Determining photon energy absorption parameters for different soil samples

Nil KUCUK1,*, Zeynal TUMSAVAS2 and Merve CAKIR1

1Department of Physics, Faculty of Arts and Sciences, Uludag University, Gorukle Campus, 16059 Bursa, Turkey
2Department of Soil Science, Faculty of Agriculture, Uludag University, Gorukle Campus, 16059 Bursa, Turkey
*Corresponding author. Department of Physics, Faculty of Arts and Sciences, Uludag University, Gorukle Campus, 16059 Bursa, Turkey. Tel: + 90-224-294-1705; Fax: + 90-224-294-1899; Email: nilkoc@uludag.edu.tr

(Received 23 July 2012; revised 23 October 2012; accepted 24 October 2012)

The mass attenuation coefficients (\(\mu_s\)) for five different soil samples were measured at 661.6, 1173.2 and 1332.5 keV photon energies. The soil samples were separately irradiated with \(^{137}\text{Cs}\) and \(^{60}\text{Co}\) (370 kBq) radioactive point gamma sources. The measurements were made by performing transmission experiments with a 2" × 2" NaI(Tl) scintillation detector, which had an energy resolution of 7% at 0.662 MeV for the gamma-rays from the decay of \(^{137}\text{Cs}\). The effective atomic numbers (\(Z_{\text{eff}}\)) and the effective electron densities (\(N_{\text{eff}}\)) were determined experimentally and theoretically using the obtained \(\mu_s\) values for the soil samples. Furthermore, the \(Z_{\text{eff}}\) and \(N_{\text{eff}}\) values of the soil samples were computed for the total photon interaction cross-sections using theoretical data over a wide energy region ranging from 1 keV to 15 MeV. The experimental values of the soils were found to be in good agreement with the theoretical values. Sandy loam and sandy clay loam soils demonstrated poor photon energy absorption characteristics. However, clay loam and clay soils had good photon energy absorption characteristics.

Keywords: soil sample; gamma-ray transmission; mass attenuation coefficient; effective atomic number; effective electron density

INTRODUCTION

Soils have chemical composition characterized by the presence of major compounds, such as SiO\(_2\), Al\(_2\)O\(_3\), CaO, Fe\(_2\)O\(_3\) and MgO, and have physical properties, including water holding capacity, moistness, particle density, appearance density, porosity, and the concentrations of sand, silt, clay and loam. Soils also contain microelements such as Zn, Cu, Fe and Mn.

The gamma-ray transmission method has been reported as the most accurate and convenient technique for non-destructive measurements of soil parameters, including the linear attenuation coefficient, field capacity, moisture content, bulk density and porosity [1]. In laboratory experiments, lead is used for shielding purposes. In field conditions, soil may be used as a radiation shielding material. The use of soil as the shielding is advantageous from the perspectives of cost and availability [2]. To interpret the behavior and performance of soils as radiation shielding materials, it is important to identify soil photon energy absorption parameters, such as the mass attenuation coefficients (\(\mu_s\)), the effective atomic numbers (\(Z_{\text{eff}}\)) and the effective electron densities (\(N_{\text{eff}}\)).

The photon attenuation coefficient is an important parameter that characterizes the penetration and diffusion of gamma-rays in composite materials such as soils [3]. This coefficient is a measure of the average number of interactions that occur between gamma-rays and the matter mass per unit area. The \(\mu_s\) depends on the chemical composition of the absorbing material and the incident photon energy. However, for the total photon interaction, the variation of \(\mu_s\) with the soil composition is large below 50 keV, and negligible above 300 keV, up to 3 MeV [4]. Studies of \(Z_{\text{eff}}\) provide conclusive information about the target related to the radiation interactions [5]. A commonly used method to determine the \(Z_{\text{eff}}\) value for a composite material is based on the determination of the \(\mu_s\) values for gamma-ray interactions using the transmission method. \(Z_{\text{eff}}\) represents the interaction of radiation with the matter being studied, and is a convenient parameter to consider when designing...
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The linear attenuation coefficient of the dry soil. The linear attenuation coefficient measurements were performed using $^{137}$Cs and $^{60}$Co radioactive sources. The gamma-ray samples, i.e. Soils 1, 2, 3, 4 and 5. The soils under consideration were collected from Bursa (Turkey). The gamma-ray attenuation measurements were performed using $^{137}$Cs and $^{60}$Co radioactive sources.

