Clay and Cement Shielding Behavior from Gamma Sources

Mohamed E. M. Eisa
Department of Physics, Northern Border University, Arar, Kingdom of Saudi Arabia
memeisa@yahoo.com (corresponding author)

Mamed D. M. Ali
Department of Physics, Sudan University of Science and Technology, Khartoum, Sudan
mohameddaffallah@yahoo.com

Mustafa J. Abualreish
Department of Chemistry, Northern Border University, Arar, Kingdom of Saudi Arabia
mustjeed_2008@hotmail.com

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ABSTRACT

Clay is a native building material in Sudan and is utilized by most low-income people. The radiation shielding characteristics of clay and cement were tested with a specific thickness to explore the behavior of gamma radiation through these materials. The results were compared and estimated by the Phy-X, XCOM, and Py-MLBUF software packages. Mass Attenuation Coefficient (MAC), Linear Attenuation Coefficient (LAC), Half-Value Layer (HVL), Tenth-Value Layer (TVL), Mean Free Path (MFP), and equivalent atomic number (Z_{eq}), which describe the shielding properties of the examined materials, were all determined and compared. The comparison of calculations by software and experimental data of all selected samples showed a high degree of agreement, with discrepancies ranging between 0.01 and 5%. The experiments were carried out in a chamber close to ^{137}Cs and ^{60}Co sources at energies of 662, 1173, and 1332 keV.

Keywords-building materials; mass attenuation coefficient; linear attenuation coefficient; gamma radiation; radiation intensity

I. INTRODUCTION

The nuclear radiation protective barrier serves various tasks, the most essential of which is to limit radiation exposure to individuals in areas where radiation episodes have occurred. Since gamma spectroscopy is the easiest method to detect and measure radiocesium [1-3], it has been extensively used in the search for radioactive horizons in ice cores. While relying on exposure time and distance necessitates continual administrative supervision over staff, shielding is frequently preferred due to its effectiveness in safe work environments. The radiation type, radiation source activity, and allowable dose influence the kind and amount of shielding that is required at the required dose rate outside the shielding materials. However, other considerations for choosing the shielding materials, including weight and cost, also play a role. The investigation of gamma and neutron radiation absorption in shielding materials has long been a focus of radiation physics [4]. When radioactive substances enter the body from the outside or interact with it internally, the result is ionizing radiation that has biological consequences on the human body [5]. Radiation shielding sheets used in medical institutes today are constructed of either a pure lead panel or mixtures of lead granules and rubber [6].

Concrete and other materials are used for linear accelerator shielding because of their density, readily, and low cost. It is convenient to research what kind of material would be most appropriate for use as additional shielding [7] because current equipment using higher energy requires updated shielding calculations. New approaches for material mixing in the production process are required to meet the goal of creating lightweight shielding sheets [4, 8]. There are numerous reasons for developing novel shielding materials. To shield personnel and equipment from hazardous penetrating photon rays, radiation protection research is vital for the nuclear industry. Conventional nuclear shielding materials such as concrete are used to reduce high-energy radiation, but their drawbacks, such as their size and weight, may not meet the demands of future nuclear and waste disposal facilities for lightweight and miniaturization [9].

Concrete is a less expensive shield for neutron and photon radiation. Concrete blocks, which are widely utilized [10, 11] as the main ingredients used in the construction of residential buildings and many other projects, are made of cement, sand, and water. High-density materials are less protective than other materials like lead and iron. Naturally occurring radionuclides with various activity levels are present in each of these components, depending on the source of the raw materials [12]. To reduce the population's exposure to ionizing radiation, the content of radioactive materials in structures must be controlled and limited [13]. Terrestrial natural radionuclides (as ^{238}U radionuclides), existing in trace quantities in the Earth's crust [14], and cosmic rays are the primary causes of this type of exposure. The presence of radionuclides in mineral water poses health risks due to human internal exposure from radionuclide decay absorbed into the body through skin ingestion [15-17].

