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ARTICLE

Comparison of mass attenuation coefficients of concretes using FLUKA, XCOM and experiment results

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Abstract – The mass attenuation coefficients of seven different types of normal and heavy concretes like ordinary, hematite-serpentine, ilmenite-limonite, basalt-magnetite, ilmenite, steel-scrap and steel-magnetite concretes has been simulated using FLUKA Monte Carlo code at high energies 1.5, 2, 3, 4, 5 and 6 MeV. The mass attenuation coefficients and linear attenuation coefficient of the concretes were found dependent upon the chemical composition, density and gamma ray energy. FLUKA Monte Carlo code results were found in good agreement with experimental and theoretical XCOM data. Our investigations for high energy gamma-ray interaction validate the FLUKA Monte Carlo code for use where experimental gamma-ray interaction results are not available.

Keywords: gamma / mass attenuation coefficients / FLUKA / XCOM

1 Introduction

Rapid increase in investigations of radiation interaction processes in computer environment using the Monte Carlo simulation has made easy nuclear engineering and technology. The Monte Carlo simulation is used in radiation transportation, shielding, detector response, medical applications and radio-biology, etc. The simulation process is the method for study of high-energy radiation interaction process where experiments are not possible. The shielding efficiency of a compound or a mixture is characterized by mass attenuation coefficients. The mass attenuation coefficients are a principle parameter for gamma-ray interaction. Other gamma-ray interaction parameters (*e.g.* half-value layer, tenth-value layer, effective atomic number and effective electron density) are being derived by using the mass attenuation coefficients. Therefore, it is essential to investigate the mass attenuation coefficients of materials used in shielding applications for nuclear reactors, accelerators, medical facilities, radiation protection and radiation dosimetry, etc. The radiation shielding has been a thrust area for optimization of radiation protection. The shielding materials are chosen as combination of low- and high-Z elements for gamma-ray and neutron (Bashter, 1997; Singh and Badiger, 2012). Various types of normal and heavy concretes shielding materials have been developed to minimize the construction cost of reactor biological shielding and containments with improved shielding efficiency materials (Bashter, 1997; Shirmardi *et al.*, 2013). The glasses as transparent shielding materials are also being used in nuclear reactors (Singh *et al.*, 2014). Various investigations have been done for calculation of shielding parameters and effectiveness of the different types of concretes (Makarious *et al.*, 1988; Bashter *et al.*, 1996; Makarious *et al.*, 1996; Bashter, 1997; Singh and Badiger, 2012; Akkurt and El-Khayatt, 2013; Shirmardi *et al.*, 2013; Singh *et al.*, 2014). Bashter (1997) experimentally investigated the attenuation coefficients (shielding parameters) of concretes. The simulations of gamma-ray for shielding application are found elsewhere in literatures. The shielding for reactor core and accelerator are designed using the Monte Carlo code simulation results.

The gamma-ray interaction is characterized by partial interactions namely, photoelectric absorption, Compton scattering and pair production depending upon the energy and atomic number of the material or effective atomic numbers of the compound or mixture. The theoretical values for mass attenuation coefficients and cross sections for different elements, compounds and mixtures have been tabulated by Berger and Hubbell and given in the form of XCOM program at energies 1 keV to 100 GeV (Berger *et al.*, 2010). The new version of this software, called WinXcom (Gerward *et al.*, 2004) is nowadays used as user-friendly software to generate the desired data in Microsoft excel file in windows operating system.

FLUKA is a general purpose Monte Carlo simulation package for calculations of particle transport and interactions