MATeRIALS AND METHODS

Theory

When a gamma-ray beam passes through a soil sample of thickness $x$ (cm), the photons are transmitted according to Beer–Lambert’s law [56]. This process is expressed as follows:

$$I = I_0 \exp(-\mu x),$$

where $I_0$ is the initial intensity of the gamma-rays, $I$ is intensity of the gamma-rays after attenuation through a soil column of length $x$, and $\mu$ (cm$^{-1}$) is the linear attenuation coefficient of the dry soil. The linear attenuation coefficient can be described as follows:

$$\mu = \left(\frac{\mu}{\rho}\right)\rho,$$

where $\mu = \mu/\rho$ (cm$^2$/g) is the mass attenuation coefficient and $\rho$ is the density of the soil sample. Equation (1) can be rewritten as follows:

$$I = I_0 \exp(-\mu_s d)$$

where $d$ (g/cm$^2$) is the mass thickness of the dry soil sample. Equation (3) may be written in the following linear form:

$$\ln I = -\mu_s d + \ln I_0$$

$\mu_s$ can be obtained from the measured values of $(I/I_0)$ and $d$. The total $\mu_s$ values for materials composed of multiple elements are the sums of the $(\mu_s)$ values of each constituent element according to the following mixture rule [57]:

$$\mu_s = \sum_i W_i(\mu_s)_i,$$

where $W_i$ is the fractional atomic mass of the elements and $(\mu_s)_i$ is the mass attenuation coefficient of the $i$th element in the mixture. For materials composed of multiple elements, the fraction by atomic mass is given by

$$W_i = n_iA_i/\left[\sum_j n_jA_j\right],$$

where $A_i$ is the atomic weight of the $i$th element and $n_i$ is the number of formula units. The total atomic cross-sections ($\sigma$) for the sample can be obtained from the measured values of $\mu_s$ using the following relation [58]:

$$\sigma_t = \left(\frac{1}{N_A}\right)\left(\frac{\mu_s}{\sum_i W_i/A_i}\right),$$

where $N_A$ is Avogadro’s number. The total electric cross-section ($\sigma_e$) is given by the following formula [22]:

$$\sigma_e = \left(\frac{1}{N_A}\right)\sum_i f_iA_i/Z_i(\mu_s)_i = \sigma_t/Z_{eff},$$

where $f_i$ is the number fraction of the atoms of element $i$ relative to the total number of the atoms of all elements in the mixture, and $Z_i$ is the atomic number of the $i$th elements in the mixture. $\sigma_t$ and $\sigma_e$ are related to the $Z_{eff}$ of the material through the following expression [22]:

$$Z_{eff} = \sigma_t/\sigma_e$$

The $N_{eff}$ (number of electrons per unit mass) can be written as following:

$$N_{eff} = (N_A/A_i)(Z_{eff})\sum n_i = \mu_s/\sigma_e$$

The $\mu_s$ values of the materials have been calculated using the WinXCom program [59]. This well-known and widely used program provides the total mass attenuation coefficient and total attenuation cross-section data for approximately 100 elements, as well as the partial cross-sections for incoherent and coherent scattering, photoelectric absorption and pair production at energies from 1 keV to 100 GeV [59]. All computations in the present work have been performed using the WinXCom program.

Experimental details

The soil samples used in this study were taken from a soil tillage depth. The soils were classified as Entisol (Soil 1, Soil 2, and Soil 5), Inceptisol (Soil 3) and Alfisol (Soil 4), according to the Soil Taxonomy [60]. According to the results of the soil analysis, the soils were primarily medium-textured, had neutral or slightly alkaline pHs,
contained different amounts of lime, and primarily had a low organic matter content. There was no salinity problem in the soils. The soil samples considered were analyzed for the percentage of clay, silt and sand using the hydrometer method [61]. Some physical characteristics of the soils, along with their sample codes, are presented in Table 1.

