ivorensis), Mahogany (*Khaya* spp.), Iroko (*Milicia excelsa)*, African walnut (*Lovoa trichilicides)*, Obeche (*Triplochiton scleroxylon)*, oxystigma (*Oxystigma spp.*) and Mammea (*Mammea africana*) were collected from the timber market in Uyo. Mangrove (*Rhizophora spp.*) was obtained from a riverine area in Akwa Ibom State. Each wood sample was carefully cut into seven rectangular blocks with thickness varying between 1.0 cm and 16.0 cm.

The experimental procedure is the same as described in previous studies [2, 17–19]. It comprised a GM tube and a scalar/timer. Two steel collimators of equal diameters and thickness arranged axially between the source and sample and between sample and detector reduced the primary and secondary gamma rays to narrow beams.

3. Results and Discussion

The relaxation length L, density ρ, half-thickness value $x_{1/2}$ and mass attenuation coefficient for the respective wood samples under study are presented in Table 1.

Table 1. Experimental results for the Relaxation length, half-thickness, density and mass attenuation coefficient of the wood samples.

Common Name	Botanical Name	Density ρ (gcm^{-3})	Relaxation Length L (cm)	Ln L	Half-Thickness $x_{1/2}$ (cm)	ln $x_{1/2}$	Mass Attenuation Coefficient μ (cm^2g^{-1})
Mangrove	Rhizophora soo	1.205	1.247	0.221	0.864	-0.146	0.143
Mammea	*Mammea africana*	0.853	8.202	2.104	5.680	1.737	0.124
Camwood	*Pterocarpus spp*	0.694	11.628	2.453	8.058	2.087	0.124
Black afara	*Terminalia ivorensis*	0.674	12.048	2.489	8.349	2.122	0.123
Owen	*Mitragyna ciliata*	0.595	13.699	2.617	9.493	2.250	0.123
Achi	*Brachystegia eurycomas*	0.556	14.706	2.688	10.191	2.322	0.122
White afara	*Terminalia superba*	0.541	15.152	2.718	10.500	2.351	0.122
Mahogany	*Khaya spp*	0.535	15.625	2.749	10.828	2.382	0.120
Iroko	*Milicia excelsa*	0.520	16.394	2.797	11.361	2.430	0.117
African Wallnut	*Lovea trichilioides*	0.500	17.241	2.847	11.948	2.481	0.116
Obechi	*Tripolochiton scleroxyton*	0.416	20.833	3.037	14.438	2.670	0.116
Oxystigma	*Oxystigma spp*	0.370	23.810	3.170	16.500	2.803	0.114

Figure 1 shows the plot of $ln\, I_\circ/I$ against thickness x for the various wood samples from which their respective relaxation lengths L were determined. The lines were approximated by using the least squares method. The mass attenuation coefficients were calculated by dividing the attenuation coefficient by the density of the wood samples, while the half-thickness was obtained from Equation 3.