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with matter. It is being used in various applications such as proton, electron accelerators shielding design, activity, dosimetry, detector design, cosmic rays, neutron physics, radiotherapy, accelerator driven system, etc. Also, it is useful in many scientific areas (high energy experimental physics and engineering, detector and telescope design, medical physics and radio-biology). FLUKA can simulate with high accuracy the interaction of more than 60 different types of particles such as heavy-ions, electrons, neutrons, photons, neutrinos, muons, and their antiparticles in many types of research fields and applications (Ferrari *et al.*, 2005; Battistoni *et al.*, 2007; Mark *et al.*, 2007). The FLUKA can be used for transport of synchrotron radiation and optical photons too. FLUKA simulation code has been used in low- and intermediate-energy gamma-ray for investigation of radiation characteristics of soil (Wielopolski *et al.*, 2005), shielding materials (Agosteo *et al.*, 2005), X-, gamma-ray or radiation protection (Nariyama *et al.*, 2003; Beskrovnaia *et al.*, 2008), neutron shielding characteristics (Korkut *et al.*, 2010), and water, concrete and bakelite (Demir *et al.*, 2013). FLUKA code has been used in low- and intermediate-energies for gamma ray calculation of mass attenuation coefficients and good agreement is observed with experimental results (Demir *et al.*, 2013). However, the FLUKA has not been tested for high-energy gamma ray with experimental results. This has encouraged us to utilize the FLUKA for gamma-ray interaction parameters for high-energies.

The aim of the present study is investigation of mass attenuation coefficients for high energy gamma-ray for ordinary, hematite-serpentine, ilmenite-limonite, basalt-magnetite, ilmenite, steel-scrap and steel-magnetite concretes using FLUKA code. First of all, the mass attenuation coefficients of the selected concretes for photon energy 1.5, 2, 3, 4, 5 and 6 MeV were calculated by using FLUKA code, and the linear attenuation coefficients were estimated. Finally the simulated results of linear attenuation coefficients were compared with the experimental data provided in the literature (Bashter, 1997). Good agreement among FLUKA code, XCOM data and experimental results for high energy gamma-ray was observed. The variation of mass attenuation coefficients determined using FLUKA code is shown graphically.

2 Materials and computational method

Different types of normal and heavy concretes have been taken in the literature of Bashter (1997), whose elemental compositions and densities are given in Table 1. These concretes are ordinary (OR), hematite-serpentine (HS), ilmenite-limonite (IL), basalt-magnetite (BM), ilmenite (IT), steel-scrap (SS) and steel-magnetite (SM) used in various applications of the shielding.

2.1 FLUKA Monte Carlo simulation code

The Monte Carlo method is based on random numbers and mathematical algorithms (Ramirez-Lopez *et al.*, 2011). It can be applied for physical systems, especially in nuclear science and engineering (Ferrari *et al.*, 2005; Battistoni *et al.*, 2007) as a Monte Carlo simulator. It is a Monte Carlo package used in interactions between all subatomic particles and matter. It has many advantages in terms of wide energy range. There are several studies using this Monte Carlo simulation code (Korkut *et al.*, 2010, 2011, 2012; Ramirez-Lopez *et al.*, 2011; Singh *et al.*, 2015).

Table 1. Elemental compositions of different types of concretes (Bashter, 1997).

Sr. No.	Type	Density ($g.cm^{-3}$)	Elemental composition (%)
1.	OR	2.3	H (0.94), C (0.09), O (53.66), Na (0.46), Mg (0.12), Al (1.32), Si (36.74), S (0.08), K (0.31), Ca (5.65) and Fe (0.63)
2.	HS	2.5	H (1.29), O (43.51), Mg (6.64), Al (1.67), Si (10.53), S (0.09), Ca (5.97) and Fe (30.31)
3.	IL	2.9	H (0.66), O (36.45), Mg (0.15), Al (0.80), Si (3.06), S (0.08), Ca (5.83), Ti (16.03) and Fe (36.93)
4.	BM	3.05	H (0.83), O (42.30), Na (1.06), Mg (2.20), Al (4.22), Si (13.20), P (0.20), S (0.09), K (0.29), Ca (8.88), Ti (0.60), Mn (0.12) and Fe (26.01)
5.	IT	3.5	H (0.57), O (35.93), Na (0.06), Mg (1.31), Al (0.61), Si (2.40), S (0.07), Cl (0.02), K (0.03), Ca (3.88), Ti (19.64) and Fe (34.78)
6.	SS	4	H (0.70), C (0.09), O (21.09), Na (0.45), Mg (0.09), Al (1.20), Si (10.49), S (0.06), K (0.30), Ca (4.28) and Fe (61.25)
7.	SM	5.11	H (0.51), O (15.70), Mg (0.58), Al (0.66), Si (2.68), P (0.08), S (0.06), Ca (3.95), Mn (0.07) and Fe (75.73)

