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Investigation of the Radiation Shielding Properties of Black Pine Wood Impregnated with Boric Acid

Osman Emre ÖZKAN

Kastamonu University, Faculty of Forestry, Department of Forest Industry Engineering, Kastamonu, TURKEY
*Corresponding Author: oeozkan@kastamonu.edu.tr

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Abstract

Aim of study: The present work is to investigate the radiation shielding properties of impregnated black pine (*Pinus nigra* Arnold subsp. *pallasiana*) wood material by measuring linear attenuations coefficient, mass attenuations coefficient, half value and tenth value layer thickness for different gamma energies from 5 keV to 1000 keV.

Material and methods: The values of linear attenuation coefficient (1/cm), mass attenuation coefficient (cm^2/g), half value and tenth value layer thickness of impregnated wood material were calculated in energy range between 5 to 1000 keV using the WinXCOM based Phy-X/PSD software and compared with concrete.

Main results: It has been found that the linear attenuation coefficient and the mass attenuation coefficient of impregnated wood decrease as photon energy increases. But, half value layer and tenth value layer of impregnated wood increased as photon energy increased. As a result, it was found that the radiation shielding properties of wood increasing with boric acid impregnation.

Highlights: The radiation shielding properties of impregnated wood are higher than pine wood because of its high density and chemical composition, which contains boron elements.

Keywords: Pine Wood, Radiation Shielding, Mass Attenuation Coefficient

Borik Asit ile Emprenye Edilmiş Karaçam Odununun Radyasyon Zırhlama Özelliklerinin İncelenmesi

Öz

Çalışmanın amacı: Bu çalışma, emprenye edilmiş karaçam (*Pinus nigra* Arnold subsp. *pallasiana*) odununun radyasyon zırhlama özelliklerini lineer zayıflatma katsayısı, kütle zayıflatma katsayısı, yarı değer ve onuncu değer katman kalınlığını 5 keV'den 1000 keV'ye kadar farklı gama enerjilerinde ölçerek araştırmaktadır.

Materyal ve yöntem: Emprenye edilmiş ahşap malzemenin doğrusal zayıflatma katsayısı (1/cm), kütle zayıflatma katsayısı (cm^2/g), yarı değer ve onuncu değer katman kalınlığı değerleri WinXCOM tabanlı Phy-X/PSD yazılımı kullanılarak 5 ile 1000 keV enerji aralığında hesaplanarak beton ile karşılaştırılmıştır.

Temel sonuçlar: Emprenyeli ahşabın lineer zayıflatma katsayısı ile kütle zayıflatma katsayısının foton enerjisi arttıkça azaldığı bulunmuştur. Ancak, emprenyeli ahşabın yarı değer kalınlığı ve onuncu değer kalınlığı foton enerjisi arttıkça artmıştır. Sonuç olarak, ahşabın radyasyon kalkanı özelliklerinin borik asit emprenyesi ile arttığı tespit edilmiştir.

Araştırma vurguları: Emprenyeli odunun radyasyonu zırhlama özellikleri, yüksek yoğunluğu ve bor elementi içeren kimyasal bileşimi nedeniyle çam odunundan daha yüksek çıkmıştır.

Anahtar Kelimeler: Çam Odunu, Radyasyon Zırhlama, Kütle Zayıflatma Katsayısı

Introduction

Human beings are continuously subjected to background radiation from the sun and cosmic rays, as well as naturally existing radioactive compounds inside Earth that remain in their bodies, homes and food. Radiation exposure consists of two separate components, namely, internal (natural) and external exposure. Natural radiation differs greatly between areas. It is not necessary protection against natural radiation sources, which scatter across the environment. However, when the radiation source is concentrated and restricted to a specific region, the radiation exposure that people receive from that source may be reduced by the use of carefully designed systems and procedures (Erdem et al., 2010).