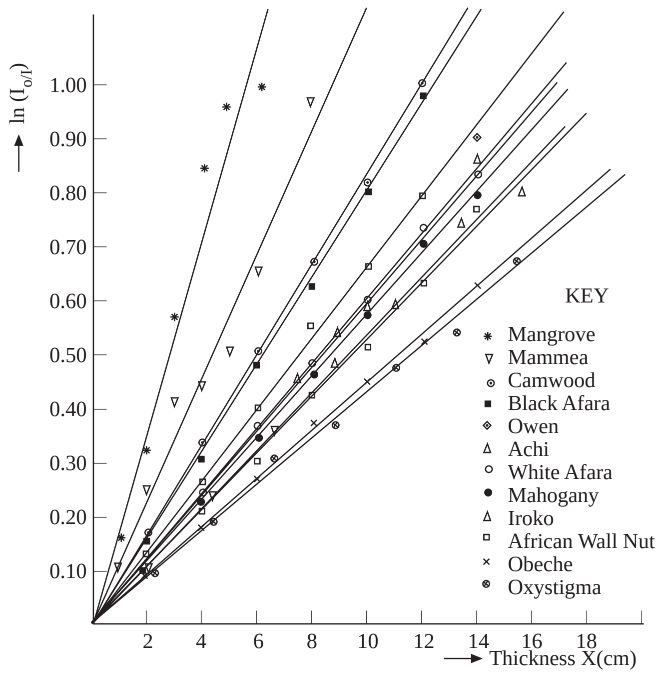

Figure 1. A plot of $ln\, I_\circ/I$ against thickness.

The experimental result showing the relationship between relaxation length L and density ρ is plotted in Figure 2, showing an exponential relationship between the variables. Figure 3 is a plot of the density against the natural logarithm of the relaxation length (ln L), resulting in a straight-line graph passing through the density axis with an intercept value of 1.520. The variations between Figures 2 and 3 could be expressed (respectively) as:

$$L = L_\circ e^{-A\rho}, \tag{4}$$

$$\rho = \frac{\ln L_\circ}{A} - \frac{\ln L}{A}. \tag{5}$$

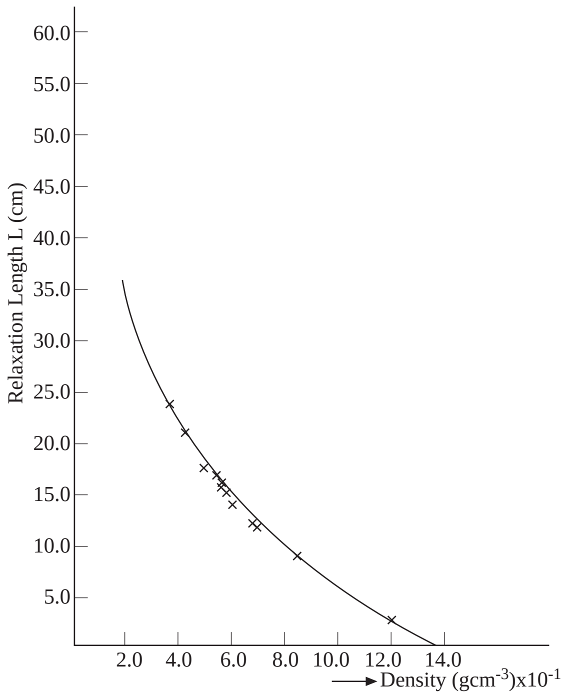

Figure 2. Variation of relaxation length with density.

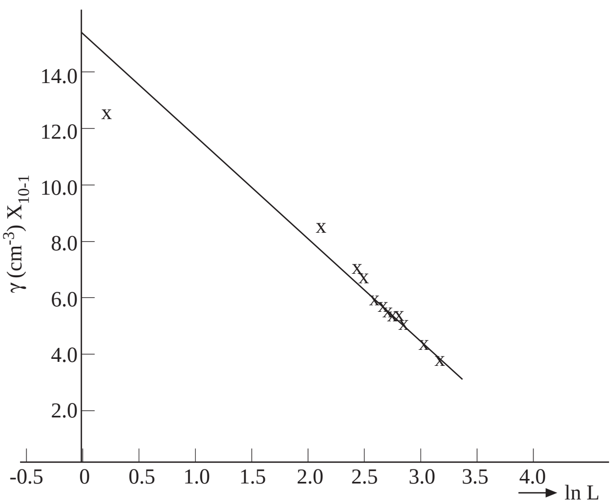

Figure 3. Variation of density ρ with $\ln L$.

