DOI: 10.15415/jnp.2013.11009

Partial as Well as Total Photon Interaction Effective Atomic Numbers for Some Concretes

Tejbir Singh[1] **and Parjit S. Singh**[2]

[1]Department of Physics, Sri Guru Granth Sahib World University, Fatehgarh Sahib, Punjab, India
[2]Department of Physics, Punjabi University, Patiala-147002, Punjab, India.

Email: dr.tejbir@gmail.com

Abstract Photon interaction effective atomic number (Z_{eff}) for partial as well as total photon interaction processes has been computed using logarithmic interpolation method for seven different concretes viz. (i) Ordinary, (ii) Hematite - Serpentine, (iii) Ilmenite - Limonite, (iv) Basalt - magnetite, (v) Ilmenite, (vi) Steel - scrap and (vii) Steel - magnetite concrete in the wide energy range from 10.0 keV to 100 GeV. It has been concluded that this method has an advantage over the atomic to electronic cross-section ratio method especially for mixtures in the intermediate energy level. However, due to lack of experimental data in the higher energy region, it is difficult to discuss, its validity in these energy regions.

Keywords: Photon interactions, mass attenuation coefficient, effective atomic number, concrete.

1. INTRODUCTION

The use of nuclear energy is ever increasing in different fields like industry, medicine and agriculture etc. However, the recent nuclear reactor explosions in Japan emphasized the need of systematic and precise studies of basic radiation shielding parameters. Mostly, the nuclear reactor shields consist of different layers of concretes with different densities. In the present work, an attempt has been made to compute effective atomic numbers for seven types of concretes, with an aim of designing effective radiation shield design.

For photon interactions, it is not possible to assign a single number to composite materials similar to atomic number of the elements has been pointed out for the first time by [1]. So, for composite materials, the "effective atomic number (Z_{eff})" is calculated from atomic numbers of the constituent elements, weighted according to the different partial interaction process by which photon interacts and hence it is an energy dependent parameter. It signifies that at a given energy, a composite material would interact with photons in the similar way as a single element of atomic number equivalent to that of a composite material.

Many researchers had contributed in finding out the effective atomic numbers of composite materials such as for solvents [2], organic acids [3], alloys [4], soils [5], glasses [6], polymers [7] and for some thermoluminescent dosimetric compounds [8] etc. Different methodologies were applied by different research groups, but the

Journal of Nuclear Physics, Material Sciences, Radiation and Applications
Vol. 1, No. 1
August 2013
pp. 97–105

CHITKARA UNIVERSITY

most common were (i) by taking the ratio of atomic to electronic cross-section of the composite material and (ii) interpolating the cross-section values of composite material among the cross-section values of the elements. In our previous work, [2, 3] the merits and demerits of both the methods have been discussed and for the present work, second method has been adopted.

For the present investigations, concrete has been selected, which is construction material, widely used than any other man-made material in the world due to its high strength and long life. There are many types of concrete available depending on the proportions of the main ingredients. Further, this variation in the ingredient materials depends on the application of concrete in different situations such as requirement of strength, chemical and thermal resistance properties etc. It has been in use for the construction of thick walls at the nuclear reactor sites also.

The radiation shielding parameters of some concretes has been provided by [9, 10, 11] in terms of very fundamental parameters such as attenuation cross-sections and attenuation coefficients. Recently, [12] had investigated the effect of adding different aggregates in concretes on radiation shielding.

In the present work, an attempt has been made to extend that work by using the fundamental tool (mass attenuation coefficient) to provide effective atomic number for partial as well as total photon interaction processes for some concretes. Present studies will definitely help in case of nuclear accidents, to compute effective dose for indoor people in the buildings made up of one of these concretes.

The chemical composition and densities of the selected concretes has been given by [10].

2. COMPUTATIONAL WORK

Using WinXCom software [13], the attenuation cross-section data for partial as well as total photon interaction processes of first twenty six elements and mass attenuation coefficient values for partial as well as total photon interaction processes of the selected concretes (by substituting the weight fraction of different constituent elements as given in Table 1) as well as of the constituent elements was generated in the wide energy range from 10 keV to 100 GeV.