II. MATERIALS AND METHODS

The shielding material removes any gamma rays that interact with it. The attenuation coefficient defines the efficiency of the shielding material. As a result, proper determination of shielding parameters is required before any material is utilized as a shield. The shielding material reduces the intensity of radiation that is governed by the Lambert-Beer law equation [3, 9]:

$$I = I_0 e^{-\mu x} \tag{1}$$

The count rate without the shielding material is denoted by I_0, while the count rate with the shielding material of thickness x and attenuation coefficient μ is represented by I.

$$\mu_m = \frac{1}{\rho x} ln \frac{I}{I_0} \tag{2}$$

where μ_m is the mass attenuation coefficient. μ_m is normally used to compare the shielding characteristics of different materials. According to existing knowledge, the Half Value Layer (HVL) is the material width needed to cut the air kinetic energy delivered to matter (kerma) of an X-ray or gamma ray in half [18-25]. Equations (3) and (4) provide relationships between the linear attenuation coefficient and the HVL and Tenth Value Layer (TVL) [26], respectively:

$$\text{HVL} = \frac{ln2}{\mu} \tag{3}$$

$$\text{TVL} = \frac{ln10}{\mu} \tag{4}$$

Equation (5) determines the Mean Free Path (MFP), which is the average distance a single particle travels through a sample's medium before interacting [27]:

$$\text{MFP} = \frac{1}{\mu} \tag{5}$$

A measurement of the energy transferred from the radiation to the matter is frequently employed as the reference value required for the calibration of dosimeters used for personal and environmental monitoring [28, 29]. In terms of dosimetry systems, the lab features a single secondary standard ionization chamber that was created and produced by the Austrian research facility Siebersdorf. This chamber's calibration at the IAEA laboratory can be traced to the German National Laboratory (PTB). As is customary for measurements using reference standards, the ionization chamber was positioned 2 m from the ^{137}Cs source [22, 30].

Cement and clay cubes (Figures 1 and 2) were measured as gamma ray shielding. Figure 3 shows the experimental setup of the determination of gamma radiation intensity before and after placing the shielding samples. Cement had density of 2.139 g/cm^3, Average Molecular Weight (AMW) equal to 72.19 g/mol whereas the clay had a density of 1.335 g/cm^3 and AMW of 63.45 g/mol and ideal moisture content of 40%. MAC, LAC, HVL, TVL, MFP, and Z_{eq} were calculated using the Py-MLBUF [31] and Py-X [18-20] software packages. Tables I and II show the calculation results. Tables III and IV show the experimental results using ^{137}Cs gamma ray with initial dose of 225.65 µGy and ^{60}Co gamma rays with initial dose of 1.906 µGy. Tables V and VI exhibit the results of cement and clay, respectively, which were calculated by XCOM, which showed small variations from those calculated by Phy-X and Py-MLBUF. All results were evaluated theoretically and experimentally. Figures 4 and 5 display the HVL against energy for cement and clay layer, Figures 6 and 7 show MAC against energy, and Figures 8 and 9 display Z_{eq} against energy. As can be seen from the data presented in Tables I-VI showed that cement has less HVL and TVL values than clay, and as a result has greater shielding qualities [11, 33].

Fig. 1. A picture of cement cubes.

Fig. 2. A picture of clay cubes.

Fig. 3. Experimental setup of the determination of gamma radiation before and after placing the shielding samples.

