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Production of a datolite-based heavy concrete for shielding nuclear reactors and megavoltage radiotherapy rooms

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Background: Biological shielding of nuclear reactors has always been a great concern and decreasing the complexity and expense of these installations is of great interest. In this study, we used datolite and galena (DaGa) minerals for production of a high performance heavy concrete. ***Materials and Methods:*** Datolite and galena minerals which can be found in many parts of Iran were used in the concrete mix design. To measure the gamma radiation attenuation of the DaGa concrete samples, they were exposed to both narrow and wide beams of gamma rays emitted from a cobalt-60 radiotherapy unit. An Am-Be neutron source was used for assessing the shielding properties of the samples against neutrons. To test the compression strengths, both types of concrete mixes (DaGa and ordinary concrete) were investigated. ***Results:*** The concrete samples had a density of 4420-4650 kg/m^3 compared to that of ordinary concrete (2300-2500 kg/m^3) or barite high-density concrete (up to 3500 kg/m^3). The measured half value layer thickness of the DaGa concrete samples for cobalt-60 gamma rays was much less than that of ordinary concrete (2.56 cm compared to 6.0 cm). Furthermore, the galena concrete samples had a significantly higher compressive strength as well as 20% more neutron absorption. ***Conclusion:*** The DaGa concrete samples showed good shielding/ engineering properties in comparison with other reported samples made, using high-density materials other than depleted uranium. It is also more economic than the high-density concretes. DaGa concrete may be a suitable option for shielding nuclear reactors and megavoltage radiotherapy rooms. **Iran. J. Radiat. Res., 2010; 8 (1): 11-15**

Keywords: *Heavy concrete, datolite, shielding, megavoltage radiotherapy, nuclear reactors.*

INTRODUCTION

The problem of shielding against ionizing radiation has always attracted a great deal of attention. Radiation shielding of a nuclear reactor is a costly and very complex process [(1)]. A nuclear reactor usually requires two shields; a shield to protect the walls of the reactor from radiation damage and at the same time reflect neutrons back into the core; and a biological shield to protect people and the environment. The biological shield reduces the level of gamma radiation and neutrons to current dose limits. The biological shield may contain some heavy materials such as iron and steel punching. The biological shield consists of many centimeters of very high-density concrete. In nuclear reactors, neutron radiation is the most difficult to shield and hydrogen is the most effective element in slowing down (thermalizing) neutrons over the entire energy spectrum.

Boron is effective in capturing thermal neutrons [(2)]. It releases alpha particles

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which are easily shielded [3]. In a nuclear reactor, as with other radiation fields, the main problem in selecting shielding materials is choosing the most efficient and economical shield against all radiations existing in the field. Concrete is an economical and effective material for shielding stationary reactors. As high-density materials are needed to shield against gamma rays, a high-density concrete is often preferred to the low density type. High -density concrete has higher linear gamma and neutron attenuation characteristics compared to ordinary concrete and therefore the use of high-density concrete leads to thinner walls. Neutron radiation is the most difficult to shield. The main design problem is the arrangement of a correct balance to achieve the most efficient and economical shield against all radiation.

Concrete that is composed of Portland cement, sand, aggregate (stones, gravel, etc.), and water [4], is one of the most common materials used in the construction of commercial buildings. Currently ordinary concrete (density about 2350 kg/m^3) is widely used for superficial and orthovoltage radiotherapy rooms [5].

Galena (PbS) is the main lead mineral [6]. Other common varieties include cerussite ($PbCO_3$), plattnerite (PbO_2) and angelsite ($PbSO_4$). Galena is a Latin word given to lead ore or the dross from the melted lead. Galena is a noticeably dense material, having a density of 7400-7600 kg/m^3, so it is nearly as dense as iron. The chemical composition and physical properties of galena are summarized in table 1. Over the past years we have produced some types of galena-based concrete samples [7] for efficient attenuation of X or gamma rays. However, this is our first experiment on production of heavy concrete samples which are capable of efficient attenuation of neutrons besides X or gamma rays.

