MEASUREMENT OF MASS ATTENUATION COEFFICIENT OF ZARIA SOIL USING GAMMA RAY TRANSMISSION METHOD

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Abstract

Gamma ray transmission method has been used for the measurement of mass attenuation coefficient of soil samples collected from various locations in Zaria for different gamma energies in the range of 59.5-1332.5 keV emitted by ^{241}Am, ^{60}Co, ^{57}Co, ^{54}Mn, and ^{22}Na standard gamma sources. Total experimental errors ranged from 0.3% to 1.9%. Good agreement was obtained when the result was compared with results obtained in previous work. The results indicated that soil mass attenuation coefficient is dependent on the composition of soil at low energy region whereas it is insensitive to soil composition in the higher energy region.

Keywords: Gamma-ray transmission, single channel analyzer, attenuation coefficient, soil, photoelectric interaction and compton interaction.

1.0 Introduction.

The mass attenuation coefficient is an important parameter in gamma ray transmission measurements involving composite materials such as soil, organic and inorganic materials, alloys and biological materials. It determines the total reduction of X- or Y-radiation at a detector, when there is energy absorption and scattering of the incident X- or Y-radiation. Gamma transmission measurements had been used for studying penetration of gamma rays in soil in order to evaluate different properties of soil and soil-water diffusion processes (Baytas and Akbal, 2002; Vaz *et al.*, 1999; Oliveira *et al.*, 1997). For example, the size distribution of particles, which is important for physical characterization of soil, can be determined using gamma ray attenuation measurements. Several other properties of soil such as soil water content, local water saturation, porosity and field capacity can be determined using gamma ray attenuation as demonstrated by Baytas and Akbal (2002).

Apart from the above applications, the knowledge of mass attenuation coefficient of soil is also important in the development of shielding for X- or γ-rays using materials having high atomic number (and hence high mass attenuation coefficients). However, the use of soil as a radiation protection material require detailed investigation of the effects of its grain size and pressure on gamma-ray attenuation in different energy regions (Mudahar and Sahota, 1988a, 1988b).

Theoretical calculations of soil mass attenuation coefficients had also been carried out in the energy interval 10-300 keV (Mudahar and Sahota, 1988b; Cesareo *et al*, 1994; Hubbel, 1982) using the literature soil concentration data for the major and minor elements

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including SiO_2, Al_2O_3, CaO, MgO, TiO_2, MnO, K_2O, Fe_2O_3, etc. There is however a need to determine experimental values of mass attenuation coefficient at different energies and compare with theoretical values. The main objective of this work is therefore to set up a gamma ray transmission arrangement and use it determine the mass attenuation coefficients of soils in Zaria in order to investigate its behaviour at different gamma energies since to the best of our knowledge such investigation had not been carried out before. Thus soil samples were collected at various locations in Zaria at sampling depths of 0-10 cm and 10-20 cm for the purpose of determining the average mass attenuation coefficient of Zaria soil in the energy range 59.5-1332.5 keV. A gamma-ray spectrometer which makes use of NaI(Tl) detector and a single channel analyzer was used for measuring attenuation in the various soil samples, from which the mass attenuation coefficient values at various gamma ray energies were obtained.

2. Theory

Gamma-rays interact with electrons in the atoms of the various elements in soil by photoelectric effect, Compton-scattering and pair production. These three processes can be expressed as a cross section or attenuation (absorption) coefficient, which depends on the thickness or surface weight x of the target material with which the gamma ray interact. In general, the attenuation of γ-rays in a medium is expressed by:

$$I = I_0 \exp(-\mu x) \qquad (1)$$

where I_0 is the initial intensity of γ-rays, I is the intensity of γ-rays after attenuation in a medium of length x, μ is the linear attenuation coefficient of the material expressed as

