Photon mass attenuation coefficients, effective atomic numbers, CT numbers and density profiles of cured DSF-SPC-based Rhizophora spp. particleboard phantoms coupled with NaOH/IA-PAE at different concentrations

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Abstract. Rhizophora spp. (R. spp.) particleboard phantoms based on defatted soy flour and soy protein concentrate were fabricated using itaconic acid polyamidoamine-epichlorohydrin (IA-PAE) at different concentrations with the incorporation of NaOH. The results showed that the mass attenuation coefficients and effective atomic numbers of the particleboard phantoms at 16.59–25.26 keV photon energies were in good agreement within 0.88% and 0.01% of the XCOM values in water with p-values of 0.072 and 0.075. In addition, DSF-SPC-R. spp. phantom with 15 wt% IA-PAE content shows the nearest CT numbers, electron density, and density profiles to water substitutes at three CT energies. These results indicate the suitability of cured DSF-SPC-R. spp. particleboards as phantom materials for the selected X-ray energies.

1. Introduction
The fundamental phantom material recommended for dosimetric studies is water because it is an ideal match to human soft tissue. However, since it is not always practical to perform dosimetry analysis in water, phantoms made from proprietary materials have found considerable popularity [1]. R. spp. has been utilized as X-ray CT phantom materials due to its easy fabrication process and potential for wide-ranged material properties [2-3]. It has prior tissue-equivalent nature and attenuation parameters close to that of water at a range of photon energies but still cannot provide ideal properties. Particleboards made with DSF-SPC-NaOH-IA-PAE are reported to reveal excellent water resistance [4]. We present cured DSF-SPC-R. spp. phantoms by NaOH-IA-PAE and compared their dosimetric nature with water.

2. Materials and Methods
2.1. Preparation and fabrication of IA-PAE-DSF-SPC-based R. spp. particleboard phantoms
DSF (30 g) was suspended into the IA-PAE content and consecutively added to distilled water (70 g), stirred for 0.5 h and keep at pH 11.0 with 2M of NaOH solution. Next, SPC (21.5 g) was dispersed into distilled water (78.5 g) and stirred for 1 h. The mixture was then mixed with the IA-PAE for 1 h.

R. spp. coarse chips were ground into smaller particle sizes and sieved (149–74 μm). The assembled mats were cold-compressed at 0.5 MPa for 3 min, and hot-pressed at 20 MPa for 20 min at 170°C.
2.2. Microstructure analysis

The morphology of the sample phantoms was studied using FE-SEM operated at 20 kV and 30°. Each sample was coated with Au for 0.5 h at 45 mA. The Z_{eff} can be determined using equation (1):

\[
Z_{\text{eff}} = \left[ \sum_{i} \frac{\omega_i Z_i A_i^{-1}}{\sum_{i} \omega_i Z_i A_i^{-1}} \right]^{1/3.4}
\]

where \(z_i\), \(A_i\) and \(\omega_i\) are the atomic number, atomic weight and fractional weight of the \(i^{th}\) element.

2.3. Preparation of plug phantoms for Computed Tomography (CT) scan

The plug phantoms compatible with CT electron density CIRS 062M were constructed in cylindrical shapes. Each sample was stacked using polyvinyl acetate resin, trimmed and then scanned (Figure 1).

2.4. Attenuation, CT numbers, and density profiles measurements

Samples were prepared for the photons of 16.59–25.26 keV energies derived from XRF resulting from 59.54 keV \(\gamma\)-irradiation from a 100 mCi \(^{241}\)Am source. X-ray CT scanner was used to acquire the CT images at 250 mAs. The \(\mu \rho^{-1}\) and CT number were measured using equation (2) and equation (3):

\[
\mu \rho^{-1} = (\rho x)^{-1} \ln[l_0 l^{-1}] \quad ; \quad \sigma_{\mu \rho^{-1}} = [\sigma_{\mu} \rho^{-1} + \sigma_{\rho} \rho^{-1}] \times [\mu \rho^{-1}]
\]

\[
\text{CT number} = [(\mu_R - \mu_w)(\mu_w^{-1})] \times 1000
\]

where \(l\), \(l_0\), \(x\), \(\sigma_{\mu}\), \(\sigma_{\rho}\), \(\mu_R\), and \(\mu_w\) denotes the intensity of the incident transmitted and primary photons, uncertainties in the \(\mu\) and density, photon attenuation coefficients for \(R.\) spp. samples and water.

