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Analysis of the radiation parameters of pumice constituent compounds using XCOM

R Wirawan[1], **N Qomariyah**[1], **T Ardianto**[1], **and D W Kurniawidi**[1]
[1] Department of Physics, Faculty of Mathematics and Natural Science, University of Mataram, Jl. Majapahit 62 Mataram 83125, Indonesia

E-mail: rwirawan@unram.ac.id

Abstract. In this study, analysis of radiation parameters (linear attenuation coefficient, mean free path and half value layer) of pumice constituent compounds was carried out. Analyzes were done on the compounds of Al_2O_3, Fe_2O_3, SiO_2, CaO, K_2O and Na_2O with a theoretical approach using the XCOM program for gamma photon energies ^{57}Co (0.122 MeV; 0.1365 MeV), ^{133}Ba (0.356 MeV), ^{54}Mn (0.835 MeV), ^{137}Cs (0.662 MeV), ^{60}Co (1.173 MeV; 1.333 MeV), ^{65}Zn (1.1155 MeV), ^{22}Na (0.511 MeV; 1.275 MeV) and ^{40}K (1.461 MeV). The results show that the Fe_2O_3 compound has the largest linear attenuation coefficient, while the largest for MFP and HVL is Na_2O among other compounds.

1. Introduction

The use of radiation is currently growing rapidly in the many fields of medicine, agriculture, security and industry. The important thing that must be considered in the utilization of radiation is avoiding the risk of excessive radiation exposure. Therefore, a type of protective material is used to reduce the radiation intensity. The use of certain materials as radiation shielding becomes an important issue in the development of radiation protection systems, especially to replace lead shield which is toxic [1, 2]. There are several investigations of various materials for radiation shielding such as basalt, marble, granite and limestone [3], gadolinium oxide and oxyfluoride glass [4], bismuth borosilicate glass [5], and pumice [6].

Pumice is a rock that results from volcanic eruptions and its utilization based on the characteristics of its properties, both physical and chemical properties. Pumice can be used as a brick material [7], fine aggregate as a base for making lightweight concrete and as a substitute for cement [8, 9]. The use of pumice can affect the strength and durability characteristics of concrete, especially in high strength concrete [10]. Despite the lead, concrete is one of the composites which applied as shielding wall [11, 12]. To develop the potential of pumice as a radiation shielding material, it is necessary to know the radiation parameters characteristic of its constituent compounds. A good radiation shielding has small half-value layer (HVL) and the mean free path (MFP) parameters. Those values depend on the linear attenuation coefficient and which determined based on the mass absorption coefficient value of the shielding material compounds.

In this study, the analysis of radiation parameters of the pumice constituent compounds was carried out, namely the linear attenuation coefficient, the mean free path and the half-value layer. The analysis used the mass absorption coefficient value which is determined from the photon cross-section (XCOM) program.

2. Method

In this study, the pumice constituent compounds analyzed were six compounds with the largest concentration, namely Al_2O_3, Fe_2O_3, SiO_2, CaO, K_2O, and Na_2O [8, 9,13]. The atomic numbers of the constituent elements are shown in Table 1.

Table 1. The atomic number and mass of the elements of the pumice constituent compounds [14]

Element	Atomic number (*Z*)	Atomic mass (*A*)
O	8	15.9994
Al	13	26.9815
Si	14	28.0855
K	19	39.0983
Ca	20	40.0780
Fe	26	55.8450
Na	11	22.9898

The mean atomic number (Z_{comp}) of a compound or mixture that makes up the pumice can be determined by the formula in equation (1) [15].

$$Z_{comp} = \frac{\sum_{i=1}^{N} w_i Z_i^2 / A_i}{\sum_{i=1}^{N} w_i Z_i / A_i} \tag{1}$$

where N is the number of elements in the compound or mixture, $w_i = \frac{N_i A_i}{M}$ is the weight fraction of *i*th element, N_i is number of atoms, Z_i and A_i are the atomic number and the atomic mass of *i*th element. Table 2 shows the mean atomic number (Z_{comp}) of pumice constituent compounds which calculated using the equation (1).

