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Neutron shielding qualities and gamma ray buildup factors of concretes containing limonite ore

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HIGHLIGHTS

- Macroscopic removal cross-sections (Σ_R, cm^{-1}) have been determined experimentally and theoretically for concrete samples.
- EABF and EBF of the concrete samples has been determined using the Geometric Progression (G-P) approximation.
- Penetration depth and energy dependence of the buildup factors evaluated.
- FCL is good shielding material for neutron and gamma radiation.

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ABSTRACT

Neutron dose transmissions for fast neutrons produced by 5.486 MeV alpha particles on beryllium are measured in concrete samples with and without limonite ore to investigate their neutron shielding qualities. Using measured values, macroscopic removal cross-sections (Σ_R, cm^{-1}) have been determined experimentally and also $\Sigma_R$values have been calculated theoretically using the elemental composition of the concrete mixes. The best neutron shielding property of concrete sample containing 100% limonite ore (FCL: fine and coarse limonite) was found. Additionally, energy absorption buildup factor (EABF) and exposure buildup factor (EBF) of concrete sample were calculated using the five-parameter Geometric Progression (G-P) approximation in the energy range of 0.015–15 MeV for penetration depths up to 40 mean free path (mfp). The incident photon energy and penetration depth dependence of buildup factors were examined. Finally, we observed that concrete samples have maximum values of buildup factors in the intermediate energy region around 0.1–0.3 MeV. FCL has the minimum values of both of the buildup factors. FCL has the excellent gamma shielding properties compared to the concrete samples.

1. Introduction

The removal cross-section for neutron interacting with a shielding material is probability of one neutron undergoing a specific reaction per unit path length of travel through the material. The probability of a certain neutron interaction with the target material is proportional to the neutron flux and to the isotopic density of the matter under consideration. The development of a comprehensive neutron macroscopic cross-section database is of importance while assessing safety and risk in different fields of nuclear technology such as nuclear power plants, nuclear waste management and accelerator-driven transmutation systems. As such, while fast neutrons passing through a shield material, they are initially slowed-down by elastic and inelastic scattering until they have been reduced to low energies. Later, neutrons are absorbed or captured in the shield medium.

Light materials, especially hydrogenous materials, attenuate neutrons as a consequence of the high cross-section of hydrogen. Limonite ($2Fe_2O_3 \cdot 3H_2O$) is a hydrous iron ore that retains its water of crystallisation up to temperatures of about 200 °C. On the more positive side, limonite ore contains a material of high atomic number (iron) and at the same time it contains high proportion of hydrogen that made it more effective for both neutrons and gamma attenuation in compare to other hydrogenous materials. Concrete,

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Table 1
Mix proportions by weight of limonite and ordinary concretes.

Material	Particle size (mm)	N	FL1	FL2	FL3	FCL
Portland cement		1.00	1.00	1.00	1.00	1.00
Normal aggregate	0–4	1.59	1.20	0.80	–	–
Normal aggregate	4–16	2.96	2.96	2.96	2.96	–
Limonite	0–4	–	0.39	0.79	1.59	1.59
Limonite	4–16	–	–	–	–	2.96
Initial mix water (water/cement)		0.50	0.50	0.50	0.50	0.50
Density ($g\,cm^{-3}$)		2.42	2.61	2.66	2.76	2.89

which is more effective for the attenuation of neutrons and gamma rays, can be produced by increasing water content through the use of hydrous aggregates such as limonite (Kaplan, 1989).