Using above obtained mass attenuation co-efficient values of the concretes $(\mu_m)_{concrete}$ for partial as well as total photon interaction processes, its attenuation cross section ($\sigma_{concrete}$) values were computed using the relation [2]:

$$\sigma_{concrete} = \frac{(\mu_m)_{concrete}}{N \sum_i \left(\frac{w_i}{A_i} \right)} \tag{1}$$

Table 1: Chemical Composition and Densities of the selected concretes

S. No.	Concrete	Chemical Composition (by weight fraction)	Density (in g/cc)
1	Ordinary	H: 0.0094, C: 0.0009, O: 0.5366, Na: 0.0046, Mg: 0.0012, Al: 0.0132, Si: 0.3674, S: 0.0008, K: 0.0031, Ca: 0.0565, Fe: 0.0063	2.30
2	Hematite-serpentine	H: 0.0129, O: 0.4351, Mg: 0.0664, Al: 0.0167, Si: 0.1053, S: 0.0009, Ca: 0.0597, Fe: 0.3031	2.50
3	Ilmenite-limonite	H:0.0066, O:0.3645, Mg:0.0015, Al: 0.0080, Si: 0.0306, S: 0.0008, Ca: 0.0583, Ti: 0.1603, Fe: 0.3693	2.90
4	Basalt-magnetite	H: 0.0083, O: 0.4230, Na: 0.0106, Mg: 0.0220, Al: 0.0422, Si: 0.1320, P: 0.0020, S: 0.0009, K: 0.0029, Ca: 0.0888, Ti: 0.0060, Mn: 0.0012, Fe: 0.2601	3.05
5	Ilmenite	H: 0.0057, O: 0.3593, Na: 0.0006, Mg: 0.0131, Al: 0.0061, Si: 0.0240, S: 0.0007, Cl: 0.0002, K: 0.0003, Ca: 0.0388, Ti: 0.1964, Fe: 0.3478	3.50
6	Steel-scrap	H: 0.0070, C: 0.0009, O: 0.2109, Na:0.0045, Mg: 0.0009, Al: 0.0120, Si: 0.1049, S: 0.0006, K: 0.0030, Ca: 0.0428, Fe: 0.6125	4.00
7	Steel-magnetite	H: 0.0051, O: 0.1570, Mg: 0.0058, Al: 0.0066, Si: 0.0268, P: 0.0008, S: 0.0006,Ca: 0.0395, Mn: 0.0007, Fe: 0.7573	5.11

where $N = 6.023 \times 10^{23}$ is the Avogadro number, w_i and A_i are weight fraction and atomic weight of the i^{th} constituent element of a concrete respectively.

The attenuation cross-section values of concretes so obtained were then interpolated in the attenuation cross-section values of elements generated from WinXCom at same selected energies to compute the effective atomic number for the concretes using the following logarithmic interpolation formula [2]:

$$Z_{eff} = \frac{Z_1(\log\sigma_2 - \log\sigma_{concrete}) + Z_2(\log\sigma_{concrete} - \log\sigma_1)}{\log\sigma_2 - \log\sigma_1} \quad (2)$$

where σ_1 and σ_2 are the elemental cross-section in between which the atomic cross-section of the concretes $\sigma_{concrete}$ lies and Z_1 and Z_2 are atomic number of the elements corresponding to the cross-sections σ_1 and σ_2, respectively.

In our previous works, [2, 3], it has been clarified that logarithmic interpolation method has advantages over the other methods for theoretical computation of effective atomic number. These are: (i) it is directly applicable to mixtures (for which weight fraction is known), (ii) along with the effective atomic number for total photon interaction process, it also provides in detail, the contribution due to different partial photon interaction processes viz. Rayleigh, Compton, photo-electric, pair production in nuclear as well as electric field.

Moreover, it has been also concluded that in the intermediate energy region, the effective atomic number values computed by this method is equally good as compared with the other methods. This method has been also preferred here as in the present case, all the selected concretes are made up of multi-elements (more than five elements). In case, the number of atoms (integer value) corresponding to each constituent element will be computed using the weight fraction (real values) of the selected concretes, it will result in introducing significant error in the computations of effective atomic number with other method (based on the ratio of atomic to electronic cross-section).

3. RESULTS AND DISCUSSION

The variation of the effective atomic number values of the selected concretes for partial as well as total photon interaction processes with the incident photon energy is shown in Figs. 1–6. Due to the presence of different constituent elements in different fractions, different effective atomic numbers are observed for different concretes. Moreover, the dependence of photon interaction processes on atomic number and incident photon energy can be clearly seen in Figs. 1–5.