The investigation of the radiation shielding properties of some materials has been interesting to researchers due to the wide use of radioactive isotopes in various fields such as nuclear power plants, radiology, radiotherapy, nuclear research, accelerator centers, agricultural, environmental and industrial applications (Aşkın & Dal, 2019). Also, there is an interest in estimating as precisely as possible due to the expanding use of radioactive isotopes in different areas, such as industries, energy production and medicine the dosage to which a population will be exposed in the situation of an accident. In the case of a nuclear accident, the most critical choice at the starting is to decide the importance of evacuating the entire community or whether it would be sufficient simply to provide shelter. Radiation shielding calculations of materials during accident have shown how much protection the house walls and ceiling could provide (Salinas et al., 2006).

Significant parameters for characterizing X-ray and γ-ray penetration and diffusion in multi-element materials are the photon attenuation coefficients. Gamma radiation scattering and absorption are related to density and effective material atomic numbers; knowledge of this is of prime importance to the mass attenuation coefficients. These coefficients of attenuation depend on the photon energy and the chemical structure of the absorption products, such as their forms, size and densities (Erdem et al., 2010). The density often has no unique value but depends on the material's physical condition, such as wood. The linear attenuation coefficient is the probability of a photon interacting in a particular way with a given material per unit path length (Saritha & Nageswara Rao, 2014). The linear or mass attenuation coefficient is defined as the probability of investigating the radiation shielding properties of any materials (Erdem et al., 2010). The determination of the radiation shielding properties of the materials is therefore of crucial importance to protect humans from the hazardous effects of ionizing radiation used in such places. Gamma rays are one of the most penetrating types of radiation, and for their effective shielding; they need high density and atomic numbers. Lead is referred to as the best attenuating material against gamma rays. In contrast, the weight, price and the toxicity of the lead make the protection of large areas impractical and expensive (Aşkın & Dal, 2019).

Recently, numerous researches on the radiation shielding properties of the different materials were carried out using theoretical methods. Some examples are summarized as follows; Içelli et al., (2004) investigated the mass attenuation coefficient (MAC) of boric acid at different concentration. Jalali & Mohammadi, (2008) determined attenuation coefficients of boric acid in an energy range from 662 to 1408 keV. Agar et al., (2019) investigated the values of linear attenuation coefficient (LAC), mass attenuation coefficient (MAC) and half value layer (HVL) of perlite added concretes in an energy range from 81 and 1333 keV. Akman et al., (2019) determined MAC and radiation protection efficiency of selected soils in an energy range from 13.94 and 88.04 keV. Salama & Maher, (2019) studied the mass attenuation coefficient of glass materials at photon energy of 662 keV. Aygün, (2020) calculated mass attenuation coefficient and half value layer of high alloyed new stainless steel. Salinas et al., (2006) carried out a study about MAC of different building materials such as asbestos, clay brick, brick and wood.

Bradley et al., (1991) investigated gamma-ray linear attenuation coefficient of various tropical woods densities from 135 to 1180 kg/m^3 at photon energy of 59.54 keV. The LAC values have increased with increasing wood densities. The LAC of *Rhizophora* spp. wood (1040 kg/m^3) has been found 0.212 cm/1. The LAC value of the *Rhizophora* spp. wood was similar compared to water 0.205 cm/1.

The radiation shielding study of building materials generally focused on concrete, steel, brick and lead. But, there has not been much focus on investigating the radiation shielding properties of wood, a very common building material. To the best of our knowledge, there is no available data about radiation shielding properties of the black pine wood impregnated with boric acid. The purpose of the present work is to investigate the gamma-ray interactions with pine wood impregnated with boric acid by measuring linear attenuations coefficient, mass attenuations coefficient, half value and tenth value layer thickness for different gamma energies from 5 keV to 1000 keV. We have obtained gamma-ray interactions of the wood material was compared with pure concrete reported by (Tekin et al., 2017) which are commonly used for radiation shielding material. The linear attenuations coefficient, mass attenuations coefficient, half value and tenth value layer thickness of the materials have been calculated by WinXCOM based Phy-X/PSD software (Gerward et al., 2004; Şakar et al., 2020).

