Production of a novel high strength heavy concrete using tourmaline and galena for neutron and photon radiation shielding

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► ***Short report***

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ABSTRACT

Background: High density concrete is extensively used for efficient radiation attenuation in radiotherapy rooms and nuclear reactors. Over the past eight years, some efficient galena-based concrete samples for shielding X or gamma rays was produced. The goal of this study was to produce a novel high density concrete against neutron and photon radiations using tourmaline and galena. ***Materials and Methods:*** Attenuation of gamma photons was measured using a Farmer type ionization chamber with a standard ^{60}Co buildup cap on a Theratron ^{60}Co therapy unit. Neutron shielding characteristics were measured by using an Am-Be source. The MCNP4C radiation transport computer code was used to investigate the effects of various shield thicknesses on the attenuation of gamma-ray photons and neutrons. ***Results:*** The concrete samples had a density of 4.0- 4.2 g/cm^3. The compressive strength was 326 - 560 kg/cm^2. The calculated value for Half Value Layer (HVL) of the tourmaline -galena concrete samples for ^{60}Co gamma rays was 2.72 cm, which is much less than that of ordinary concrete (6.0 cm). The MC-derived HVL for photons with the same energy was 2.77 cm, which is in a good agreement with the experimental data. Moreover, ToGa concrete had up to 10 times greater neutron attenuation compared to that of the reference concrete. ***Conclusion:*** Tourmalin-Galena Concrete opens a new horizon in economic and efficient gamma/neutron shielding in high-energy radiotherapy bunkers, nuclear power plants, and shielding of radioactive sources.

Keywords: *Heavy concrete, boron rich mineral, radiation shielding, Monte Carlo simulation.*

INTRODUCTION

High density (heavy) concrete, which is composed of heavy weight aggregates, cement, water and coarse and fine aggregates, is extensively used for prevention of radiation leakage from radioactive sources as well as construction of radiotherapy bunkers and nuclear reactors. One of the main reasons for its popularity is its capability in overcoming space limitations and providing the required radiation shielding with lower thicknesses compared to ordinary concretes [1].

High density concrete is an inexpensive shield for neutron and photon radiation compared to other shielding materials such as lead and iron [2]. It can be easily produced in different mixtures and has the ability to form complex shapes [3, 4]. More importantly, by changing its mix design and also type of aggregates used in the mixture, the mechanical and radiation properties of the concrete can be controlled within a wide range [5, 6]. In addition, since it contains hydrated cement as well as hydroxide minerals, it can be an appropriate choice for neutron shielding too. Moreover, using materials such as boron and cadmium, with high neutron absorption cross sections, can maximize its shielding efficiency against neutrons[4, 7].

Galena is the main mineral of lead ore used for extraction of lead. Its density is about 7.0-7.5 g/cm^3 [8, 9]. Tourmaline is among the most important boron ores (containing 9-11% B_2O_3) suitable for shielding against neutron radiation. Tourmaline and galena minerals can be found in many parts of Iran. Over the past eight years, we have produced some efficient galena-based concrete samples for shielding X or gamma rays [10-13]. Moreover, heavy concrete samples which were capable of efficient attenuation against neutrons as well as X or gamma rays have been developed [11].The goal of this study was to produce a novel high density concrete against neutron and photon radiation using tourmaline and galena. In this work, different proportions of tourmaline in the mix design were used in evaluating the mechanical and radiation shielding properties of the tourmaline-galena (ToGa) concrete.

MATERIALS AND METHODS

Concrete mix design

The tourmaline and galena used in this study were obtained from Torkaman Village (Hamedan) and Nakhlak (Isfahan) mines in Iran, respectively. Table 1 shows the physical properties of these two main minerals used in this study. The specific volume method, as the most reliable way for concrete mix design, was used [14]. The concrete mix design was selected according to our previously published basic protocols [10, 11].

Density of the samples was measured and compressive strength of the produced concrete was evaluated using standard sized concrete cubes. For radiation shielding tests, 20×20×2.5 cm^3 slabs were developed. Finally, the results obtained were compared with ordinary (reference) concrete with density of 2.3 g/cm^3. The mix designs utilized in the heavy concrete and also the reference samples used in this study are summarized in table 2.

Table 1. Physical properties of the tourmaline and galena minerals used in this study.