The soil samples were passed through a 2-mm sieve. Each soil was then dried in a 105°C oven for 24 h and packed in a Perspex box. The chemical composition of the soil samples were analyzed using an energy-dispersive X-ray fluorescence (EDXRF) spectrometer from SPECTRO (X-LAB 2000), which had a 400 W Pd end-window X-ray tube, sample trays for 32 mm (20 positions) and 40 mm (12 positions) samples, 47 mm Teflon filters, and an N2-cooled Si (Li) detector with the required electronics (i.e. amplifier, ADC and multichannel analyzer). The EDXRF analyses (major-element compositions and trace-element analyses) were performed in the Bursa Test and Analysis Laboratory (BUTAL). The chemical compositions of these soil samples are given in Table 2. The soil samples studied have different chemical composition and different fractions (i.e. sand, silt and clay).

The schematic arrangement of the experimental set-up used in the present study is shown in Fig. 1. The soil samples were kept in a polyethylene box that was 6.5 cm high and 11 cm in diameter. The point sources were placed on the symmetry axis of the polyethylene box and over the soil level. The samples were separately irradiated with $^{137}$Cs (661.6 keV) and $^{60}$Co (1173.2 and 1332.5 keV) radioactive point sources. Each source had an activity of 10 µCi (370 kBq). The pulse-height spectra of the gamma-rays transmitted through the soil were measured using a $2\times2$ cylindrical NaI(Tl) detector connected to the Canberra Series 40 Multi-Channel Analyzer (MCA) system with 2048 channels. The detector was positioned on the symmetry axis of the box. The detector assembly was surrounded by lead shielding. Both the soil sample and the point source were also surrounded by lead collimators inside the lead castle.

The measurements for all samples were taken to have good statistics and performed three times for each energy value to improve the statistical error. The transmitted spectra were recorded with the MCA for a time period that was sufficient to obtain the desired precision and accuracy of the results. The peak areas were calculated from the

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**Table 1. Some physical characteristics of the soils**

| Soil code | Geographic coordinate of the soils | Soil type | Particle size distribution (%) |
|-----------|-----------------------------------|-----------|--------------------------------|
|           | X(East) | Y (North) | Sand | Silt | Clay | TC | $\rho$ (g/cm$^3$) |
| Soil 1    | 599956  | 4449947   |      |      |      | L  | 1.38         |
| Soil 2    | 598362  | 4451236   |      |      |      | SL | 1.45         |
| Soil 3    | 698495  | 4491031   |      |      |      | SCL| 1.42        |
| Soil 4    | 651463  | 4449239   |      |      |      | C  | 1.24         |
| Soil 5    | 633706  | 4425913   |      |      |      | CL | 1.34         |

TC = Soil Texture Class, L = Loam, SL = Sandy Loam, SCL = Sandy Clay Loam, C = Clay, CL = Clay Loam. (The texture classes are based on USDA classification).

**Table 2. EDXRF analysis results of the dry soil samples**

| Soil code | Na$_2$O | MgO | Al$_2$O$_3$ | SiO$_2$ | P$_2$O$_5$ | K$_2$O | CaO | TiO$_2$ | Cr$_2$O$_3$ | MnO | Fe$_2$O$_3$ | LOI |
|-----------|---------|-----|-------------|---------|------------|--------|-----|---------|------------|------|-------------|-----|
| Soil 1    | 1.39    | 2.44 | 14.62       | 63      | 0.170      | 2.79   | 6.78| 0.5951  | 0.01781   | 0.0733 | 4.312       | 3.6 |
| Soil 2    | 2.02    | 1.3  | 12.75       | 78.4    | 0.32105    | 2.51   | 1.76| 0.5031  | 0.01097   | 0.0735 | 2.79        | <1  |
| Soil 3    | 2.45    | 1.04 | 16.1        | 68.3    | 0.12585    | 1.644  | 3.89| 0.6386  | 0.00738   | 0.1095 | 5.791       | <1  |
| Soil 4    | 0.2305  | 1.94 | 13.14       | 55.9    | 0.11255    | 1.91   | 11  | 0.59955 | 0.027951  | 0.0964 | 4.53        | 10  |
| Soil 5    | 0.11    | 9    | 10.66       | 39.62   | 0.2214     | 0.37945| 15.9| 0.4131  | 0.03778   | 0.0535 | 4.38        | 19.2|

LOI = Loss of Ignition
spectra obtained for each measurement. The \( \mu_s \) values of
the soils were calculated from Equation (4) for known
physical densities using the gamma transmission measure-
ments for the dry soil samples.