Material and Methods

Material

Black pine (*Pinus nigra* Arnold subsp. *pallasiana*) wood was obtained from a rural timber trader in Kastamonu, Turkey. The pine sapwood was dried at 20±2 °C for 1 month. The air-dried sapwood samples were powdered with a hammer mill in size <0.25 mm. Boric acid was purchased from Tekkim Chemistry (Turkey).

Elemental and ICP-OES Analyze

The elemental compositions of the pine wood were determined in Kastamonu University Central Research Laboratory by using CNH elementary analyzer Eurovector™ EA3000-Single and Spectro™ Xepos II electron X-ray fluorescence spectroscopy. The total elemental composition of the concrete, pine wood and impregnated wood is given in Table 1.

Table 1. Total elemental composition of the pine wood and impregnated wood

Symbol	Concrete* (2.26 g/cm^3)	Pine Wood (0.443 g/cm^3)	Impregnated Wood (0.515 g/cm^3)
H	-	4.231	5.649
B	-	-	15.138
C	-	47.628	42.189
N	-	0.295	0.391
O	49.2	47.452	36.179
Na	0.5	-	0.413
Mg	0.3	-	-
AI	3.7	-	-
Si	37	-	-
Ca	8.2	0.213	-
Fe	1.1	-	-

*Tekin et al., 2017.

Impregnation Process

The wood samples were immersed in the 10% boric acid solution using a vacuum drying oven (0.75 bar, 24 h). After 24 h of impregnation at 60 ℃, vacuum released and impregnation process carried out for another 24 h. The retention level of boric acid is 72.84 kg/m^3.

Theoretical Calculations

The theoretical calculation of the mass and linear attenuation coefficient, half and tenth value layers of the pine wood have been performed using the WinXCOM based Phy-X software. The Phy-X is developed by (Şakar et al., 2020) to calculate of parameters relevant to photon shielding and dosimetry for elements, compounds or mixtures at energies from 1 keV to 100 GeV.

Mass attenuation coefficient (MAC) is a significant parameter defining the penetration and diffusion of gamma ray photons within the mass per unit area for a material (Aşkın & Dal, 2019). The mass and linear attenuation coefficient is calculated by using

Beer-Lambert law is given following equation 1. (Şakar, 2020) :

$$\mu_m = \frac{\mu}{\rho} = \frac{\ln(\frac{I}{I_0})}{t_m} \quad (1)$$

where μ (cm/1) is linear attenuation coefficient, μ_m (cm^2/g) is mass attenuation coefficient, I_0 is transmitted photon and I is incident photon intensities and t_m (g/cm^2) is mass per unit area of the material.

The half-value layer (HVL, cm) is the material thickness needed to reduce incident gamma rays by half. The tenth value layer (TVL, cm) is the thickness of material needed to decrease 90% of the incident gamma rays. These parameters are determined with the equation 2 and 3 (Agar et al., 2019).

$$HVL = \frac{ln2}{\mu} \quad (2)$$

$$TVL = \frac{ln10}{\mu} \quad (3)$$

Results and Discussion

The results of the impregnated pine wood was compared with pure concrete which are commonly used for radiation shielding material reported by (Tekin et al., 2017). The calculated mass and linear attenuation coefficient, half and tenth value layers of the pine wood lists in Table 2. According to this table, the LAC values are between 9.10 1/cm and 0.03 1/cm for wood at 5.888 and 1000 keV, respectively. The LAC values are between 8.65 1/cm and 0.03 1/cm for impregnated wood at same energy range. However, the LAC values of concrete are between 248.82 1/cm and 0.14 1/cm at same energy range. The highest and lowest MAC values of wood are 20.54 cm^2/g and 0.07 cm^2/g at 5.9 and 1000 keV, respectively. The maximum and minimum MAC values of impregnated wood are 16.79 cm^2/g and 0.07 cm^2/g at 5.9 and 1000 keV, respectively. However, highest and lowest MAC values of concrete are 110.10 cm^2/g and 0.06 cm^2/g at same energy range, respectively. In the low energy region, the LAC and MAC values are high, but show a rapid downward trend with increasing photon energy (Agar et al., 2019; Aygün, 2020). This finding related to the prominence of the photoelectric absorption process. The effective cross section in this area is inversely proportional to the frequency of the incident photons. Another essential process which is called Compton scattering dominates the middle energy area. The MAC values in this area gradually decrease with the increase in energy (Aygün, 2020).

