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An investigation of X-ray and radio isotope energy absorption of heavyweight concretes containing barite

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Abstract. **This study investigated the X-ray and radioisotope energy absorption capacity of heavyweight concrete containing barite aggregate. Concrete plates were prepared using differing amounts of barite aggregate instead of normal aggregate. Density–thickness–energy variations of these concretes for 85 keV, 118 keV, 164 keV, 662 keV and 1250 keV ray energies were recorded. It was observed that the concretes with greater barite content had a higher density and energy absorption capacity.**

Keywords. **Barite; heavyweight concrete; radiation shielding; concrete.**

1. Introduction

Barite was first produced in the United States in 1845 and was used as a filling material in production of white paint. In 1926, the consumption and importance of barite increased significantly when it was began to be used in drilling mud. In Turkey, barite production first started in Antalya province in 1956. Barite production increased particularly after 1964.

Today, barite is one of the main materials used in heavyweight concrete production. Heavyweight concretes are used to increase protective moment in some special-purpose buildings which had the risk of sliding and overturning. However, the main fields of use of heavyweight concretes include protective concrete curtains for protection from radiation such as neutron and gamma radiation, which have the ability to penetrate objects. The uses of heavyweight concretes include radiotherapy and radiography facilities in hospitals, protective curtains of nuclear power plants, electron storage circuits, walls of military ammunition storage facilities, bridge abutments, concrete weight dam bodies, retaining walls, underwater oil pipelines, oil borehole periphery and pre-tensioned reactor silos where radioactive substances are stored (Topcu 2003). For protection from γ and X-rays occurring in atomic reactors or similar places and protecting body organs from damage, a concrete with a unit weight of $>3{\cdot}2$ kg/dm^3 should be produced. A concrete with such properties can only be produced with the use of heavy aggregates.

Several previous studies have been performed to obtain μ, theoretically and experimentally, for different elements, compounds and mixtures (Hubbell 1982; Teli and Chaudhari 1995; Bashter 1997; Singh *et al* 2001; Akkurt *et al* 2004). Akkurt *et al* (2004) carried out studies using barite aggregate in concretes as a protective shield from gamma (γ) rays. Mass attenuation coefficients were calculated at photon energies of 1 keV to 100 GeV using XCOM and the results were compared with measurements at 0·66 and 1·25 MeV. The barite concrete results were also compared with ordinary concretes (Akkurt *et al* 2005, 2006). Abdo El-Sayed (2002) is concerned with the theoretical calculation of both the total mass attenuation coefficients for gamma rays and the effective removal cross-sections for fast neutrons. The effective removal cross-sections were calculated using the elemental composition of the concrete mixes. The calculated values are widely needed and used as a database for radiation shielding design of research reactors, power station and particle accelerators (Abdo El-Sayed 2002). Akyuz (1997) studied heavyweight concrete produced with barite for protection from gamma rays. For this purpose, heavyweight concrete produced with barite had 1·25 meV of γ-ray absorption capacity. These are formulated as $\mu = 0{\cdot}055e^{1{\cdot}36c}$ cm^{-1} (c is the percentage of barite in the aggregate) according to the ratio of barite aggregate used in the aggregate and also the concrete unit weight, $\mu = 0{\cdot}006e^{1{\cdot}04\Delta}$ cm^{-1} (Δ is concrete unit weight, kg/dm^3) (Akyuz 1997).

In this study, six-series of barite concrete were prepared in the form of plates. The series contained 10%, 20%, 30%, 40% and 50% barite, according to absolute volume method. The concretes were exposed to 85 keV, 118 keV, 164 keV, 662 keV and 1250 keV ray energy. For each series, variations in thickness and radiation permeability were measured experimentally and the results are presented in the form of graphs.

