GAMMA-RAY SHIELDING PARAMETERS OF CONCRETE WITH DIFFERENT COMPOSITES USING PHITS; A SIMULATION STUDY

[1]MYAT MON AYE, [2]THAW TUN KO

Department of Nuclear Engineering, Mandalay Technological University
E-mail: [1]myatmonaye206@gmail.com, [2]thawtunko@gmail.com

Abstract - The gamma-ray shielding properties of concrete with different composites at 0.661, 1.172 and 1.332 MeV photon energies were investigated using Particle and Heavy Ion Transport Code System (PHITS). The gamma shielding parameters of concrete samples such as mass attenuation coefficient, half value layer, tenth value layer and mean free path were compared with the results by using XCOM database. The obtained results show that PHITS is very effective for investigation of radiation shielding properties to good accuracy comparing to the results by XCOM database. In this study, the outstanding results of gamma-ray shielding properties of concrete samples obtained using PHITS code are presented.

Keywords - Concrete, Gamma-Ray, PHITS, XCOM.

I. INTRODUCTION

Concrete is the most common shielding material for ionizing radiation. It is extensively used in facilities such as nuclear reactors, spent nuclear fuel repositories, particle accelerators, radiotherapy rooms, among others. As a shielding material, concrete is very attractive because its attenuation properties which can be easily tailored by controlling its chemical composition. Moreover, concrete has relatively inexpensive fabrication cost and can be cast in many complex forms exhibiting good mechanical, structural and physicochemical properties[1]. The aggregate component of concrete that contains a mixture of many heavy elements plays an important role in improving concrete shielding properties and therefore has good shielding properties for the attenuation of photons and neutrons [3]. The density of heavyweight concrete is based on the specific gravity of the aggregate and the properties of the other components of concrete. Some of the natural minerals used as aggregates in high density concrete are hematite, magnetite, limonite, barite and some of the artificial aggregates including materials like steel punching and iron shot. Presently, heavyweight concrete is extensively used as a shield in nuclear plants and radio therapy rooms, and for transporting, and storing radioactive wastes. For this purpose, concrete must have high strength and high density.

Heavyweight and high strength concrete can be used for shielding purposes ifitmeets the strength andradiation shielding properties. Such concrete that normally utilizes magnetite aggregate can have a density in the range of 2.6-3.6 g/cm^3, which is significantly higher than the density of concrete made with normal aggregates [2].Recently, Monte Carlo simulation codes by carefully modelling the geometry have been recognized as an effective tool in the investigation of gamma ray shielding properties when experiments are limited or hard to make a measurement [9]. PHITS (Particle and Heavy Ion Transport Code System) is a multi-purpose tool for simulating particle transport phenomena developed by JAEA (Japan Atomic Energy Agency) and several other institutes. PHITS is a Monte Carlo particle transport simulation code. It is used in many fields such as radiotherapy, accelerator technology, space radiation, etc. This Monte Carlo code is capable of transport and collision of nearly all particles such as neutron, proton, photon, etc, in 3D virtual space over a wide energy range (10^{-4} eV to 1 TeV/u) [10].In this work a simulation study has been carried out in which the mass attenuation coefficient, half value layer, tenth value layer and mean free path for concrete samples at 0.661, 1.172 and 1.332 MeV using PHITS code and compared these parameters with the obtained results by XCOM database.

II. MATERIALS AND METHODS

A. Material Specification of Concrete Samples

In this research work five concrete samples were selected to investigate their shielding properties. For the first one as the ordinary concrete with no special addition and the other four concrete samples mixes [6] were prepared by using the coarse aggregates of magnetite along with addition of 10% silica fume, 20% fly ash, 30% ground granulated blast-furnace slag and with the fine portions of magnetite along with 10% Silica Fume to the total content of ordinary Portland cement (OPC) for each mix.Test samples with different thickness of 2-10 cm were arranged in front of a collimated beam emerged from gamma sources (^{137}Cs and ^{60}Co). The attenuation measurements of gamma rays were performed using sodium iodide NaI(Tl) scintillation detector.

To achieve the high-performance concrete (HPC-grade M60), all concrete mixes had a constant water/cement ratio of 0.35, cement content of 450 kg/m^3 and sand-to-total aggregate ratio of 40%, where the mix proportions of samples and the density of specimens were shown in Table 1.

