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Research Paper

Photon Absorption Buildup Factors for Different Concrete Types

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Abstract

Concrete is one of the most widely used materials for structural radiation shielding application. However, the shielding capacity of a concrete has been argued to depend largely on its constituent materials and sometimes its mass density. Hence concretes with different composite materials are expected to perform differently when used for shielding purpose. This research reports the estimation of the equivalent atomic numbers and photon Energy Absorption Buildup Factors (EABF) for eleven different species of concrete. The relationship between equivalent atomic number, density and EABF was also investigated. The concretes considered were categorised into light and heavy concretes based on their mass density. The EABF were calculated using the well-known geometric progression fitting procedure for photon energies from 0.015 MeV to 15 MeV and for penetration depth up to 40 mfp. An appreciable variation in the EABF was observed at different depth, energy and for each concrete type. The EABF were found to be high in the low and high energy regions and maximum in the intermediate energy section. The variation of EABF with energy and depth was attributed to the photoelectric, Compton scattering andpair production interaction modes. Although most high density concretes show lower buildup factor irrespective of depth and energy, an indication of good photon shielding coefficient. However, based on this study, it is the equivalent atomic number that can be best used to accurately compare the buildup factors amongst concrete rather than density.

Keywords: Concrete; Photons; Buildup factor, Radiation protection; G.P Fitting Method

Introduction

Nuclear radiation and radioisotopes are applicable in medicine (for diagnosis and therapy), agriculture, food processing industries, power generation, and security amongst others. Nuclear (ionising) radiations are often released in many nuclear processes involved in these applications. Unfortunately, uncontrolled exposure of man, his environment, and devices to components of nuclear radiation has detrimental effects on man, the environment and devices depending on radiation dose and quality factor. The continuous and effective use of nuclear energy and technology consequently depends to a large extent the protection of man and his environment against harmful effect of nuclear radiation. One of the practical ways of radiation protection is through the use of radiation shield.

In different areas of ionising radiation application, neutrons and photons (gamma rays) are of major concern to nuclear engineers when designing radiation shield. This is due to their abilities to penetrate deeper into any given medium. Traditionally, materials for photon attenuation are required to be of high density; on the other hand, fast neutron shields require low density hydrogenous materials as moderators and materials rich in elements (B, Eu, Pu, Cd) that have high neutron absorption cross-section. However, low density materials emit gamma rays whose energy is in the range 0.10- 10 MeV [1] when used for neutron shielding.

Obviously, effective shielding of photons is very important even if it is not the primary product of a nuclear process.

Traditionally, photon shielding materials include; lead, water, depleted uranium, polythene, light and heavy concretes. Nevertheless, some of these materials have major drawbacks. The use of lead is discouraged due to environmental consideration; depleted uranium is relatively less abundant, and also has radiation issues. Water on the other hand, is a liquid and thus require a container. Concrete however, has been used for effective structural shielding for different nuclear applications. This is perhaps due to its availability, workability and non-radioactive nature compare to depleted uranium. Concrete is the commonest building material whose application cut across social economic strata. Ordinarily it is a composite material obtained by mixing together coarse aggregates, fine aggregates, cement, and water in suitable proportions depending on the structural strength and flexibility required. The function of the water is to initiate the chemical reactions leading to hardening, after which the strength and durability of the material is comparable to some of the hardest rocks.

One of the parameters than can be used to describe the photon shielding effectiveness of a medium is the mass attenuation coefficient. The mass attenuation coefficient is a quantity that describes how much photon is absorbed or transmitted by a medium. However, the use of the Beer- Lambert law [2] which is the most used method to evaluate the attenuation coefficient assumes that photon beams are monochromatic, narrow beam geometry and shielding material are thin. Most practical situations do not fulfill these assumptions. The correction to the attenuation coefficients outside this assumption requires the estimation of the photon buildup factors (B) for each practical scenario. The B accounts for the ratio of broad beam to that of narrow beam and directly influences radiation absorption for dose or shielding calculations. Also, B depends on the photon energy (eV) and penetration depth.

