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The Study of the Compaction Effect on Gamma-Ray Shielding

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***Abstract*—Mass attenuation coefficient (μ_m) is the most important gamma-ray shielding parameter of materials used in very sensitive areas of research such as medical sciences, nuclear industry, engineering and space science. The review of related literature indicates that experimentally measured values of μ_m for various materials are underestimated in comparison to their theoretical values. The major reasons behind such a trend may be the lack of perfect narrow beam geometry used in experiments, thickness of the sample above the optimum thickness (OT) value and lower compaction (density) of the samples. In the present study it has been verified that the agreement between experimental and theoretical values of μ_m is better for highly compacted (hydraulically, IS: 1077, 1992) bricks than poorly compacted (manually, IS: 2117, 1991) bricks made from the same material. The theoretical values of μ_m were computed using a self designed computer program, GRIC-toolkit, validated to work in wide energy range 15keV-15 MeV.**

***Index Terms*—Mass attenuation coefficient, building materials, GRIC-toolkit, gamma-ray shielding**

I. INTRODUCTION

GAMMA-RAY shielding behaviour of any material can be studied from its total mass attenuation coefficient (μ_m). For the precise measurement of μ_m (cm^2g^{-1}) perfect narrow beam irradiation geometry is a prime requirement. The deviation of practical geometries from perfect-narrowness due to multiple scattered photons can be minimized by using the sample's thickness below its optimum value of thickness. In the present study, both experimental and theoretical calculations have been performed to investigate the effect of absorber's compaction on μ_m of six low-*Z* ($10 < Z_{eff} < 14$) building materials (cement-black; cement-white; clay; red-mud; lime-stone and plaster of paris) at gamma-ray energies 661.66 keV, 1173.24 keV and 1332.50 keV. A good agreement of theoretical and measured values of μ_m was observed for all absorbers samples made with high compaction. White cement was found to possess maximum shielding effectiveness for the selected gamma rays.

II. THEORY

The attenuation of gamma rays can be expressed by the following equation [1]:

$$\mu_m = \frac{1}{x}\ln\left({}^{I}\!/_{I_O} \right) \tag{1}$$

where *I* and I_o are incident and transmitted gamma ray intensities, $\mu_m = \mu/\rho$ (cm^2 g^{-1}) is total mass attenuation coefficient and $x=\rho.t$ (g cm^{-2}) is areal density (mass per unit transverse area for gamma rays) of the absorber. Thickness of the absorber which reduces intensity of gamma ray to one-half (50%) of the incident intensity is termed as half-value layer (HVL).

The photon interaction cross section gives the probability of an interaction to occur between an incident photon and the absorber. It represents the effective area of the particle for given interaction thus it has dimensions of area, barn ($1barn=10^{-24}$ cm^2). The total cross-section for a molecule of a given compound possessing n_i atoms, is given by:

$$\sigma_{a,m} = \frac{\mu}{\rho}\left(\frac{\sum_i n_i.A_i}{\sum_i n_i}\right)\frac{1}{N} \tag{2}$$

Where *N* is the Avogadro's number and A_i is atomic weight of the i^{th} element. The effective atomic weight (A_{eff}) for the compound is the ratio of the molecular weight divided by the total number of all types of atoms present in it [1]. The mass attenuation coefficient of a composite mixture of different compounds can be calculated as [1]:

$$\mu_m = \frac{N}{A_{eff}}\sum_i m_i\left(\sigma_{a,m}\right)_i \tag{3}$$

Where m_i is the number of molecules for i^{th} compound in the mixture and σ_m is the total cross section of the mixture (sample).

III. MATERIALS AND METHODS

A. Selection of samples

Six commonly used low-*Z* building materials were selected for the present investigation due to their good moulding properties, stability and easier availability.