2. Materials and methods

In this study, two types of materials were used: barite aggregate and normal crushed stone aggregate, supplied by Muş

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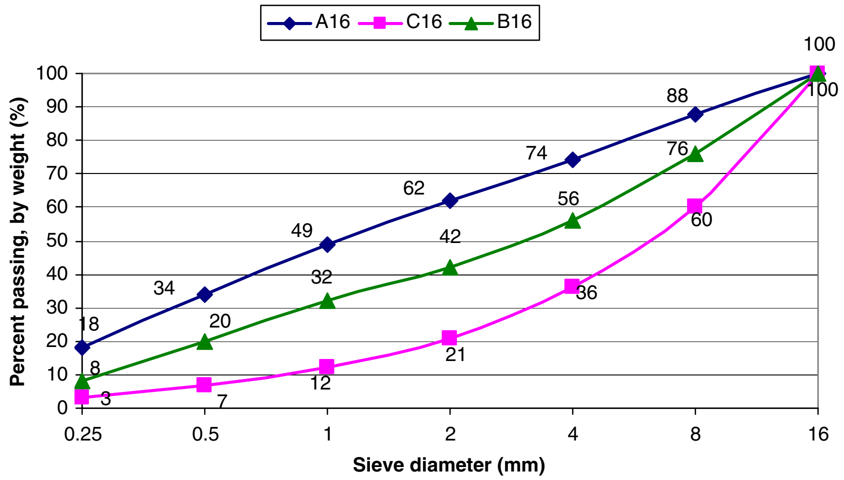

Figure 1. Granulometry curve of the aggregates used in the experiments.

End. Dış Ticaret A.Ş. Aggregate mixture ratios were determined according to TS 706 EN 12620 (TS 706 2003) with sieve analysis, based on the B16 curve between A16 and C16 curves. Granulometry curves of the aggregates used in the experiment are given in figure 1. Mixture calculations were performed according to the absolute volume method in such a way as to produce a concrete of plastic thickness with a grain size of 16 mm (TS 802 1985). In unit weight experiments performed on aggregates, a unit of barite aggregate was measured as 4·0 g/cm^3 and the unit weight of the normal aggregate was measured as 2·60 g/cm^3.

Since the aim of this study was to observe the thickness capacity of energy absorption of the concretes after increasing barite ratio in the mixture, control samples (C series) were produced for comparison. According to the absolute volume method, normal aggregate volume in the mixture was decreased by 10% (B10 series) and substituted by 10% barite aggregate. A total of 6 experimental series containing 20%, 30%, 40% and 50% barite were prepared. The series were termed B20, B30, B40 and B50 series, respectively. Table 1 shows the amount of aggregates used for 1 dm^3 concrete mixture in the experiment.

In preliminary experiments, it was decided that the cements used should be CEM I 42·5 R; w/c ratio for all mixtures should be taken as 0·60 to obtain a workable and substitutable mortar; and that cement dose should be 400 kg/m^3.

Table 1. Amount of aggregates used in the mixture (g/dm^3).

Samples	C	B10	B20	B30	B40	B50
Barite aggregate	0	260·4	520·8	781·2	1041·6	1302
Normal aggregate	1687	1517·5	1348·9	1180·2	1011·7	843

Slump value was measured as 4–5 cm. The cement used in the concrete mixtures was supplied from Elazığ Altınova Cement Factory. Table 2 shows chemical composition of the cement and barite aggregate. Physical and mechanical properties of the cement are given in table 3.

In order to measure radioactive permeability of the experimental concrete samples, 2-plate specimens of 300 × 300 × 10 mm and 3-plate specimens of 300 × 300 × 35 mm were prepared for each series of concretes. The specimens were kept in a curing room with 98% relative humidity at 20°C. The specimens were then stored in lime-saturated water for 28 days (TS 3068 1978). In concrete mixture calculations, the absolute volume method was used (Postacıoglu 1955).

In order to measure radiation permeability of the prepared concretes, a Standard dosimetry device and Segatech CNC computer program were used at the Turkish Atomic Energy Authority, Çekmece Nuclear Research and Training Centre.

Table 2. Chemical composition of CEM I 42·5 and barite.