MATERIALS AND METHODS

Datolite and galena (DaGa) minerals were used for production of a high-density concrete. The datolite and galena minerals were from Neyshapour (Khorasan province, Iran) and Firouzabad (Fars province, Iran) mines, respectively. The concrete mix design was selected according to our basic protocols. To be used as a shield in nuclear reactors, concrete must contain a large amount of water. Higher water content makes concrete more effective than ordinary concrete for neutron attenuation. In this

Table 1. Physical properties of the two main minerals used in this study.

Properties \ Minerals	Datolite	Galena
Chemical composition	$CaBSiO_4(OH)$ Alkaline calcium boron silicate (35.0% CaO, 21.8% B_2O_3, 37.6% SiO_2, 5.6% H_2O)	Lead sulfide (PbS)
Molecular weight	159.98 g	239.26 g
Lead content	---	86.59 % Pb 13.40 % S
B_2O_3 content	21.8%	---
Stiffness	5.0-5.5	2.5
Density (g/cm^3)	2.8 – 3 Average = 2.9	7.0-7.5
Color	Colorless, white	Gray

regard, two types of concrete mixes were produced. Reference concrete mixes consisted of gravel (865 kg/m^3), sand (1000 kg/m^3), cement (440 kg/m^3), water (222 kg/m^3) and microsiliceous (44 kg/m3). The water to cement (w/c) ratio was 0.39. In the DaGa samples, 896 g of Datolite and 3548 g of Galena minerals were used to completely replace sand in a total of 5897 g concrete mixture. In this sample the w/c ratio was 0.39. For each concrete mix design, 5-6 slabs of 2 cm thickness were made. To measure the gamma radiation attenuation of DaGa concrete samples, they were exposed to both narrow and wide beams of 1.25 MeV gamma rays emitted from a Theratron cobalt-60 therapy unit (Best Theratronics, Canada) in the Radiotherapy Department of Namazi Hospital, Shiraz, Iran. Neutron shielding properties of the samples was measured using an Am-Be (S = 1.221 × 10^8 neutron/s) source in the Secondary Standard Dosimetry Laboratory, Atomic Energy Organization of Iran. The neutron energy spectrum of Am-Be source is illustrated in the figure 1.

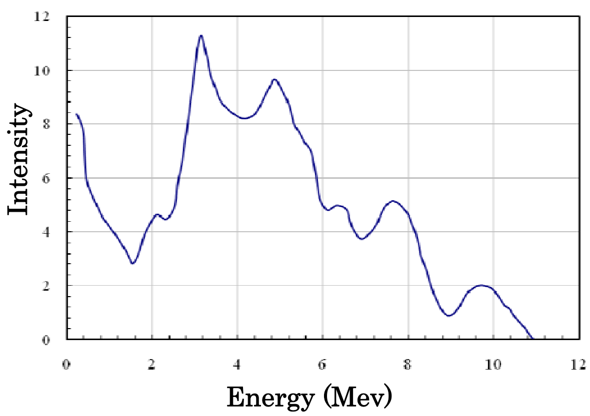

Figure 1. The neutron energy spectrum of Am-Be source.

RESULTS

The datolite and galena minerals used in this study had densities of 3000 and 7500 kg/m^3, respectively. The concrete samples made in this project had a density of 4420-4650 kg/m^3 compared to that of ordinary concrete (2350 kg/m^3) or barite high-density concrete (up to 3500 kg/m^3). The measured half value layer (HVL) thickness of the DaGa concrete samples for cobalt-60 gamma rays (1.25 MeV) was much less than that of ordinary concrete (2.56 cm compared to 6.0 cm). Furthermore, the DaGa concrete samples had a significantly higher compressive strength (448-522 kg/m^2 compared to 300 kg/m^2). DaGa concrete samples (densities of 3000 and 7500 kg/m^3) had a 20% more neutron absorption compared to reference concrete (density 2600 kg/m^3). Table 2 presents the engineering/shielding properties of the DaGa concrete samples compared to those of ordinary concrete.

