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DETERMINATION OF MOISTURE CONTENT AND DENSITY OF SELECTED WOOD SAMPLES USING GAMMA RAYS

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ABSTRACT

Wood is hygroscopic in nature which means it naturally absorbs or releases water to balance its internal moisture content with surrounding environment. The present study reports the determination of mass attenuation coefficients of *Dek* and *Poplar* wood samples at varying moisture levels using gamma ray transmission method. Measurements were performed using NaI (Tl) scintillation detector and a radioactive source ^{137}Cs having energy 0.662 MeV and strength of 1.0 micro-Curie. The moisture content of wood samples was varied by placing them in an oven for fixed duration of time. A graph was plotted between the measured relative transmitted intensities versus the thickness of wood samples and the mass attenuation coefficient as the slope of the fitted plot was obtained. These mass attenuation coefficients when plotted against the relative moisture content of wood samples showed that attenuation coefficient increased with decreasing moisture content, i.e. mass attenuation coefficient was the lowest for completely wet samples and the highest for the oven dried samples.

Key words: Mass attenuation coefficient, Moisture content, Relative transmission intensity, Radioactive source, Scintillation detector

The moisture in wood and wood composites plays an important role in determining both physical stability and mechanical performance. The moisture content is usually 30-60% in woody parts of plants. The water content of wood depends on the relative humidity and temperature of the surrounding air. If wood remains long enough in air where the relative humidity and temperature remain constant, the water content will also become constant at a value known as the equilibrium moisture content (EMC).

Wood consists of a large number of small cells, which are generally tubular in shape. The cells in a living tree always contain water. It is in the form of 'free' water in the cell cavities, and 'bound' water in the cell walls, which are fully saturated. The amount of free or bound water contained in any wood sample can be expressed as its moisture content and content varies from one wood type to another. Wood used indoors will eventually stabilize at 8-14% moisture content; outdoors at 12-18%. Hygroscopicity is the property which allows wood to absorb the moisture itself from the surroundings and this property of wood helps to control the natural humidity in our houses.

The moisture content of many wood samples has been estimated by various people using either of the following methods: oven drying method including microwave oven drying, electrical resistance method, dielectric method, by using a neutron moisture gauge by nuclear magnetic resonance (NMR) and by the measurement of electromotive force (emf) developed in between rotating discs (Negi, 1997). Most of the time it is measured by the weight of water as a percentage of the oven dry weight of the wood fiber. The decay of wood can be controlled by controlling the water content in it. Water by itself does not harm the wood, but rather, wood with consistently high water content enables fungal organisms to grow. Wood destroying fungus causes more damage to the structures than all the fires, floods, and termites combined. Fungus occurs generally when the moisture content of wood exceeds 20 to 30 percent, coupled with the optimal temperatures (32^o - 90^o F), an adequate supply of oxygen and a suitable source of energy and nutrients. This fungus secretes enzymes that break down the wood into usable food for it thereby reducing the strength of wood if this condition continues over a large period of time.

Many researchers started searching non-destructive methods for measuring moisture in wood since early 1900 and it was first thought to be determined from the electrical resistance method. Instead of using single parameter i.e. electrical resistance, researchers employed many devices to study radio frequency signals to determine water content in wood (Steele and Cooper, 2006). All these methods which were based on the principle of electrical resistance, capacitance and phase had their own limitations so relationship between water content in wood and its electrical properties was not fully understood.

Radiation techniques can also be used to determine water content and density of wood and other materials. The principle of these radiation techniques is that penetration of the radiation (X-ray, beta ray or gamma ray) into materials is dependent on gross density of the material and how deep radiation got penetrated into the material. Studies of attenuation of gamma radiation are of great interest since several decades. A proper knowledge of various properties of

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penetration and diffusion of gamma rays in exterior medium is of great use for a detailed scientific study of interaction of radiation with matter. The mass attenuation coefficient (usually depends upon the energy of incident radiations and nature of the absorbing material) plays very important role for characterization and penetration of gamma radiation in any medium. In the present work, the mass attenuation coefficient was obtained for selected wood samples at various moisture levels by plotting relative transmission intensity versus thickness. The obtained mass attenuation coefficients were varied with the measured water content of the wood samples which are *Dek (Melia dubia)* and *Poplar (Populus)* and are selected from the local region.