In the simulations, the latest version of FLUKA (2011.2b.4) was used. We have obtained I/I_0 photon transmission values at 1.5, 2, 3, 4, 5 and 6 MeV photon energies by means of FLUKA code. The simulation has been done for all types of concretes. Linear attenuation coefficient is calculated using Lambert Beer Law ($I/I_0 = \exp(-\mu x)$). In this law, I_0 is photon transmission, I is linear attenuation coefficient and x is the thickness of the sample. After the simulation process gamma transmission values have been read from FLUKA output file.[1]

2.2 XCOM program

The transmission of gamma-ray ($I = I_0 \exp(-\mu t)$) is dependent upon the thickness, t of the interacting medium and linear attenuation coefficient, μ. The μ is calculated by multiplication of mass attenuation coefficients, μ/ρ and density. The μ/ρ of the concretes are calculated by the mixture rule $\left((\mu/\rho)_{concrete} = \sum_{i}^{n} w_i (\mu/\rho)_i\right)$ where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the *i*th element by using XCOM or WinXcom. The linear

[1] Detailed information can be seen in the fluka web page www.fluka.org.

Table 2. Linear attenuation coefficients of the concretes by XCOM, experiment (Bashter, 1997) and FLUKA Monte Carlo code at 1.5, 2, 3, 4, 5 and 6 MeV ordinary, hematite-serpentine, ilmenite-limonite, basalt-magnetite, ilmenite, steel-scrap and steel-magnetite.

Energy (MeV)	Ordinary			Hematite-Serpentine			Ilmenite-limonite		
	XCOM	Exp.	FLUKA	XCOM	Exp.	FLUKA	XCOM	Exp.	FLUKA
1.5	0.1193	0.1640	0.1178	0.1289	0.1240	0.1292	0.1463	0.1590	0.1451
2	0.1028	0.1160	0.1027	0.1115	0.1050	0.1111	0.1268	0.1180	0.1258
3	0.0837	0.0990	0.0828	0.0917	0.0930	0.0917	0.1052	0.1010	0.1046
4	0.0730	0.0870	0.0721	0.0809	0.0880	0.0806	0.0937	0.0920	0.0932
5	0.0661	0.0780	0.0649	0.0742	0.0800	0.0744	0.0867	0.0860	0.0861
6	0.0615	0.0780	0.0600	0.0699	0.0820	0.0695	0.0823	0.0860	0.0821

Energy (MeV)	Basalt-Magnetite			Ilmenite			Steel-Scrap		
	XCOM	Exp.	FLUKA	XCOM	Exp.	FLUKA	XCOM	Exp.	FLUKA
1.5	0.1566	0.1390	0.1568	0.1761	0.2000	0.1752	0.2013	0.1960	0.1998
2	0.1355	0.1100	0.1351	0.1527	0.1538	0.1522	0.1749	0.2080	0.1741
3	0.1114	0.0950	0.1110	0.1266	0.1284	0.1260	0.1460	0.1790	0.1452
4	0.0984	0.0820	0.0980	0.1127	0.1148	0.1124	0.1310	0.1580	0.1306
5	0.0902	0.0850	0.0900	0.1044	0.1121	0.1039	0.1223	0.1720	0.1217
6	0.0849		0.0844	0.0991		0.0984	0.1169		0.1170

Energy (MeV)	Steel-Magnetite		
	XCOM	Exp.	FLUKA
1.5	0.2545	0.2200	0.2526
2	0.2216	0.2030	0.2205
3	0.1861	0.1840	0.1861
4	0.1681	0.1800	0.1674
5	0.1579	0.1740	0.1569
6	0.1519		0.1512

attenuation coefficient of the concrete is multiplication of μ/ρ and the density of the concrete. The atomic number and atomic mass of elements have been taken from atomic weight of elements 2011, IUPAC (Michael *et al.*, 2013). The uncertainties in μ/ρ values is about 1% for low-Z ($1 < Z < 8$) in Compton region (30 keV to 100 MeV). Below 30 keV energy, the uncertainties are as much as 5–10% because of correction to experiments for high-Z impurities and departure of Compton cross section from Klein-Nishina theory.