A compilation of photon buildup factors for 23 elements, one compound (water) and two mixtures (air and concrete) for standard photon energies in the range 0.015 MeV -15 MeV and for penetration depth up to 40 mean free path (mfp) by the American Nuclear Society [3].The Geometric Progression (GP) fitting method of evaluating B been known to be accurate within a few percent errors [4, 5]. Consequently, many researchers have reported buildup factors for materials not mentioned in the ANS report, using the GP fitting Method [6, 7]. This report presents the energy absorption buildup factors (calculated via the G.P. fitting procedure) of different types of concrete with the view to compare their photon shielding competence. This research also hopes to highlight if mass density can be used exclusively as an indicator for the relative shielding effectiveness of concretes.

Materials and Methods

Generally, the evaluation of buildup factors using the G.P method requires three distinct procedures:

Calculation of equivalent atomic number, Z_{eq}

To do this for any material, the Compton partial interaction coefficient (μ_c) and mass attenuation coefficients (μ_t) (both in cm^2/g) were calculated for the photon energy range 0.015 MeV– 15 MeV using the WinXCom computer code. The ratio $R = {}^{\mu_C}/_{\mu_t}$ of each material is then calculated and matched at the standard energies to the corresponding ratios of elements up to the heaviest element. If the value of the radio matches any of the elements', then the atomic number of that element becomes the equivalent atomic number of the material. However, if the value of R obtained for the considered material does not match that of any element but rather falls between the ratios for two successive elements then, the Z_{eq} of such material is interpolated using the expression [4, 6, 7]:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \qquad (3)$$

Here, R_1 and R_2 are the ratios $({}^{\mu_C}/_{\mu_t})$ of the two successive elements of atomic numbers Z_1 and Z_2 respectively within which R falls at each energy.

Evaluation of GP fitting parameters

Five (5) fitting parameters are required for the evaluation of photon buildup factors by the GP fitting method [4, 6, 7]. These parameters (b, c, a, X_k, and d) depend on Z_{eq} and photon energy. The ANS [3] has provided these coefficients for 23 elements at 25 standard photon energies. If the $({}^{\mu_C}/_{\mu_t})$ of a material did not match that of any of the 23 elements, their GP fitting coefficients are also interpolated using the logarithmic interpolation formula:

$$F = \frac{F_1(\log Z_2 - \log Z_{eq}) + F_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \qquad (4)$$

where F_1 and F_2 are the G-P fitting parameters obtained from ANS data base corresponding to the atomic numbers Z_1 and Z_2 respectively. However, if the ratio of any material matches that of any of the given elements, the fitting parameters of that element automatically is that of the investigated material at any given energy.

Estimation of buildup factor

The buildup factors ($B(E,x)$) for the given material are estimated for a given incident energy (E) in the spectrum (0.015 MeV -15 MeV) for different penetration depth (x) up to 40 mfp by the equations [4]:

$$B(E,x) = 1 + \frac{(b-1)(K^x-1)}{K-1}, \text{ for } K \neq 1 \qquad (5)$$

$$B(E,x) = 1 + (b-1)x, \text{ for } K = 1 \qquad (6)$$

where,

$$K(E,x) = cx^a + d\,\frac{\tanh\left(x/X_K - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \text{ for } x \leq 40\, mfp$$

Computation of buildup factors of concrete samples

For the evaluation of buildup factors, a total of 10 different concretes were considered. The considered concretes vary in composition and also density as given in table 1. The compositions of the sample concretes were obtained from the literature [5, 8, 9]. They are composed of various elements ranging from hydrogen, to iron as the element with maximum atomic number. The densities of the concretes range from 2.30 – 5.11gcm^{-3}. Consequently, they are categorized using their densities (ρ) to light (LYT) concretes (ρ= 2.30 – to 3.05gcm^{-3}) and heavy (HVY) concretes (ρ= 3.50−5.11gcm^{-3}).

The energy absorption buildup factors of the concretes were calculated using the well-known G.P. fitting method compliant computer code. The GP procedure is laborious and required a lot of data, to ease the calculation, a user interface friendly program (called EXABCal) [10] was written using Python programming language following the G.P procedure. The program was validated using standard data and manual calculations and found to be accurate within 2%. The program can be used for calculating equivalent atomic number, exposure and absorption buildup factors buildup factors of any compound or mixture.