Theoretical LAC values of concrete, pine wood and impregnated wood sample were compared in Figure 1. It is seen that the LAC values of the pine wood reduced rapidly from 9.10 to 0.11 1/cm for photon energy 5.9 and 40.1 keV, respectively. After this photon energy the LAC values of the pine wood reduced slowly from 0.10 to 0.03 1/cm for photon energy 44.5 and 1000 keV, respectively. Similarly, the LAC values of the impregnated wood reduced rapidly from 8.65 to 0.12 1/cm for photon energy 5.9 and 40.1 keV, respectively. After this photon energy the LAC values of the impregnated wood reduced slowly from 0.11 to 0.03 1/cm for photon energy 44.5 and 1000 keV, respectively. The LAC values of the concrete reduced rapidly from 248.82 to 0.47 1/cm for photon energy 5.9 and 81 keV, respectively. After this photon energy the LAC values of the concrete reduced gradually from 0.44 to 0.14 1/cm for photon energy 88 and 1000 keV, respectively (Figure 1). The LAC values of black pine wood (0.08 cm/1) and impregnated wood (0.10 cm/1) are different from the LAC values of *Rhizophora* spp. wood (1040 kg/m3) is 0.212 cm/1 at photon energy of 59.5 keV reported by (Bradley et al., 1991). This case has shown that the LAC values have increased with increasing wood densities at same photon energy.

