Original Research Articles

Application of Gamma-Ray Attenuation in Studying Soil Properties

ABSTRACT

The total mass attenuation coefficients, effective atomic numbers and electron densities in some soil samples have been calculated for total and partial photon interactions in the wide energy range of 1 keV–100 GeV. The values of these parameters have been found to change with composition of soil and change in energy whereas their behavior has been found to be identical with all energies. The variations of these parameters with energy are shown graphically for all photon interactions. WinXCOM program was used to calculate theoretically soil mass attenuation coefficients. There is a satisfactory agreement between experimental and theoretical values. The reported data should be useful for comparing these soil in terms of radiation sensitivity and radiation detection.

Kew words: Soil; Mass attenuation coefficients; Effective atomic number; Effective electron number.

INTRODUCTION

Soils have many important functions. Perhaps the best appreciated is the function to support the growth of agricultural crops. The soil's natural cycles go a long way in ensuring that the soil can provide an adequate physical, chemical and biological medium for crop growth. Soil has very much attractive for future not only due to its potential applications in the field of agriculture but also in other applications in constructions, electronics and energy efficient savers. So, it is important to study all possible interactions between photons and atomic nuclei in the superconductor materials. The mass attenuation coefficients, effective atomic number, effective electron density, are basic quantities required to study all possible interactions, they depend on the incident photon energy and the nature of the absorbing material.

In literature, a variety of work relevant to estimating of mass attenuation coefficients, effective atomic numbers for different compound materials has been published by several authors in different categories such as chemical compounds, alloys, glass, minerals, and biological materials and so on. The objective of this study is to calculate mass attenuation, effective atomic numbers and electron densities of some soil samples.

METHOD OF COMPUTATION AND THEORETICAL BASIS

When a material of thickness x is placed in the path of a beam of monoenergetic γ-ray or X-ray radiations, the intensity of the beam will be attenuated according to the Beer–Lambert's law,

$$\mathrm{I} = I_0 e^{-\mu x} \tag{1}$$

where I_0 and I are the incident and attenuated photon intensity, respectively, and μ (cm^{-1}) is the linear attenuation coefficient of the material. Mass attenuation coefficient is a density-independent and more accurately characterizing a given material. Mathematical rearrangement of Eq. (1) yields the following equation for the mass attenuation coefficient ($cm^2.g^{-1}$):

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

where ρ ($g.cm^{-3}$) is the measured density of the material. The total mass attenuation for a material composed of multi elements is the sum of the $(\mu/\rho)_i$ values of each constituent element by the following mixture rule:

$$\left(\frac{\mu}{\rho}\right) = \sum_i c_i \left(\frac{\mu}{\rho}\right)_i \quad (3)$$

where c_i and $(\mu/\rho)_i$ are the weight fraction and the mass attenuation coefficient of the *i*-th component in the absorber, with the condition that:

$$\sum_i c_i = 1 \quad (4)$$

For a chemical compound the weight fraction is given by:

$$c_i = \frac{n_i A_i}{\sum_j n_j A_j} \quad (5)$$

The average atomic cross-section σ_a can be obtained by dividing the molecular cross-section by the total number of formula units as follows:

$$\sigma_a = \sigma_m \frac{1}{\sum_i n_i} \quad (2)$$

Similarly, the average electronic cross-section σ_e is given by

$$\sigma_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i \quad (3)$$

where $f_i = n_i / \sum_j n_j$ and Z_i are fractional abundance and atomic number of constituent element, respectively. n_j is the number of atoms of the constituent element, $\sum_j n_j = n$ is the total number of atoms present in the molecular formula. The effective atomic number, Z_{eff} can now be defined through the relation:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (4)$$

The effective electron number or electron density N_{el} (number of electrons per unit mass) of the material can be derived from:

$$N_{el} = \frac{\left(\frac{\mu}{\rho}\right)}{\sigma_e} = \left(\frac{Z_{eff}}{M}\right) N_A \sum_i n_i \quad (5)$$

RESULTS AND DISCUSSION

Calculations of the mass attenuation coefficients of soil samples were carried out by the WinXCOM program (Gerward et al., 2004). The software can generate cross-sections and attenuation coefficients for elements, compounds or mixtures in the energy range between 1 keV and 100 GeV.