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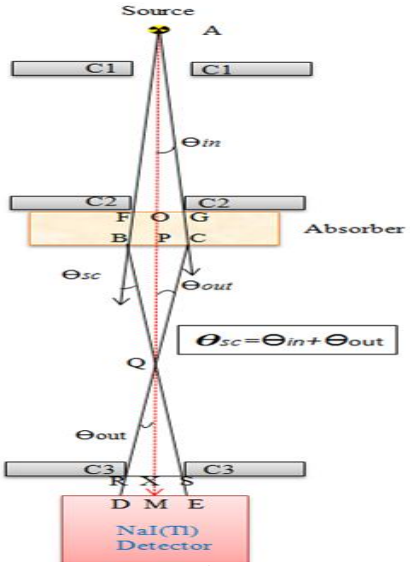

Fig.1. Narrow beam geometry for mass attenuation coefficients measurements using absorber thickness < 0.5 mfp (Mann et al., 2015) and scatter acceptance angle < 3° (Midgley 2006).

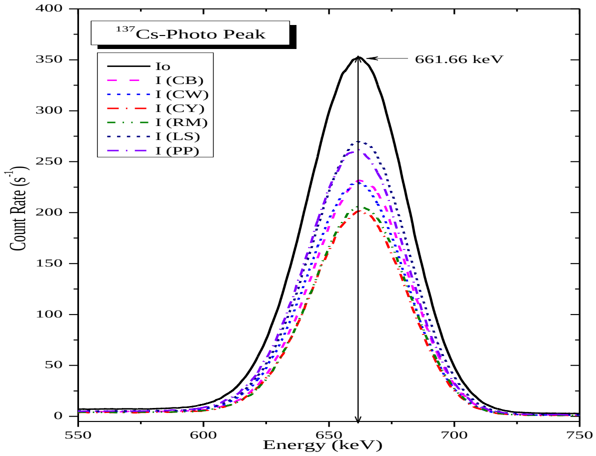

Fig.2. Photo peaks (data normalized to same energy value) intensities without and with the sample absorbers for ^{137}Cs (661.66 keV).

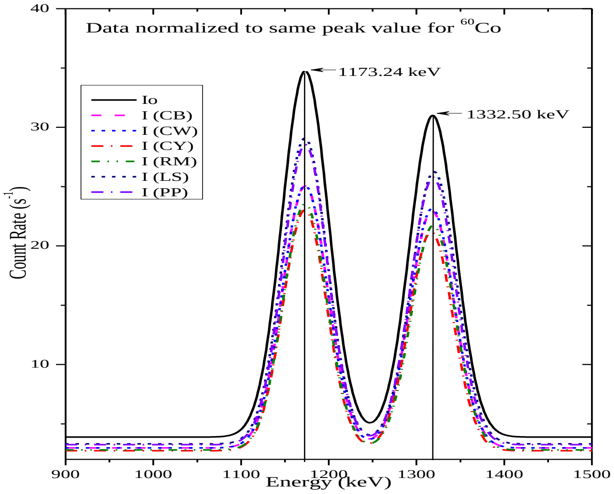

Fig.3. Photo peaks (data normalized to same energy value) intensities without and with the sample absorbers for ^{60}Co (1173.24 and 1332.50 keV).