Minerals / Properties	Tourmaline	Galena
Chemical Composition	Alumina borosilicate with fluorine(42.65%SiO_2, 25.14%Al_2O_3, 13.02% Fe_2O_3, 0.21% TiO_3, 0.89%CaO, 0.51%MgO, 2.04% NaO_2, 1.07% K_2O, 0.05% SO_3, 0.59%P_2O_5, 11.08% B_2O_3)	Lead Sulfide (PbS)
Molecular Weight	Varied related to composition	239.26 g
Lead Content	---	86.59 %
B_2O_3 Content	%11.08	---
Hardness	7.0-7.5	2.5
Density (g/cm^3)	3.00-3.25	7.0-7.5
Color	Black, green, brown, blue, pink (varied, related to sodolithic pegmatites)	Gray

Table 2. Tourmalin-Galena (ToGa) and reference concrete mix designs used in this study.

	Mix design (g)							
	Galena mineral	**Tourmaline**	**Distilled water**	**Micro siliceous**	**Cement**	**Gravel**	**Sand**	**Water to cement ratio**
High density basic protocol	3011	400	296	65	1102	-	-	0.25
Reference concrete	-	-	222	60	440	865	850	0.44

Photon and neutron attenuation
Experimental measurement

To measure the attenuation of gamma photons, a Theratron ^{60}Co therapy unit with 1.17 and 1.33 MeV photon energies (Best Theratronics, Canada) at the Radiotherapy Department of Namazi Hospital, Shiraz, Iran was used. The samples were exposed to gamma radiation in both narrow and broad field sizes of 4.5×4.5 cm^2 and 20×20 cm^2, respectively. To measure the transmission through the concrete samples, a Farmer type ionization chamber with a standard ^{60}Co buildup cap was used.

Neutron shielding characteristics of both the reference concrete and concrete samples of ToGa concrete were measured by using an Am-Be source in the Secondary Standard Dosimetry Laboratory, Atomic Energy Organization of Iran, with a flux of 1.221×10^8 neutron/s. Due to practical difficulties associated with exposing thick ToGa concrete to a neutron source, neutron attenuation measurements were performed for thin slabs (less than 10 cm thickness). In order to achieve a collimated neutron beam, the source was placed inside a sealed hollow tube of aluminum and plastic which could rotate within a cylindrical polyethylene container with a diameter of 150 cm. For measurements, a spherical neutron detector (Nuclear Enterprises MK27NH model) was used. The distance between the center of the detector and the center of the source was set at 100 cm. Then, obtained values were evaluated using the analyzer and interpolator software Origin Pro 8. For thick ToGa concrete (up to 60 cm thickness), neutron shielding properties were calculated by Monte-Carlo (MC) modeling.

Monte Carlo simulation

The general-purpose Monte Carlo N-particle radiation transport computer code, version 4C (MCNP4C) was used to investigate the effects of shield thicknesses on the attenuation of gamma-ray photons and neutrons. Since the accuracy of the results of MC simulations are strongly dependent on the cross-section tables used in the simulation, in this study, an improved cross section file using Nuclear Data File B-VI (ENDF/B-VI) was employed for the simulations [15].

For photon calculations, two distinct steps were considered[16]. Firstly, 'unattenuated' monoenergetic photon beams of 1.17 and 1.33 MeV photon energies (average 1.25 MeV) in the absence of any sample with the Theratron head components were simulated to develop the best-match results with the measured data (tuning the code). As a next step, the tuned code was used to simulate the attenuation of gamma-ray photons in ToGa concrete samples. For neutron calculations, the MC-simulated neutron source was used to calculate the attenuation of neutrons in ToGa slabs. For photon and neutron calculations, tally F4 was used which scores the average flux over the cell in number/cm^2/particle[15].

RESULTS

Concrete mix design

The concrete samples made had a density of 4.0- 4.2 g/cm^3, significantly higher than that of reference concrete which is 2.35 g/cm^3. Also, the compressive strength of the manufactured concrete samples was 326 - 560 kg/cm^2 which is of a larger value than that of the reference sample (compressive strength of 300 kg/cm^2).

Density and compressive strength of the samples were associated with the amount of tourmaline used in the concrete mix design. As shown in figure 1, as the tourmaline content increases (7 to 9%), ToGa concrete density and compressive strength increases considerably up to 4.2 g/cm^3 and 560 kg/cm^2, respectively.

Photon and neutron attenuation

The measured narrow-beam HVL thickness of the ToGa concrete samples for ^{60}Co gamma rays (1.25 MeV) was much less than that of ordinary concrete (2.72 cm compared to 6.0 cm). The narrow-beam HVL calculated by MCNP simulation was 2.77 cm for photons with the same energy, which matches the experimental measurements. Figure 2 shows this more clearly. Table 3 presents a comparison between the engineering and gamma-ray shielding properties of the ToGa concrete samples and those of ordinary concrete and other produced heavy concretes.