The mass attenuation coefficients (μ/ρ), Z_{eff} and N_{el} of all soil samples were calculated. The result of total mass attenuation coefficients of the studied superconductors is shown in Fig.1. The variation of (μ/ρ) due to chemical composition is energy dependent. In the low energy region, mass attenuation coefficients have the highest values, where the photoelectric absorption is significant and its cross-section is proportional to Z^4. In the intermediate energy region, there is a linear Z-dependence of incoherent scattering and the mass attenuation coefficient is found to be constant. In the high energy region, mass attenuation coefficients increase again, where the pair production is significant and mass attenuation is proportional to Z^2.

For total photon interaction process, the variations of Z_{eff} and N_{el} with photon energy are shown in Figs. 2 and 3. In all materials, the interaction of gamma- or X-rays is related to Z_{eff} value of materials and the energy of photons. There is energy transfer from photon to matter in these interactions. Although the dependence on the photon energy is dominant in interaction with low energies, it can be negligible at high energies. From Fig. 2, it is clear Z_{eff} increases in the investigated superconductors and then decreases up to 10 MeV. Above 100 MeV, Z_{eff} remains almost constant. This may be due to the dominance of pair production in high energy region. The effective atomic numbers of almost all soil higher due to the presence of some high Z constituent elements.

The behavior of Z_{eff} for total interaction reflects the importance of the partial photon interaction processes. At low-energy range ($E < 0.01$ MeV), the maximum value of Z_{eff} is found. At intermediate energies (0.05 MeV < E < 5 MeV), where Compton scattering is the main photon interaction process, Z_{eff} is approximately equal to the arithmetic mean of the atomic number calculated from the chemical formula of the soil samples, $< Z >= \frac{1}{n}\sum_i n_i Z_i$. At high energies, (E > 100 MeV), Z_{eff} is again constant but smaller than in the low-energy range. This is due to the dominance of pair production and the cross-section has Z^2 dependence. It is seen from Table 1, there is a good agreement in Compton scattering region is the main photon interaction process.

The variations of N_{el} with photon energy for total interaction processes (Fig.3) are similar to that of Z_{eff} and can be explained on the similar manner. It can be seen that the value of N_{el} is were found to lie within range of 2.94–3.07×10^{23}electron.g^{-1} as shown in Table 2. This expected behavior for electron densities can be explained on the similar basis as for Z_{eff}. Calculated atomic and electronic cross section of the investigated soil is shown in Fig.4 and 5. Both of σ_a and σ_e are decreased sharply up to 10 MeV and then it is increased slightly with photon energy.

CONCLUSION

The present study has been undertaken to get some information on the mass attenuation coefficients and related parameters, effective atomic numbers and electron density for different types of soil samples. The results of this work can stimulate research for other soil samples. In the interaction of photons with the matter, (μ/ρ) values are dependent on the chemical compositions of the samples. The obtained values of (μ/ρ) are varied with photon energy regions (photoelectric absorption, Compton scattering and pair production). The electron density and effective atomic number are closely related and they are qualitative energy dependence. The dependence on the atomic number indicates that soil having high Z_{eff} absorb powerfully incoming photons. The minimum value is found in the intermediate region, where Compton scattering is dominating and Z_{eff} is approximately equal to the mean atomic number of the soil. The maximum value of Z_{eff} is found in the low energy range, where photoelectric absorption is dominating.

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Table 1. Effective atomic number (Z_{eff}) of investigated soils at different energy (MeV) for total photon interaction.

Energy (MeV)	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
10^{-3}	11.20	10.57	9.96	10.49	10.59
10^{-2}	10.67	10.11	9.49	10.06	10.11
10^{-1}	11.15	10.43	9.85	10.32	10.45
10^{0}	11.38	10.50	10.18	10.39	10.54
10^{1}	11.28	10.47	10.07	10.36	10.50
10^{2}	11.14	10.14	9.94	10.31	10.44
10^{3}	11.14	10.40	9.93	10.30	10.34
10^{4}	11.13	10.40	9.93	10.30	10.34
10^{5}	11.13	10.40	9.93	10.30	10.34

Table 2. Effective electron number ($N_e \times 10^{23}$ electrons/g)) of investigated soil at different energy (MeV) for total photon interaction.