TABLE I. CEMENT RESULTS BY PYMLBUF AND PHY-X FOR ENERGIES FROM 0.1 TO 1332 KEV

Energy (KeV)	**Gamma source**	**Cement (PyMLBUF)**						**Cement (Phy-x)**					
		Mass coefficient (cm²/g)	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	Z_{eq}	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	Z_{eq}
1.00E-01		2.07E-01	4.43E-01	1.5651	5.1991	2.25	16.3028	0.207	0.444	1.563	5.191	2.255	16.81
1.50E-01		1.52E-01	3.24E-01	2.1372	7.0997	3.08	16.234	0.151	0.324	2.141	7.111	3.088	16.90
2.00E-01		1.30E-01	2.79E-01	2.4872	8.2625	3.58	16.1793	0.130	0.278	2.494	8.285	3.598	16.96
3.00E-01		1.09E-01	2.33E-01	2.9769	9.8891	4.29	16.2012	0.108	0.232	2.987	9.924	4.310	17.01
4.00E-01		9.63E-02	2.06E-01	3.3646	11.1771	4.85	16.0771	0.096	0.205	3.376	11.216	4.871	17.04
5.00E-01		8.75E-02	1.87E-01	3.7039	12.304	5.34	16.0982						
6.00E-01		8.07E-02	1.73E-01	4.0153	13.3387	5.78	16.0265	0.080	0.172	4.030	13.387	5.814	17.07
6.62E-01	^{137}Cs	7.72E-02	1.65E-01	4.1962	13.9395	6.06	17.1798	0.077	0.165	4.212	13.993	6.077	17.08
8.00E-01		7.07E-02	1.51E-01	4.5837	15.2269	6.62	16.0718	0.070	0.151	4.600	15.282	6.637	17.08
1.00E+00		6.35E-02	1.36E-01	5.1047	16.9574	7.35	16.2012	0.063	0.135	5.123	17.019	7.391	17.08
1.17E+00	^{60}Co	5.86E-02	1.25E-01	5.5291	18.3673	8.00	16.2012	0.058	0.125	5.549	18.433	8.005	-
1.33E+00	^{60}Co	5.49E-02	1.18E-01	5.8991	19.5964	8.47	16.2012	0.055	0.117	5.922	19.674	8.544	-

TABLE II. CLAY RESULTS BY PYMLBUF AND PHY-X FOR ENERGIES FROM 0.1 TO 1332 KEV

	Gamma Source	**Clay (PyMLBUF)**						**Clay (Phy-x)**					
Energy (KeV)		**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	Z_{eq}	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	Z_{eq}
6.62E-01	^{137}Cs	7.65E-02	1.02E-01	6.7845	22.5377	9.8	10.9134	0.076	0.101	6.831	22.693	9.855	18.92
8.00E-01		7.01E-02	9.36E-02	7.4088	24.6114	10.68	10.9071	0.070	0.093	7.463	24.792	10.767	18.92
1.00E+00		6.29E-02	8.40E-02	8.2491	27.4029	11.90	10.9018	0.062	0.083	8.314	27.619	11.995	18.93
1.17E+00	^{60}Co	5.81E-02	7.75E-02	8.939	29.6948	12.90	10.9017	0.058	0.077	9.007	29.921	12.995	
1.33E+00	^{60}Co	5.45E-02	7.27E-02	9.5347	31.6735	13.75	10.9027	0.054	0.072	9.613	31.934	13.869	
1.50E+00		5.13E-02	6.84E-02	10.1309	33.6541	14.61	10.904	0.051	0.068	10.210	33.916	14.730	16.52
2.00E+00		4.43E-02	5.91E-02	11.7278	38.959	16.92	10.9234	0.044	0.059	11.803	39.209	17.028	15.26
2.51E+00		3.95E-02	5.28E-02	13.1352	43.6342	18.93	10.9591	0.039	0.053	13.190	43.816	19.029	
3.00E+00		3.62E-02	4.84E-02	14.3291	47.6003	20.66	10.9904	0.036	0.048	14.348	47.661	20.699	14.87
4.00E+00		3.18E-02	4.24E-02	16.3311	54.2509	23.58	11.0712	0.032	0.043	16.256	54.002	23.453	14.77
5.00E+00		2.90E-02	3.87E-02	17.8994	59.4606	25.83	11.1538	0.029	0.039	17.711	58.836	25.552	14.72
6.00E+00		2.72E-02	3.62E-02	19.1241	63.5288	27.62	11.2356	0.028	0.037	18.816	62.507	27.146	14.69
8.00E+00		2.49E-02	3.32E-02	20.8514	69.2668	30.12	11.3859	0.026	0.034	20.307	67.459	29.297	14.66
1.00E+01		2.37E-02	3.16E-02	21.9293	72.8475	31.64	11.5167	0.025	0.033	21.177	70.350	30.553	14.64
1.50E+01		2.24E-02	2.99E-02	23.1942	77.0494	33.44	11.7652	0.024	0.031	22.054	73.263	31.818	14.62