MATERIALS AND METHODS

To measure density, Beer-Lambert Law, expressed in terms of density (ρ) of the material absorbers (composite materials like wood), given below was used.

$$I = I_o e^{-\mu\rho t} \quad (1)$$

where I_o is the radiation counts during a certain time duration without any absorber, I is the photon counts during the same time with a thickness t of absorber between the source of radiation and the detector, and μ is the attenuation coefficient. The mathematical rearrangement of equation (1) yields density as:

$$\rho = \frac{1}{\mu t}\ln\left(\frac{I}{I_0}\right) \quad (2)$$

The densities of two wood samples namely *Dek* and *Poplar* were also obtained using the conventional method given as follow:

$$\rho = m/V \quad (3)$$

where, ρ is density (g/cm^3); *m* is mass (g); V is volume (cm^3). To obtain the density at 6 % moisture, the following equation was used:

$$\rho = \rho_{m\%}\frac{(1+6/100)}{(1+m/100)} \quad (4)$$

where, ρ_6 is the density in g/cm^3 at $\rho_{m\%}$ moisture content; $\rho_{m\%}$ is the density in g/cm^3 at m% moisture content; m is obtained in the oven tests. The water content of the sample, after determining its density for state having moisture content m and for oven dry state, can be calculated from the following equation:

$$\text{Water content} = \frac{\rho_m - \rho_O}{\rho_O} \times 100 \quad (5)$$

where, ρ_m is the density of the sample with the moisture content (m), ρ_O is the density of oven dry state (where density of the sample becomes constant).

For measuring the mass attenuation coefficients of the selected wood samples, narrow beam transmission geometry was used as shown in Fig. 1. Photon beam of 662 keV from radioactive isotope ^{137}Cs having strength of 1.0 micro-curie, procured from BARC India was used in the present investigation. Transmitted pulse height spectra was recorded using compact sodium iodide (thallium activated) scintillation detector (1” ×1”) procured from Nuclenoix India; having resolution of 7.5 % at 662 keV coupled with single channel analyser.

The detector and source were kept at the distance of 22 cm. To minimize the exposure of gamma rays to the radiation workers, the lead housing with sufficient thickness was used to keep the gamma ray source. The whole experimental setup was placed in the centre of the room at the height of 50 cm from the floor so as to minimize the contribution of scattered photons from the walls and floor. The calibration of experimental set up was done by passing 662 keV gamma rays through aluminum plates of varying thickness. Figure 2 shows the fitted plot of relative transmitted intensity versus thickness of aluminum plates. The obtained mass attenuation coefficient of aluminum using 662 keV gamma radiations was 64.74±5.3 cm^2/kg which is in good agreement with Hubbell and Seltzer (1995) values. The above procedure and results confirmed the validity of experimental setup and method adopted to obtain the mass attenuation coefficient of the selected wood samples.

Wood samples of *Dek (Malia dubia)* and *Poplar (Populus deltoides)* were taken from fields of Punjab Agricultural University, Ludhiana. Fresh wood samples were collected from tree and immediately taken to the laboratory and kept at room temperature of 30°C. The other information about the wood samples is listed in Table 1. The freshly procured wood samples were sliced into the radial direction having dimensions of (8 x 8 x 1) cm with the help of microtome knife. The thickness and weight measurement of these slices

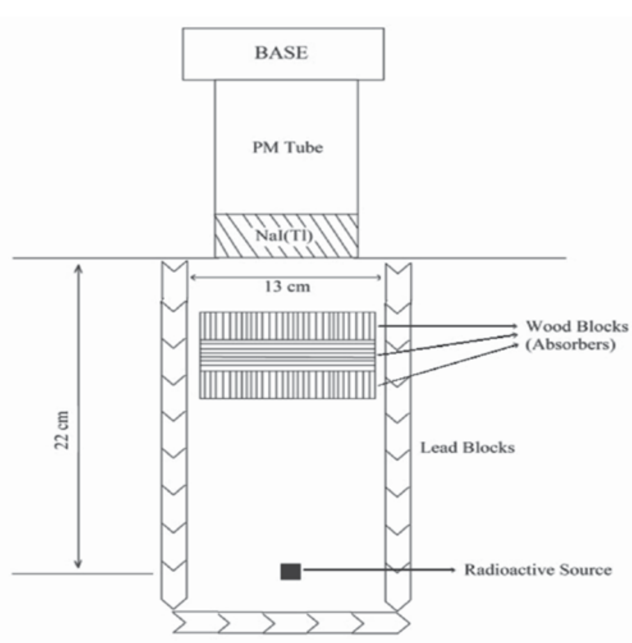

Fig. 1. Schematic diagram of the experimental setup

Table 1. List of wood materials used in present study

Wood type	Scientific Name	Family	Density (gm/cm^3)
Dek	*Melia dubia*	Meliaceae	0.54
Poplar	*Populus deltoides*	Salicaceae	0.44

were done by using Vernier calliper having accuracy of 0.1 mm and weighing them on Shimazu digital balance having an accuracy of 0.1 mg, respectively.