The effective atomic number for different concretes computed on the basis of Rayleigh scattering (coherent scattering) has been shown in Fig. 1. Almost constant behavior of effective atomic number with incident photon energy has been observed for different concretes. Steel magnetite concrete shows maximum values for the effective atomic number in the entire energy region, whereas minimum values were observed for ordinary concrete. It can be explained on the basis of weight fraction of iron ($_{26}Fe$). In all the selected concrete, the maximum atomic number constituent element is iron and the weight fraction of iron is maximum in steel magnetite (75.73%).

Similarly, depending on the weight fraction of iron (highest - Z constituent element) in different concretes, different effective atomic numbers has been observed. Almost similar behavior for effective atomic numbers of concrete with incident photon energy has been observed in other photon interaction processes such as for Compton scattering in Fig. 2, photoelectric absorption in Fig. 3, pair production in nuclear field in Fig. 4 and pair production in electric field in Fig. 5. Further, Fig. 4 and 5 have been plotted on different energy scales due to different threshold values of pair production in nuclear (1.022 MeV) and electric fields (2.044 MeV).

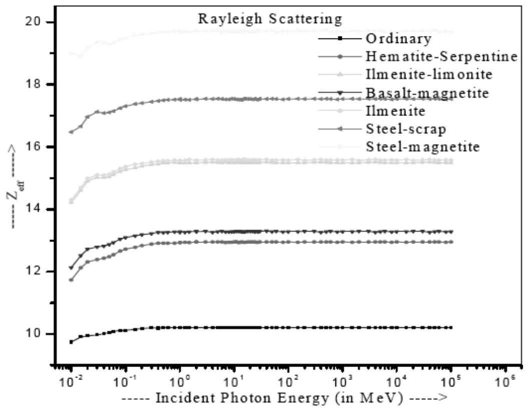

Figure 1: Variation of effective atomic number (Rayleigh) with incident photon energy for the selected concretes.

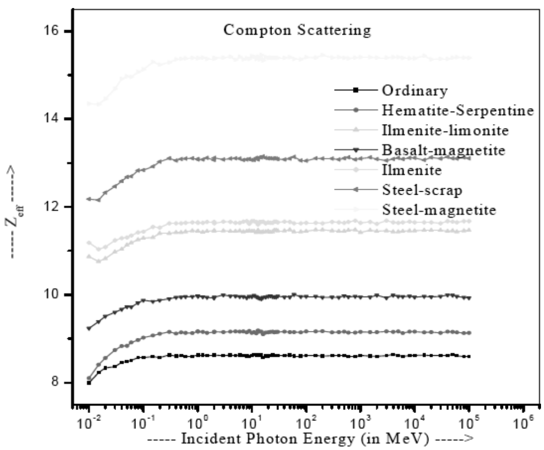

Figure 2: Variation of effective atomic number (Compton) with incidentphoton energy for the selected concretes.

The combined contribution of different partial photon interaction processes has been shown in Fig. 6. Since different photon interaction processes behaves differently in different energy regions, hence significant variation in effective atomic number for the selected concretes with incident photon energy has been observed. Broadly, it can be divided into three parts.

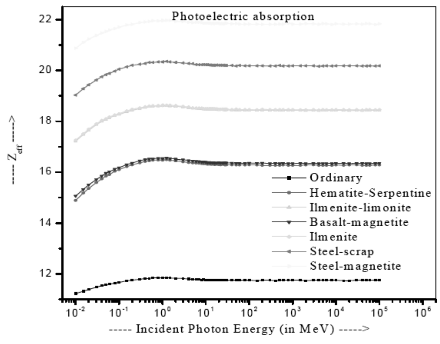

Figure 3: Variation of effective atomic number (Photoelectric) with incident photon energy for the selected concretes.

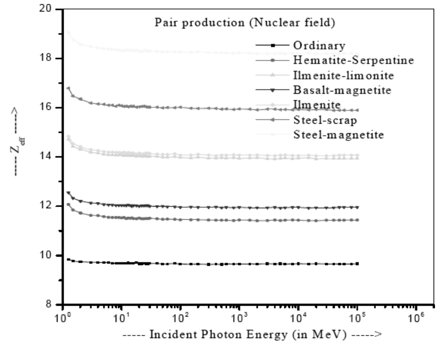

Figure 4: Variation of effective atomic number (pair production in nuclear field) with incident photon energy for the selected concretes.