Table 2. Mean atomic number (Z_{comp}) and density of pumice constituent compounds

Compounds	Atoms of compounds (Z : mass fraction)		Z_{comp}	Density [16] (gr/cm^3)
Fe_2O_3	8:0.30057	26:0.69943	20.315873	5.250
Al_2O_3	8:0.47075	13:0.52925	10.599996	3.965
CaO	8:0.28531	20:0.71469	16.571419	3.340
K_2O	8:0.16985	19:0.83015	17.086981	2.320
SiO_2	8:0.53257	14:0.46743	10.799970	2.320
Na_2O	8:0.25814	11:0.74186	8.280026	2.270

The linear attenuation coefficient (μ) is a radiation parameter that states the total interaction probability (photoelectric, Compton, pair production) of photons with the material, and its value varies depending on the material density (ρ).These coefficients can be determined based on the mass absorption coefficient in equation (2) [17].

$$\mu(E) = \left(\frac{\mu}{\rho}(E) \right) \rho \tag{2}$$

Mass absorption coefficients $\frac{\mu}{\rho}(E)$ of pumice constituent compound are calculated using the photon cross-section program (XCOM Ver. 3.1) with input parameters are element type and the number of

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atoms. The photon energies analyzed are the gamma photon energies from the following sources ^{57}Co (0.122 MeV; 0.1365 MeV), ^{133}Ba (0.356 MeV), ^{54}Mn (0.835 MeV), ^{137}Cs (0.662 MeV), ^{60}Co (1.173 MeV; 1.333 MeV), ^{65}Zn (1.1155 MeV), ^{22}Na (0.511 MeV; 1.275 MeV), and ^{40}K (1.461 MeV). Meanwhile, the mean free path (MFP) and half-value layer (HVL) parameters are determined using the following formula [12].

$$MFP = \frac{1}{\mu} \tag{3}$$

and

$$HVL = \frac{\ln 2}{\mu} \tag{4}$$

3. Result and Discussion

Figure 1 shows a graph of the total mass absorption coefficient of the XCOM output results for six pumice constituent compounds and the mass absorption coefficient of lead (PbO) which is generally used as a radiation shielding material in the photon energy range 0.01 - 20 MeV. The graph of the total mass absorption coefficient shown is a combination of photoelectric interactions, Compton (incoherent) scattering effect and pair production.

