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Fabrication and characterisation of phantom material made of Tannin-added *Rhizophora spp*. particleboards for photon and electron beams

M F Mohd Yusof[1,3], P N K Abd Hamid[1], A A Tajuddin[1], R Hashim[2], S Bauk[1], N Mohd Isa[4] and M J Md Isa[4]

[1] School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia
[2] School of Industrial Technology, Universiti Sains Malaysia, 11800 Penang, Malaysia
[3] School of Health Sciences, Universiti Sains Malaysia, 16150 Kelantan, Malaysia
[4] Health Physics Group, Malaysian Nuclear Agency, 43000 Selangor, Malaysia

E-mail: mfahmi@usm.my

Abstract. Particleboards made of *Rhizophora spp*. with addition of tannin adhesive were fabricated at target density of 1.0 g/cm^3. The physical and mechanical properties of the particleboards including internal bond strength (IB) and modulus of rupture (MOR) were measured based on Japanese Industrial Standards (JIS A-5908). The characterisation of the particleboards including the effective atomic number, CT number and relative electron density were determined and compared to water. The mass attenuation coefficient of the particleboards were measured and compared to the calculated value of water using photon cross-section database (XCOM). The results showed that the physical and mechanical properties of the particleboards complied with Type 13 and 18 of JIS A-5908. The values of effective atomic number, CT number and relative electron density were also close to the value of water. The value of mass attenuation coefficients of the particleboards showed good agreement with water (XCOM) at low and high energy photon indicated by the χ^2 values.

1. Introduction

Phantom material is defined as materials that simulated the absorption and scattering properties of human tissues towards ionising radiation (Khan, 2010). Phantom materials are used mainly in quality assurance and dosimetry works involving ionising radiation. Water is commonly used as phantom materials it has mas density near to human soft tissues at 1.0 g/cm^3. The use of water however is not always convenience due to its liquidity. Several solid-state phantom materials are introduced and made water-equivalent to replace water such as acrylic and perspex. These water equivalent materials however do not always give attenuation properties similar to water as they still differs to water in term of effective atomic number and electron density. These phantom materials also may develop electron contaminations that could alter the dose measurement.

Earlier studies have suggested that *Rhizophora spp*. as potential phantom material as it has mass density and attenuation coefficient close to water (Bradley at al., 1991; Tajuddin et al., 1996). However the use of *Rhizophora spp*. solid woods as phantom materials has several limitations including tendency to crack over period of times. The size of *Rhizophora spp*. trunk is also limited to construct a full size phantom besides its density inhomogeneity across the trunk. The binderless particleboards made of *Rhizophora spp*. was introduced with advantages includes better density uniformity and able to be fabricated at various size and shapes without compromising its attenuation properties (Marashdeh et al., 2011). However, the strength of the binderless particleboards made of *Rhizophora spp*. becoming a concern due to rigidity and heavy workload as phantom materials. To date, studies had been carried out to improve the strength of the particleboards made of *Rhizophora spp*. Addition of adhesives or binder becoming major option to increase the strength of the particleboards with at the same time retaining its water-equivalent properties.

The synthetic-based adhesives such as urea-formaldehyde (UF) commonly used in industrial particleboards manufacturing failed to retain the attenuation properties of *Rhizophora spp*. particleboards in comparison to water (Surani, 2008, Ngu et al., 2015). Tannin has been used as alternative binder for particleboards and plywood to replace commonly used formaldehyde-based adhesives (Pizzi and Merlin, (1981); Pizzi and Scharfetter, (1989); Oo, et al, (2008). Tannin is a biological-based adhesive that can be extracted mainly from barks including *Rhizophora spp*. (Mohd Yusoff et al., 1988). Previous study had suggested the suitability of tannin adhesive for *Rhizophora spp*. particleboards as phantom at low energy photons (Safian, 2012). However, the tannin-based particleboards with low treatment level of tannin (5%) still failed to satisfy the industrial standards for physical and mechanical properties. Previous studies had suggested that the suitable percentage of biological-based adhesives for *Rhizophora spp*. is within 10% without changing their attenuation properties (Ghasemi, 2012; Tousi et al., 2014; Abu Arra et al., 2014). This study focused on the fabrication and characterisations of *Rhizophora spp* particleboards with 10% percentage of tannin adhesive as phantom materials in application of photon and electron beams.