Sample	Different mixes	Density (g/cm^3)
S1	100 % Ordinary Concrete	2.3
S2	10% silica fume	2.37
S3	20% fly ash	2.39
S4	30% ground granulated blast-furnace slag	2.42
S5	the fine portions of magnetite along with 10% Silica Fume	2.74

Table 1. Mix proportions of Concrete samples with density

B. Monte Carlo Simulation

The calculation conditions on PHITS are identified by a text file which is called the input file.In PHITS, "t-track" tally was specified to obtain the photon fluence inside the detector cell which determined by summing the track length per source divided by the cell volume. Incident (φ_0) and transmitted (φ) photon fluence were then tallied and applied in the Lambert-Beer law to determine the mass attenuation coefficients [10]:

$$\frac{\mu}{\rho} = \frac{\ln\left(\frac{\phi_0}{\phi}\right)}{\rho d} \qquad (1)$$

where μ represents the linear attenuation coefficient, ρ is the density and d is the thickness of the sample. The number of particles histories for each simulation was 10^6 - 10^7values so that our tally results have statistical error of less than 0.1% [5]. From the μ/ρ values we can determine the half value layer (HVL), the tenth value layer (TVL) and mean free path (MFP). Fig. 1 shows the simulation geometry designed by PHITS.

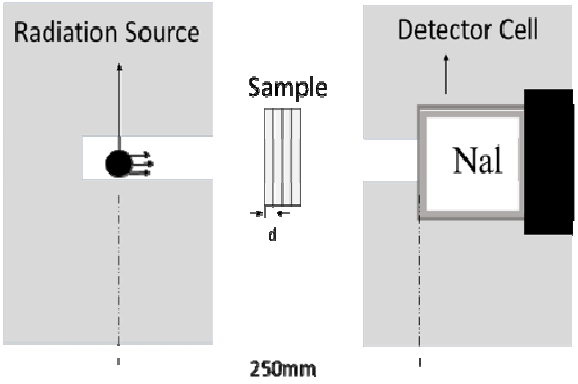


Fig. 1 PHITS Simulation geometry

C. XCOM calculations

XCOM is an online database using a mixture of pre-existing databases for calculation the total attenuation coefficients for various compound in the range from 1keV to 100GeV photon energy [1]. In the present investigation, the mass attenuation coefficient for the selected concrete sample in the gamma rays transport calculations are expressed in the equation:

$$\left(\frac{\mu}{\rho}\right) = \sum_i^n \omega_i \left(\frac{\mu}{\rho}\right)_i \qquad (2)$$

where $(\mu/\rho)_i$ represents the mass attenuation coefficient ofthe i^{th} element obtaining from XCOM database.

IV. RESULTS AND DISCUSSION

The mass attenuation coefficients (MAC) of the selected sample S1-S5concrete samples were calculated as a function of ^{137}Cs and ^{60}Co photon energy by using PHITS code and XCOM database.

Table 2 shows the calculated values of MAC including the percentage deviation (Dev%) for concrete samples S1-S5 by PHITS and XCOM programs at 0.661, 1.172 and 1.332 MeV photon energy respectively. The values of MAC based on both PHITS and XCOM programs are in good agreement where the relative deviation is in the range of (0.8-3.88 %).

Fig. 2 represents the variation of mass attenuation coefficient (MAC) for concrete samples at 0.661, 1.172 and 1.332 MeV photon energy. The results show that MAC is increasing with the densities of concrete increasing up at ^{137}Cs energy and decreases at ^{60}Co energy of photon to become almost constant which are due to the dominance of partial photon interaction. [8]

