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Determination of radiation attenuation coefficients of heavyweight- and normal-weight concretes containing colemanite and barite for 0.663 MeV γ-rays

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ABSTRACT

Accurate measurements have been made to determine radiation transmission of concretes produced with barite, colemanite and normal aggregate by using beam transmission method for 0.663 MeV γ-rays energy of ^{137}Cs radioactive isotopes by using NaI(Tl) scintillation detector. Linear and mass attenuation coefficients of thirteen heavy- and four normal-weight concretes were calculated. It was determined that the linear attenuation coefficient (μ, cm^{-1}) decreased with colemanite concentration and increased with barite concentration in both type of the concretes. Mass attenuation coefficient values of our concretes were compared with the values proposed by the United States National Institute of Standards and Technology (NIST).

1. Introduction

Barite ore includes $BaSO_4$ which is well photon radiation absorbent. As known colemanite is a boron ore. Boron is one of the most important underground richness of Turkey. Boron is employed as a constituent material of neutron shielding because of its high absorption of thermal neutrons.

Heavyweight concrete is defined as concrete with unit weight ranging from about 2900 and 6000 kg/m^3 while unit weight of conventional concrete (i.e. normal-weight concrete) varied between 2200 and 2450 kg/m^3 (Nawy, 1997; Erdoğan, 2003). A great number of experimental and theoretical researches have been conducted on heavyweight concretes recently (Abdo, 2002; Abdo et al., 2002; Akkurt et al., 2005, 2006; Bashter et al., 1996a,b, 1997, Bashter, 1997; Dealmeid et al., 1974; Demir et al., 2010; Kaplan, 1989; Kitis et al., 1993; Mollah et al., 1992; Yarar and Bayülken, 1994). In NCRP report (2005), Tenth–Value Layers (TVLs) were reported for concrete, lead and steel at 6 MV and 18 MV beams. The TVLs of concrete are 6–8 times lower than that of lead and 3.5–4.5 times lower than that of steel at 6 MV and 18 MV beams. Facure and da Silva (2007) theoretically calculated TVLs for heavyweight concretes with ferrophosphorus, limonite, ilmenite, magnetite and barite at 4 MV, 6 MV and 10 MV beams using Monte Carlo Simulation Code MCNP. They were concluded that TVLs decreased with increasing density of the concrete.

Abdo (2002) and Abdo et al. (2002) theoretically calculated and determined cross section by using XCOM computer program for photon and neutron radiations shielding. In these studies, the total mass attenuation (μ/ρ) decrease with increasing from 0.1 to 100 MeV the photon energy for barite concretes. According to these papers, the decrease of μ/ρ with increasing the photon energy is almost the same for all mentioned concretes, and this may be attributed to the fact that, the Compton scattering and pair production are the predominant reactions. Akkurt et al. (2005, 2006) measured radiation transmission of heavyweight concretes including normal and barite aggregates for different γ-ray energies and calculated linear attenuation coefficients. These results are about 0.138–0.157 cm^{-1} for barite concretes and are about 0.102–0.107 cm^{-1} at 1.25 and 1.33 MeV, respectively. Bashter et al. (1996a,b) studied heavyweight concretes including hematite–serpentite, ilmenite–limonite as control absorber in nuclear reactors γ-rays and neutron particles shielding. Bashter (1997) and Bashter et al. (1997) studied heavyweight concretes including hematite–serpentite, ilmenite–limonite, basalt–magnetite, ilmenite, basalt, steel and magnetite for only photon radiation shielding and calculated linear and mass attenuation coefficients from 10 keV to 1 GeV. Dealmeid et al. (1974) studied radiation transmission and angular distribution for 25 MV X-rays by using LINAC. Kaplan (1989) reported a lot of studies about heavyweight concretes in his book. Kitis et al. (1993) studied heavyweight con-

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Table 1
Water absorption capacity and relative specific gravity of the aggregates.

Aggregate	Water absorption capacity (mass %)	Relative specific gravity
River sand	3.72	2.56
Barite (0–4 mm)	0.53	4.04
Barite (4–16 mm)	0.91	4.06
Colemanite (0–4 mm)	2.24	2.42
Colemanite (4–16 mm)	4.99	2.17
Normal agg. (4–8 mm)	2.79	2.46
Normal agg. (8–16 mm)	1.88	2.66

Table 2
Chemical composition and physical characteristics of the cement.

Chemical composition (mass %)		Physical characteristics		
SiO_2	19.94	Specific gravity		3.13
Al_2O_3	5.28	Blaine (cm^2/g)		3324
Fe_2O_3	3.45	Initial setting time (min)		130
CaO	62.62	Final setting time (min)		195
MgO	2.62	Expansion in the Le Chatelier apparatus (mm)		3
SO_3	2.46	Compressive	2-day	23.5
Loss on ignition	1.99	Strength	7-day	35.3
		(MPa)	28-day	47.0

cretes including barite aggregates for cyclotron shielding. Mollah et al. (1992) studied concretes including ilmenite and magnetite aggregates for neutron shielding by using ^{252}Cf radioactive source and BF_3 neutron detector. Yarar and Bayülken (1994) studied concretes including colemanite aggregates for neutron shielding.