2. Methodology

2.1. Preparation of Sample

The *Rhizophora spp*. trunk was obtained from a charcoal factory in Kuala Sepetang, Perak, Malaysia. Only trunk from the middle part of the tree was chosen according to the study by Shakhreet et al., (2013). The trunk was cleaned and dried before planed in order to reduce it into smaller wood chips. The wood chips were then ground into smaller wood particle and screened using horizontal screen machine to obtained only wood particle with particle size of 104 μm according to the study by Marashdeh et al., (2011). Particleboards were fabricated using hot press machine with target density of 1.0 g/cm^3. The target density of the particleboards was determined based on the calculation of the mass wood particle required to fabricate the particleboards at density of 1.0 g/cm^3. And amount of 10% tannin is added into the wood particle based on the dried mass of wood particle. The actual density of the fabricated particleboards were measured based on the external dimension and mass of the particleboards given by the equation of

$$\rho = \frac{m}{V} \quad (1)$$

With m is the measured mass of the particleboards and V is the volume of the particleboards measured based on its external dimension given by the equation of

$$V = length \times width \times thickness \quad (2)$$

The particleboards were cut into smaller piece sample with size 5.0 cm x 5.0 cm as shown in Figure 1(a) for mechanical and characterisation tests. A replication of particleboard was sawn circularly as shown in Figure 1(b) to construct density plug phantoms that will be discussed in chapter 2.4. The internal bond (IB) strength of the particleboards were measured based on the Japanese Industrial Standard (JIS A 5908: 2003). The IB strength was calculated using the equation

$$Internal\ Bond = \frac{P_{max}}{2wl} \quad (3)$$

With P_{max} is the maximum load at failure of the particleboards and w and l is the width and length of the particleboard sample respectively.

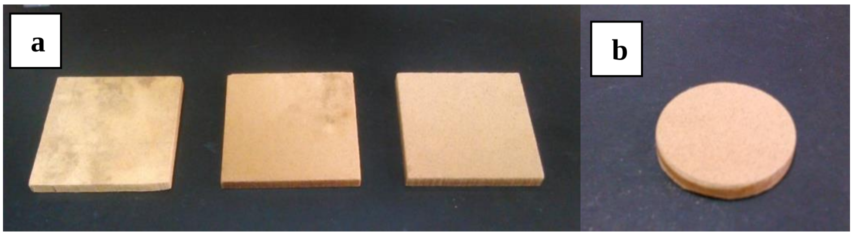

Figure 1. The test piece for mechanical test (a) and circularly sawn

2.2. Elemental Composition and Effective Atomic Number

The percentages of elemental composition of the particleboards were determined using energy dispersive x-ray analysis (EDXA) from the scanning electron microscopy (SEM). The percentages of elemental composition were used to calculate the effective atomic number, Z_{eff} of the particleboards. The attenuation properties of medium are related to the effective atomic number, therefore the effective atomic number value is used to determine the water equivalent and attenuation properties of the particleboard in comparison to water. The effective atomic number is calculated according to the study by Duvauchelle et al., (1999) using the equation

$$Z_{eff} = \left[\sum_{i=1}^{n} (\alpha_i \, z_i^{m})\right]^{\left(\frac{1}{m}\right)} \quad (4)$$

where a_i and z_i are electron fraction and atomic number of i^{th} element in the sample respectively. m is the experimental coefficient for biological materials and water with value of 3.4. The electron fraction of the i^{th} element can be calculated by the equation

$$\alpha_i = \frac{wi\left(\frac{z_i}{A_i}\right)}{\Sigma w_i\left(\frac{z_i}{A_i}\right)} \quad (5)$$

where w_i and A_i are fractional weight and atomic mass of the i^{th} element respectively.