TABLE III. EXPERIMENTAL RESULT FOR CEMENT CUBES USING ^{137}CS GAMMA RAYS WITH INITIAL DOSE 225.65 µGY (LEFT) AND USING ^{60}CO GAMMA RAYS WITH INITIAL DOSE 1.906 µGY (RIGHT) FOR VARYING THICKNESSES

Cement cube results using ^{137}Cs with initial dose of 225.65 µGy							**Cement tubes results using ^{60}Co with initial dose1.906 µGy**					
Thickness (cm)	**Dose (µGy)**	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	**Dose (µGy)**	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**
10	49.99	0.070	0.150	15.35	4.598	6.45	0.636	0.051	0.109	21.12	6.314	9.17
20	12.10	0.068	0.146	15.77	4.737	6.84	0.218	0.050	0.108	21.32	6.392	9.25
25	7.04	0.064	0.138	16.68	4.996	7.24	0.141	0.048	0.104	22.14	6.653	9.61
35	2.81	0.058	0.125	18.42	5.530	8.00	0.072	0.043	0.093	24.75	7.403	10.75

TABLE IV. EXPERIMENTAL RESULT FOR THE CLAY SHIELDING CUBES USING ^{137}CS GAMMA RAYS WITH INITIAL DOSE 225.65 µGY(LEFT) AND USING ^{60}CO GAMMA RAYS WITH INITIAL DOSE1.906 µGY (RIGHT) FOR VARYING THICKNESSES

Clay cubes results using ^{137}Cs with initial dose 225.65 µGy							**Clay cube results using ^{60}Co with initial dose1.906 µGy**					
Thickness (cm)	**Dose (µGy)**	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**	**Dose (µGy)**	**Mass coefficient (cm²/g)**	**Linear coefficient (cm^{-1})**	**HVL (cm)**	**TVL (cm)**	**MFP (cm)**
10	49.99	0.080	0.107	21.51	6.449	9.34	0.856	0.062	0.080	28.78	8.657	12.5
20	12.10	0.079	0.105	21.92	6.557	9.52	0.396	0.058	0.078	29.52	8.820	12.82
25	7.04	0.075	0.100	23.02	6.887	10	0.301	0.055	0.073	31.54	9.386	13.69
35	2.81	0.071	0.095	24.23	7.224	10.52	0.177	0.050	0.067	34.36	10.205	14.92

TABLE V. SCATTERING AND ATTENUATION COEFFICIENT RESULTS BY XCOM FOR CEMENT

Photon Energy	Scattering	
	Coherent	Incoherent
MeV	cm^2/g	cm^2g^{-1}
6.620E-01	2.555E-04	7.697E-02
8.000E-01	1.751E-04	7.064E-02
1.000E+00	1.121E-04	6.353E-02
1.022E+00	1.073E-04	6.286E-02
1.173E+00	8.152E-05	5.869E-02
1.250E+00	7.178E-05	5.682E-02
1.332E+00	6.322E-05	5.498E-02
1.500E+00	4.986E-05	5.164E-02
2.000E+00	2.805E-05	4.408E-02

TABLE VI. SCATTERING AND ATTENUATION COEFFICIENT RESULTS BY XCOM FOR CLAY

Photon Energy	Scattering	
	Coherent	Incoherent
MeV	cm^2/g	cm^2g^{-1}
6.620E-01	4.585E-04	7.532E-02
8.000E-01	3.136E-04	7.064E-02
1.000E+00	2.010E-04	6.353E-02
1.022E+00	1.925E-04	6.286E-02
1.173E+00	1.462E-04	5.869E-02
1.250E+00	1.288E-04	5.682E-02
1.332E+00	1.134E-04	5.498E-02
1.500E+00	8.944E-05	5.164E-02
2.000E+00	5.036E-05	4.408E-02