Results

The chemical compositions of the concretes given in table 1 show a wide variation in their elemental constituents. Out of all the elements present in the samples, only five (O, Al, Si, Ca and Fe) are common to all the concretes considered. This is due to the fact that four of these elements (O, Al, Si, and Ca) form the major elemental composites of the major components (cement, aggregates and water) generally used for concrete making while Fe is in trace amount.

The Z_{eq} of composite (compound or mixture) material is a parameter similar to the atomic number (Z) of a chemical element. Most times, photon interaction modes depend on the atomic number of the interacting medium, consequently, the Z_{eq} of a composite medium play the role of Z in such interactions. The value of Z_{eq} for any given material depends on the constituent elements and also varies with photon energy unlike Z. the variation of Z_{eq} of the 11 concretes species considered with energy (E) is presented in figure 1. From the figure the variations were all similar, increasing slightly with E in the low energy region and with a sharp decrease at 1 MeV.

Energy Absorption Buildup Factor (EABF)

The energy dependence of the concrete's EABF at different depths are presented in figures 2-12. Generally, the behaviour of the EABF energy are similar though with different magnitudes with respect to concrete specie. From the figures, the buildup factors were minimum in the low and high energy regions of the spectrum. The energy (E) range 0<E<0.1 MeV and 0.1<E<2 MeV were designated as as the low and intermediate energy range, while energies greater than 2 MeV were classified as the high energy region.

