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Determination of gamma and fast neutron shielding parameters of magnetite concretes

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ABSTRACT

In this study, some gamma shielding parameters such as mass attenuation coefficient (μ_ρ), effective atomic number (Z_{eff}), electron density (N_{el}) and buildup factors have been investigated for concretes with and without magnetite aggregate. The measurements have been carried out using 1.25 MeV (mean energy of 1.1732 MeV and 1.3325 MeV photons of a ^{60}Co radioactive source) gamma photons. The theoretical values of μ_ρ have been calculated in the energy range from 1 keV to 100 GeV by WinXCom computer code and these values were used in order to calculate the values of Z_{eff} and N_{el}. And fast neutron shielding parameter namely effective removal cross-sections (Σ_R, cm^{-1}) have been calculated. In addition, Energy absorption buildup factors (EABF) and exposure buildup factors (EBF) values of concrete samples have been calculated for photon energy 0.015–15 MeV up to 40 mfp (mean free path) penetration depths. The results of this study showed that the magnetite concrete is more efficient than the ordinary concrete for fast neutrons and gamma rays.

1. Introduction

Nowadays, radioisotopes have been used widely in many areas such as industry, agriculture, scientific investigation and medicine. A radioactive isotope of the element cobalt with a mass of 60 (^{60}Co) emits 1.173 and 1.332 MeV gamma rays (with a mean energy value of 1.25 MeV) and it is mostly used in radiotherapy units for medical treatment. Exposure to ^{60}Co radiation may cause danger to persons (admittedly, it is of course depend on the amount of the exposure). In order to prevent the harmful effects of ^{60}Co radiation, the wall and ceiling materials of radiotherapy room should be selected as high density. Concretes produced with high density aggregate, may be preferred to provide a greater protection from gamma radiation (Demir et al., 2010; Akkurt et al., 2005). The use of high density concrete results in a reduction in the thickness of the concrete required for gamma shielding. Magnetite ore (Fe_3O_4) can be used to serve this purpose as it has high density. Magnetite ore is an oxide of iron which is strongly magnetic and it is most widely used types of heavy aggregate for high-density radiation shielding concrete (Kaplan, 1989).

For a composite material such as concrete, the attenuation of gamma radiations is mostly represented by the mass attenuation coefficients (μ_ρ), effective atomic numbers (Z_{eff}) and electron densities (N_{el}). μ_ρ is a measure of probability of interactions of incident gamma-rays with the thickness (g/cm^2) of shielding material (Hubbell, 1999, 2006). The values of Z_{eff} and N_{el} can be derived from the mass attenuation coefficient for all gamma energies (Akman et al., 2015). The effective atomic number is a measure of the mean number of electrons of the shielding material and it is not constant (Hine, 1952). The value of Z_{eff} varies depending on gamma energy due to different partial photon interaction processes with matter (Kurudirek et al., 2010).

A great number of researchers reported results of effective atomic number in different materials such as alloys (Singh and Badiger, 2014b; El-Kateb et al., 2000), compound and mixtures (Sidhu et al., 2012; İçelli et al., 2012; Polat et al., 2011; Baştuğ et al., 2010), glasses (Sharma et al., 2012; Kirdsiri et al., 2009; Chanthima et al., 2012; Kaewkhao and Limsuwan, 2010; Kaewkhao et al., 2010). El-Khayatt and Akkurt (2013) calculated Z_{eff} and N_{el} for a wide range of photon energy for concrete containing marble in different

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concentrations (El-Khayatt and Akkurt, 2013). Un and Demir (2013) determined mass attenuation coefficients, effective atomic numbers and effective electron numbers for different types of concretes (Un and Demir, 2013).

Some computer programs have been developed to estimate effective atomic number (Taylor et al., 2012; Yalçın et al., 2012).

Fast neutron attenuation in shielding medium is characterized by the macroscopic effective removal cross-sections (Σ_R, cm^{-1}) and it has been described in many works (Blizard and Abbott, 1962; Kaplan, 1989). In literature, most studies have been reported to calculations of effective removal cross-sections in different types of concretes. El-Khayatt (2010) calculated Σ_R of concretes containing different lime/silica ratios. The values of Σ_R for four types of concrete of different densities have been calculated by El-Sayed Abdo (2002) using the elemental composition of concretes. Yılmaz et al. (2011) calculated values of Σ_R for 12 concrete samples with and without supplementary cementitious materials.