Table 2. MAC, LAC, HVL and TVL values of concrete, wood and impregnated wood

Energy	X-Ray &	MAC (cm2/g)			LAC (cm/1)			HVL (cm)			TVL (cm)		
(KeV)	Isotopes	Conc.	Wood	Imp.	Conc.	Wood	Imp.	Conc.	Wood	Imp.	Conc.	Wood	Imp.
5.888	*Fe (55)*	110.10	20.54	16.79	248.82	9.10	8.65	0.00	0.08	0.08	0.01	0.25	0.27
8.91	*Cu (29)*	36.32	5.94	4.84	82.08	2.63	2.49	0.01	0.26	0.28	0.03	0.88	0.92
13.37	*Rb (37)*	11.33	1.84	1.52	25.60	0.82	0.78	0.03	0.85	0.89	0.09	2.82	2.94
17.44	*Mo (42)*	5.28	0.92	0.78	11.93	0.41	0.40	0.06	1.70	1.73	0.19	5.64	5.75
19.63	*Mo (42)*	3.77	0.70	0.60	8.52	0.31	0.31	0.08	2.24	2.24	0.27	7.43	7.46
25	*Cd (109)*	1.93	0.43	0.39	4.35	0.19	0.20	0.16	3.61	3.49	0.53	12.00	11.60
30.82	*Ba (133)*	1.11	0.32	0.29	2.51	0.14	0.15	0.28	4.94	4.62	0.92	16.42	15.35
35	*Ba (133)*	0.81	0.27	0.26	1.84	0.12	0.13	0.38	5.73	5.25	1.25	19.02	17.45
40.12	*Eu (152)*	0.60	0.24	0.23	1.35	0.11	0.12	0.51	6.49	5.86	1.71	21.56	19.45
45.9	*Eu (152)*	0.45	0.22	0.21	1.03	0.10	0.11	0.68	7.15	6.37	2.24	23.76	21.16
50.38	*Tb (65)*	0.38	0.21	0.20	0.87	0.09	0.10	0.80	7.56	6.68	2.66	25.11	22.20
53.16	*Ba (133)*	0.35	0.20	0.20	0.79	0.09	0.10	0.88	7.78	6.85	2.91	25.83	22.75
59.54	*Am (241)*	0.30	0.19	0.19	0.67	0.08	0.10	1.04	8.20	7.18	3.45	27.24	23.84
81	*Ba (133)*	0.21	0.17	0.17	0.47	0.08	0.09	1.47	9.19	7.96	4.90	30.52	26.43
88.04	*Cd (109)*	0.19	0.17	0.16	0.44	0.07	0.08	1.58	9.43	8.16	5.25	31.34	27.10
103	*Am (241)*	0.17	0.16	0.16	0.39	0.07	0.08	1.77	9.90	8.54	5.87	32.89	28.38
121.8	*Eu (152)*	0.16	0.15	0.15	0.36	0.07	0.08	1.95	10.41	8.97	6.46	34.60	29.80
160.6	*Ba (133)*	0.14	0.14	0.14	0.31	0.06	0.07	2.22	11.34	9.76	7.36	37.68	32.41
200		0.13	0.13	0.13	0.29	0.06	0.07	2.43	12.19	10.47	8.06	40.48	34.79
223.4	*Ba (133)*	0.12	0.12	0.12	0.27	0.05	0.06	2.53	12.65	10.87	8.42	42.04	36.12
244.7	*Eu (152)*	0.12	0.12	0.12	0.26	0.05	0.06	2.63	13.06	11.22	8.73	43.40	37.28
276.4	*Ba (133)*	0.11	0.11	0.11	0.25	0.05	0.06	2.76	13.65	11.72	9.16	45.34	38.94
283.5	*Cs (137)*	0.11	0.11	0.11	0.25	0.05	0.06	2.78	13.78	11.83	9.25	45.76	39.31
284	*I (131)*	0.11	0.11	0.11	0.25	0.05	0.06	2.79	13.78	11.84	9.26	45.79	39.33
295.9	*Eu (152)*	0.11	0.11	0.11	0.24	0.05	0.06	2.83	14.00	12.02	9.41	46.49	39.93
302.9	*Ba (133)*	0.11	0.11	0.11	0.24	0.05	0.06	2.86	14.12	12.13	9.50	46.90	40.28
347.1	*Co (60)*	0.10	0.11	0.11	0.23	0.05	0.05	3.02	14.87	12.77	10.03	49.39	42.42
364.5	*I (131)*	0.10	0.10	0.10	0.23	0.05	0.05	3.08	15.15	13.01	10.23	50.34	43.23
383.9	*Ba (133)*	0.10	0.10	0.10	0.22	0.04	0.05	3.15	15.47	13.28	10.45	51.38	44.12
411.1	*Eu (152)*	0.09	0.10	0.10	0.21	0.04	0.05	3.24	15.89	13.65	10.75	52.80	45.34
444	*Eu (152)*	0.09	0.10	0.10	0.21	0.04	0.05	3.34	16.40	14.08	11.10	54.47	46.77
511	*Na (22)*	0.09	0.09	0.09	0.20	0.04	0.05	3.55	17.38	14.92	11.78	57.75	49.58
637	*I (131)*	0.08	0.08	0.08	0.18	0.04	0.04	3.91	19.13	16.42	12.98	63.54	54.55
661.7	*Cs (137)*	0.08	0.08	0.08	0.17	0.04	0.04	3.97	19.45	16.70	13.20	64.63	55.48
688.7	*Eu (152)*	0.08	0.08	0.08	0.17	0.04	0.04	4.05	19.81	17.00	13.44	65.80	56.48
723	*I (131)*	0.07	0.08	0.08	0.17	0.03	0.04	4.14	20.25	17.38	13.74	67.26	57.74
778.9	*Eu (152)*	0.07	0.07	0.07	0.16	0.03	0.04	4.28	20.95	17.99	14.23	69.60	59.75
826.1	*Co (60)*	0.07	0.07	0.07	0.16	0.03	0.04	4.40	21.54	18.49	14.62	71.54	61.42
867.4	*Eu (152)*	0.07	0.07	0.07	0.15	0.03	0.04	4.51	22.04	18.92	14.97	73.22	62.86
964.1	*Eu (152)*	0.06	0.07	0.07	0.15	0.03	0.03	4.74	23.18	19.90	15.75	77.02	66.12
1000		0.06	0.07	0.07	0.14	0.03	0.03	4.83	23.60	20.26	16.03	78.39	67.29