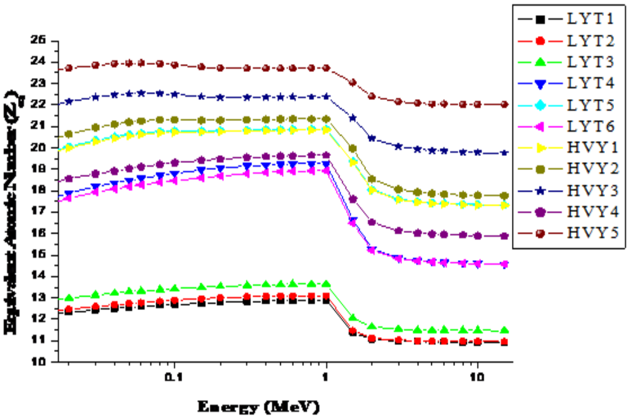

Figure 1. **Equivalent atomic number variation with photon energy**

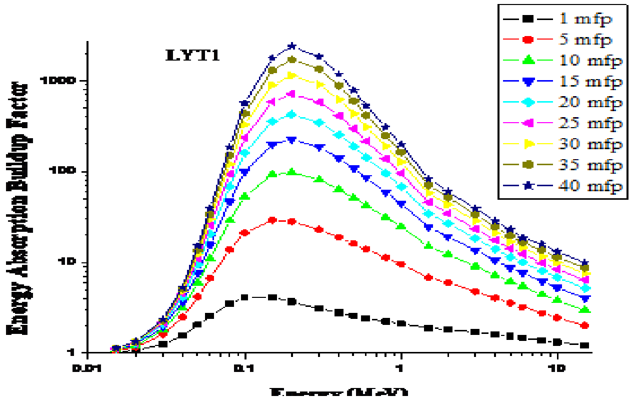

Figure 2. **Variation of EABF with energy at various depth for LYT1**

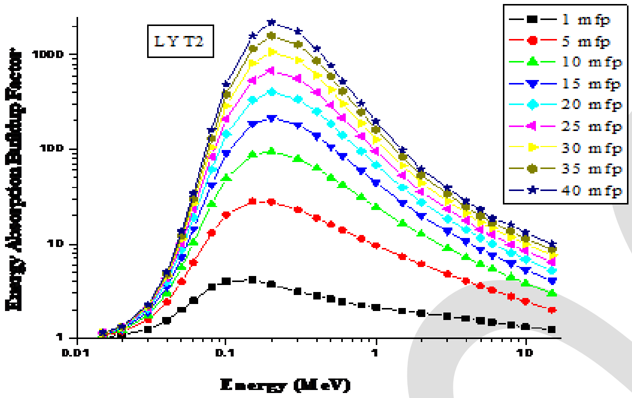

Figure 3. **Variation of EABF with energy at various depth for LYT2**

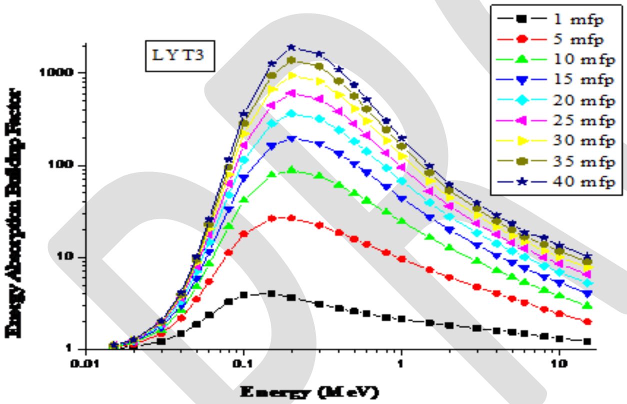

Figure 4. **Variation of EABF with energy at various depth for LYT3**

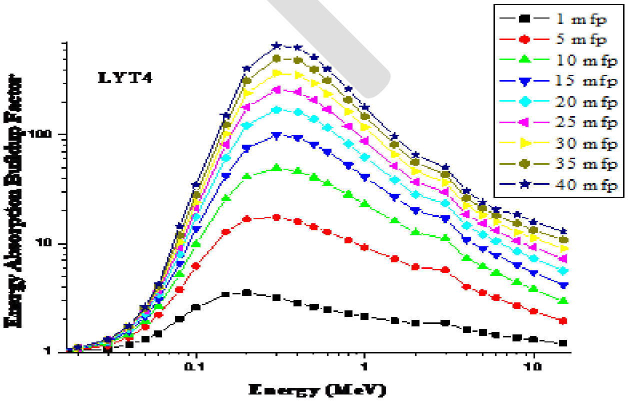

Figure 5. **Variation of EABF with energy at various depth for LYT4**

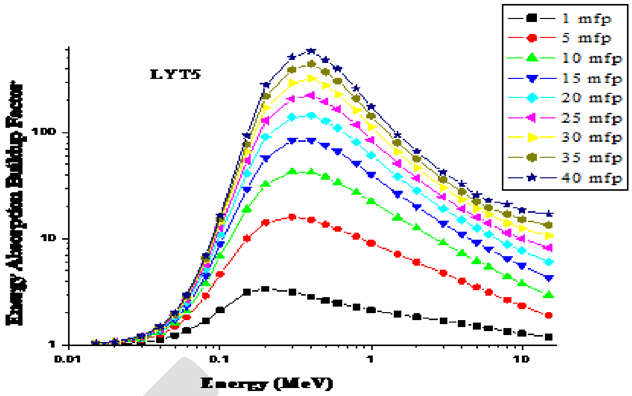

Figure 6. **Variation of EABF with energy at various depth for LYT5**

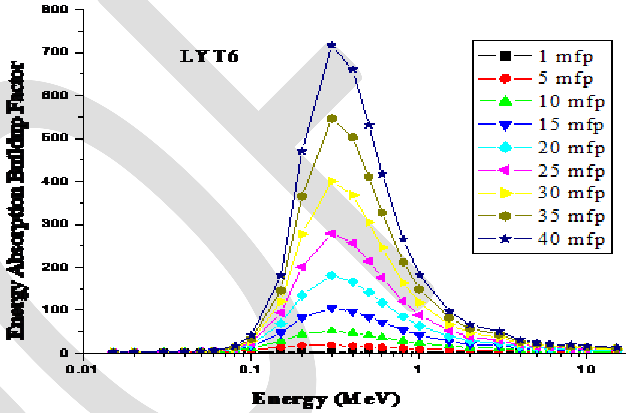

Figure 7. **Variation of EABF with energy at various depth for LYT6**

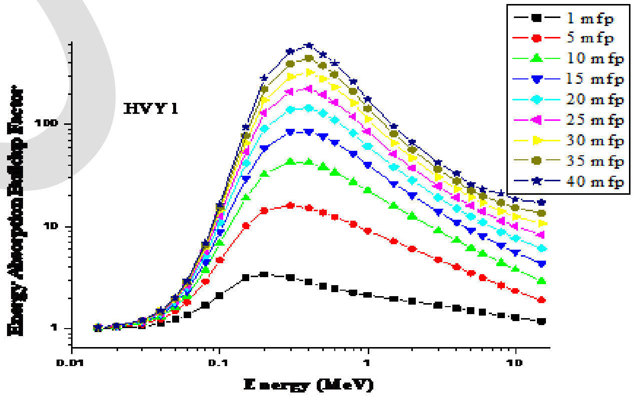

Figure 8. **Variation of EABF with energy at various depth for HVY1**

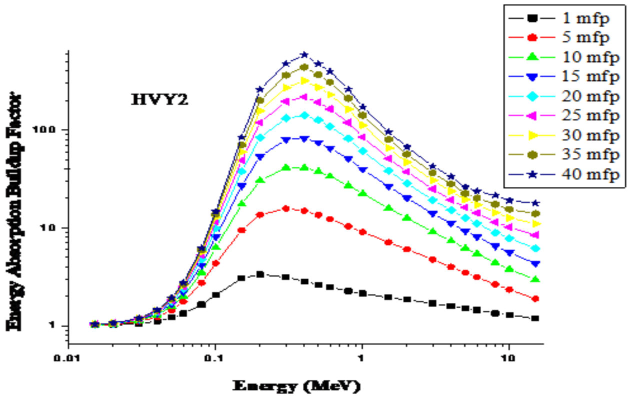

Figure 9. Variation of EABF with energy at various depth for HVY2

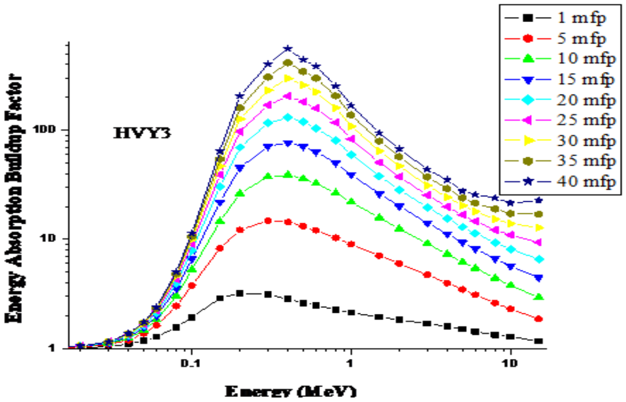

Figure 10. **Variation of EABF with energy at various depth for HVY3**

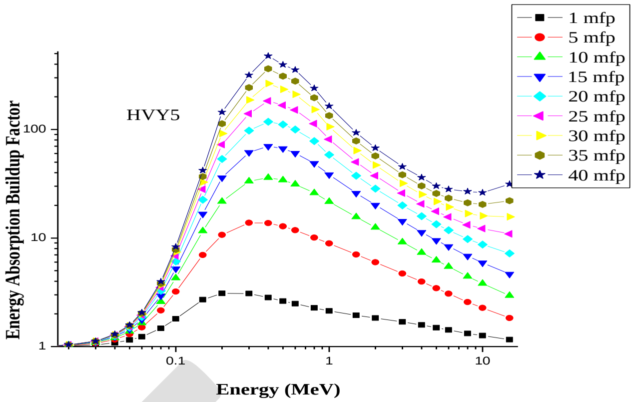

Figure 12. **Variation of EABF with energy at various depth for HVY5**

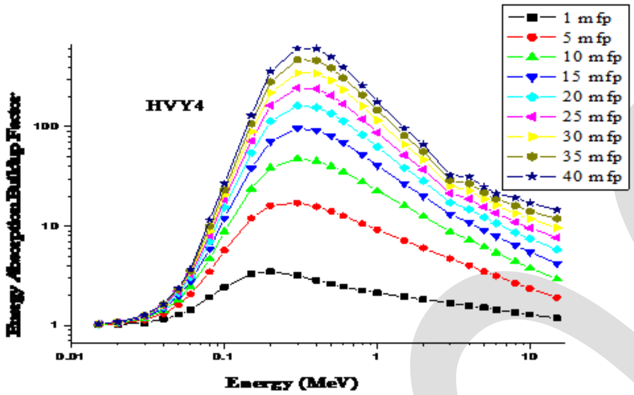