During gamma rays interact with matter through Compton scattering, the incident photon energy reduces and its direction also changes which give rise to scattered secondary photons which can be estimated by the buildup factor. The gamma ray buildup factor is a multiplicative factor used to obtain the corrected response to the uncollided photons by including the contribution of scattered photons. It can be defined as the ratio of the total detector response to that of uncollided photons. There are two types of buildup factor; the energy absorption buildup factor (EABF) that is the buildup factor in which the quantity of interest is the absorbed or deposited energy in the interacting material and the detector response function is that of absorption in the interacting material; the exposure buildup factor (EBF) is the buildup factor in which the quantity of interest is the exposure and the detector response function is that of absorption in air (Singh et al., 2008). There are various studies about buildup factors of different concrete composition (Oto et al., 2015; Sharaf and Saleh, 2015; Singh et al., 2010; El-Sayed and Bourham, 2015).

In the present study, mass attenuation coefficients (μ_ρ) of ordinary and magnetite concrete samples have been measured at 1.25 MeV average gamma energy and calculated in the wide energy region (1 keV–100 GeV) using WinXCom code. Then effective atomic number (Z_{eff}) and electron density (N_{el}) have been calculated in same energy region. And also macroscopic effective removal cross-sections (Σ_R) for fast neutrons were calculated using chemical compositions of concrete samples. Lastly, the data for buildup factors up to 40 mfp for concrete samples have been generated using G-P fitting formula. The main emphasis has been focused on the dependence of EABF and EBF on the incident photon energy, penetration depth or equivalent atomic number of concrete samples. This work could be very useful in utilizations of magnetite concretes in radiotherapy units and the nuclear reactor design for radiation shielding.

2. Theory

2.1. The total mass attenuation coefficient, effective atomic number and electron density

The attenuation of gamma or X-rays passing through a material is determined according to Lambert-Beer law,

$$I = I_0 e^{-\mu_\rho t} \tag{1}$$

where I_0 and I are the incident and the attenuated intensities of photons, respectively, t is the mass thickness of the sample that corresponds to the mass per unit area in g/cm^2 and μ_ρ (cm^2/g) is the mass attenuation coefficient. The theoretical mass attenuation coefficients for any mixture, compound or alloy are calculated by WinXCom code (Gerward et al., 2004), based on the mixture rule

$$\mu_\rho = \sum w_i \left(\mu_\rho\right)_i \tag{2}$$

where $(\mu_\rho)_i$ is the mass attenuation coefficient and w_i is the fractional weight of the ith constituent element. The effective atomic number (Z_{eff}) for total photon interaction is given by (Manohara et al., 2008; El-Khayatt and Akkurt, 2013):

Table 1
Amounts of concrete composition (kg/m^3).

Concrete	Water	Cement	Fine aggregate	Coarse aggregate	Fine magnetite	Coarse magnetite
C	180	360	745	1118	0	0
M50	180	360	372.5	559	372.5	559
M100	180	360	0	0	745	1118

Table 2
The calculation results of the effective removal cross-sections for C sample.

Elements	Σ_R/ρ (cm^{2}g^{-1})	C (2.32 g/cm^3)		
		Weight fraction	Partial density (g/cm^3)	Σ_R(cm^{-1})
H	0.598	8.51E-03	1.97E-02	1.18E-02
O	0.0405	4.71E-01	1.09E+0	4.43E-02
Na	0.0341	2.48E-03	5.75E-03	1.96E-04
Mg	0.0333	7.37E-02	1.71E-01	5.69E-03
Al	0.0293	2.52E-02	5.85E-02	1.71E-03
Si	0.0295	2.21E-01	5.12E-01	1.51E-02
S	0.0278	3.13E-03	7.26E-03	2.02E-04
K	0.0247	1.01E-03	2.34E-03	5.79E-05
Ca	0.0243	1.74E-01	4.04E-01	9.81E-03
Mn	0.0202	1.34E-03	3.11E-03	6.28E-05
Fe	0.0214	1.89E-02	4.39E-02	9.39E-04
Cu	0.0188	0.00E+0	0.00E+0	0.00E+0
Total Σ_R(cm^{-1})				8.98E-02