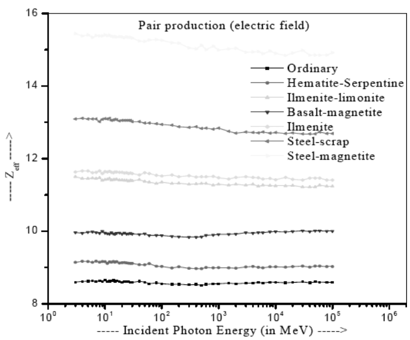

Figure 5: Variation of effective atomic number (pair production in electric field) with incident photon energy for the selected concretes.

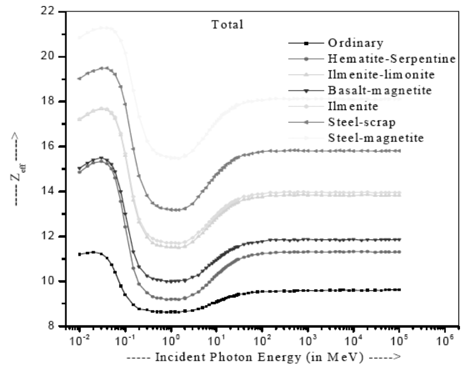

Figure 6: Variation of effective atomic number (total) with incident photon energy for the selected concretes.

First part is the lower energy region (10 keV – 300 keV), in which photoelectric effect is dominant photon interaction process. The rapid decrease in the effective atomic number values with increasing energy has been observed in this region. The cross-section for photoelectric absorption varies with atomic number as Z^{4-5} and with incident photon energy as $E^{-3.5}$. Due to the strong dependence of photoelectric process on atomic number and energy, maximum variation has been observed in this region.

Second part is the intermediate energy region (300 keV – 3 MeV), in which Compton scattering is the dominant photon interaction process. The effective atomic number values remains almost constant in this region. The cross-section for the Compton scattering varies linearly with the atomic number and it decreases with the increase in incident photon energy. Hence, minimum variation has been observed in this region due to weak dependence of Compton scattering on atomic number and energy.

Finally, the third part is the high energy region (3 MeV – 100 GeV), in which pair production is the dominant photon interaction process. Effective atomic number values increases slowly and thereafter becomes almost constant in this region. The cross-section for pair production varies with atomic number as Z^{2-3} and with incident photon energy as log(E). Hence, significant variation has been observed in this energy region.

From Figure 6, it has been also observed that the variation of effective atomic number for concretes with higher weight fraction of iron (i.e. more than 30%) is more, such as in case of steel scrap ($_{26}$Fe ~ 61%, minimum value of Z_{eff} =13.18 and maximum value of Z_{eff} =19.49 and ΔZ_{eff} = 6.31), steel magnetite ($_{26}$Fe ~ 76%, minimum value of Z_{eff} =15.47 and maximum value of Z_{eff} =21.28 and ΔZ_{eff} = 5.81). Whereas variation of effective atomic number for concretes with lower weight fractions of iron is less, such as ordinary concrete ($_{26}Fe$ ~ 0.6%, minimum value of Z_{eff} =8.63 and maximum value of Z_{eff} =11.30 and ΔZ_{eff} = 2.67). Further, the less variation in effective atomic number of ordinary concrete can also be explained on the basis of its major constituent elements which are oxygen ($_{8}O$ ~ 54%) and silicon ($_{14}Si$ ~ 37%). Since the difference in the atomic number of major constituent elements is less, hence the difference in the effective atomic number is also less.

It has been also observed from all the figures that in the entire energy region, the steel magnetite concrete shows maximum values for effective atomic number (for partial as well as total photon interaction) and moreover, its density is also maximum among the selected concretes (as shown in Table 1). Therefore, it will act as better gamma rays shielding material amongst the selected concretes.

4. CONCLUSIONS

From the present investigation, following conclusions can be made:

- The logarithmic interpolation method not only provides easier methodology for effective atomic number computations for mixtures but also provides effective atomic numbers for partial interaction processes viz. Rayleigh scattering, Compton scattering, photoelectric absorption, Compton scattering, pair production in nuclear as well as electric field.
- The effective atomic numbers for partial interaction processes viz. Rayleigh scattering, Compton scattering, photoelectric absorption, Compton scattering, pair production in nuclear as well as electric field confirms that for a particular process, the effective atomic number remains almost constant (within deviation of less than 5%) in the wide energy region from 10 keV to 100 GeV.
- Using higher weight fraction of higher atomic number elements as concrete constituents; results in providing better shielding from gamma ray photons.
- Among the selected concretes, *steel magnetite* possesses highest effective atomic number as well as density; hence it will offer better gamma ray shielding. In case of nuclear reactor accidents, the building made from this concrete will offer better shielding from radiations to indoor people.