2.3. Measurement of CT Number and Relative Electron Density

A study by Saito, (2012) had suggested that the electron density of a medium is very much related to it CT number. Thus the electron density of a medium can be derived directly from it CT number. A density plug phantom was constructed from the particleboard made compatible with computed tomography (CT) electron density phantom model CIRS 062M. The particleboard was sawn circularly and stacked together using wood adhesive to obtain a cylindrical-shaped phantom with approximate diameter of 3.0 cm. The density plug phantoms were scanned using the CT scanner at 120 kVp CT energy along with the water, liver muscle, and fat equivalent density plug phantoms. The average CT numbers of samples were measured and the relative electron density curves were plotted based on the recommendation by the manufacturer as shown in Figure 2. The relative electron density of tannin-added *Rhizophora spp*. particleboards was determined from the electron density curve.

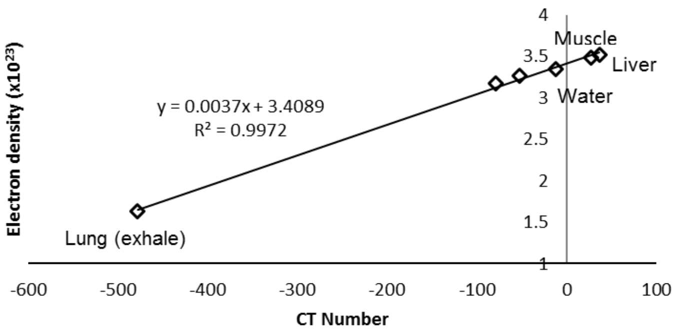

Figure 2. The relative electron density curve of various tissue equivalent density plug phantoms based on CT number at 120 kVp CT X-ray energy.

The relative electron density of tannin-added *Rhizophora spp*. particleboard can be calculated using equation (6)

$$RED = 0.0037x + 3.4089 \quad (6)$$

with x is the Hounsfield unit or the CT number of the sample

2.4. Measurement of Mass Attenuation Coefficient

The mass attenuation coefficients of the particleboards were measured at low and high energy x-ray. The mass attenuation coefficient at low energy photons were carried out according to the study by Maarashdeh et al., (2012) based using the x-ray fluorescent (XRF) set up as shown in Figure 3 (a). A ^{241}Am source were used in conjunction with metal plates of Niobium, Palladium, Molybdenum and silver were used to obtain $K_{\alpha 1}$ x-ray between 16.59 and 25.26 keV. The mass attenuation coefficient at high energy photon were measured using Ladlum set up in as shown in Figure 3 (b). The Ladlum set up was used conjunction with ^{137}Cs and ^{60}Co gamma sources that provided the gamma energy of 0.662 and 1.2 MeV respectively.

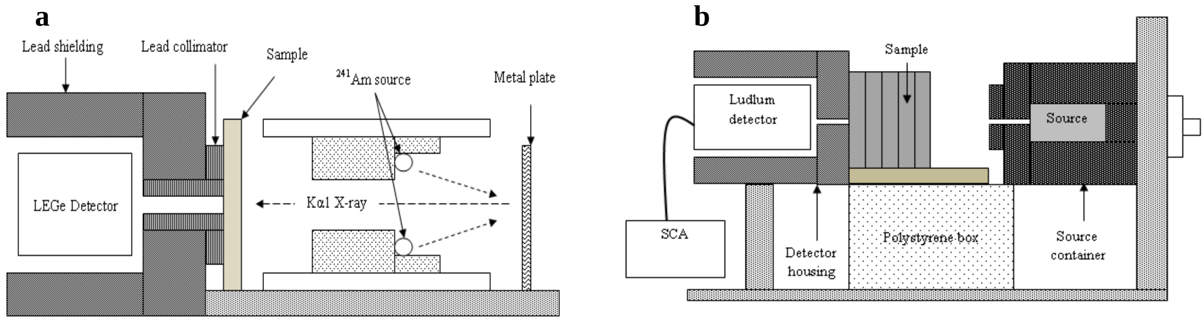

Figure 3. The experimental set up of X-ray fluorescent set up (a) and Ladlum set up (b) for measurement of mass attenuation coefficient.