Constituent wt. (%)	Cement	Barite
SiO_2	19·3	2·23
Al_2O_3	5·57	0·30
Fe_2O_3	3·46	0·13
CaO	63·56	0·04
MgO	0·86	0·15
Na_2O	0·13	–
K_2O	0·80	–
SO_3	2·91	–
Cl^-	0·013	–
SrO	–	2·61
$BaSO_4$	–	94·24
Loss of ignition	2·78	0·14
Insoluble ruin	0·42	–

Table 3. Physical and mechanical properties of CEM I 42·5.

Time of setting (min)		Specific surface Blaine (cm^2/g)	Specific gravity (g/cm^3)	Compressive strength, 28 days (MPa)	Volume expansion (mm)
Initial	Final				
119	210	352	3·15	52·7	1·00

Today short-wavelength and high-energy X-rays are widely used in medicine. In chemotherapy they are used to prevent the spread of disease and in X-ray devices, they are used for diagnostic purposes. An X-ray dosimetry device is shown in figure 2 and an X-ray measurement device is shown in figure 3.

Figure 4 shows a cesium ray measurement device and ion room. Electron beams obtained from γ-ray, or an electron accelerator obtained from Co60 irradiation process and Co60 are used in industry. Ionizer rays are used in the production or alteration of the properties of some elements. They are most widely used in industrial processes to enable link breakage, link formation and cross link formation in chain polymers and to improve the physical and chemical properties of plastics used in the production of foam, electrical insulation and packaging materials. In addition, they are also used to sterilize medical tools and devices such as surgical sutures, hypodermic needles; to treat wastewater and to remove disease-inducing microbes (pathogens) in municipal water infrastructure. In recent years, the preservation of foods by irradiation has gained importance as an alternative to canning and freezing. Although some changes occur in the properties of the irradiated substance, the irradiated substance does not become radioactive. Figure 5 shows a cobalt ray measurement device and an ion room (Yılmazer 2009).

In order to prevent potential harm from radiation and to identify appropriate materials for use in processes involving radiation, the radiation permeability of materials should be measured.

3. Test results and suggestions

Computer software is available to estimate the radiation permeability of various materials. However, to obtain precise results, dosimetry devices comprising of different rays passing through various filters are used. Table 4 indicates some protectives used in the filters in these devices and the linear energy coefficients of standard concrete (Cember 1992).

In this study, a filter was selected for each ray according to the density. This filter absorbs the above average and the lowest energies radiated from the source. The remaining energy first penetrates through the filter, then through the specimen. The level of the penetrating ray is processed by the detector and the numerical value is displayed by the dosimeter device.

The experimental results of the measurements for X-ray source, Cs-137 ray source and Co-60 ray source are given in figures 6–10.

As indicated in the figures, in all ray types, as the barite ratio in the concrete increased, radiation permeability decreased. This indicates the radiation shielding property of barite. Analysis of the results at 85 keV shown in figure 6, for 10 mm thickness, indicates that the radiation shielding of B50 specimen increased by ∼86% when compared to the control (C series) specimen. For 20 mm thickness, the

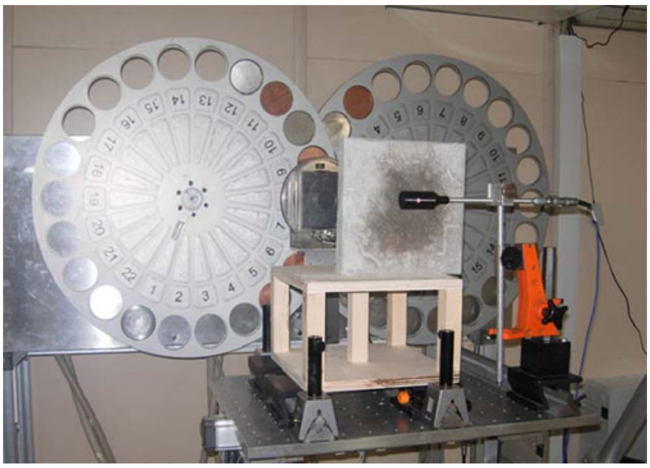

Figure 2. X-ray dosimeter device.

Figure 3. X-ray measurement device.