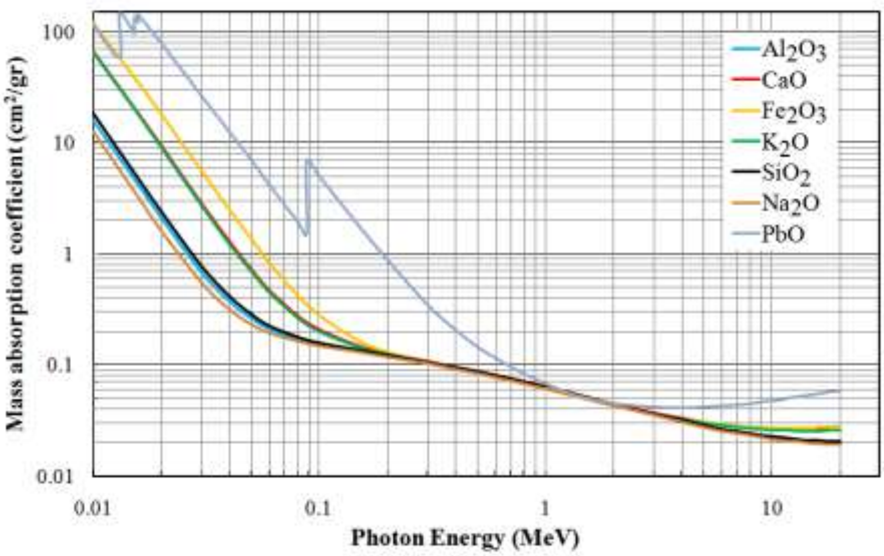
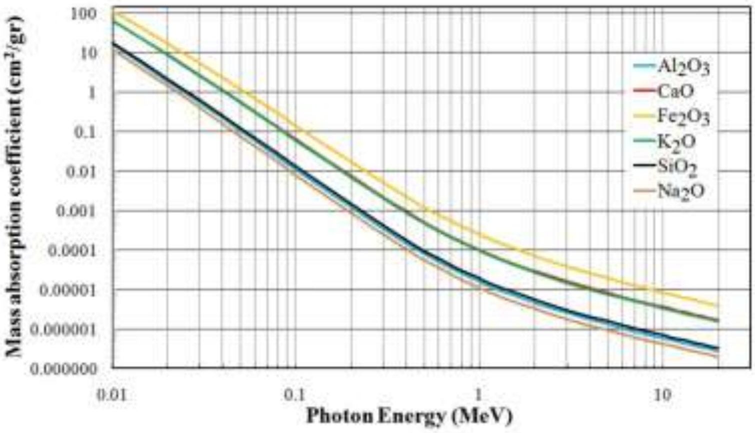
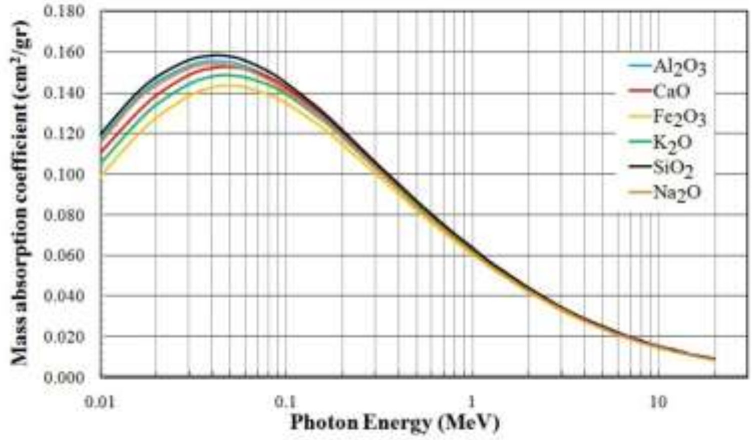


Figure 1. Graph of a mass absorption coefficient of pumice constituent compounds

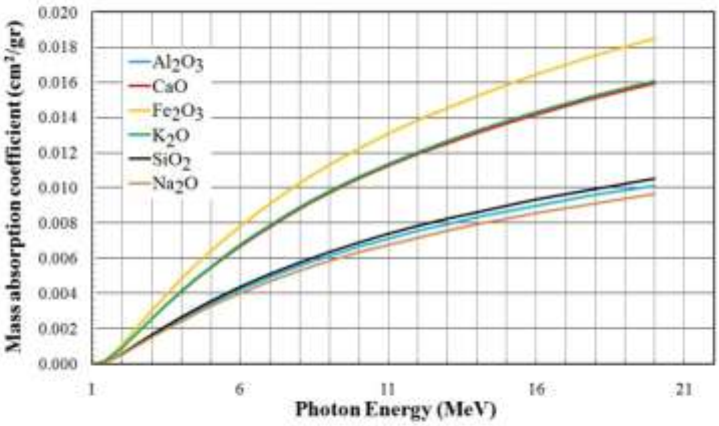
If we observe the graphs in Figure 2(a) and Figure 2(c), it appears that the Fe_2O_3 compound has a higher coefficient value for photoelectric interaction and pair production. The high coefficient value can be explained based on the mean atomic number in Table 2 where the Fe_2O_3 compound has an atomic number greater than the five other forming compounds, is about 20.315873. Meanwhile, the graph of the mass absorption coefficient for the Compton scattering interaction (Figure 2b) shows that the SiO2 compound is higher than the other five compounds. Table 3 shows the mass absorption coefficient for gamma energies from radioactive sources ^{57}Co, ^{133}Ba, ^{54}Mn, ^{137}Cs, ^{60}Co, ^{65}Zn, ^{22}Na and ^{40}K.