The maximum errors in the total mass attenuation coeffi-
cients were calculated from the errors in the intensities
\( I_0 \) (without sample) and \( I \) (with sample) and the errors in the
physical densities, using the following relation:

\[
\Delta \mu = \frac{1}{\rho \chi} \left[ \left( \frac{\Delta I_0}{I_0} \right)^2 + \left( \frac{\Delta I}{I} \right)^2 + \left[ \ln \left( \frac{I_0}{I} \right) \right]^2 \left( \frac{\Delta \rho}{\rho} \right)^2 + \left( \frac{\Delta \chi}{\chi} \right)^2 \right]^{\frac{1}{2}},
\]

where \( \chi \) is the sample thickness in centimeters, \( \Delta I_0, \Delta I \) and
\( \Delta \rho \) are the errors in the intensities \( I_0 \) and \( I \) and the density
\( \rho \), respectively. In these experiments, the net counts \( I_0 \) and
\( I \) were obtained for the same amount of time and under the
same experimental conditions. The overall uncertainty in the
experimental measurements was <3%. This uncertainty is
mainly due to the counting statistics, the thickness measure-
ments, the evaluation of the peak areas, and the scattered
photons reaching the detector.

RESULTS AND DISCUSSION

The \( \mu_s \) values for the different soil samples were also calcu-
lated for photon energies in the range of 1 keV–15 MeV. The
results were plotted versus the photon energy with the
measurement values for energies of 661.6, 1173.2 and
1332.5 keV in Fig. 2. The experimental and theoretical
results are clearly in good agreement for all of the studied
soil samples. Figure 2 shows that the \( \mu_s \) values are large
and show a decreasing trend, with strong energy dependence in the low incident photon energy range of 1–100 keV. In the intermediate (100 keV–1 MeV) and high (1–15 MeV) energy regions, the $\mu_s$ values show a less energy-dependent behavior and gradually decrease with the increasing incident photon energy. Fig. 3 shows the incident photon energy dependence of the measured $\mu_s$ values for all of the studied soils.

Note that $\mu_s$ depends on the incoming photon energies because the partial photon-matter interactions (such as photoelectric absorption, Compton scattering and pair production) in the nuclear and electric fields are different for different photon energies. Due to the dominant photoelectric absorption, the $\mu_s$ values show a strong incident photon energy dependence in the low energy range because $\mu_s$ is inversely proportional ($1/E^{3.5}$ dependence) to the incident energy. The differences observed in the $\mu_s$ values for the soils in the low energy region can be attributed to the dominance of photoelectric absorption because the photoelectric cross-section is strongly dependent ($Z^2$ or $Z^5$ dependence) on the atomic number of the constituent elements [16, 62].

Compton (inelastic) scattering starts to dominate over the photoelectric absorption process when the incident photon energy exceeds ~100 keV, up to ~1 MeV. In this intermediate energy range, no significant differences in the behavior of the different soils are observed because the composition effects play a less significant role in Compton scattering (linear $Z$ dependence) relative to photoelectric absorption.

In the high energy region, the pair production processes in the nuclear and electric fields come into prominence after certain thresholds above 1 MeV are exceeded. The energy dependence of $\mu_s$ thus changes its slope relative to the intermediate energy region.