Many studies have focussed on the radiation shielding of concrete using different aggregate and additive (Voronko et al., 2012; Agosteo et al., 2007; Yarar and Bayülken, 1994). Gencel et al. (2011) performed experimental measurements and simulations to obtain the gamma and neutron shielding properties of hematite concrete. Mollah et al. (1992) investigated neutron shielding characteristics of heavy concretes produced by ilmenite and magnetite sand. Kase et al. (2003) researched shielding properties of concrete samples comprise of about 80 percent by weight of oxygen and silicon. There are also some further studies on neutron-shielding properties of different materials such as polymer (Sundar et al., 1996; Harrison et al., 2008), ore (Korkut et al., 2012; Okuno, 2005) and paraffin wax (Ghassoun and Senhou, 2012). Today, gamma radiation is used in many different fields such as medical diagnosis, nuclear medicine, nuclear industry, radiation technology, scientific researches etc. for various purposes in the world. Therefore gamma ray shielding gains great importance. When gamma radiations have interacted with matter through Compton scattering, the energy of incident photon reduces and its direction also changes in the way that the results in creating scattered photons can be estimated by the buildup factor (Singh et al., 2010). The buildup factors have been widely studied by a few researchers (Küçük, 2010; Singh et al., 2010; Manohara et al., 2010; Mann and Korkut, 2013; Kavaz et al., 2015; Singh et al., 2014a, 2014b). The buildup factors can be summarised by the following types:

- The energy absorption buildup factor 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 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).

The recent studies in the literature revealed that, the most widely used methods for calculating buildup factors are G.P. fitting method (Harima et al., 1986) and Monte Carlo method (Sardari et al., 2009, 2011; Kharrati et al., 2012). The geometric progression (G-P) fitting formula is a theoretical method and is presented to determine the EABFs and EBFs in most of the elements. This method has been developed by Harima et al. (1986). The fitting parameters obtained by the GP formula and Taylor's formula (Taylor, 1954) are compiled in ANSI/ANS 6.4.3 (ANSI/ANS-6.4.3, 1991). American National Standards ANSI/ANS 6.4.3 (1991) has presented buildup factor data for 23 elements, one compound and two mixtures (i.e. air and water) and concrete at energies in the range of 0.015–15 MeV up to penetration depths of 40 mean free path (mfp) by using the G-P method.

In this study, concrete samples were produced utilizing limonite ore and normal aggregate in order to determine their effectiveness as a neutron shielding material. As a result, it was found that the elemental composition, hydrogen content and the density of concrete samples were important parameters for fast neutron shielding. Moreover, energy absorption buildup factor (EABF) and exposure buildup factor (EBF) of the concrete samples were calculated by using G-P fitting approximation in the energy region of 0.015–15 MeV up to penetration depths of 40 mfp. Finally, variations of EABF and EBF values of concrete samples with incident photon energy and penetration depths were evaluated.

2. Materials and methods

2.1. Preparation of concrete samples

In this study, the concrete samples were grouped into five categories (*N*, FL1, FL2, FL3, and FCL) according to particle size and concentration of limonite and normal aggregates as in Table 1. Elemental analysis of limonite ore, cement and normal aggregate were obtained by X-ray fluorescent method (Table 2). Normal concrete (*N*) mortar consisting of 1 Portland cement: 1.59 fine normal aggregate: 2.96 coarse normal aggregate: 0.5 initial mix water by weight was produced. The concrete mortars with limonite aggregate were prepared by mixing portland cement, fine and coarse normal aggregates, fine and coarse limonite aggregates and initial mix water in the ratios given in Table 1. Prepared mortars were poured into moulds with dimension of $15 \times 15 \times 4\,cm^3$. Twenty four hours later, concrete samples were removed from moulds and left to containers filled with water for 28 days at room temperature. The elemental compositions of concrete samples are given in Table 3.

2.2. Neutron dose transmission measurements

In order to determine the attenuation of fast neutrons passing through a shielding material, values of macroscopic cross-section (Σ, cm^{-1}) are calculated by using the following equation:

$$N = N_0 e^{-\Sigma x} \quad (1)$$

Table 2
The chemical content of limonite ore.

Compound	Limonite (%)	Standard sand (%)	Cement (%)
SiO_2	0.001	54.97	20.8
CaO	5.73	18.16	61.4
MgO	2.08	14.29	2.78
Al_2O_3	1.90	4.537	5.53
Fe_2O_3	70.94	–	3.41
K_2O	0.77	–	0.8
MnO	0.08	0.24	0.11
SrO	0.005	–	–
SO_3	–	0.026	5.02
Na_2O	2.94	0.38	0.1
CuO	0.03	–	–
P_2O_5	0.34	–	–
TiO_2	0.30	–	–
FeO	–	6.44	–
CuO	–	0.0075	–
H_2O	13.7	–	–