These wooden slices were dipped in water for period of 6-7 days so as to maximize their weight and water content. The air between the source and detector shows the zero absorber value. Fifteen absorbers of thickness around 1.0 cm each were placed close to detector one by one. Counts were recorded for 50 seconds for both *Dek* and *Poplar* samples at each absorber thickness and sufficient number of sets were taken so as to make the statistical error below 1%. The complete experiment was repeated 3-4 times for reproducibility of results for oven dry state and completely wet state of the samples.

The samples were heated in an electric oven at (100-105°C) for about 3 hours. The intensity measurements were again recorded to calculate moisture content and mass attenuation coefficient of the wood samples at a given moisture level. The above procedure was repeated for same durations till the wood samples became completely dried.

RESULTS AND DISCUSSION

A fitted semi-logarithmic plot of relative intensity as a function of *Dek* wood absorber thickness (gm/cm^2) for oven dry and completely wet samples is shown in Fig. 3. A polynomial of order one was used to fit the obtained data for completely wet and dry samples of *Dek*. Similar fit was applied for the samples (both wet and dry) of *Poplar* as shown in Fig. 4. Data of relative transmission versus thickness of wood absorbers were analyzed by fitting the data corresponding to linear portion of experimental transmission curve using the equation:

$$I = I_0 a^x \qquad (6)$$

where x is the absorber thickness (gm/cm^2), and I_0 and ‘a’ are the fitting constants. Using logarithmic, the above equation can be written as:

$$\ln I = \ln I_0 + x \ln a \qquad (7)$$

Hence, the mass attenuation coefficient corresponds to the negative of slope of equation (7):

$$\mu\ (cm^2/kg) = -1000 \ln a \qquad (8)$$

where factor 1000 appears as μ and has been expressed as (cm^2/kg).The estimated values of mass attenuation coefficients (cm^2/kg), moisture content (%) and coefficient of determination (R^2) for the absorbers of *Dek* and *Poplar* at different moisture levels using 662 keV gamma ray photons from ^{137}Cs are listed in Table 2. The variation of mass attenuation coefficient at different moisture levels for *Dek* (*Poplar*) has been shown in Fig. 5. Solid line represents the least square fit to estimated values of mass attenuation coefficients at different moisture levels.

The negative slope from the Fig. 5 and Fig. 6 depicts that the attenuation coefficient increased with the decreasing moisture content of wood samples. As evidenced by Table 2, mass attenuation coefficients for oven dry samples were higher than that for wet wood samples. It can be explained on the basis of effective atomic number. The effective atomic number of water is 3.33 (according to weighted fraction method) and composition of wood is complex (Bradley *et al.,* 1991), the estimated effective atomic number of wood is between 4 to 5. With the increase in the moisture level in wood, its effective atomic number as compared to dry wood

Table 2. Mass attenuation coefficients (cm^2/kg) using absorbers of *Dek* and *Poplar* wood at different moisture levels and 0.662 MeV gamma ray photons from ^{137}Cs source

Samples	State	[μ (cm^2/kg)±SE]	Coff. of multiple determination (R^2)
Dek	85.6% Completely Wet	58 ± 0.70	0.99*
	57.7% moisture level	62 ± 0.98	0.99*
	28.7% moisture level	64 ± 0.77	0.99*
	16.7% moisture level	67 ± 0.75	0.99*
	7.51% moisture level	68 ± 0.74	0.99*
	Oven Dry	69 ± 1.05	0.99*
Poplar	98.7% Completely Wet	52 ± 0.67	0.99*
	61.7% moisture level	55 ± 0.87	0.99*
	35.5% moisture level	59 ± 0.48	0.99*
	18.6% moisture level	60 ± 1.13	0.99*
	4.70% moisture level	62 ± 0.97	0.99*
	Oven Dry	64 ± 1.19	0.99*

(*) Regression is significant at level of significance $p < 0.0001$ where SE is the standard error in μ.