The $Z_{\text{eff}}$ values for all soil samples have been calculated using Equation (9) for photon energies in the range of 1 keV–15 MeV in 36 energy steps. The results have been plotted against the photon energies, as shown in Fig. 4. In this figure, the theoretical results were also compared with the experimental results performed with photon energies of 661.6, 1173.2 and 1332.5 keV. A good agreement between the theoretical and measurement results has clearly been obtained. The $Z_{\text{eff}}$ values of the soil samples change with a change in the energy. However, the behavior of $Z_{\text{eff}}$ with respect to the energy is rather interesting. The $Z_{\text{eff}}$ values for all of the soil samples show a small decrease with increasing energy in the range of 1–1.5 keV and a sharp increase with increasing energy in the range of 1.5–2 keV. The $Z_{\text{eff}}$ values then sharply decrease again with increasing energy up to 8 keV (up to 10 keV for Soils 2 and 4). The $Z_{\text{eff}}$ values are nearly constant between 8 and 40 keV photon energies (in the energy region of 10–30 keV for Soils 2 and 4). Beyond this energy region, the $Z_{\text{eff}}$ values increase again with increasing energy in the range of 40–300 keV. The $Z_{\text{eff}}$ values are then nearly constant again in the energy region of 300 keV–5 MeV and decrease again with increasing energy, up to 15 MeV. This decrease in the $Z_{\text{eff}}$ values is small but continuous.

This significant variation in the $Z_{\text{eff}}$ values for all of the soil samples is because of the relative domination of the partial photon interaction mechanism (e.g. photoelectric absorption, Compton scattering and pair production). This variation also depends on the range of the atomic numbers of soil constituent elements and the number of elements in the composite material. The atomic numbers of the elements of the selected soils vary from 8 (O$_2$) to 26 (Fe), and a total of 12 elements are considered. As expected, the $Z_{\text{eff}}$ values of the soils lie within the range of the atomic numbers of their constituent elements (8 <$Z_{\text{eff}}$ <26).

The $N_{\text{eff}}$ values for all of the soil samples have been calculated using Equation (10) for photon energies in the range of 1 keV–15 MeV in 36 energy steps. The results have been plotted against photon energies, as shown in Fig. 5. In this figure, the theoretical results were also compared with the experimental results obtained with photon

**Fig. 3.** Measured mass attenuation coefficients of the soil samples at 661.6, 1173.2 and 1332.5 keV.
energies of 661.6, 1173.2 and 1332.5 keV. There are slight differences in the $N_{\text{eff}}$ values for different soils, where a higher value of the electron density would indicate an increased probability of a photon-electron energy transfer and an energy deposition into the material. The $N_{\text{eff}}$ values show a photon–energy dependence similar to that observed for $Z_{\text{eff}}$. This is confirmed in Fig. 6, which shows the correlation of the $Z_{\text{eff}}$ and $N_{\text{eff}}$ values obtained from the theoretical calculation and experimental results.

Different proportions of sand, silt and clay give rise to the different types of loam soils: loam (L), sandy loam (SL), sandy clay loam (SCL), clay (C), clay loam (CL), silt loam and silt clay loam. Sandy loam, due to the larger size of its particles, feels gritty. Clay loam, due to the smaller size of its particles, feels sticky. Silt loam, being moderate in size, has a smooth or floury texture. From Table 1, it can be observed that Soils 1, 2, 3, 4 and 5 have the texture classes of L, SL, SCL, C and CL, respectively. Soils 2 (SL) and 3 (SCL) demonstrate poor photon energy absorption characteristics (i.e. low $\mu_s$, $Z_{\text{eff}}$ and $N_{\text{eff}}$). However, Soils 5 (CL) and 4 (C) soils have good photon energy absorption characteristics (i.e. high $\mu_s$, $Z_{\text{eff}}$ and $N_{\text{eff}}$). These results may be due to the compositional variation among the different types of the soils and the effects of the soil grain size on the gamma-ray attenuation. Furthermore, it can be observed from Table 2 that Soil 5 (CL) has the minimum percentage of SiO$_2$ (39.62%) and the maximum contribution of CaO (15.9%), whereas Soil 2 (SL) has the minimum amount of CaO (1.76%) and the maximum percentage of SiO$_2$ (78.4%). The photon energy-absorption parameters of the

Fig. 4. The effective atomic number of the soil samples as a function of photon energy.

Fig. 5. The effective electron density of the soil samples as a function of photon energy.
clay loam are higher where the CaO weight percentage is greater and that of SiO2 is smaller. The photon energy absorption parameters of sandy loam are also lower where the SiO2 weight percentage is greater and that of CaO is smaller.