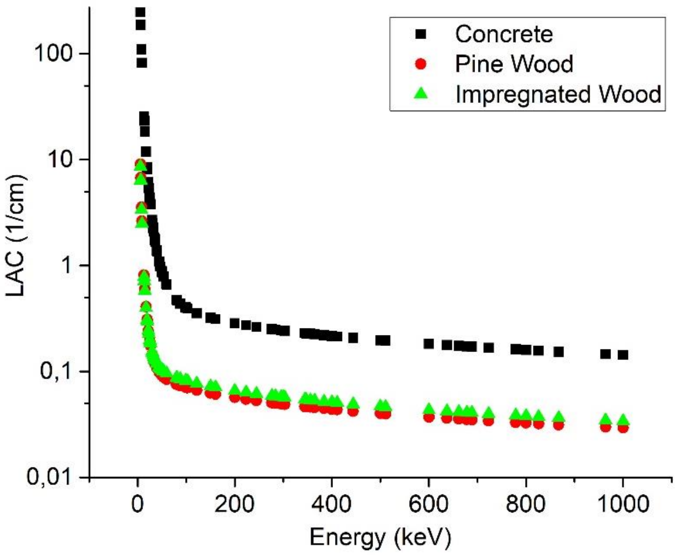

Figure 1. The linear attenuation coefficient

Theoretical MAC values of concrete and wood sample were compared in Figure 2. It is seen that the MAC values of the pine wood reduced gradually from 20.54 to 0.16 cm^2/g for photon energy 5.888 and 103 keV, respectively. After this photon energy the MAC values of the pine wood reduced slowly from 0.16 to 0.07 cm^2/g for photon energy 103 and 1000 keV, respectively. Similarly, the MAC values of the impregnated wood reduced gradually from 16.79 to 0.16 cm^2/g for photon energy 5.888 and 103 keV, respectively (Figure 2.). Similarly, Saritha & Rao, (2013) found that the mass attenuation coefficient decreases as photon energy increases. Shakhreet et al. (2009) found that the MAC of Rhizophora wood for energy 25.27 keV is 0.410 cm^2/g. Marashdeh et al. (2012) showed that the MAC of *Rhizophora* spp. binderless particleboard for energy 25.26 keV is 0.498 cm^2/g. Similarly, in this study, the MAC of pine wood and impregnated wood were found 0.43 and 0.39 cm^2/g at 25 keV, respectively.