Figure 4. Cesium measurement device.

Figure 5. Cobalt measurement device.

radiation shielding of the B50 specimen increased by ∼97% when compared to the C specimen. As indicated in the curve, for 35 mm thickness, there was no significant radiation measurement in B20, B30, B40 and B50 specimens. This result indicates that 35 mm is the optimal thickness of B20, B30, B40 and B50 concretes to provide protection against 85 keV X-rays. When the radiation permeability results for 118 keV and 164 keV X-rays are analysed, it can be suggested that 70 mm thickness could be considered as sufficient for these energy levels.

In figure 9, when data of the 662 keV cesium (Cs-137) ray was analysed, it was found that as the barite ratio and thickness increased, the radiation shielding capacity of the specimen increased significantly; however, radiation penetration was never reduced to zero even at 105 mm thickness. Similarly, when the graph of the 1250 keV Cobalt (Co-60) (figure 10) is analysed, for B50, while 168 v/s dose measurement was recorded at 10 mm thickness, 52·8 v/s dose was measured at 105 mm. This indicates that at 95 mm concrete thickness, there was ∼69% decrease. The concrete thickness and barite ratio required to achieve zero radiation permeability can be calculated mathematically, based on the graph curves.

When linear attenuation coefficient is defined as the ray attenuation capacity of the material for 1 cm thickness, then it can be suggested that a material with high linear attenuation coefficient will have higher radiation shielding. The linear attenuation coefficient, μ, was obtained by Lambert's law (Akkurt *et al* 2005):

$$N = N_0 e^{-\mu x}, \tag{1}$$

where x is the sample thickness and N and N_0 are the number of counts recorded in the detector with and without the shielding targets, respectively. Plotting each ln (N_0/N) versus x would give a straight line and μ was obtained using the value of the slope. Figure 11 indicates the linear attenuation coefficients of the specimens according to energy. As indicated in figure 11, up to 164 keV energy, there was a sharp decrease in linear attenuation coefficient; between 164 and 662 keV energy, depending on the variations in barite ratio,

Table 4. Linear energy coefficients, μ (1/cm).

		Energy (keV)							
		100	150	200	300	500	800	1000	1500
Materials	Density (g/cm)^3	Linear energy coefficients, μ (1/cm)							
Al	2·7	0·435	0·362	0·324	0·278	0·227	0·185	0·166	0·135
Fe	7·9	2·72	1·445	1·09	0·838	0·655	0·525	0·47	0·383
Cu	8·9	3·8	1·83	1·309	0·96	0·73	0·581	0·52	0·424
Pb	11·3	59·7	20·8	10·13	4·02	1·64	0·945	0·771	0·579
Cement	2·35	0·397	0·326	0·291	0·251	0·204	0·166	0·149	0·122

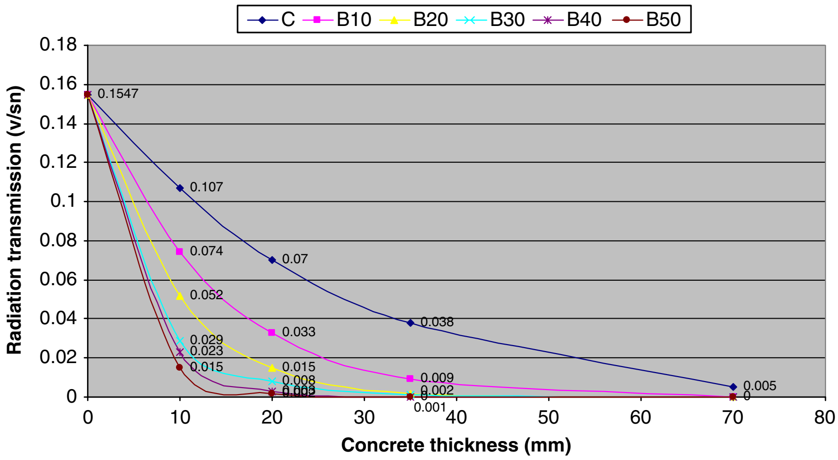

Figure 6. X-ray 100 kV (85 keV) measurement results of the concretes.