$$\mu = (^{\mu}/_{\rho})\rho = \mu_m \rho \qquad (2)$$

where μ_m is the mass attenuation coefficient and ρ is the physical density. μ_m depends on the γ-ray energy, cross section for photon interaction σ and the atomic properties of the material according to the equation:

$$\mu_m = \frac{\sigma Z N_A}{A} \qquad (3)$$

Where N_A is the Avogadro's number, A is the atomic mass of the material and Z is charge number. The linear attenuation coefficient μ is thus given by

$$\mu = \frac{\rho N_a z}{A}\sigma \qquad (4)$$

The term ($\rho N_A Z/A$) is equivalent to δ_e, the number of electrons per cubic centimeter, which is approximately constant for all elements except hydrogen.

In the region covering energy range 5-30 keV, where photoelectric effect is prevalent, the mass attenuation coefficient is proportional to the third power of the effective atomic number, whereas in the region between 300 keV and a few MeV, where Compton effect predominates, the linear attenuation coefficient is a function of the physical density only. The total cross section σ_{tot} is the sum of the contributions from the individual photon interactions processes in the energy range of about 50 keV to > 1 MeV (Cesareo *et al*, 1994) and is given by

$$\sigma_{tot} = \sigma_R + \sigma_{PE} + \sigma_C + \sigma_{pp} \qquad (5)$$

where R, PE, C and PP designate Rayleigh (coherent) scattering, photoelectric effect, Compton (incoherent scattering) and pair production respectively.

3. Materials and Method

Soil samples were collected at various locations in Zaria, namely, Samaru (SM), Shika (SK), Bassawa (BS), Sabon-Gari (SG), and Tudun-Wada (TW). At each location five sampling units were selected. In each of the sampling units, samples were collected at depths of 0-10 cm and 10-20 cm. Samples collected at identical depth interval from the same sampling unit were then combined together to obtain Sub-composite samples. Sub-composite samples from identical depth interval from the various sampling units at each sampling location were subsequently mixed together to obtain composite sample and systematically labeled to reflect the sampling location and sampling depth to avoid mistaken identity. For example, composite sample collected from Samaru sampling location at the sampling depth of 0-10 cm was labeled SM10.

Soil collected from the field, were air-dried and then taken to the laboratory. Each composite sample from each sampling location and sampling depth was spread on a tray and subjected to repeated quartering process to obtain a laboratory sample which is reasonably representative of the composite sample. A portion of the laboratory sample was then ground to finer particles using agate mortar and pestle. The soil samples were then sieved using stainless steel sieve (Endecotts Ltd. London) with an aperture of 250 micron and systematically labeled to reflect the sampling location and depth. The agate mortar and pestle were always washed, dried and cleaned with Acetone and de-ionized water whenever a new sample was to be pulverized in order to avoid cross contamination. Approximately five grams (5g) of each soil sample of particle size 250 μm was again ground in agate mortar and palletized using hydraulic press. The resulting soil pellet was weighed and the process repeated to obtain five pellets each for the 10 composite soil samples. With the soil samples in form of pellets, the thickness of the sample can be varied by stacking several pellets together.

A schematic diagram of the experimental arrangement used for γ-ray attenuation measurement is shown in Fig. 1. It consists of a 7.6 x 7.6-cm NaI(Tl) scintillation detector, which has a resolution of 7% at 662 keV line of ^{137}Cs (Jonah *et al*, 2001) mounted on a photomultiplier tube. The output of the detector was connected directly to the input of the amplifier coupled to a single channel analyzer (Model TC246, Oxford Instruments Inc, 601 Oak Ridge, USA). The choice of single channel analyzer (instead of multi-channel analyzer) was predicated on its higher sensitivity for discrete photon energy with additional compensation for inadequacy in the design of gamma ray shielding for the NaI(Tl) detector. The NaI (Tl) detector was biased to a high voltage of 950 volts and counting of γ-rays transmitted through 2.5 cm diameter discs of soil sample of varying thickness carried out for a preset time.