Figure 11. **Variation of EABF with energy at various depth for HVY4**

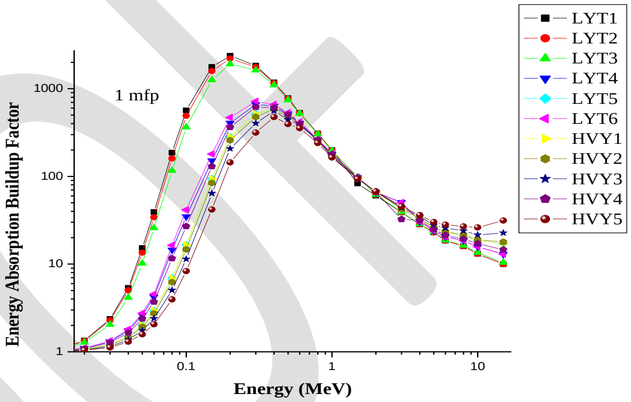

Figure 13. **Comparison on EABF of all the Concretes at 1 mfp**

Table 1. The elemental composition of the shielding materials

Code	Density (g/cm^3)	Composition (%)														
		H	C	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Mn	Fe
LYT1	2.30	0.94	0.09	53.66	0.46	0.12	1.32	36.74		0.08		0.31	5.65				0.63
LYT2	2.30	1.00	0.10	53.00	1.60		3.60	33.67					5.64				1.39
LYT3	2.35	0.56		49.83	1.71	0.24	4.56	31.58		0.12		1.92	8.26				1.22
LYT4	2.50	1.29		43.51		6.64	1.67	10.53		0.09			5.97				30.31
LYT5	2.90	0.66		36.45		0.15	0.80	3.06		0.08			5.83	16.03			36.93
LYT6	3.05	0.83		42.30	1.06	2.20	4.22	13.20	0.20	0.09		0.29	8.88	0.60		0.12	26.01
HVY1	3.50	0.57		35.93	0.06	1.31	0.61	2.40		0.07	0.02	0.03	3.88	19.64			34.78
HVY2	3.70	0.40		34.50		1.90	1.00	6.90					4.80				50.50
HVY3	4.00	0.70	0.09	21.09	0.45	0.09	1.20	10.49		0.06		0.30	4.28				61.25
HVY4	4.50		0.06	36.7	0.88	5.93	5.35	4.43		0.61			3.64		34.23		8.04
HVY5	5.11	0.51		15.70		0.58	0.66	2.68	0.08	0.06			3.95			0.07	75.73

Discussion

Equivalent atomic number (Z_{eq}) and photon energy

The elements (O, Al, Si, Ca and Fe) makeup more than 80% of the chemical composition of the concretes. The concentration of Fe has a direct impact on the density of the materials, increasing as the density increases while Si and O concentration drops. This is due to the fact that in high density concretes, materials rich in Fe and consequently of high density such as steel, steel scraps, hematite, magnetite *etc.* are used as additives. Consequently, such concretes owe their density to those additives. The photon interactions of the concrete species can thus be explained in terms of their elemental composition and perhaps their density.

The Z_{eq} had a relatively constant and lowest values beyond 2 MeV. These behaviours could be attributed to the dominance of the energy dependent different interaction (photoelectric, incoherent, and pair production) cross sections at the different energies. From the values of the equivalent atomic numbers, it can be concluded that the minimum and maximum boundary values of Z_{eq} of each of the concrete through the energy spectrum was dictated by the minimum and maximum Z of the constituent elements [6]. Thus concretes with denser atomic constituents had relatively higher Z_{eq} and vice versa. Although there appears to be a direct relationship between Z_{eq} and concrete density, however, this relationship failed betweenLYT4, LYT5, LYT6 AND HVY1.