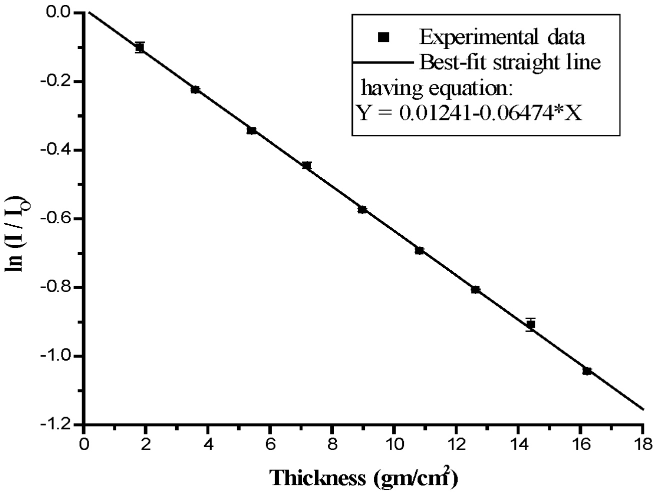

Fig. 2. The fitted curve of measured logarithmic relative transmission of 662 keV gamma photons versus aluminum plate absorber thickness (gm/cm²)

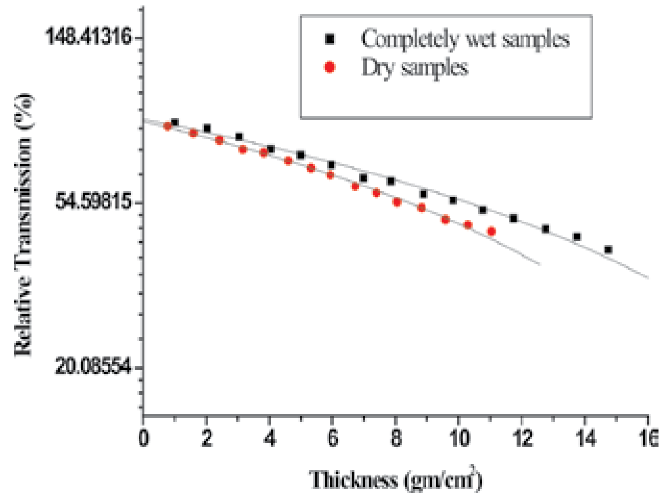

Fig. 3. Relative transmission of gamma rays vs thickness for completely wet and dry samples of *Dek* wood samples

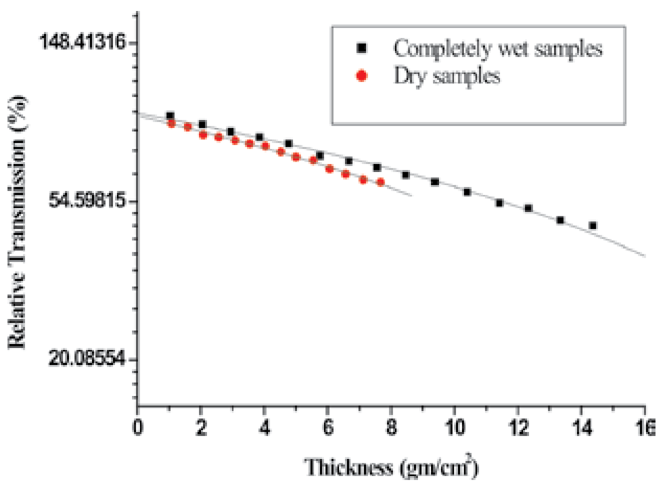

Fig. 4. Relative transmission of gamma rays vs thickness for completely wet and dry samples of *Poplar* wood samples

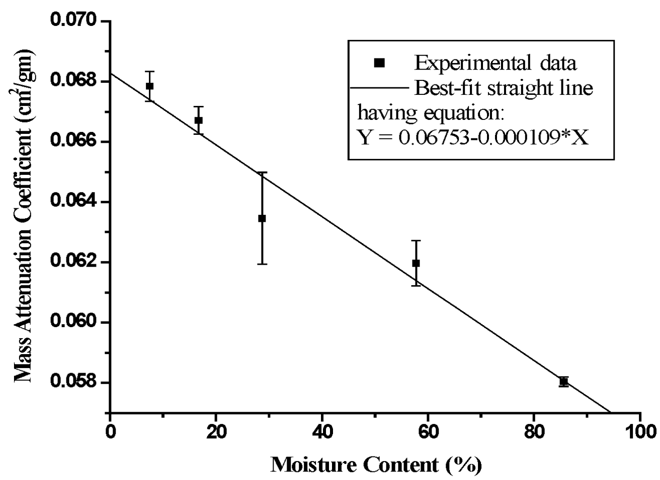

Fig. 5. Plot of relative moisture content (%) versus mass attenuation coefficient (cm²/gm) for wood samples of *Dek*