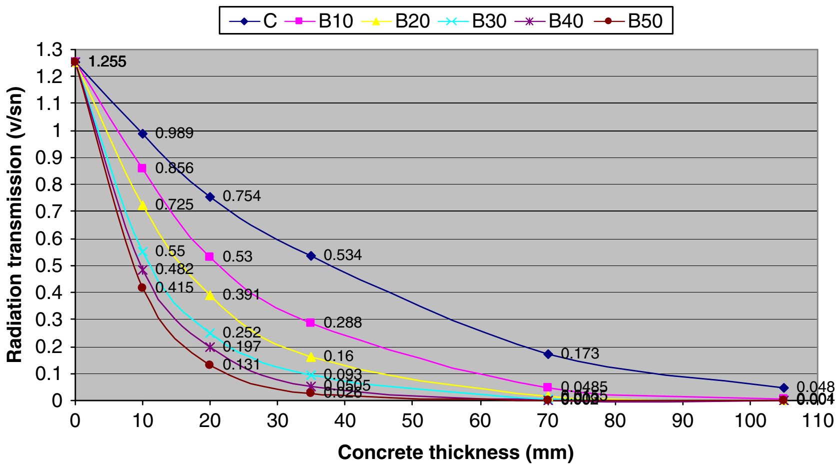

Figure 7. X-ray 150 kV (118 keV) measurement results of the concretes.

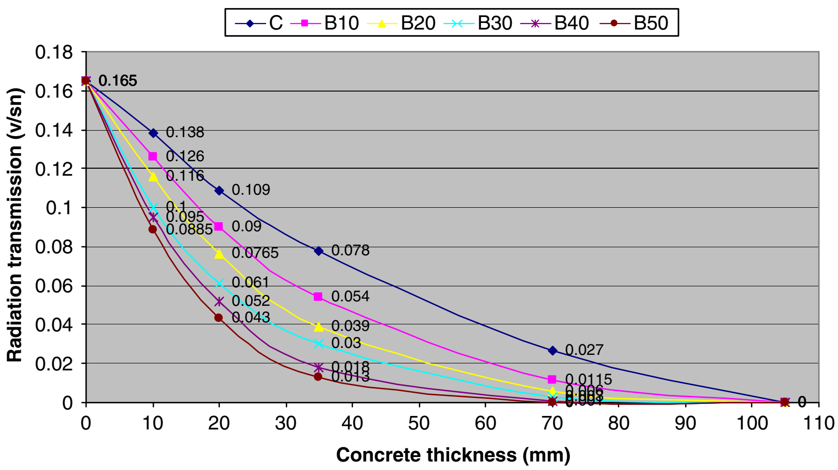

Figure 8. X-ray 200 kV (164 keV) measurement results of the concretes.

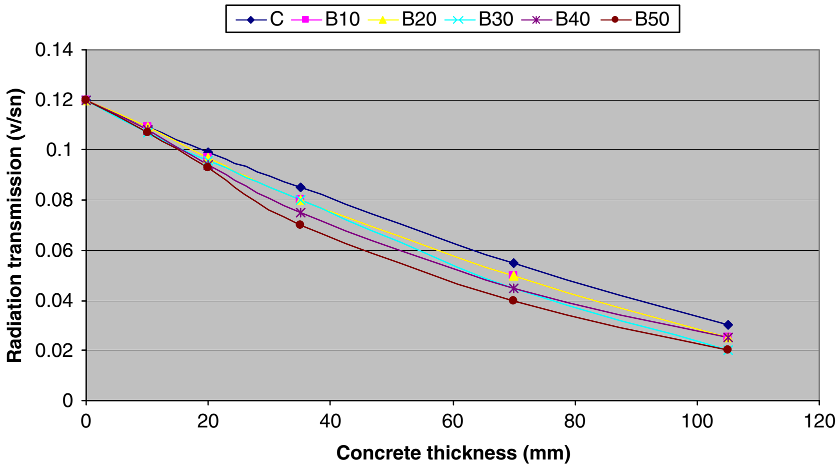

Figure 9. Cs-137 ray (662 keV) measurement results of the concretes.