3 Result and discussion

The linear attenuation coefficients, μ and mass attenuation coefficients, μ/ρ of the concretes have been investigated for high-energy (1.5, 2, 3, 4, 5 and 6 MeV) gamma-rays. Comparison of linear attenuation coefficients by using FLUKA code and experiment are provided in Table 2. The variation of mass attenuation coefficients for the ordinary concrete is shown in Figure 1.

3.1 Linear attenuation coefficients

The linear attenuation coefficient, μ of the concretes by FLUKA code, XCOM and experiment are shown for photon energies 1.5, 2, 3, 4, 5 and 6 MeV in Table 2. It is observed that the linear attenuation coefficients simulated using FLUKA, XCOM and the experiment are in very good agreement. Therefore, it is concluded that the FLUKA is a useful simulation code for high energy gamma-rays interactions where data may not be available, analogous to the experiment.

3.2 Mass attenuation coefficient

The mass attenuation coefficients, μ/ρ using FLUKA code for ordinary concrete (as an example) with gamma-ray energy is shown in Figure 1. These μ/ρ values of the concretes decrease with the increase of gamma energy. The similar variation of the μ/ρ values with XCOM program can be found. The variation of the μ/ρ can be explained based on the partial interaction process Compton scattering and pair-production in the high energy gamma-rays. The experimental data of μ/ρ of the concretes at energies 1.5, 2, 3, 4, 5 and 6 MeV can be calculated using the linear attenuation coefficients. The mass attenuation coefficients are parameterized by polynomial fitting of order two.

The linear attenuation coefficients of various types of high photon energies (1.5, 2, 3, 4, 5 and 6 MeV) concretes using FLUKA simulation in the present investigation shows that FLUKA simulation is a very effective and capable tool for simulation of shielding materials at low, medium [19] as well as high energies.

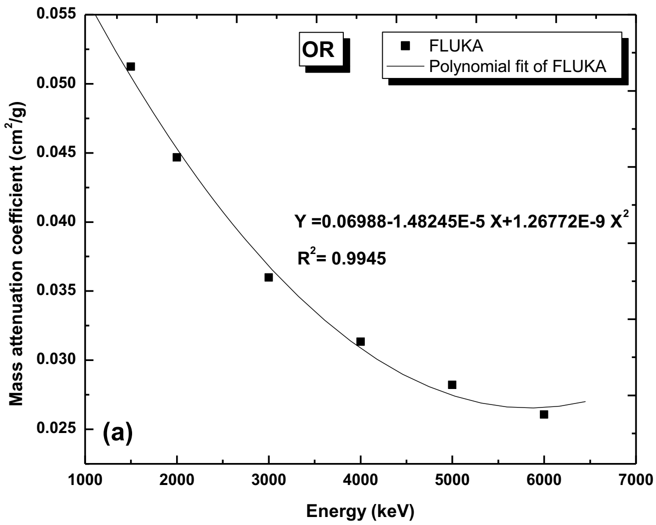

Fig. 1. Mass attenuation coefficients of ordinary concretes using FLUKA Monte Carlo simulation codes.

4 Conclusion

The mass attenuation coefficients, μ/ρ and linear attenuation coefficients, μ of different types of normal and heavy concretes, ordinary, hematite-serpentine, ilmenite-limonite, basalt-magnetite, ilmenite, steel-scrap and steel-magnetite are compared for FLUKA simulation, experimental and XCOM theoretical data for energies 1.5, 2, 3, 4, 5 and 6 MeV. It was observed that the experimental and theoretical results are in very good agreement for the mass attenuation coefficients and linear attenuation coefficients. It is concluded that the FLUKA Monte Carlo simulation code is a useful tool for high energy gamma-ray interactions where data may not be available, analogous to the experiment.

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