Applying the above numerical value, Equation (5) becomes

$$\rho = -0.368 \ \ln L + 1.520, \tag{6}$$

which we will denote as Model 1. Considering Equation (5), illustrated by the straight line graph in Figure 3, the slope of the graph gives the value of 1/A, while the reciprocal of the slope gives the numerical value of A as 2.717, which we regard as the coefficient of relaxation for the material. The value of $\ln L_\circ/A$ is indicated by the intercept. The quotient of the intercept and slope gives $\ln L_\circ$, from where the value of $L_\circ$ could be derived. $L_\circ$, which is approximately 62.178 cm, is assumed to be the relaxation length of an arbitrary wood sample of negligible density.

Equation (6) (Model 1) gives the required model for predicting the density of any wood specimen. It is observed from Figure 2 that, for low density values of the wood samples investigated, the relaxation length of the attenuated gamma radiation increases, while the relaxation length decreases for higher values of wood sample density. Mangrove had the least relaxation length of 1.247 cm and half-thickness value of 0.864 cm; while oxystigma (*oxystigma* spp.) had the highest relaxation length and half thickness value of 23.810 cm and 16.500 cm, respectively (see Table 1). Since attenuation depends on several factors, some of which include density and atomic cross-section, denser materials attenuate radiation more than less dense materials [13, 14, 20]. Materials with larger particles size have greater pore spaces than the small particle size material [21] and therefore attenuate or scatter less radiation than the small size particle materials, for radiation passing through the pore spaces encounter little resistance. This implies that hard woods (e.g., Mangrove) offer greater attenuation of radiation than soft woods (e.g., oxystigma). This may be attributed to the fact that, in hard woods, component material is more closely packed (denser) than in soft woods. Soft woods are characterized by long fibers [22], implying large particle sizes and pore spaces.

It is obvious from Table I and Figure 4, which shows the variation of half-thickness value $x_{1/2}$with density ρ, that as the density of the wood sample increases, the half-thickness value decreases. This means that half-thickness value has an exponential relationship with density. It is observed that the mass attenuation coefficient is nearly constant (Table 1) for the investigated wood samples. The result agrees with experimental observations [16].

Figure 4 gives an exponential relationship between the variables. While Figure 5 a plot of density against the natural logarithm of half-thickness value ($\ln x_{1/2}$), a straight-line graph passing through ρ-axis with the intercept value 1.198. In terms of the half- thickness value of Figures 4 and 5, respectively, one has:

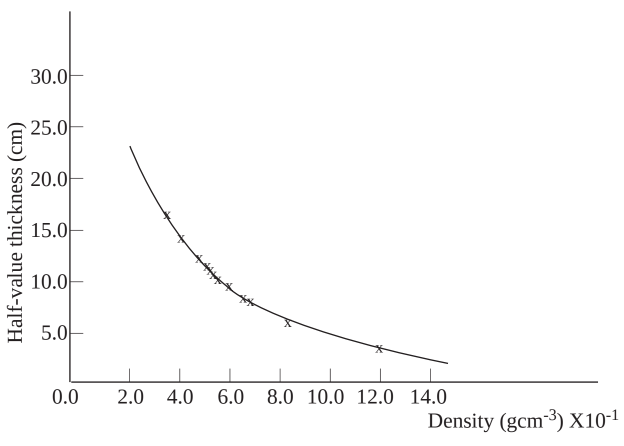

Figure 4. Variation of half-thickness with density.

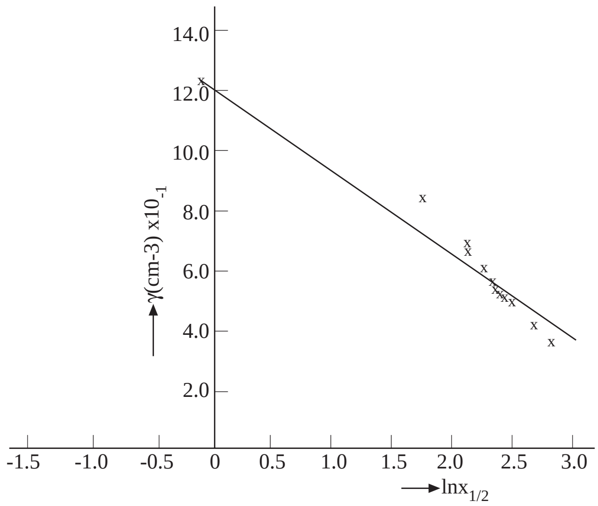

Figure 5. Variation of density ρ as function of $\ln x_{1/2}$.