In this paper, we have measured radiation transmission of seventeen different heavy concrete and normal concretes produced by using barite, colemanite and normal aggregates for 0.663 MeV γ-ray energy of ^{137}Cs radioactive isotope by using NaI(Tl) scintillation detector and calculated linear and mass attenuation coefficients. Results were compared to X-ray mass attenuation coefficient values of NIST.

2. Experimental procedures

2.1. Materials and sample preparation

Three different aggregates such as barite, colemanite and normal were used in the study. Barite and colemanite were supplied from Barite Mine Turkish Industry and Bigadic Boron Works (in Turkey), respectively. The water absorption capacity and the relative specific gravity of aggregates were determined according to Turkish Standard for Aggregates (TS EN 1097-6) given in Table 1. CEM I 42.5 was used as cement in all mixtures. Table 2 shows the chemical composition and physical characteristics of the cement. A hyperplasticizer (Glenium™ C303, a product of the Degussa Corporation) made of polycarboxylic ether was employed as chemical admixture. The relative specific gravity of this admixture was between 1.02 and 1.06.

The maximum particle size of aggregate was kept constant at 16 mm in all mixtures. Coarse aggregate was separated into two size fractions, 4–8 mm and 8–16 mm, and fine aggregate was divided into 0–2 mm and 2–4 mm, before being used. Additionally, 0–2 mm of size friction of barite aggregate was also separated into two sub fractions, 0–0.125 mm and 0.125–2 mm.

Four different series of concrete (totally 17 different mixtures) were prepared in the study. The first, second, third and fourth series consisted of barite–colemanite, barite–colemanite-normal aggregate, barite-normal aggregate and normal aggregate-colemanite, respectively. In all mixtures, cement, hyperplasticizer and water content were kept constant as 350 kg/m^3, 150 kg/m^3, and 5.3 kg/m^3, respectively. Proportions of all mixture ingredients used were given in Table 3.

In Table 3 and through the paper, the mixtures were designated with the following codes: the letter (or letters) shows the type of coarse aggregate (B = Barite, K = Colemanite, N = Normal aggregate), the digits following each letter are the percentage of this aggregate. Thus, B80K10N10 indicates a mixture that has a 80% barite, 10% colemanite and 10% normal aggregate as a coarse aggregate. All mixture beginning with B contain barite, while mixes beginning with N contain normal aggregate as a fine aggregate (0–4 mm).

All mixtures were prepared in a rotary planetary mixer with capacity of 60 L. The batching sequence consisted of mixing the all aggregates and cement for 1.5 min. After adding 60% of the total mixing water, the mixtures were also mixed for 1.5 min. Then, remaining water which was premixed with the hyperplasticizer was added to the mixer and mixed for 2 min. After 1.5 min of rest, mixing for an additional 2 min was carried out. Hence, the total mixing time for the mixtures was 8.5 min.

Each hardened concrete sample was divided into five different thicknesses (1, 3, 5, 7, and 9 cm) and radiation measurements were carried out on these samples. Average values of data obtained from these samples were used for radiation calculations.

2.2. Radiation transmission

The schematic arrangement of experimental set up and block diagram describing all the electronic part of the measuring system used in the present study are shown in Fig. 1. The measurements were repeated 10 times to decrease the statistical error. The photons with incident intensity I_0, penetrating a layer of material with mass thickness x (mass-per-unit area) with intensity I given by the exponential attenuation law is

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

where μ (μ/ρ) is linear (mass) attenuation coefficient. In this experiment the net counts I_0 and I were obtained at the same time and under the same experimental conditions.

The intensity of the first measurement without sample taken from digital counter defined was as I_0. Then other measurements with concrete samples are taken from digital counter and, the intensities of these results were defined as I. The values of linear attenuation coefficient μ (cm^{-1}) were calculated by means of Eq. (1).

According to the exponential attenuation law, the measurements are relative. The maximum errors in the measurement of linear attenuation coefficient were calculated from errors in intensities I_0 (without concrete), I (with concrete) and densities using the following relation

$$\Delta(\mu) = \frac{1}{x}\left\{\left(\frac{\Delta I_0}{I_0}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left[\ln\left(\frac{I_0}{I}\right)^2\right]\left[\frac{\Delta x}{x}\right]^2\right\} \tag{2}$$

where ΔI_0, ΔI and Δx are the errors in the intensities I_0, I and thickness x, respectively. In this experiment the net counts I_0 and I were obtained at the same time and under the same experimental conditions.

2.3. Apparatus

- Radioactive sources: ^{137}Cs
- Detectors: NaI(Tl) scintillation detector