Energy Absorption Buildup Factor (EABF)

The energy dependence of the concrete's EABF at different depths are presented in figures 2-12. Generally, the behaviour of the EABF energy are similar though with different magnitudes with respect to concrete specie. From the figures, the buildup factors have minimum values in the low and high energy regions of the spectrum. The energy (E) range 0<E<0.1 MeV and 0.1<E<2 MeV were designated as the low and intermediate energy range, while energies greater than 2 MeV were classified as the high energy region. The variation of EABF in these energy regions can be explained on the basis of photon interaction cross sections. Throughout the considered energy spectrum, three interaction procedures are of major importance and are responsible for the observed variations in EABF of the concretes with respect to energy of interacting photons. These are the photoelectric effect, Compton or incoherent scattering, and the pair (electron (e^-)-positron (e^+)) production with interaction cross-sections τ,σ, and κ respectively. These cross-sections vary with energy according to the following expressions [6, 11]:

$$\tau = p\,{Z^5}/{E^3} \quad (7)$$

$$\sigma = q\,{Z}/{E} \quad (8)$$

$$\kappa = rZ^2(E - 1.022) \quad (9)$$

where p, q, and r, are all constants. Both the photoelectric and Compton effects have no threshold energy, however, the threshold of the pair production is the equivalent energy of two electrons (1.02 MeV).In the low energy region, τ has the highest value while σ, and κ are dominant in the intermediate and high energy regions respectively. Consequently, the low values of EABF at low and high energy regions are due to the dominance interaction processes that tend to remove photon completely from a beam of photons during interaction. The photoelectric process produces photo-electrons through the absorption of photons hence the observed low (almost equal to unity) of the EABF in the low energy region. Similarly, the pair production process, removes photons from interacting photon beam by the production of e^--e^+ pair once the energy of the photon is greater than 1.02 MeV. These created pairs may escape from the medium especially at low depth and thus EABF is low at the high end of the energy spectrum [12-14].

EABF variation with Depth

From figures 2 to 12, the EABF increases with depth for all concretes and energy. This can be attributed to the high number of scattering that occurs at the intermediate energy region. At high depth, due to multiple scattering, lower value energy photons are produced which leads to the slight increase in the EABF in the photoelectric region [13]. The increase is more conspicuous in the intermediate region. At higher depth the e^--e^+pair produced in the high energy region do not escape from the medium but rather annihilate each other to produce secondary photons of energy 1.02 MeV which increase buildup in the region and in the intermediate region as more photons are produced. These pair may also surfer multiple collisions which prevents them from escaping but producing lower energy photons (buildup). The EABF is generally lower for all depth in the low energy region for all concrete material as well.

EABF and equivalent atomic number (Z_{eq})

A comparison of the EABF of the concretes at the same energy and depth indicated a decrease in buildup factor with Z_{eq} as shown in figure 13 for depth of 1 mfp. The direct relationship shows that the Z_{eq}can be used as a rough estimate to compare between EABF of shielding materials. However, the same cannot be said of the density.Consequently, it safe to conclude that the EABF of composite materials are better dictated by the elemental composition (Z_{eq}) andnot mass density. Furthermore, between 1 and 2 MeV, the EABF of all the concrete are almost the same. This suggests that EABF at these energies is independent of the material and composition [6, 12-14}.

Conclusions

The equivalent atomic numbers and energy absorption buildup factors of eleven concrete types were evaluated for different energies (0.015-15 MeV) and depth up to 40 mfp using the well-known geometric progression fitting method. The concretes were divided into light and heavy concretes based on the range of their physical densities. The elemental composition of the concretes varied based on their different composite materials. Furthermore, their mass density reflected the atomic density of their compositions. The calculated equivalent atomic number changes with energy and atomic composition. Also, the estimated buildup factors were found to vary inversely with $Z_{eq}$for all depth and energies considered. The changes in the value of EABF were explained in terms of dominance of different photon interaction cross sections at different energies and depth. The study concludes that the buildup factor and photon shielding capacity of concrete cannot bedescribed exclusively using their physical density but rather by their elemental compositions (Z_{eq}). Heavy concrete with higher values of Z_{eq} are better photon shield compare to those with lower Z_{eq}. Concretes with higher Z_{eq} have lower EABF due to low scattering due to lower scattering. This explains why HVY5 could be adjudged the best concrete for photon shielding amongst the concrete considered in this research and the photon energy range considered.

Abbreviations

EABF: Energy Absorption Buildup Factor (EABF); MFP: Mean Free Path; GP: Geometric Progression; ANS: American Nuclear Society.

Author Contributions

O. O. designed the study and prepared the manuscript; M. M. performed the experiments. All authors gave their final approval.

Competing Interests

The authors have declared that no competing interest exists.

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