Energy	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5

(MeV)					
10^{-3}	2.94	3.08	2.94	3.09	3.07
10^{-2}	2.80	2.94	2.80	2.97	2.93
10^{-1}	2.93	3.03	2.91	3.04	3.03
10^{0}	2.99	3.06	3.00	3.06	3.05
10^{1}	2.96	3.05	2.97	3.05	3.04
10^{2}	2.92	3.03	2.93	3.04	3.02
10^{3}	2.92	3.03	2.93	3.04	3.02
10^{4}	2.92	3.03	2.93	3.04	3.02
10^{5}	2.92	3.03	2.93	3.04	3.02

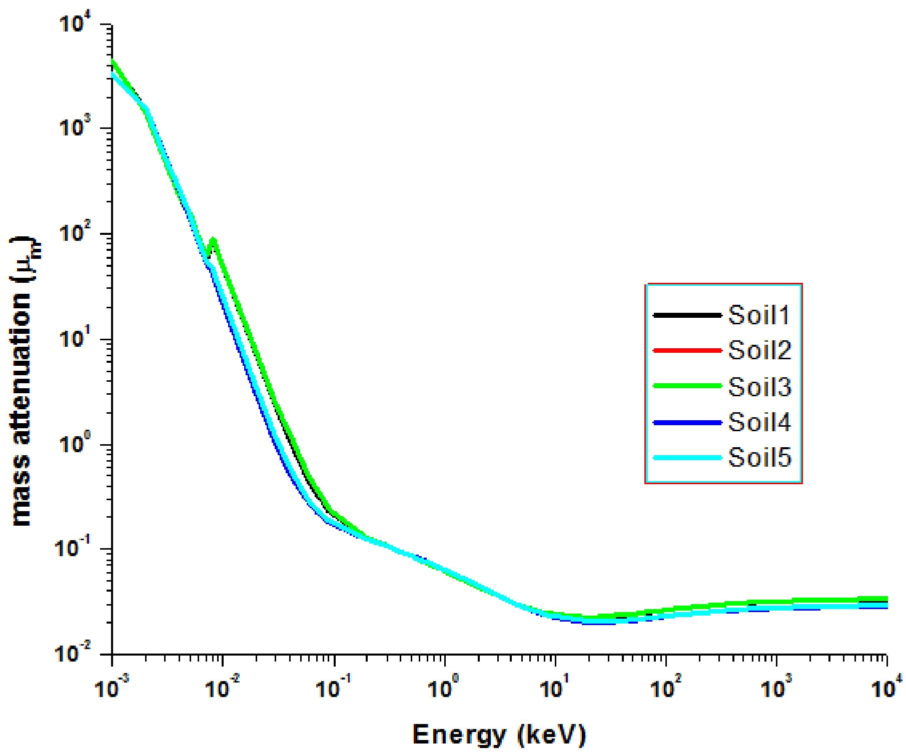

Fig. 1.Variation of photon mass attenuation coefficient of some soil samples with photon energy for total photon interaction.