CONCLUSION

It can be concluded from this work that the photon energy-absorption parameters depend on the photon energies and the chemical composition of the soil samples. A good agreement was observed between the theoretical calculations and experimental results. The dependence of $\mu_s$ on both the photon energy and soil composition is remarkable in the low incident energy range due to the dominant photoelectric absorption mechanism. The compositional effects and photon energy dependencies are reduced from the intermediate energy range to the high energy range because Compton scattering and pair production processes start to dominate the photon absorption process.

Among the investigated soil samples, the photon absorption effectively increases in the following order: Soil 5 (clay loam) > Soil 4 (clay) > Soil 1 (loam) > Soil 3 (sandy clay loam) > Soil 2 (sandy loam). The sandy loam and sandy clay loam soils demonstrate poor photon energy absorption characteristics (i.e. low $\mu_s$, $Z_{eff}$ and $N_{eff}$). However, the clay loam and clay soils have good photon energy absorption characteristics (i.e. high $\mu_s$, $Z_{eff}$ and $N_{eff}$).

ACKNOWLEDGEMENTS

This work was supported by the Commission of Scientific Research Projects of Uludag University, Project Number UAP(F)-2011/74. We are thankful to the Bursa Test and Analysis Laboratory (BUTAL) and Dr M. Akif Cimenoglu for the EDXRF analysis.

FUNDING

This work was supported by the Commission of Scientific Research Projects of Uludag University, Project Number UAP(F)-2011/74.