goes down. The photon attenuation is directly proportional to the effective atomic number, hence with decreased effective atomic number the photon attenuation will decrease and consequently mass attenuation coefficient will decrease in moist wood. The same behavior has been verified for *Dek* and *Poplar* samples in the present study. Further, the regression analysis proved that the attenuation is solely dependent on the thickness of wood sample at 1% level of significance.

Wood density, which is related to the amount of mass contained in the unit volume is another vital parameter to have knowledge about anatomical and physical properties of wood and thus it can be a useful parameter for determination of quality of wood. There are many methods and instruments to determine the wood density in both the laboratory and field. The conventional methods are based upon the determination of core sample mass and volume (gravimetric methods). The gamma ray attenuation measurements have also been used extensively to determine the wood density (Gilberto and Leonardo, 2014).

Table 3. The densities (g/cm³) of *Dek* and *Poplar* calculated using conventional method, at 6% moisture level and nuclear method

Type of wood	Density (g/cm³)			Standard Deviation
	$\rho_{m/V}$	ρ_6		
Dek	0.54	0.53	0.51	0.01
Poplar	0.44	0.43	0.44	0.01

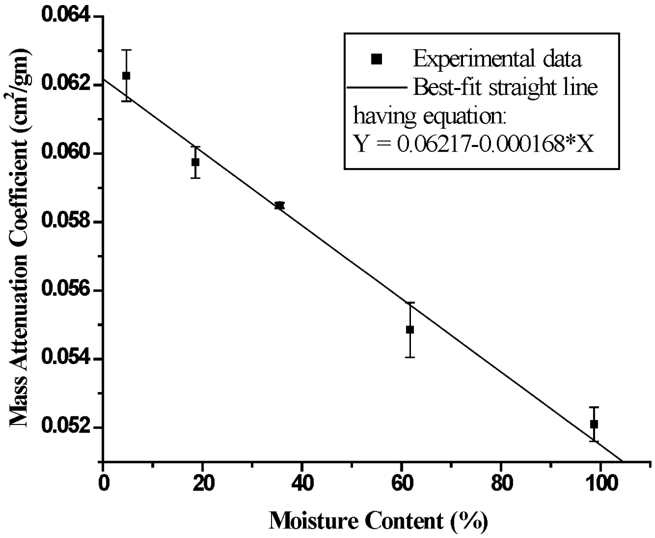

Fig. 6. Plot of relative moisture content (%) versus mass attenuation coefficient (cm^2/gm) for wood samples of *Poplar*

The density of the selected wood samples was measured using three different methods which are conventional method, at 6% moisture content and radiation method with ^{137}Cs gamma source. The density obtained using conventional method for *Dek* at 7.50% moisture level was 0.539 (gm/cm^3) and for *Poplar* at 4.70% moisture level was 0.438 (gm/cm^3). These density values obtained using conventional method were compared with density obtained at 6% moisture level. The density obtained at 6% moisture level for *Dek* was 0.532 (gm/cm^3) and for *Poplar* it was 0.431 (gm/cm^3). The percentage difference between the densities of two wood samples obtained at m% (oven test) and at 6% moisture level was1.3% for *Dek* and 1.6% for *Poplar*. The density value obtained using radiation method for *Dek* was 0.512 (gm/cm^3) and for *Poplar* 0.441 (gm/cm^3). The percentage difference for the values obtained from both the methods, conventional (oven test at m %) and nuclear is 5.27% for *Dek and* 0.68% for *Poplar*. The obtained values of density of wood samples under study are summarized in Table 3.

The water content and mass attenuation coefficient of wet and dry samples of *Dek* and *Poplar* samples using ^{137}Cs were studied. The results depicted that with the decrease of moisture content the attenuation increases i.e. mass attenuation coefficient goes on increasing with the decrease of moisture content in the wood samples. It is concluded from these measurements that this technique of determining the water content of wood sample can be highly beneficial, being rapid and non-destructive.

Authors' contribution

Conceptualization of research work and designing of experiments (RK); Execution of field/lab experiments and data collection (HK, RK); Analysis of data and interpretation (HK, RK); Preparation of manuscript (HK, RK)

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