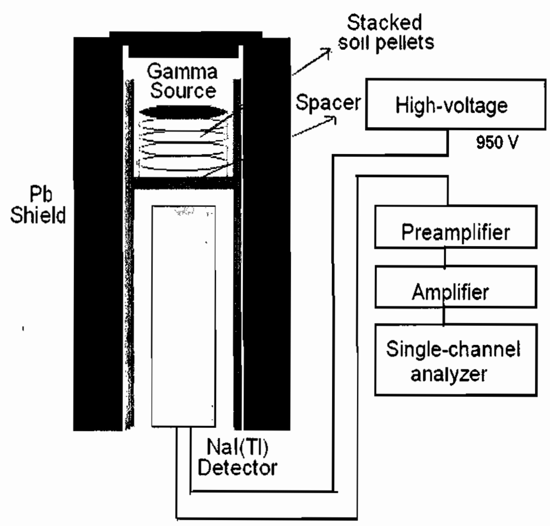

Fig1. Experimental arrangement for gamma transmission measurement

Three sets of measurements were taken in order to determine the mass attenuation coefficient of the soil samples. These are (i) the incident beam intensity (ii) the attenuated beam intensity and (iii) the background. The sample/source holder was marked to

indicate the position where the sample and source were to be placed in order to obtain a reproducible geometry. For measurements involving only the γ-ray source and γ-ray/sample arrangement, the source was positioned normal to the NaI(Tl) detector and the distance between the source/sample and the detector maintained at 5 cm. Errors introduced by variation in the average thickness of the sample was minimized by carrying out attenuation measurement for several thicknesses of the pellets which may be varied by stacking a fixed number of pellets together.
The thickness of each pellet (or disc) was measured at various locations across its surface using Vernier calipers to determine a thickness profile for each pellet. The value of the integrated column was determined as the product of the density and the thickness of the soil pellets. The average integrated column density represents the three-dimensional variation of the density within the absorber and thus provides the best macroscopic measure of the total amount of absorbing material in the path of the γ-rays. The masses of the soil pellets were determined by weighing using a Mettler balance that can measure as low as 100μg. The samples were weighed a number of times to determine the repeatability and stability of the mass measurements. The bulk density of the soil samples were also determined by measuring the mass and volume of the loose soil that had been pulverized and reduced to a particle size of 250 μm. The mass attenuation coefficient was determined from the average of the attenuation for various thicknesses of the soil pellets using the physical density, in the equation
The value calculated using equation (6) is in respect of the physical density of the various soil sample thicknesses. Thus a correction factor based on the bulk density of the soil was incorporated to determine the value of the mass attenuation coefficients for soil samples collected at various locations in Zaria. The above procedures was then repeated for the various soil samples for various γ-ray sources including ^{241}Am, ^{60}Co, ^{57}Co, ^{54}Mn, and ^{22}Na whose characteristics are displayed in Table 1, with the pellet density thickness maintained at 4.048-4.288 g/cm^2. The distance between source/sample and the NaI(Tl) detector was also set at 5.0 cm.

4. Results and Discussion

Table 2 shows the values obtained for the mass attenuation coefficients of dry soil collected at various locations in Zaria at γ-ray energy of 661.6 keV. The value for each sampling site is the mean value obtained from the measurements of the various thicknesses of the soil pellets. The uncertainties in the measurement were determined by