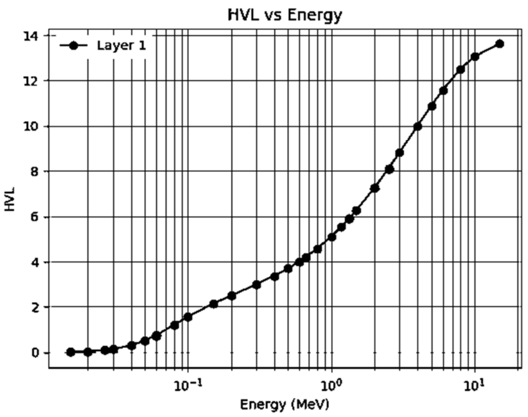

Fig. 4. HVL vs Energy for cement.

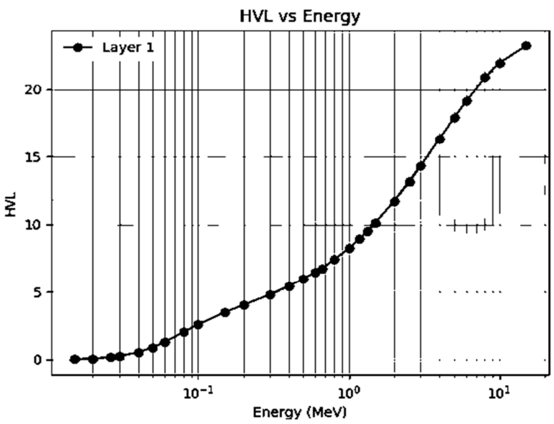

Fig. 5. HVL vs Energy for clay.

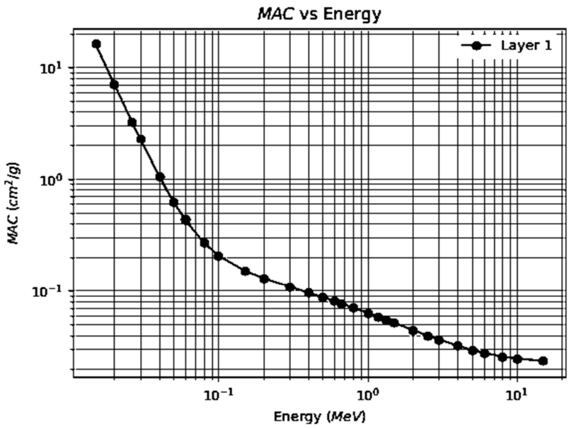

Fig. 6. MAC vs Energy for clay.

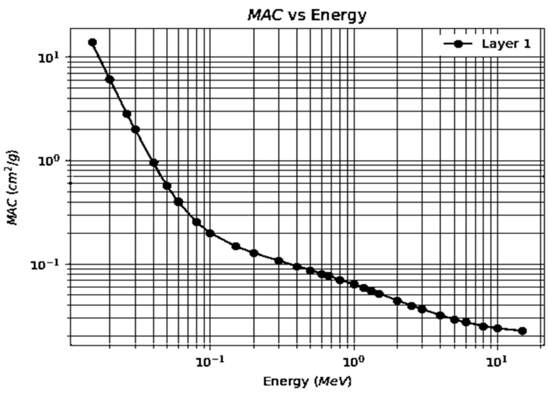

Fig. 7. MAC vs Energy for cement.

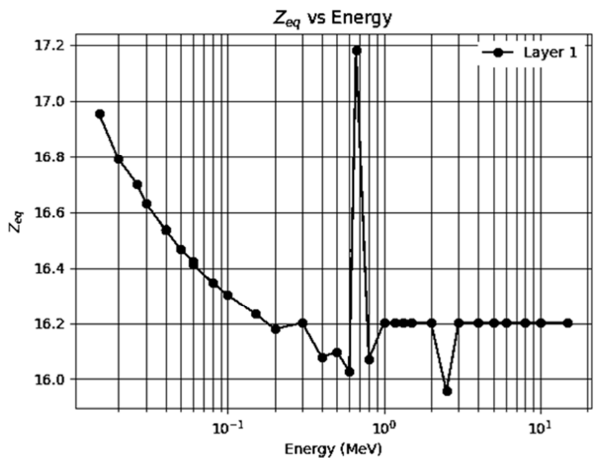

Fig. 8. Z_{eq} vs Energy for clay.