3. Results and Discussion

3.1. Determination of physico-mechanical properties and dimensional stability

As evidenced in table 1, all samples complying with JIS A 5908:2003 [5]. The results revealed that \(A_5\) has the highest internal bonding (IB), modulus of rupture and elasticity (MOR and MOE) values. The water absorption (WA) and thickness swelling (TS) abated drastically. This could be ascribed to the reduction of the water-soluble factors of the bond line while the cross-linking network was formed [4].

| Sample | Density (g/cm³) | IB (MPa) | MOR (MPa) | MOE (GPa) | WA (%) | TS (%) |
|--------|----------------|----------|-----------|-----------|--------|--------|
| A_5/B_5 | 0.89 ± 0.10 | 0.08 ± 0.06 | 1.99 ± 0.74 | 1.55 ± 0.17 | 71.1 ± 7.4 | 60.5 ± 4.9 |
| A_4 | 0.98 ± 0.07 | 0.54 ± 0.02 | 3.13 ± 0.79 | 2.58 ± 0.16 | 60.5 ± 8.0 | 42.5 ± 4.8 |
| B_1 | 0.94 ± 0.06 | 0.28 ± 0.04 | 4.03 ± 0.60 | 1.81 ± 0.33 | 52.3 ± 3.2 | 59.5 ± 1.9 |
| A_3 | 1.07 ± 0.05 | 0.63 ± 0.02 | 13.55 ± 3.53 | 5.66 ± 0.85 | 37.7 ± 3.3 | 29.9 ± 2.6 |
| B_4 | 0.96 ± 0.04 | 0.54 ± 0.01 | 10.80 ± 2.17 | 4.40 ± 1.03 | 26.7 ± 2.6 | 22.5 ± 4.0 |
| A_2 | 1.00 ± 0.04 | 0.64 ± 0.02 | 18.80 ± 5.08 | 7.29 ± 1.84 | 37.2 ± 3.5 | 11.6 ± 3.8 |
| B_2 | 1.01 ± 0.03 | 0.55 ± 0.02 | 13.20 ± 2.23 | 6.18 ± 1.15 | 19.6 ± 3.0 | 15.0 ± 5.9 |
| A_1 | 0.98 ± 0.06 | 0.69 ± 0.06 | 18.95 ± 3.15 | 7.83 ± 0.17 | 37.0 ± 2.2 | 10.8 ± 5.2 |
| B_1 | 1.00 ± 0.03 | 0.56 ± 0.01 | 18.11 ± 3.28 | 7.48 ± 1.85 | 18.3 ± 3.0 | 11.3 ± 2.7 |
3.2. Microscopy images

The presence of void spaces as shown in figure 2(a-c) illustrate that the existence of gaps occur at certain parts of the particleboards resulting in high WA. Figure 2(d-f) reveals the smooth surface of DSF resulting in good compatibility. Figure 2(g-i) shows the fracture surface of the SPC, indicating a few cracks and a compact surface. The results reveal that samples $A_{15}$ and $B_{15}$ have values of $Z_{\text{eff}}$ similar to that of water with a difference of 0.88% and 0.01% (table 2).

![Figure 2](image)

**Figure 2.** FE-SEM images of: (a-c) $A_0$ /$B_0$, (d-f) $A_{15}$, and (g-i) $B_{15}$ at 200x, 500x, and 1000x magnifications

### Table 2. Percentage elemental composition and estimated $Z_{\text{eff}}$ for DSF-SPC phantoms and water.

| Sample | H (%) | C (%) | N (%) | O (%) | F (%) | Na (%) | Mg (%) | P (%) | S (%) | Cl (%) | K (%) | Ca (%) | Fe (%) | Zn (%) | $Z_{\text{eff}}$ |
|--------|-------|-------|-------|-------|-------|--------|--------|-------|-------|--------|-------|--------|-------|-------|---------|
| $A_0$ /$B_0$ | 50.44 | 1.62 | 47.90 | - | - | - | - | - | - | - | - | - | - | - | 7.15 |
| $A_{15}$ | 51.39 | 4.77 | 42.63 | 0.20 | 0.04 | 0.12 | 0.05 | 0.32 | 0.18 | 0.14 | 0.07 | 0.09 | 7.72 |
| $B_{15}$ | 49.73 | 4.88 | 44.35 | 0.25 | 0.10 | - | - | 0.27 | 0.25 | 0.15 | - | 0.02 | 7.49 |
| Tannin | 51.25 | 4.31 | 5.64 | - | - | - | - | - | - | - | - | - | - | 7.22 |
| Water | 11.11 | - | 88.89 | - | - | - | - | - | - | - | - | - | - | 7.50 |