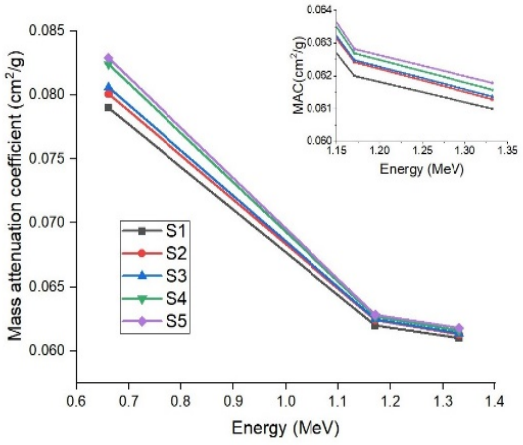


Fig. 2 Mass attenuation coefficients for concrete samples versus energy sources

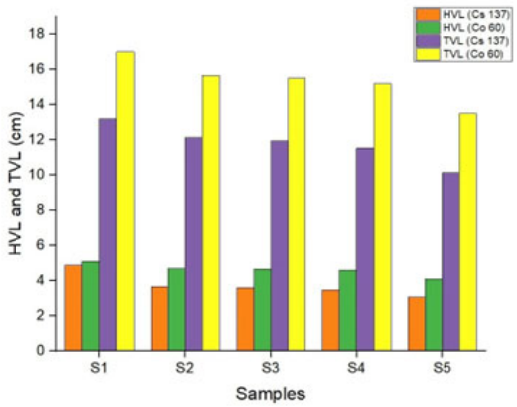


Fig. 3 Comparison of HVL and TVL of concrete samples at 137Cs and 60Co energy

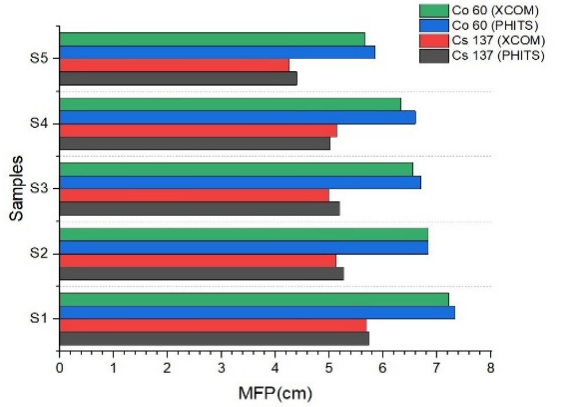


Fig. 4 Comparison of Mean Free Path of concrete samplesat ^{137}Cs and ^{60}Co energy

Samples	0.661 MeV			1.172 MeV			1.332 MeV		
	PHITS	XCOM	Dev. %	PHITS	XCOM	Dev. %	PHITS	XCOM	Dev. %
S1	0.0792	0.0762	3.78	0.0623	0.0611	1.96	0.0612	0.0633	3.43
S2	0.0801	0.08157	1.84	0.0624	0.0613	1.76	0.0613	0.0632	3.10
S3	0.0806	0.0836	3.72	0.0624	0.0629	0.80	0.0614	0.0636	3.58
S4	0.0824	0.0856	3.88	0.0627	0.0638	1.75	0.0616	0.0637	3.40
S5	0.0829	0.0861	3.86	0.0628	0.0645	2.71	0.0618	0.0638	3.23
Dev. %=100×|(MAC(PHITS)-MAC(XCOM))/MAC(PHITS)|									

Table2. Comparison of Mass attenuation coefficients (MAC) obtained using PHITS and XCOM

Fig. 3 shows the HVL and TVL values of concrete samples for different gamma energies emitted by ^{137}Cs and ^{60}Co sources as a function of concrete thickness. The effectiveness of gamma-ray shielding is described in termsof the HVL or the TVL of a material. HVL is the thickness at which an absorber will reduces the radiation to half andTVL is the thickness at which an absorber will reduces the radiation to one tenth of its original intensity [11]. As the results showed, the values of HVL and TVL are inversely proportional to the concrete density therefore, sample S5 (2.74 g/cm^3) showed lower HVL and TVL values than the other low density concrete samples for different gamma energies.

Fig. 4 represents the mean free path (MFP) values which results from S1-S5, where the MFP is an average distance travelled by photon in a sample before interaction [7].It is obviously seen that the MFP values decreases with increasing the densities of concrete samples as well as illustrating that radiation shielding properties are enhanced with the high-density concrete. As shown in the comparison, at photon energies of ^{137}Cs and ^{60}Co, the results are in a good agreement, where the HVL, TVL and MFP of samples decrease with increasing the density of concrete. Therefore, in this study sample (S5) incorporating magnetite fine aggregate, could be considered as the best for gamma radiation shielding.

		Cs 137	Co 60
HVL	PHITS	3.03	4.07
	XCOM	2.94	3.88
	Experiment	3.38	3.51
TVL	PHITS	10.11	13.12
	XCOM	10.04	12.14
	Experiment	11.23	11.65
MFP	PHITS	4.40	5.86
	XCOM	4.23	5.61
	Experiment	4.88	5.06

Table 3. Comparison of HVL, TVL and MFP results from PHITS, XCOM, Experiment

The values of HVL, TVL and MFP of the optimum S5 sample which was compared to that of the fine portions of magnetite along with 10% SFinvestigated by Ahmed S. Ouda [6] with the PHITS simulated, XCOM results and experimental results [6]at photon energies of ^{137}Cs and ^{60}Co is presented in Table 3. According to these results, the simulated results by PHITS code and XCOM database are close to the experimental resultsand deviations do not exceed 10%.

III. CONCLUSION

The radiation shielding parameters in terms of mass attenuation coefficient, HVL, TVL and MFP for concrete with difference mixtures have investigated in the photon energy range of ^{137}Cs and ^{60}Co gamma energy using PHITS and XCOM programs. According to the simulated and calculated results, high-performance heavy density concrete made with the fine portions of magnetite aggregate (S5) enhances the shielding efficiency against at photon energy of 0.661, 1.172 and 1.332 MeV. The simulated and calculated results from two methods are not far from each other. Therefore, the simulation geometry technique by PHITS is found appropriate to be used as an alternative approach to study shielding parameters of other samples.

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