Thicker shields are required against strong gamma radiation (Figure 1) and the steady rise in HVL as photon energy increases. The HVL parameter can be utilized to differentiate samples based on how well they protect. Figures 6 and 7 showed that MAC is decreasing exponentially with photon energy. Figures 8 and 9 showed that Z_{eq} versus photon energy is not stable and has resonance between 10^{-1} MeV and 1 MeV and different behavior due to thickness.

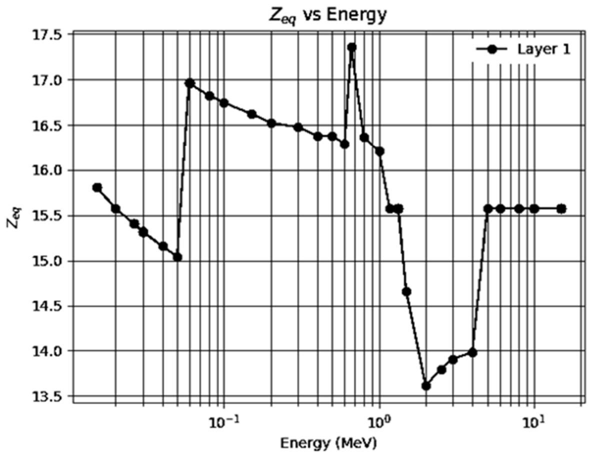

Fig. 9. Z_{eq} vs Energy for cement.

III. RESULTS AND DISCUSSION

The radiation shielding materials measured in this study (clay and cement) provided similar or better protection than even pure Pb per unit mass depending on thickness. The choice of the material depends on the quality of radiation requiring attenuation [34-36]. The radiation shielding capabilities of a material depend on its material properties along with origin, type and exposure time of radiation, secondary radiations, and material thickness [37]. The choice of radiation shielding material depends on the type of radiation for which it is designed [33, 38]. It is necessary to develop new buildings materials with radiation shielding abilities and for attenuating the radiation.

The radiation attenuation coefficients were experimentally and theoretically determined in this study. The work also concentrated on calculating the attenuation coefficient for cement and clay samples using the software packages Phy-X, XCOM and Py-MLBUF. The comparison revealed that the simulated and XCOM data agreed. The results showed that the efficiency of the shielding material is affected by interaction energy and material thickness. HVL, TVL, and MFP values assist in determining which material successfully minimizes radiation intensity. Low-density materials attenuate less than high-density materials, whereas higher gamma-ray energy results in reduced attenuation. The outcomes for the tested parameters correlate well with the theoretical calculations. As a result, it may be possible to build a shielding purely analytically assuming all interactions at all energies have a cross-section that includes the attenuation and absorption coefficients. With this information, further research will help us to better manage the radiation, particularly for those who are using local materials in buildings.

IV. CONCLUSION

In this study, clay and cement were investigated and compared as protective shielding materials. The choice of radiation shielding material depends on the type of radiation for which it is designed, however these materials provided similar or better protection than even pure Pb per unit mass, in most cases. Results were calculated by Phy-X, Py-MLBUF and WinXcom software packages. MAC, LAC, HVL, TVL, MFP, and Z_{eq}, which describe the shielding properties of the examined materials, were all determined and compared. The comparison of calculations by software and experimental data for all selected samples showed a high degree of agreement, with discrepancies ranging between 0.01 and 5%. The results of the present study revealed that the clay is significantly affecting the shielding. Both clay and cement may present a suitable block for radiation shielding composites, especially due to their abundance in nature and unique physical and chemical properties.

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