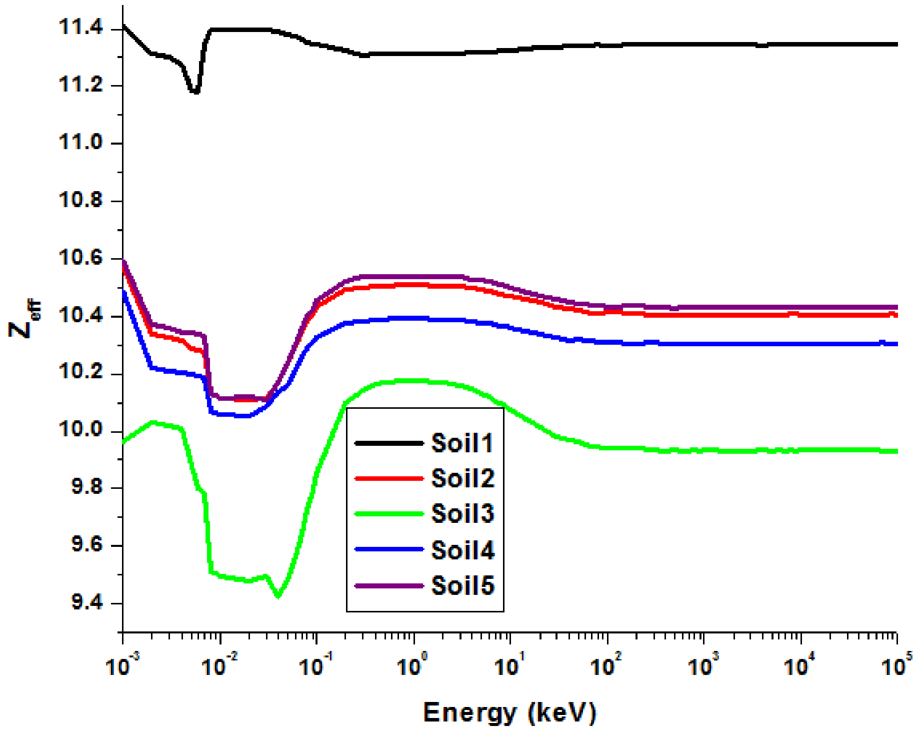

Fig. 2.Variation of Z_{eff} with photon energy of the soil samples for total photon interaction.

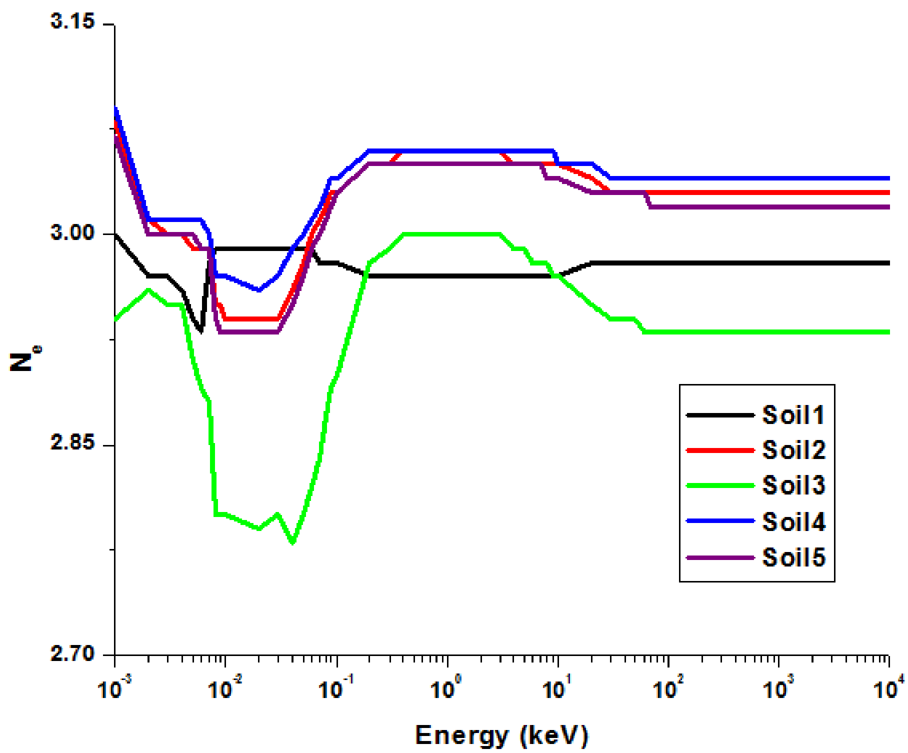

Fig. 3.Variation of $N_{el}$with photon energy of the soil samples for total photon interaction (with coherent).