Table: Standard gamma sources used for gamma transmission measurement

Parent radionuclide	Date of production	Activity (kBq)	Half-life $T_{1/2}$	Energy (keV)	Abundance
^{241}Am	1st July 2004	36.50	432.2 years	59.5	35.50
^{60}Co	15th July 2004	38.40	5.263 years	1173.2	99.87
				1332.5	99.98
^{137}Cs	15th July 2004	36.90	30.00 years	661.6	85.00
^{54}Mn	15th July 2004	38.40	312.5 days	834.8	100.0
^{22}Na	1st July 2004	36.90	2.6 years	1274.5	99.70
^{57}Co	1st July 2004	36.90	271.80 days	122.1	85.60
				136.5	10.60

calculating the standard error obtained from the repetitive measurements in order to account for variation in the counts due to the random nature of γ-ray emission. The slight variation of the mass attenuation coefficient with location and depth as observed in Table 2 can be attributed to natural Inhomogeneity of the soil samples and to the low intensity of the ^{137}Cs used for the measurement. The mean value of 0.084±0.003 obtained for Zaria soil at γ-ray energy of 661.6 keV compares reasonably well with values obtained by other workers as indicated in Table 3. The slight difference can only be attributed to differences in experimental arrangement and procedure and not to the differences in soil composition since at 661.6 keV the Compton contribution to the photon interaction process is almost 100%.

Table 3 also shows the variation of the mass attenuation coefficients as a function of γ-ray energies with literature values included. This is also depicted in Fig. 2. It is readily observed that the mass attenuation coefficient decreases with γ-ray energy within the low energy region of γ-rays, but exhibit negligible variat-ion at higher energy region of γ-rays, most especially in the Compton region. Since the mass attenuation coefficient is dependent on the effective atomic number at low energy region where the photoelectric interaction process is dominant, it can be deduced that at low energy region of γ-rays, the mass attenuation coefficient is dependent on the composition of soil. However at high energy region where the mass attenuation coefficient exhibit negligible variation with energy, it can be deduced that it is insensitive to soil composition due to the fact that the dominant Compton interaction process is independent of Z.

Table 2. Mass attenuation coefficient of Zaria soil.

Sampling location	Sampling depth (cm)	Mass atten. Coeff. (cm^2/g)
Samaru	0-10	0.079±0.002
	10-20	0.083±0.001
Sabongari	0-10	0.082±0.002
	10-20	0.084±0.001
Basawa	0-10	0.083±0.001
	10-20	0.087±0.002
Shika	0-10	0.084±0.002
	10-20	0.086±0.001
Tudunwada	0-10	0.086±0.001
	10-20	0.087±0.001
Mean Value	0-10&10-20	0.084±0.001

Table 3. Measured soil mass attenuation coefficient as a function of γ-ray energy.

Energy (keV)	Present work μ_m (cm^2/g)	Appoloni and Rio (1994) μ_m (cm^2/g)	Corey *et al* (1971) μ_m (cm^2/g)	Davisson *et al* (1968) μ_m (cm^2/g)
59.5	0.204±0.019	0.267±0.001	0.370	
122.1	0.140±0.005	0.140±0.002		
661.6	0.084±0.003	0.080±0.002	0.078	0.077
1275.0	0.078±0.003			
1332.5	0.079±0.004	0.068±0.002		

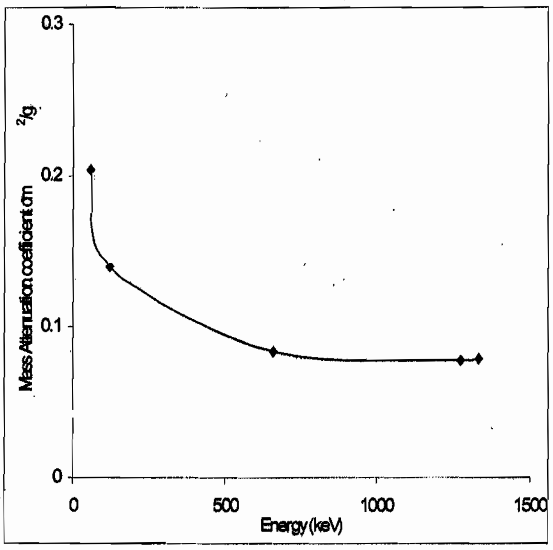

Fig.2: Mass attenuation coefficient vs. energy for Zaria Soil.

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