TABLE I
CHEMICAL COMPOSITION AND SYMBOLS ASSIGNED TO THE CHOSEN MATERIALS

Oxide	Compounds composition (by wt. fraction)					
	Cement black (CB)	Cement white (CW)	Clay (CY)	Red-mud (RM)	Lime-stone (LS)	Plaster of Paris (PP)
CaO	4.84E-01	6.62E-01	1.21E-01	1.15E-01	9.66E-01	4.30E-01
SiO2	2.95E-01	2.10E-01	5.28E-01	5.45E-01	1.07E-02	2.60E-02
Al2O3	1.20E-01	4.48E-02	1.69E-01	1.66E-01	2.30E-03	9.72E-03
Fe2O3	4.59E-02	3.61E-03	6.69E-02	6.46E-02	2.30E-03	4.71E-03
SO3	2.39E-02	4.33E-02	2.11E-03	1.61E-03	7.40E-03	5.19E-01
MgO	9.75E-03	2.33E-02	4.93E-02	4.71E-02	1.05E-02	6.51E-03
TiO2	9.45E-03	2.30E-03	7.42E-03	7.32E-03	0.00E+00	6.01E-04
K2O	6.74E-03	7.51E-03	3.71E-02	3.50E-02	2.00E-04	2.81E-03
Na2O	2.51E-03	1.90E-03	1.54E-02	1.59E-02	0.00E+00	7.01E-04
P2O5	2.51E-03	3.00E-04	1.40E-03	1.40E-03	2.00E-04	0.00E+00
MnO	8.04E-04	1.00E-04	9.02E-04	1.00E-03	1.00E-04	1.00E-04
V2O5	4.02E-04	3.00E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cr2O3	9.35E-05	1.00E-04	2.00E-04	2.01E-04	0.00E+00	0.00E+00
CuO	8.95E-05	4.51E-05	1.00E-04	1.00E-04	4.40E-05	3.81E-05
NiO	8.65E-05	1.00E-04	8.52E-05	9.33E-05	6.30E-05	0.00E+00
ZnO	2.01E-06	2.20E-05	1.00E-04	1.00E-04	0.00E+00	2.60E-05

TABLE II
COMPUTED AND EXPERIMENTALLY MEASURED VALUES OF MASS ATTENUATION COEFFICIENTS FOR BRICKS MADE BY TWO STANDARDS (IS:2117, 1991 AND IS 1077, 1992)

Sample's Symbol	Energy (keV)	Total mass attenuation coefficient ($cm^2 g^{-1}$)		
		Theoretical (GRIC-toolkit)	Compressed Manually (88 kPa) [IS: 2117, 1991]	Compressed Hydraulic (5 Mpa) [IS: 1077, 1992]
CB	661.66	7.64E-02	7.47E-02 (-2.23%)	7.52E-02 (-1.57%)
	1173.24	5.81E-02	5.70E-02 (-1.89%)	5.76E-02 (-0.86%)
	1332.50	5.45E-02	5.29E-02 (-2.94%)	5.44E-02 (-0.18%)
CW	661.66	8.03E-02	7.87E-02 (-1.99%)	7.90E-02 (-1.62%)
	1173.24	5.85E-02	5.74E-02 (-1.88%)	5.82E-02 (-0.51%)
	1332.50	5.49E-02	5.39E-02 (-1.82%)	5.47E-02 (-0.36%)
CY	661.66	7.96E-02	7.76E-02 (-2.51%)	7.83E-02 (-1.63%)
	1173.24	5.81E-02	5.70E-02 (-1.89%)	5.78E-02 (-0.52%)
	1332.50	5.44E-02	5.36E-02 (-1.47%)	5.44E-02 0.00%
RM	661.66	7.96E-02	7.80E-02 (-2.01%)	7.86E-02 (-1.26%)
	1173.24	5.81E-02	5.69E-02 (-2.07%)	5.80E-02 (-0.17%)
	1332.50	5.45E-02	5.35E-02 (-1.83%)	5.44E-02 (-0.18%)
LS	661.66	8.05E-02	7.95E-02 (-1.24%)	8.00E-02 (-0.62%)
	1173.24	5.87E-02	5.74E-02 (-2.21%)	5.87E-02 0.00%
	1332.50	5.51E-02	5.39E-02 (-2.18%)	5.50E-02 (-0.18%)
PP	661.66	8.04E-02	7.89E-02 (-1.87%)	7.92E-02 (-1.49%)
	1173.24	5.86E-02	5.75E-02 (-1.88%)	5.82E-02 (-0.68%)
	1332.50	5.50E-02	5.38E-02 (-2.18%)	5.45E-02 (-0.91%)

These materials were cement-black (CB); cement-white (CW); clay (CY); red-mud (RM); lime-stone (LS) and plaster of paris (PP). The samples of CY and RM were collected from Gill-Patti (30.276°N, 74.940°E), Bathinda, Punjab (India) while samples of CB, CW, LS and PP were collected from Ultra Tech cement distributer located at Bathinda, Punjab (India). In order to remove moisture content the chosen samples were dried in oven (105°C for 12 hours) and then grinded to obtain a very fine powder (grain size < 75 micro meter).