REFERENCES

1. Mudahar GS, Sahota HS. A new method for simultaneous measurement of soil bulk density and water content. Int J Appl Radiat Isot 1986;37:563.
2. Brar GS, Sidhu GS, Sandhu PS et al. Variation of buildup factors of soils with weight fractions of iron and silicon. Appl Radiat Isot 1998;49:977–80.
3. Singh M, Mudahar S. Energy dependence of total photon attenuation coefficients of composite materials. Appl Radiat Isot 1992;43:907–11.
4. Mudahar GS, Modi S, Singh M. Total and partial mass attenuation coefficients of soil as a function of chemical composition. Appl Radiat Isot 1991;42:13–8.
5. Singh K, Kaur R, Vandana et al. Study of effective atomic numbers and mass attenuation coefficients in some compounds. Radiat Phys Chem 1996;47:535–41.
6. Hine GJ. The effective atomic numbers of materials for various gamma interactions. Phys Rev 1952;85:725.
7. Henriksen T, Baarli J. The effective atomic number. Radiat Res 1957;6:415–23.
8. Murty RC. Effective atomic numbers of heterogeneous materials. Nature 1965;207:398–9.
9. Parthasaradhi K. Studies on the effective numbers in the alloy for gamma ray interactions in the energy region 100-662 keV. *Indian J Pure Appl Phys* 1968;6:609–13.
10. Jayachandran CA. Calculated effective atomic number and Kerma values for tissue equivalent and dosimetry materials. *Phys Med Biol* 1971;16:617–23.
11. White DR. An analysis of the Z-dependence of photon and electron interactions. *Phys Med Biol* 1977;22:219–28.
12. Manninen S, Koikkakainen S. Determination of the effective atomic number using elastic and inelastic scattering of γ-rays. *Appl Radiat Isot* 1984;35:965–8.
13. Yang NC, Leichner PK, Hawkins WG. Effective atomic number for low-energy total photon interactions in human tissues. *Med Phys* 1987;14:759–66.
14. El-Kateb AH, Abdul-Hamid AS. Photon attenuation coefficient study of some materials containing hydrogen, carbon and oxygen. *Appl Radiat Isot* 1991;42:303–7.
15. Bhandal GS, Ahmed I, Singh K. Determination of effective atomic number and electron density of some fatty acids by gamma-ray attenuation. *Appl Radiat Isot* 1992;43:1185–8.
16. Bhandal GS, Singh K. Photon attenuation coefficient and effective atomic number study of cements. *Appl Radiat Isot* 1993;44:1231–43.
17. Kumar TK, Reddy KV. Effective atomic numbers for materials of dosimetric interest. *Radiat Phys Chem* 1997;50:545–53.
18. Gill H, Kaur G, Singh K et al. Study of effective atomic numbers in some glasses and rocks. *Radiat Phys Chem* 1998;51:671–2.
19. Koç N, Özyol H. Z-dependence of partial and total photon interactions in some biological samples. *Radiat Phys Chem* 2000;59:339–45.
20. Nayak NG, Vijaya MG, Siddappa K. Effective atomic numbers of some polymers and other materials for photoelectric process at 59.54 keV. *Radiat Phys Chem* 2001;61:559–61.
21. Shivaramu, Vijayakumar R, Rajasekaran L et al. Effective atomic numbers for photon energy absorption of some low-Z substances of dosimetric interest. *Radiat Phys Chem* 2001;62:371–7.
22. Singh K, Singh H, Sharma V et al. Gamma-ray attenuation coefficients in bismuth borate glasses. *Nucl Instrum Meth B* 2002;194:1–6.
23. Shakhreet BZ, Chong CS, Bandyopadhyay T et al. Measurement of photon mass–energy absorption coefficients of paraffin wax and gypsum at 662 keV. *Radiat Phys Chem* 2003;68:757–64.
24. İçelli O, Erzeneoğlu S. Effective atomic numbers of some vanadium and nickel compounds for total photon interactions using transmission experiments. *J Quant Spectrosc Radiat Transf* 2004;85:115–24.
25. Akkurt I, Mavi B, Akkurt A et al. Study on Z dependence of partial and total mass attenuation coefficients. *J Quant Spectrosc Radiat Transf* 2005;94:379–85.
26. Manjunathaguru V, Umesh TK. Effective atomic numbers and electron densities of some biologically important compounds containing H, C, N and O in the energy range 145-1330 keV. *J Phys B At Mol Opt Phys* 2006;39:3969–81.
27. Akar A, Baltaş H, Çevik U et al. Measurement of attenuation coefficients for bone, muscle, fat and water at 140, 364 and 662 keV γ-ray energies. *J Quant Spectrosc Radiat Transf* 2006;102:203–11.
28. Manohara SR, Hanagodimath SM. Studies on effective atomic numbers and electron densities of essential amino acids in the energy range 1 keV–100 GeV. *Nucl Instrum Meth B* 2007;258:321–8.
29. Singh MP, Sandhu BS, Singh B. Measurement of effective atomic number of composite materials using scattering of γ-rays. *Nucl Instrum Meth A* 2007;580:50–3.
30. Kaliman Z, Orlić N, Jelovica I. Calculations of effective atomic number. *Nucl Instrum Meth A* 2007;580:40–2.
31. Suresh KC, Manjunatha HC, Rudsarwamy B. Study of Zeff for DNA, RNA and RETINA by numerical methods. *Radiat Prot Dosim* 2008;128:294–8.
32. İçelli O, Erzeneoğlu S, Sağlam M. Effective atomic numbers of polypyrrole via transmission method in the energy range 15. 74–40.93 keV. *Ann Nucl Energy* 2008;35:432–7.