$$x_{1/2} = x^{\circ}_{1/2} e^{-B\rho} \tag{7}$$

$$\rho = \frac{\ln x^{\circ}_{1/2}}{B} - \frac{\ln x_{1/2}}{B} \tag{8}$$

Equation (8) yields Model 2 as:

$$\rho = -0.275 \, \ln x_{1/2} + 1.198 \tag{9}$$

Figure 5 shows the straight line graph of Equation (8); the reciprocal of the slope of the graph gives the numerical value of B as 3.636, which could be regarded as the coefficient of half-thickness value for the material. The intercept of the graph gives the value of $\ln x^{\circ}_{1/2}/B$. The quotient of the intercept and slope gives $\ln x^{\circ}_{1/2}$, and thus $x^{\circ}_{1/2}$, which we calculate as 77.95 cm. $x^{\circ}_{1/2}$is assumed to be the half-value thickness for an arbitrary wood that has negligible density.

Table 2. Comparison of experimental results and the estimated values of density from our models.

Wood sample	MODEL 1 ρ (g cm^{-3})			MODEL 2 ρ (g cm^{-3})		
	Measured	Estimated	Percentage error (%)	Measured	Estimated	Percentage error (%)
Mangrove	1.205	1.439	19.42	1.205	1.238	2.74
Mammea	0.853	0.746	12.54	0.853	0.720	15.60
Camwood	0.694	0.617	10.10	0.694	0.624	10.09
Black afara	0.674	0.604	10.39	0.674	0.615	8.75
Owen	0.595	0.557	6.39	0.595	0.579	2.69
Achi	0.556	0.531	4.50	0.556	0.560	-0.72
White afara	0.541	0.520	3.88	0.541	0.552	2.03
Mahogany	0.535	0.508	5.05	0.535	0.543	1.50
Iroko	0.520	0.491	5.58	0.520	0.530	1.92
African Wallunt	0.500	0.472	5.60	0.500	0.516	-3.20
Obechi	0.416	0.402	3.37	0.416	0.464	11.54
Oxystigma	0.370	0.353	4.60	0.370	0.427	15.41

As a test of our models, we present in Table 2 a comparison between the experimental results and the estimated values of density from Models 1 and 2. The percentage error of less than 19.50% was obtained between the measured values and values estimated from Model 1. This means the density of wood ρ can be estimated with 80.5% accuracy using Model 1; and that Model 2 offers less than 16% error. This implies that about 84% accuracy of the value of density ρ for the wood samples could be estimated from model 2. The percentage error discussed above implies that model 2 should be used for estimating the density of wood samples.

4. Conclusion

From our experimental results, we conclude that Oxystigma (softwood) has the highest relaxation length (23.810 cm) and half-thickness value (16.500 cm). Mangrove, a hardwood, has the least relaxation length and half thickness of 1.247 cm and 0.864 cm, respectively. This suggests that hardwoods can also be used with other best known radiation protective shield that reduces to a safe level the accessible radiation from any radioactive source. For wood, the attenuation increases linearly with density.

The result of the experiment has shown that relaxation length and half thickness values of woods depend on density. Ekpe et al [2] show that density value of completely dry wood sample can be use for classification of wood into soft and hard wood. It implies that relaxation length as well as half thickness values can be used for such classifications since density is a function of half thickness value and relaxation length of a material.

We also conclude that, from the two models developed for the prediction of density of wood samples, Model 2 can effectively be employed in estimating the density of wood samples.

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