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Comparative study of different concrete composition as gamma-ray shielding materials

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A B S T R A C T

The addition of some materials with various fractions in the composition of concrete has provided concrete forms more efficient for gamma ray shielding when compared to ordinary concrete. Selected materials were added and the γ-ray linear and mass attenuation coefficients, the mean free path and half value layer (HVL) were calculated. These parameters of dosimetric interest have been investigated in the energy range 0.015–15 MeV. The photon interactions with the concretes have been discussed. The blended composition with 39.195% magnetite Fe_3O_4 and 15.678% lead oxide PbO, named Concrete 6 in this study, has shown the best mass attenuation coefficient, exposure buildup factor and HVL values among other mixes thus minimizing the exposure rate to the acceptable levels.

1. Introduction

Exposure to gamma rays can occur in a range of nuclear facilities such as reactors, nuclear research and medical diagnostic centers, and nuclear waste storage sites. It is essential to reduce the intensity of external radiation to the standard acceptable level, and hence the attenuation property of a shielding material is of great importance. While the attenuation is thickness and density dependent, however, having large thickness may cause economic concerns and space consideration. It is also important to ensure mechanical integrity of the shield and its resistance to fracture, corrosion and degradation.

Concrete has proven to be an excellent and versatile shielding material with a well-established linear attenuation coefficient for gamma rays and neutrons. It is widely used in nuclear facilities such as nuclear research and power reactors, high-energy particle accelerators, hot cells, high-level waste dry casks, and medical facilities using nuclear systems and X-rays, research facilities including biological and chemical laboratories. The relatively inexpensive cost of concrete, and its high mass attenuation coefficient, has been an attractive factor as a shielding material in addition to its excellent structural property as a construction material. Additionally, concrete mixing and preparation is not sophisticated and casting into shapes is quite easy. The concrete mix from the cement and the aggregates contains a good blend of elements, which provides a material with good nuclear properties for the attenuation of photons and neutrons (Kaur et al., 2012; Singh et al., 2009). Modifying the composition of concrete with additives of different specific density will alter the shielding characteristics such that thinner thicknesses may be obtained while having higher mass attenuation coefficient. Concrete has high compressive, low tensile strength, low coefficient of thermal expansion, and low thermal conductivity. It is considered to be an ideal shielding material and is widely used for radiation shielding in nuclear systems and other radiation-user facilities (Lee et al., 2007; Rezaei-Ochbelaghand and Azimkhani, 2012). The change in the aggregates with the cement will change the concrete properties in terms of radiation shielding effectiveness and the structural properties. Several studies investigated production of high-density concretes to lower the thickness while achieving a higher linear attenuation coefficient, which may be achieved by special additives instead of changing the percent of the aggregates (Akkurt et al., 2010a,b; El-Khayatt, 2010; Stankovic et al., 2010; Ochblagh et al., 2011; Gencel et al., 2011; Singh et al., 2013a,b).

As well known, the linear and mass attenuation coefficients are calculated from the exponential law. The linear attenuation and mass attenuation coefficient will be used to evaluate the ability of a material to shield a photon of a specific energy. The mass attenuation coefficient will be calculated from the following equations (Seltzer, 1993; Kaplan, 1989; Wood, 1982) using the Microshield.v5.03 (MicroShield):

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$$\mu_i = N_i \sigma_i \quad (1)$$

$$\mu_i/\rho_i = \ln(I_0/I)/\rho\ t \quad (2)$$

Where μ_i is the total linear attenuation coefficient, N_i is the number of atoms per cm^3, σ_i is the microscopic cross section (cm^2), μ_i/ρ_i is the mass attenuation coefficient (cm^2/g), ρ_i is the density (g/cm^3), I_0 and I are the incident and transmitted intensities, respectively, and t is thickness of absorber. The mass attenuation coefficient for mixture of elements is given by:

$$W_{total} = \sum W_i (\mu/r)_i \quad (3)$$

Where W_{total} is the total mass attenuation coefficient for the mixture of elements and W_i is the weight fraction of the mass of composition i.