* present study, $^*$[2], $^*$[6]

3.3. Determination of the mass attenuation coefficient, CT numbers, and density distribution profiles

The mass attenuation coefficient values of all the samples diminished exponentially with increasing photon energy which can be attributed to the dominance of the photoelectric interaction processes (figure 3). The results are close to the value of water and in good agreement with previous studies [2]. Samples $A_{15}$ and $B_{15}$ with p-values of 0.072 and 0.075 show no significant difference to that of water (table 3). Figure 4 shows that the CT images were substantially better and reveals similar degrees of images. The CT imaging of $A_{15}$ and $B_{15}$ were found to have mean HU and electron densities values closest to water (table 4). Also, the $\chi^2$ test showed a good similarity of HU values to water substitutes.

### Table 3. Paired t-test of DSF-SPC particleboard phantoms compared to water (XCOM)

| Pair | Mean | Std. Dev. | Std. Error Mean | 95% Confidence Interval diff. | $t$ | df | Sig. (2-tailed) |
|------|------|-----------|----------------|-----------------------------|-----|----|----------------|
| $A_0$ /$B_0$ | 0.095 | 0.034 | 0.017 | 0.0350, 0.1439 | 5.229 | 3 | 0.014 |
| $A_{15}$ | 0.069 | 0.042 | 0.021 | -0.0095, 0.1249 | 2.734 | 3 | 0.072 |
| $B_{15}$ | 0.142 | 0.068 | 0.034 | -0.0169, 0.1999 | 2.687 | 3 | 0.075 |

The densities of all the samples were in better agreement with that of water. Samples with 15 wt% IA-PAE content indicate the closest density profiles to water substitutes (figure 5).

### Table 4. Calculated mean CT numbers, densities, electron densities, and $\chi^2$ values.

| Samples | $\mu$ (kVp) | $\rho$ (g/cm$^3$) | $\epsilon$ (10$^{-6}$ cm$^2$/g) | $\chi^2$ to water substitute |
|---------|-------------|------------------|-----------------|-----------------|
| $A_0$ /$B_0$ | 1.86 | 39.26 | 1.03 | 3.39 | 21.4 | 24.21 | 1.05 | 3.45 | 7.22 | 18.92 | 1.03 | 3.39 | 0.54 | 0.96 | 0.88 |
| $A_{15}$ | -12.19 | 35.26 | 1.01 | 3.34 | -9.89 | 19.96 | 1.01 | 3.34 | -11.9 | 20.28 | 1.01 | 3.33 | 0.06 | 0.06 | 0.08 |
| $B_{15}$ | -13.69 | 35.48 | 1.01 | 3.33 | -9.67 | 20.22 | 1.01 | 3.34 | -9.99 | 19.63 | 1.01 | 3.34 | 0.05 | 0.06 | 0.03 |
| Water | -8.58 | 32.46 | 1.00 | 3.34 | -5.26 | 15.58 | 1.00 | 1.00 | -4.90 | 14.48 | 1.00 | 3.34 | 0.04 | 0.06 | 0.04 |
Figure 3. The Mass attenuation coefficients of DSF and SPC particleboards in comparison to water

Figure 4. CT images of the plug phantoms at: (a) 80, (b) 120, and (c) 135 kVp X-ray CT energies

Figure 5. Density profile curves of particleboard phantoms: (a) 80, (b) 120, and (c) 135 kVp CT energies

4. Conclusions
The mass attenuation coefficients and $Z_{eff}$ values were found to be satisfactory. The results revealed that $A_{15}$ and $B_{15}$ have values similar to that of water with a difference of 0.88% and 0.01%. Also, the HU, density profiles, and $\chi^2$ values showed good similarities to water substitutes, indicating the quality of having the proportionate properties that are proper as a suitable water-equivalent phantom material.

5. References
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