DISCUSSION

Concrete samples made of DaGa showed a significantly better performance in radiation shielding, as well as compressive strength compared to ordinary concrete. Based on the preliminary results obtained in this study, DaGa concrete has been a highly suitable option where high-density concrete is required in megavoltage radiotherapy rooms, and nuclear reactors. It should be noted that the most common material for shielding the radiation from particle accelerators is concrete. In our last experiment [7], we made concrete samples

Table 2. The mix design used in concrete samples used in this study.

Concrete mix design (g)						Density (g/cm^3)	Compression strength (kg/m^2)
Lead ore	Datolite	Distilled water	Cement	Microsiliceous	Water to cement ratio		
3548	896	408	950	95	0.39	4.42 – 4.65	448 - 522

with characteristics comparable to our new samples (except for shielding against neutrons). The density, HVL and compression strength of the previous samples made of galena alone were 4200-4600 kg/m3, 2.56 cm and 500 kg/m^2, respectively. These parameters in the present study have been changed to 4420-4650 kg/m3, 2.56 cm and 448-522 kg/m^2, respectively (table 3). The main outcome of this study was to obtain the same density and compression strength while using minerals containing low atomic number elements such as boron.

As stated before, concrete can be made using various materials of different densities as aggregates. These different concrete mixes can have very different attenuation characteristics [8]. Kan and his co-workers [9] added iron ore to concrete. They found that the compressive strength of heavy concrete had increased with iron ore content, while the tensile strength decreased. In their study, the concrete including 40% metallic aggregate content by volume exhibited higher compressive strength and fracture toughness.

Furthermore, Facure *et al.* [10] found that the scattered neutron energies were lower in wood and barite concrete. They concluded that barite concrete as well as wood can be used for lining the maze walls in order to reduce neutron dose at the room door.

As far as it is known, the DaGa concrete samples we made had the best shielding/engineering properties compared to all samples made by using high-density materials other than depleted uranium (DU). Considering the possible hazards of DU, it can be claimed that the DaGa concrete is one of the best non-radioactive shield for applications such as shielding megavoltage radiotherapy rooms. To highlight the importance of DaGa concrete in shielding, we can compare its properties to the heavy-concrete samples for which specifications are reported in some recent publications [11-14].

In an attempt to produce heavy concrete for protection against radiation, investigators produced concretes with densities of 3800-4200 kg/m^3, which the authors called “Superheavy High-Strength concrete” [11]. They used waste products of heavy silicate-lead glasses. Bouzarjomehri *et al.* [12] produced heavy concrete samples using barite mineral. The samples they made had densities in the range 3180-3550 kg/m^3. The measured HVL for 1.25 MeV energy gamma radiation and compressive strength of their samples were 3.6-4.0 cm and 140-394 kg/m^2, respectively. Other

Table 3. Density, half value layer and compression strength of the concrete samples made in this study compared to those produced by other investigators.

Physical properties / Concrete type	Density (kg/m^3)	HVL for Co-60 (cm)	Compression strength (kg/m^2)
Ordinary concrete	2300-2500	5.25-6.2	300
***Barite concrete** [12]	3180-3550	3.6-4.0	140-394
Barite concrete [14]	3490	3.8	NI
Barite Concrete [13]	NI	4.4	NI
Super heavy concrete [11]	3800-4200	NI	NI
Galena concrete [7]	4200-4600	2.56	500
Datolite- galena (DaGa) concrete (Current study)	4420-4650	2.56	448 - 522

NI: Not indicated by the authors. *Number in brackets indicate reference number investigators reported HVLs much greater than that is obtained in this study (13, 14).

Currently, our research group is in the process of finding the optimum level of constituents for best shielding and engineering properties. Moreover, we are in the process of adding the optimum level of different minerals containing boron for constructing an efficient shield against neutrons in a nuclear reactor.

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