The half-value layer HVL can be calculated by using the relation:

$$\mathrm{HVL} = 0.693/\mu \quad (4)$$

The computational methodology herein is based on using the MicroShield to calculate the theoretical mass attenuation coefficient for the different concrete composition. MicroShield was also used to analyze shielding and to estimate the exposure from gamma radiation. MicroShield® is a comprehensive photon/gamma ray shielding and dose assessment program used for designing shields, estimating source strength from radiation measurements, and minimizing exposure to environment (MicroShield). Several of the specific uses of this type of analysis include assessing radiation exposure to people and equipment, selecting temporary shielding for maintenance tasks, inferring source strength for waste characterization and disposal from external gamma radiation measurements. Entry to MicroShield includes the geometry and physical dimensions, materials, and the radiation source data. For the case study in this research, concrete forms of Table 1 were run in MicroShield as the overpack material for a cylindrical geometry where the γ-ray linear and mass attenuation coefficients, the mean free path and half value layer (HVL) were calculated.

2. Composition of blended concretes

Composition and densities for different concrete types are given in Table 1. Density was increases by decreasing the aggregate percent and increasing the additives such as magnetite, lead oxide, barites and ferrophosphorus. Substitution of magnetite and lead oxide by aggregate causes lowering of volume and increases the specific density of the concrete. The impact of different additives on the specific gravity of the concrete is shown in Fig. 1.

The value of the linear and mass attenuation coefficients and the other parameters of dosimetric interest have been calculated using the Microshield.v5.03 (MicroShield), as will be shown in detail in Section 3.

3. Results and discussion

3.1. Mass attenuation coefficient of selected concrete forms

The mass attenuation coefficients of the selected concrete forms, including the custom form (concrete 6) are shown in

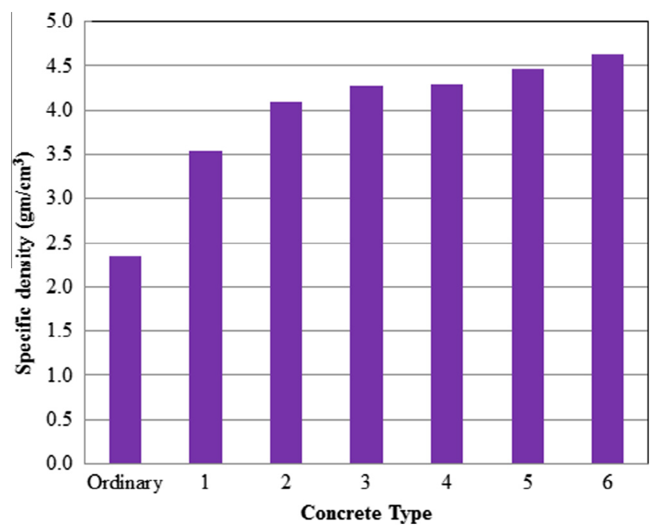

Fig. 1. Specific density of the different concrete forms.

Table 1
Chemical composition of different synthesized concrete types.

Material Density	Concrete Composition			
	Cement (%)	Water (%)	Aggregate	Additive
Ordinary Concrete 2.350 g/cm^3	13.98	7.63	78.39% "gravel and sand"	–
Concrete 1 3.542 g/cm^3	13.98	7.63	39.195	39.195 magnetite(Fe_3O_4)
Concrete 2 4.089 g/cm^3	13.98	7.63	31.356	39.195 magnetite(Fe_3O_4), 7.839 lead oxide(PbO)
Concrete 3 4.265 g/cm^3	13.98	7.63	23.517	39.195 magnetite(Fe_3O_4), 7.839 lead oxide(PbO), 3.9195 barite($BaSO_4$), 3.9195 ferrophosphorus(Fe_3P)
Concrete 4 4.285 g/cm^3	13.98	7.63	23.517	39.195 magnetite(Fe_3O_4), 7.839 lead oxide(PbO), 7.839 ferro-phosphorus (Fe_3P)
Concrete 5 4.463 g/cm^3	13.98	7.63	23.517	39.195 magnetite(Fe_3O_4), 11.7585 lead oxide(PbO), 3.9195 ferrophosphorus (Fe_3P)
Concrete 6 4.64 g/cm^3	13.98	7.63	23.517	39.195 magnetite(Fe_3O_4), 15.678 lead oxide(PbO)

*Cement (Portaland) chemical composition 63%SiO_2, 22%CaO, 3%Al_2O_3, 5%Fe_2O_3, 3%MgO, 3%SO_3, 0.3%Na_2O, 0.7%K_2O.
*Aggregate chemical composition 80%SiO_2, 20%$CaCO_3$.