33. Demir L, Han I. Mass attenuation coefficients, effective atomic numbers and electron densities of undoped and differently doped GaAs and InP crystals. *Ann Nucl Energy* 2009;36:869–73.
34. Özdemir Y, Kurudirek M. A study of total mass attenuation coefficients, effective atomic numbers and electron densities for various organic and inorganic compounds at 59.54 keV. *Ann Nucl Energy* 2009;36:1769–73.
35. Manohara SR, Hanagodimath SM, Third KS et al. The effective atomic number revisited in the light of modern photon-interaction cross-section databases. *Appl Radiat Isot* 2010;68:784–7.
36. Baştuğ A, Gürol A, İçelli O et al. Effective atomic numbers of some composite mixtures including borax. *Ann Nucl Energy* 2010;37:927–33.
37. Medhat ME. Studies on effective atomic numbers and electron densities in different solid state track detectors in the energy range 1 keV–100 GeV. *Ann Nucl Energy* 2011;38:1252–63.
38. Baştuğ A, İçelli O, Gürol A et al. Photon energy absorption parameters for composite mixtures with boron compounds. *Ann Nucl Energy* 2011;38:2283–90.
39. Danla N, Baltas H, Celik A et al. Calculation of radiation attenuation coefficients, effective atomic numbers and electron densities for some building materials. *Radiat Prot Dosim* 2011;128:1–9.
40. Kurudirek M. Estimation of effective atomic numbers of some solutions for photon energy absorption in the energy region 0.2–1.5 MeV: An alternative method. *Nucl Instrum Meth A* 2011;659:302–6.
41. Han I, Aygun M, Demir L et al. Determination of effective atomic numbers for 3d transition metal alloys with a new semi-empirical approach. *Ann Nucl Energy* 2012;39:56–61.
43. Mudahar GS, Sahota HS. Effective atomic number studies in different soils for total photon interaction in the energy region 10-5000 keV. *Appl Radiat Isot* 1988;39:1251–4.
44. Oliveira JCM, Appoloni CR, Coimbra MM et al. Soil structure evaluated by gamma-ray attenuation. *Soil Till Res* 1998;48:127–33.
45. Elias EA, Bacchi OOS, Reichardt K. Alternative soil particle-size analysis by gamma-ray attenuation. *Soil Till Res* 1999;52:121–3.
46. Akbal S, Baytas AF. Determination of the photon attenuation coefficients for Turkish soils by gamma transmission. *Bulg J Phys* 2000;27:1–4.
47. Alam MN, Miah MMH, Chowdhury MI et al. Attenuation coefficients of soils and some building materials of Bangladesh in the energy range 276-1332 keV. *Appl Radiat Isot* 2001;54:973–6.
48. Baytaş AF, Akbal S. Determination of soil parameters by gamma-ray transmission. *Radiat Meas* 2002;35:17–21.
49. Elias EA. A simplified analytical procedure for soil particle-size analysis by gamma-ray attenuation. *Comput Electron Agr* 2004;42:181–4.
50. Pires LF, Bacchi OOS, Reichardt K. Soil water retention curve determined by gamma-ray beam attenuation. *Soil Till Res* 2005;82:89–97.
51. Demir D, Ün A, Özgül M et al. Determination of photon attenuation coefficient, porosity and field capacity of soil by gamma-ray transmission for 60, 356 and 662 keV gamma rays. *Appl Radiat Isot* 2008;66:1834–7.
52. Groot AV, Graaf ER, Meijer RJ et al. Sensitivity of in-situ y-ray spectra to soil density and water content. *Nucl Instrum Meth A* 2009;600:519–23.
53. Raje DV, Chaudhari LM. Mass attenuation coefficients of soil samples in Maharashtra State (India) by using gamma energy at 0.662 MeV. *Bulg J Phys* 2010;37:158–64.
54. Ün A, Demir D, Şahin Y. Determination of density and volumetric water content of soil at multiple photon energies. *Radiat Phys Chem* 2011;80:863–8.
55. Medhat ME. Application of gamma-ray transmission method for study the properties of cultivated soil. *Ann Nucl Energy* 2012;40:53–9.
56. Wang CH, Willis DL, Loveland WD. Characteristics of ionizing radiation. In: Wang CH, Willis DL, Loveland WD (eds). *Radiotracer Methodology in the Biological, Environmental and Physics Sciences*, Englewood Cliffs, NJ: Prentice-Hall, 1975, pp. 39–74.
57. Hubbell JH, Seltzer SM. Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV-20 MeV for elements Z=1 to 92 and 48 additional substances of dosimetric interest. National Institute of Standards and Physics Laboratory NISTIR 1995, 5632.
58. Wang DC, Ping LA, Yang H. Measurement of the mass attenuation coefficients for SiH₄ and Si. *Nucl Instrum Meth B* 1995;95:161–5.
59. Gerward L, Guilbert N, Jensen KB et al. WinXCom—a program for calculating X-ray attenuation coefficients. *Radiat Phys Chem* 2004;71:653–4.
60. USDA NRCS [United States Department of Agriculture Natural Resources Conservation Service]. *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys*, 2nd edn, Agriculture Handbook Number: 436, Washington, DC: Government Printing Office, 1999, 863.
61. Gee GW, Bauder JW. Particle size analysis. In: Klute A (ed). *Methods of Soil Analysis. Part 1*. 2nd edn. Madison, WI: Argon. Monogr. 9. ASA, 1986, pp. 383–411.
62. Singh T, Rajni, Kaur U et al. Photon energy absorption parameters for some polymers. *Ann Nucl Energy* 2010;37:422–7.