The linear attenuation coefficient of the particleboards were measured using the transmitted photon through the sample according to the Beer-Lambert equation of

$$I = I_{\circ}\, e^{-\mu x} \tag{7}$$

with $I_{\circ}$ is initial intensity of photons, and μ is linear attenuation coefficient of sample in. The value of linear attenuation coefficient is calculated using the equation

$$\mu = \frac{1}{\chi} \ln\left(\frac{I_{\circ}}{I}\right) \tag{8}$$

The value of mass attenuation coefficient is obtained by dividing the value of linear attenuation coefficient with the gravimetric calculation of sample density. The measured mass attenuation cofficient is compared to the calculated value of water using photon cross-section database (XCOM) according to the study by Berger and Hubbell, (1987).

3. Results

The average mass density of tannin-added *Rhizophora spp*. particleboards measured using gravimetric method is presented in Table 1. The results showed that the particleboards were able to be fabricated at target density of 1.0 g/cm^3. The particleboards were also showed good density uniformity shown by the standard deviation (SD) of measured density.

Table 1. The average density of tannin-added *Rhizophora spp*. particleboards in comparison to binderless *Rhizophora spp*. and binderless *Rhizophora spp*. particleboards.

Sample	Measured Density (g/cm^3)			Standard Deviation
	Average	Max.	Min.	
R. spp. raw wood	0.991	1.004	0.973	0.011
Binderless *R. spp*.	1.037	1.095	0.955	0.061
Tannin-added *R. spp*.	1.004	1.040	0.980	0.023

The average IB strength of the particleboards measured based on JIS A 5908: 2003 were illustrated in Figure 4. The results showed that the tannin-added *Rhizophora spp*. in this study satisfied the JIS A 5908: 2003 for particleboard Type 18 in comparison to the binderless particleboard from the previous study by Marashdeh et al., (2012). A comparison to the tannin-based *Rhizophora spp*. particleboards with lower percentage of tannin showed that the tannin-based particleboards from the previous study by Safian (2012) did not satisfy any of the industrial standards.

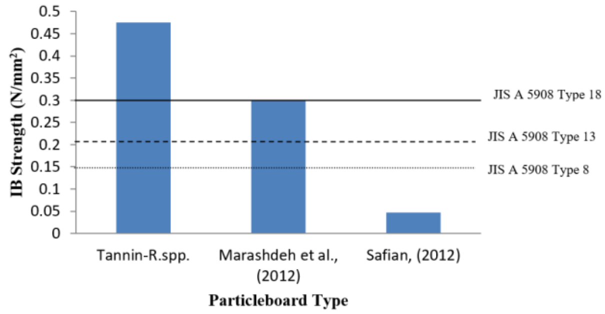

Figure 4. Average IB strength of the particleboards based on JIS A 5908: 2003.

3.1. Elemental Compositions and Effective Atomic Number

The percentage of elemental compositions and calculated effective atomic number of samples are presented in Table 2. The results showed that the particleboards made of *Rhizophora spp*. consists of mainly carbon and oxygen similar to that in human soft tissues. Addition of tannin did not give significant change of elemental compositions to the particleboards indicating the similarities of elemental compositions of tannin to the wood particles. The effective atomic number can be used to determine the attenuation coefficient of a medium (Duvauchelle et al., 1999). One medium can be said to have water equivalent properties if the effective atomic numbers are equal. The calculated effective atomic number of samples as shown in Figure 2 indicated that the value of tannin-added *Rhizophora spp*. were close to the value of water. This had indicated the addition of tannin had improved the effective atomic number and water equivalent property of tannin-added *Rhizophora spp*.