(a)



(b)



(c)

Figure 2. Graph of the mass absorption coefficient of (a) photoelectric effect, (b) Compton scattering, and (c) pair production

Table 3. Mass coefficient absorption of pumice constituent compounds for specific gamma energy

Gamma photon energies (MeV)	Mass coefficient absorption (μ/ρ) of pumice compound (cm^2/g)					
	Fe_2O_3	Al_2O_3	CaO	K_2O	SiO_2	Na_2O
0.122 (^{57}Co)	0.2076	0.1422	0.1717	0.1664	0.1457	0.1389
0.1365 (^{57}Co)	0.1817	0.1368	0.1580	0.1534	0.1399	0.1340
0.356 (^{133}Ba)	0.0975	0.0978	0.1005	0.0982	0.0996	0.0965
0.511 (^{22}Na)	0.0830	0.0846	0.0864	0.0845	0.0862	0.0835
0.662 (^{137}Cs)	0.0739	0.0756	0.0772	0.0755	0.0770	0.0746
0.835 (^{54}Mn)	0.0663	0.0680	0.0693	0.0678	0.0693	0.0672
1.115 (^{65}Zn)	0.0575	0.0591	0.0603	0.0589	0.0602	0.0584
1.173 (^{60}Co)	0.0561	0.0577	0.0588	0.0575	0.0587	0.0569
1.275 (^{22}Na)	0.0538	0.0553	0.0563	0.0551	0.0563	0.0546
1.333 (^{60}Co)	0.0526	0.0540	0.0551	0.0539	0.0550	0.0533
1.461 (^{40}K)	0.0503	0.0516	0.0526	0.0515	0.0525	0.0509

Figure 3 shows a graph of the linear attenuation coefficient for the pumice constituent compounds which calculate using equation (2). In the graph, it appears that lowering the linear attenuation coefficient due to the increasing energy of gamma photons. Since the linear attenuation coefficient depends on the material density parameter, and Fe_2O_3 has a greater density compared to the density of the five other constituent compounds. So, Fe_2O_3 has a higher linear attenuation coefficient value than the other five compounds as shown in the graph.

The MFP value indicates a distance between two successive interactions. The MFP will get longer along with the increasing of incoming photon energy. Na_2O has a shorter MFP than other compounds. In addition, an increase of density value of a compound, MFP of the compound is shorter as shown in Figure 4. This is related to the number of atoms of material, where the high density material has a lot of atoms. These results are similar to the results of experimental investigations for MFP of concrete samples obtained by Agar et al. [12].

The HVL value states the thickness of a material needed to be able to pass 50 percent of the radiation intensity that penetrates the material. Table 4 shows the results of the calculation of the HVL value of the pumice constituent compounds for different photon energies. It is observed that the greater of incoming photon energy, requiring the thick material shield. The contribution of the radiation parameters of a compound to the total parameters of pumice radiation depends significantly on that compound content in the pumice. Pumice with a large enough Fe_2O_3 content will makes a significant contribution for attenuating photon radiation intensity.