REFERENCES

[1] Hine G.J., 1952. The Effective Atomic Numbers of Materials forVarious Gamma Ray Interactions. *Phy. Rev.,* **85,** 725.

[2] Singh T., Kaur P., Singh P.S., 2007. A study of photon interaction parameters in some commonly used solvents. *J. Radiol. Prot.*, **27,** 79-85. http://dx.doi.org/10.1088/0952-4746/27/1/005

[3] Singh T., Kaur P., Singh P.S., 2007a. Variation of mass attenuation coefficient, effective atomic number and electron density with incident photon energy of some organic acids. *Nucl. Sci. Engg.* **156,** 229-243.

[4] Kurudirek M., Buyukyildiz M., Ozdemir Y., 2010. Effective atomic number study of various alloys for total photon interaction in the energy region of 1 keV–100 GeV. *Nucl. Instru. Meth. A*. **613,** 251-256. http://dx.doi.org/10.1016/j.nima.2009.11.061

[5] Mudahar G.S., Modi S., Singh M., 1991, Energy dependence of the effective atomic numbers of soils, *Ind. J. Phys*. **65B,** 226.

[6] Kaewkhao J., Limsuwan P., 2010. Mass attenuation coefficients and effective atomic numbers in phosphate glass containing Bi_2O_3, PbO and BaO at 662 keV. *Nucl. Instru. Meth. A*. **619,** 295-297. http://dx.doi.org/10.1016/j.nima.2009.11.033

[7] Icelli O., Erzeneoglu S., Saglam M., 2008. Effective atomic numbers of polypyrrole via transmission method in the energy range 15.74–40.93 keV. *Ann. Nucl. Energy.* **35,** 432-437. http://dx.doi.org/10.1016/j.anucene.2007.07.007

[8] Gowda S., Krishnaveni S., Yashoda T., Umesh T.K., Gowda R., 2004. Photon Mass Attenuation Coefficients, Effective Atomic Numbers and Electron Densities of Some Thermoluminescent Dosimetric Compounds *Pramana J. of Phys*. **63,** 529-541.

[9] Abdo El-S., 2002, Calculation of the cross-sections for fast neutrons and gamma-rays in concrete shields, *Ann. Nucl. Energy* **29,** 1977-1988. http://dx.doi.org/10.1016/S0306-4549(02)00019-1

[10] Bashter I.I., 1997. Calculation of radiation attenuation coefficients for shielding concretes *Ann. Nucl. Energy* **24,** 1389-1401. http://dx.doi.org/10.1016/S0306-4549(97)00003-0

[11] Akkurt I., Basyigit C., Kilincarslan S., Mavi B., Akkurt A., 2006. Radiation shielding of concretes containing different aggregates. *Cem. Conc. Comp*. **28,** 153-157. http://dx.doi.org/10.1016/j.cemconcomp.2005.09.006

[12] Kharita M.H., Yousef S., AlNassar M., 2009. The effect of carbon powder addition on the properties of hematite radiation shielding concrete. *Prog. Nucl. Energy*. **51,** 388-392. http://dx.doi.org/10.1016/j.pnucene.2008.10.002

[13] Gerward L., Guilbert N., Jensen K.B., Levring H., 2001. X-ray absorption in matter. Reengineering XCOM. *Radiat. Phys. Chem.* **60,** 23-24. http://dx.doi.org/10.1016/S0969-806X(00)00324-8

Dr. Tejbir Singh is Assistant Professor in Physics at Sri Guru Granth Sahib World University, Fatehgarh Sahib, Punjab. He has been working in the field of Radiation Physics since last ten years. He has published and presented more than fifty research papers in journals of international repute and conferences of national and international level. His research interest includes theoretical computation of various photon interaction parameters and experimental analysis of gamma rays spectroscopic data.

Dr. Parjit S. Singh is Professor of Physics at Punjabi University, Patiala, Punjab. He has been working in the field of Radiation Physics since last twenty five years. His research interests includes handling radioactive sources, Nuclear Radiation Detectors and counting systems such as multiple channel analyzer, Electronic equipment's, analysis of gamma rays spectroscopic data, Designing and Fabricating various experimental geometries relating to nuclear radiation spectroscopy.