Table 2. The percentage of elemental composition and calculated effective atomic number of particleboards made of *Rhizophora spp*. in comparison to water.

Sample	Elemental composition (%)					Z_{eff}
	H	C	O	N	F	
Water[a]	11.11		88.89			7.50[a]
R. spp raw wood[b]	5.41	40.16	54.40	0.03		5.85
Binderless *Rhizophora. spp*.[c]		32.93	38.98	28.08		7.18[c]
Tannin-added *Rhizophora spp*.[c]		51.25	43.11		5.64	7.22[c]

[a]AAPM-21 (1983) [b]Che Wan Sudin (1991) [c]Current study

3.2. CT Number and Relative Electron Density

The average CT number and relative electron density of *Rhizophora spp*. particleboards in comparison to various tissue equivalent density plug phantoms is presented in Table 3. The results showed that the average CT number of tannin-added *Rhizophora spp*. particleboards was close to the value of water equivalent density plug phantoms.

Table 3. The average CT number and relative electron density of tannin-added *Rhizophora spp*. particleboards and various tissue equivalent density plug phantoms.

Sample	Average CT number (HU)	Relative electron density (x 10^{23} electron/cm^3)
Lung (exhale)	-477.74	1.632
Adipose tissue	-78.75	3.171
Breast (50/50)	-52.09	3.261
R. spp. raw wood	-34.07	3.193
Tannin-added *R. spp*.	-13.69	3.341
Water	-11.61	3.340
Muscle	27.36	3.483
Liver	36.45	3.516

The calculation of relative electron density also showed close value of tannin-added *Rhizophora spp*. to water. This had indicated good agreement of attenuation coefficient of tannin-added *Rhizophora spp*. to water as the CT number is very much related to the attenuation coefficient of medium to the x-ray. A study by Kurudirek, (2014) suggested that the electron density of tissue is very much related to the attenuation coefficient of the tissue. Therefore, the results also indicated the similarity of attenuation coefficient of tannin-added *Rhizophora spp*. particleboards to water in based on their close value of relative electron density.

3.3. Mass Attenuation Coefficient

The mass attenuation coefficient of tannin-added *Rhizophora spp*. particleboards in comparison to water (XCOM) and previous studies at low energy photon measured using XRF set up is illustrated in Figure 5. The detailed value of linear and mass attenuation coefficient of the samples is presented in Table 4. The results showed that the linear and mass attenuation coefficient of tannin-added *Rhizophora spp*. particleboards was in good agreement to the value of water (XCOM). This had indicated the water equivalent property and similar attenuation properties of tannin-added *Rhizophora spp*. particleboards. The results also showed that the mass attenuation coefficient of tannin-added *Rhizophora spp*. particleboards was in good agreement with the binderless *Rhizophora spp*. particleboards from the study by Marashdeh et al., (2012). The addition of tannin was found to retain the attenuation properties of the particleboards made of *Rhizophora spp*.