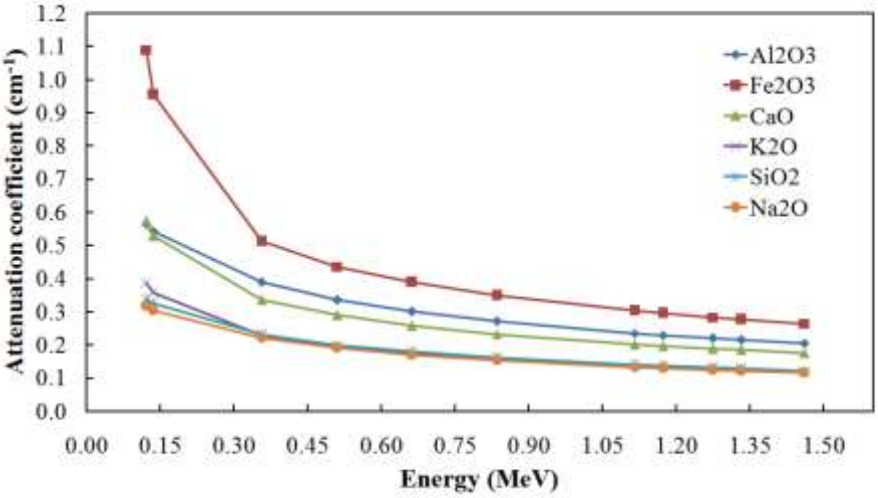


Figure 3. Linear attenuation coefficient of pumice constituent compounds

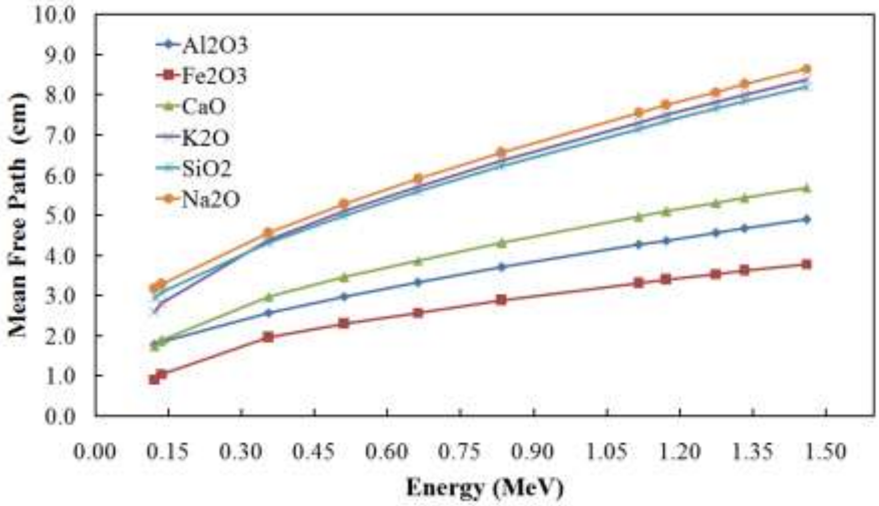


Figure 4. Photon mean free path of pumice constituent compounds.

Table 4. Half-value layer (HVL) of pumice constituent compounds for specific gamma energy

Gamma photon energies (MeV)	HVL pumice constituent compounds (cm)					
	Fe_2O_3	Al_2O_3	CaO	K_2O	SiO_2	Na_2O
0.122 (^{57}Co)	0.6360	1.2294	1.2087	1.7955	2.0506	2.1984
0.1365 (^{57}Co)	0.7266	1.2779	1.3135	1.9477	2.1356	2.2787
0.356 (^{133}Ba)	1.3548	1.7871	2.0650	3.0431	2.9988	3.1639
0.511 (^{22}Na)	1.5907	2.0664	2.4011	3.5362	3.4680	3.6569
0.662 (^{137}Cs)	1.7875	2.3112	2.6896	3.9598	3.8791	4.0910
0.835 (^{54}Mn)	1.9914	2.5697	2.9929	4.4060	4.3125	4.5473
1.115 (^{65}Zn)	2.2949	2.9565	3.4428	5.0699	4.9613	5.2331
1.173 (^{60}Co)	2.3534	3.0318	3.5318	5.1996	5.0881	5.3665
1.275 (^{22}Na)	2.4541	3.1624	3.6835	5.4223	5.3077	5.5976

Gamma photon energies (MeV)	HVL pumice constituent compounds (cm)					
	Fe_2O_3	Al_2O_3	CaO	K_2O	SiO_2	Na_2O
1.333 (^{60}Co)	2.5096	3.2349	3.7671	5.5451	5.4302	5.7257
1.461 (^{40}K)	2.6274	3.3912	3.9462	5.8070	5.6909	6.0014

4. Conclusion

In this work, it was found that Fe_2O_3 has the largest linear attenuation coefficient compared to the other five of the pumice constituent compound. In addition, Na_2O have the largest HVL and MFP parameters. Contribution of those radiation compound parameters to the radiation shielding parameters of pumice depends on its composition in the pumice.

Acknowledgments

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