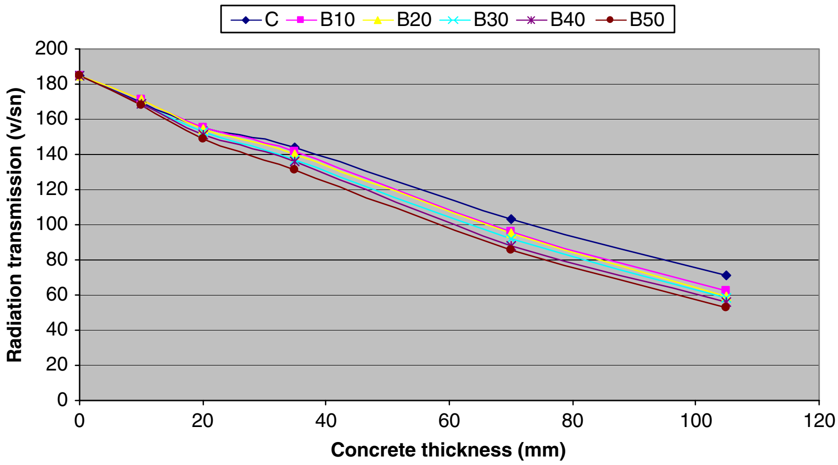

Figure 10. Co-60 ray (1250 keV) measurement results of the concretes.

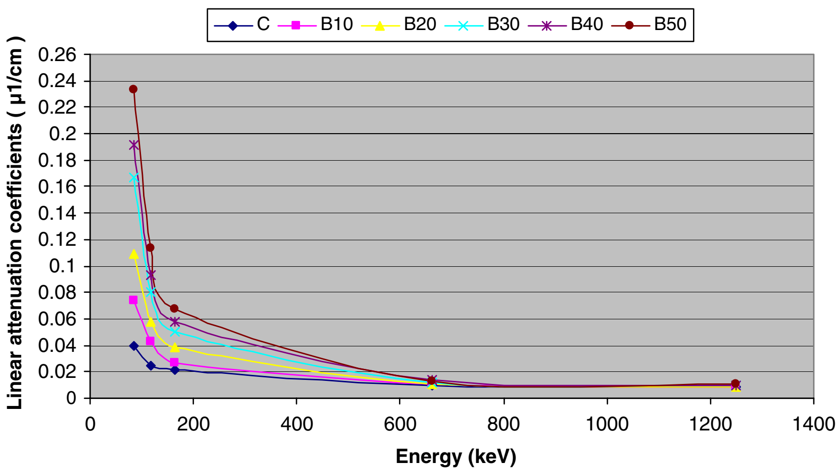

Figure 11. Linear attenuation coefficient according to energy.

this value became horizontal, and after 662 keV energy, it became totally constant.

4. Conclusions

In all concrete series, there was a significant relationship between the increase of barite ratio, density and radiation permeability of the concretes. As the specimen thickness and barite ratio increased, radiation permeability decreased and became zero after a certain thickness. Similarly, in the specimens that were measured using Cs-137 and Co-60 rays, as the thickness increased, radiation permeabilities were found to decrease. However, this radiation value did not become zero at the barite ratios and specimen thicknesses used in the present study. The fact that the specimens at these two rays are quite similar is a result of the high energy of cesium and cobalt rays. As the energy level increases, the results show greater similarity.

Increased barite ratio had a positive effect on linear attenuation coefficient. As the energy increased, up to $\sim$200 keV, linear attenuation coefficient decreased significantly. Between 200 and 650 keV, there was a slower decrease in linear attenuation coefficient and at energies $>$650 keV, the concretes were observed to have constant values.

The experimental results indicated that increased barite content decreased radiation permeability. In this context, it was found that for different energy levels, concrete shields of different densities and different thicknesses can be utilized.

Acknowledgements

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