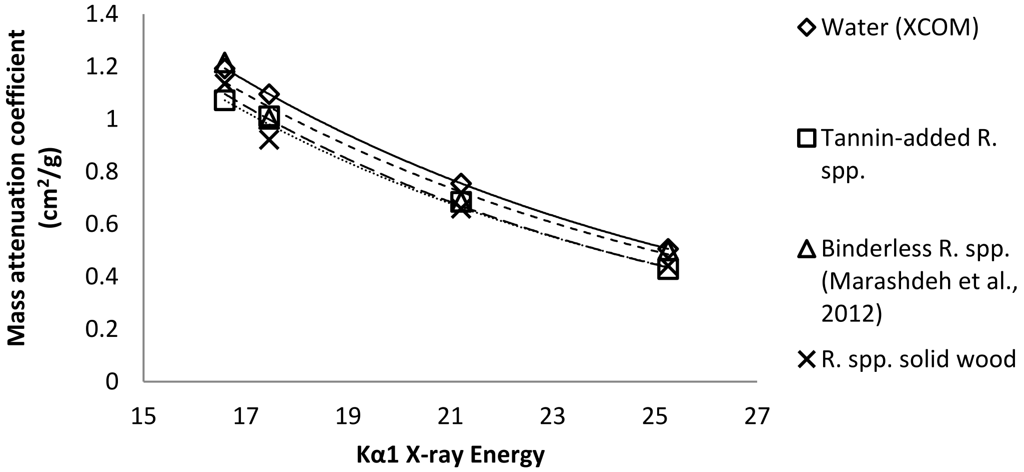

Figure 5. Mass attenuation coefficient of tannin-added *Rhizophora spp*. particleboards in comparison to water and previous studies.

Table 4. The linear and mass attenuation coefficient of samples at low energy photons measured using XRF set up.

Kα1 Energy (keV)		**Tannin-added *R. spp.***	***R.spp*. raw wood**	**Water (XCOM)**
16.59	μ	1.142	1.136	1.193
	μ/ρ	1.072	1.135	1.193
	$\sigma_{(\mu/\rho)}$ ±%	2.23	2.18	-
17.46	μ	1.072	0.921	1.095
	μ/ρ	1.011	0.921	1.095
	$\sigma_{(\mu/\rho)}$ ±%	2.69	2.02	-
21.21	μ	0.696	0.659	0.755
	μ/ρ	0.685	0.659	0.755
	$\sigma_{(\mu/\rho)}$ ±%	2.24	2.34	
25.26	μ	0.436	0.440	0.506
	μ/ρ	0.429	0.440	0.506
	$\sigma_{(\mu/\rho)}$ ±%	1.57	1.40	-

The mass attenuation coefficient at high energy photon measured using Ladlum set up is presented in Table 5. The results showed that the mass attenuation coefficient of tannin-added *Rhizophora spp*. particleboards were close to the value of water (XCOM). The mass attenuation coefficient at ^{137}Cs gamma energy was slightly lower to the value of water with percentage of discrepancies of 17% to that in water. The mass attenuation coefficient at ^{60}Co gamma energy however was in good agreement to water with lower percentage of discrepancies of 11%. The results had indicated that tannin-added *Rhizophora spp*. having attenuation coefficient close to to the value of water at both low and high energy photons.

Table 5. The linear and mass attenuation coefficient of samples at high energy photons measured using Ladlum set up.

Gamma energy (MeV)		Tannin-added *R. spp.*	*R.spp*. raw wood	Water (XCOM)
0.622	μ	0.071	0.067	-
	μ/ρ	0.071	0.067	0.086
	$\sigma_{(\mu/\rho)}$ ±%	0.017	0.030	-
1.20	μ	0.052	0.057	-
	μ/ρ	0.052	0.048	0.059
	$\sigma_{(\mu/\rho)}$ ±%	0.012	0.009	-

4. Conclusion

The addition of tannin had increased the mechanical property of particleboards made of *Rhizophora spp*. shown by the average IB strength. The calculation of effective atomic number based on the percentage of elemental composition showed close value of tannin-added *Rhizophora spp*. particleboards to the value of water by AAPM-21 (1983). The measurement of CT number and relative electron density also showed value of tannin-added *Rhizophora spp*. particleboards to water indicating close attenuation coefficient to water. The measurement of mass attenuation coefficient showed good agreement of tannin-added *Rhizophora spp*. particleboards to the calculated value of water using XCOM at both low and high energy photons. The results had indicated the suitability of tannin-added *Rhizophora spp*. particleboards as phantom materials in applications of low and high energy photons.

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