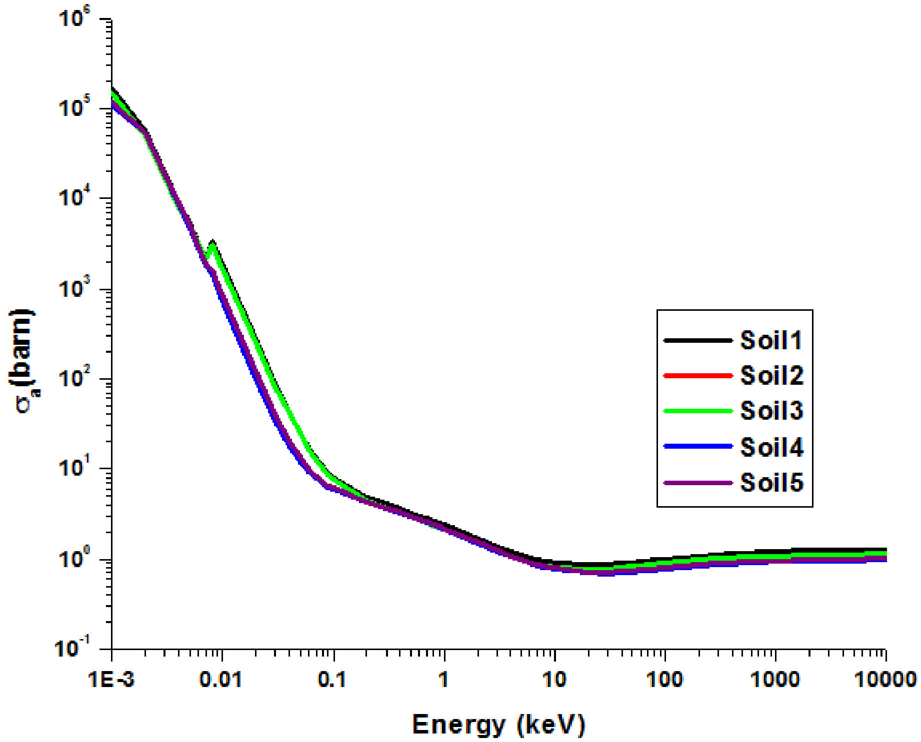

Fig. 4. Variation of atomic cross sections σ_a (b/atom) with photon energy.

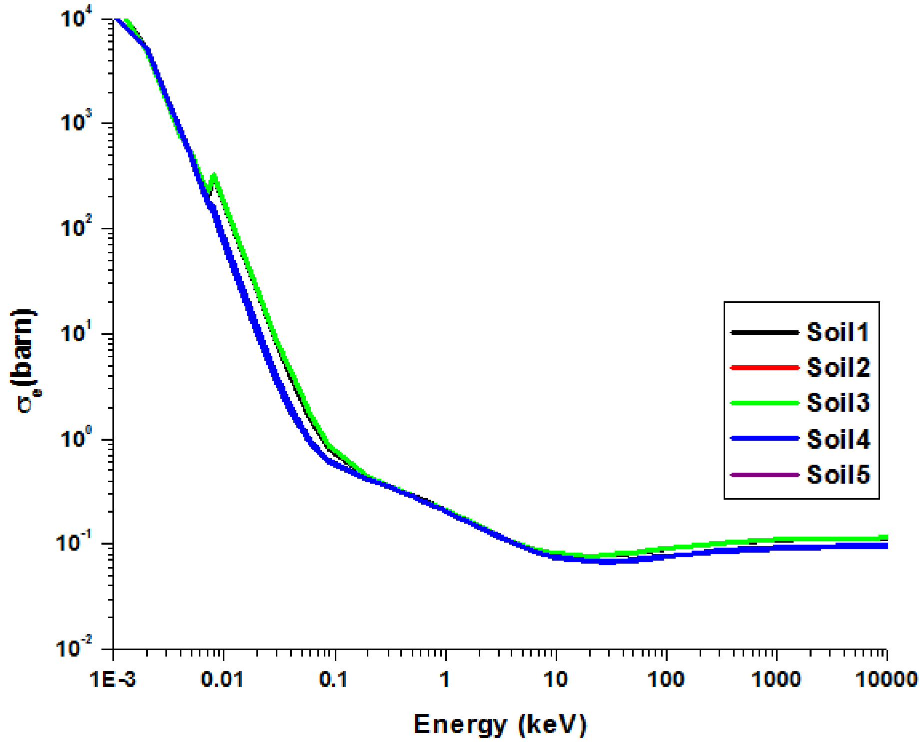

Fig. 5. Variation of atomic cross sections σ_e (b/atom) with photon energy.