B. Sample preparation

For the experimental evaluation of μ_{m}, bricks of the samples were formed using a steel mould of dimensions (95mm x 93mm x 50mm). Each powdered sample was mixed with a very little amount of distilled water to form a paste. The paste was then filled in the mould and two types of bricks for each sample were obtained viz. (a) manually pressed at 88 kPa as per Indian Standard [2] and (b) hydraulically pressed at 5 MPa as per Indian Standard [3]. These bricks were dried first in sun light for 40 days (by changing their side towards the sun daily for uniform drying and avoiding cracks) and then in oven at 105°C for 24 hours (to remove the remaining moisture). After drying, only healthy sample-bricks (without cracks) were retained for the measurements.

IV. THEORETICAL MEASUREMENTS

Various gamma-ray interaction coefficients were computed using the GRIC-toolkit developed by our research group [4]. GRIC-toolkit is user-friendly computer program with capability to compute various gamma ray interaction coefficients in the energy range 10-1400keV. It has been designed using the tables of Hubbell and Seltzer [5] and database obtained from WinXCom [6].

V. EXPERIMENTAL DETAILS

A. Density measurement

The densities of the sample bricks were evaluated by using the conventional formula, density (ρ) = mass/volume. The mass of each sample was measured with an electronic physical balance with accuracy ±0.01g and the volume with a digimatic vernier-calipers of accuracy ±0.002mm, procured from Mitutoyo Corp., Kawasaki, Japan.

B. Chemical composition measurement

The chemical compositions of the selected samples were estimated using Wavelength Dispersive X-Ray Fluorescence (WDXRF) technique. Pellets (diameter 34mm and thickness 10mm) of each sample were formed by using the corresponding dried powder of the sample (≤75μm) with binder (boric-acid) in ratio 4:1 in a hydraulic press (20 MPa). By putting these pellets into the spectrometer (BRUKER-S8 TIGER) WDXRF-analysis were obtained for full scan for 1200s. The raw-data was analysed using the SPECTRA^{plus} software to obtain the chemical compositions of the chosen samples. The obtained compositions have been listed in Table 1.

C. Measurement of mass attenuation coefficients

The measurements of μ_{m} were carried out at three different gamma-ray energies; 661.66 keV obtained from point isotropic source ^{137}Cs (100 mCi), 1173.24 keV and 1332.50 keV from point isotropic source ^{60}Co (10 mCi) which were procured from Board of Radiation and Isotope Technology (BRIT), Mumbai, India. The gamma-ray spectrometer was procured from ORTEC, USA. It is suitable for research experiments due to its accuracy and stability. The narrow beam irradiation geometry was setup using the concept of acceptance angle ($\theta_{SC}<3^{o}$) as shown in Fig. 1 [7].The measured spectrums of gamma-rays photo peaks with and without the sample bricks have been indicated in Fig.2 and Fig.3.

VI. RESULTS AND DISCUSSION

Table 2 indicates that for the chosen samples theoretical values of μ_{m} differ considerably from their experimentally measured values. The reason behind it seems to be the low density of the prepared samples than theoretical expected values. The low density is due to low compaction provided during the preparation of the samples. We have found that the manually pressed bricks as per the Indian standards (IS: 2117, 1991) [2] and hydraulic made bricks as per Indian standard (IS: 1077, 1992) [3] have different values of μ_{m}. The experimental values of μ_{m} for hydraulic pressed bricks show a better agreement with the theoretical values than handmade (manually pressed) bricks. Thus it is concluded that the compaction plays a very important role in the brick's shielding properties. Thereby it is also concluded that the shielding properties of a given sample cannot be determined accurately without the knowledge of its density or the compaction applied during its manufacture.

The high compaction minimizes the trapped air or free space from the brick samples. Thereby improves the shielding behaviour of the brick. It has been noted that from the three mono-energetic gamma-rays, for the gamma-ray energy 1332.50 keV the measured mass attenuation coefficients values approach to corresponding theoretical values better than other two energy values.

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