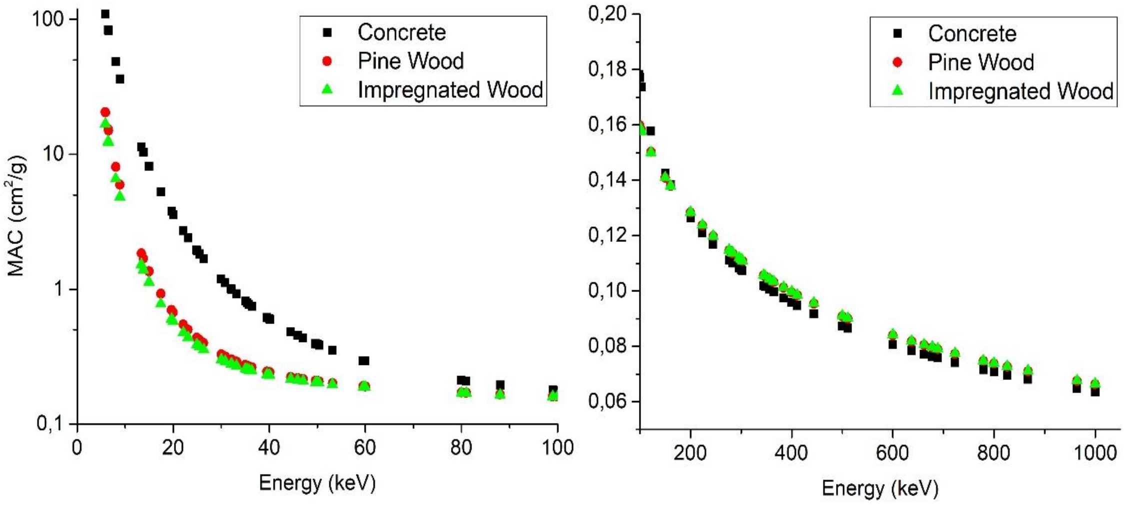

Figure 2. The mass attenuation coefficient

Theoretical values of HVL and TVL of concrete, pine wood and impregnated wood sample were compared in Figure 3. Half-value-layer (HVL) is the quantitative factor most frequently used to describe both the penetrating ability of specific radiations and the penetration through particular materials (Akkaş, 2016). The HVL values of wood change from 0.08 to 23.60 cm for photon energy 5.888 and 1000 keV, respectively. The HVL values of impregnated wood change from 0.08 to 20.26 cm for photon energy 5.888 and 1000 keV, respectively. However, the HVL values of concrete change from 0.003 to 4.826 cm for photon energy 5.9 and 1000 keV, respectively. The HVL is indication of the radiation protection performance, the lower HVL of any sample is showed the better radiation shielding performance due to lower thickness requirements (Agar et al., 2019). The TVL values of pine wood change from 0.25 to 78.39 cm for photon energy 5.9 and 1000 keV, respectively. The TVL values of impregnated wood change from 0.27 to 67.29 cm for photon energy 5.888 and 1000 keV, respectively. However, the TVL values of concrete change from 0.01 to 16.03 cm for photon energy 5.888 and 1000 keV, respectively. The impregnated wood has shown the lower HVL and TVL values than pine wood. The smaller HVL means a better ability to absorb radiation for the materials (Aygün, 2020). The penetrating radiation through a specific thickness of material depends on the energy of the photons and the characteristics (density and atomic number) of the material (Akkaş, 2016). In this study, referenced concrete is a high-density material compared to pine wood and impregnated wood. Also, the shielding performance of the concrete increases as the density increases (Agar et al., 2019).

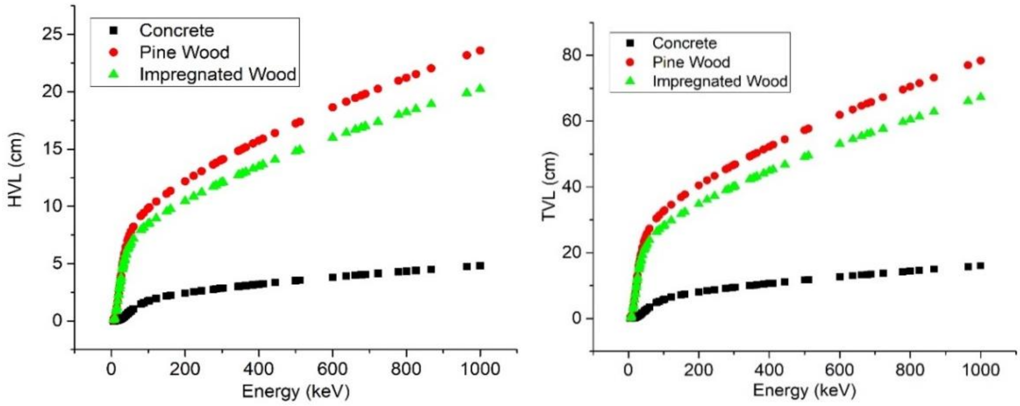

Figure 3. The half value layer and tenth value layer

Conclusion

The present study was carried out to investigate linear attenuation coefficient, mass attenuation coefficient, half value and tenth value layer thickness of pine wood and impregnated wood material. The radiation shielding properties of wood are improved with impregnation with boric acid.

The findings allow the comparison of radiation shielding properties for different building materials and can be used in emergency preparedness models and public exposure estimation in polluted urban areas. This kind of study gives some insight about radiation shielding performance of wood materials. Finally, it may be suggested to work on increasing the shielding performance of wood with different impregnation chemicals, which has a high gamma radiation protection feature compared to concrete.

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