Neutron attenuation measurements showed that thin ToGa concrete samples had 16% greater neutron absorption in comparison with the reference concrete (density of 2.35 g/cm³). Although there is a negligible discrepancy (5%), the MC simulation matches the experimental measurements reasonably well. Furthermore, MC-calculated results showed that thick ToGa concrete shields had up to 10 times greater neutron attenuation compared to ordinary concrete. Figure 3 demonstrates a comparison among the ratios of intensities for ToGa, Ulexite-Galena (UlGa) and ordinary concretes to the intensity for an unattenuated neutron beam.

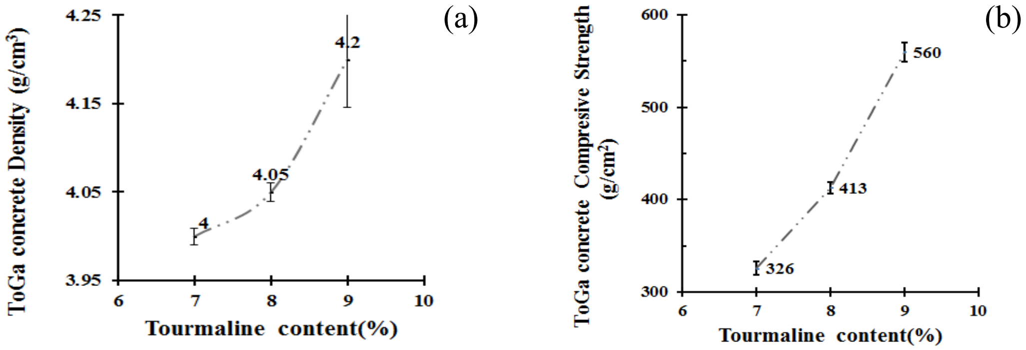

Figure 1. The relationship between the tourmaline content and concrete density (a) and compressive strength (b).

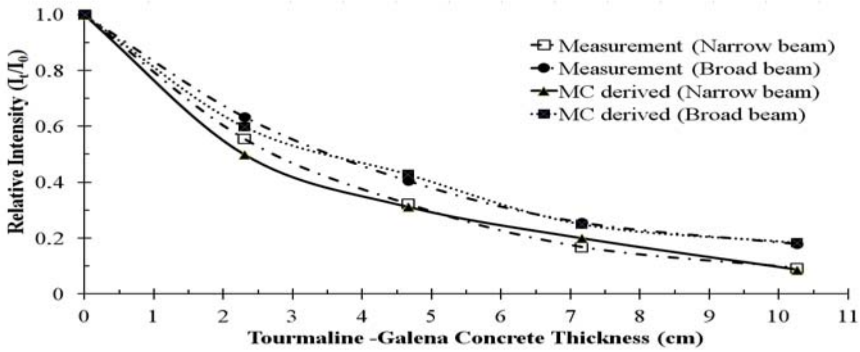

Figure 2. Measured and MC-derived ^{60}Co HVL for the Tourmalin-Galena (ToGa) concrete made in this study and the ordinary reference concrete in the narrow and broad beams.

Table 3. Engineering and gamma-ray shielding properties of the ToGa concrete samples compared to those of ordinary concrete

Concrete Type \ Physical Properties	Density (kg/m^3)	HVL for ^{60}Co gamma rays (cm)	Compression Strength (kg/cm^2)
Ordinary Concrete	2300-2500	5.25-6.2	300
Barite Concrete[17](Bouzarjomehri *et al.* 2006)	3180-3550	3.6-4.0	140-394
Barite Concrete[18](Sayed Abdo *et al.* 2002)	3490	3.8	NI
Barite Concrete[19])(Akkurt *et al.* 2006)	NI	4.4	NI
Super Heavy Concrete[20](Proshin *et al.* 2005)	3800-4200	NI	NI
Galena Concrete[10](Mortazavi *et al.* 2007)	4200-4600	2.56	500
Datolite-Galena (DaGa) Concrete[11](Mortazavi *et al.* 2010)	4420-4650	2.56	448-522
Colemanite-Galena (CoGa) Concrete[13](Mortazavi *et al.* 2010)	4100-4650	2.49	398-464
Ulexite-Galena (UlGa) Concrete[12](Aghamiri *et al.* 2012)	3640- 3900	2.84* / 2.87**	144-377
Tourmalin-Galena (ToGa) Concrete (Current study)	4000-4200	2.72*	326 - 560

*Measured HVL **Calculated by MCNP Simulation NI: Not indicated by the authors.

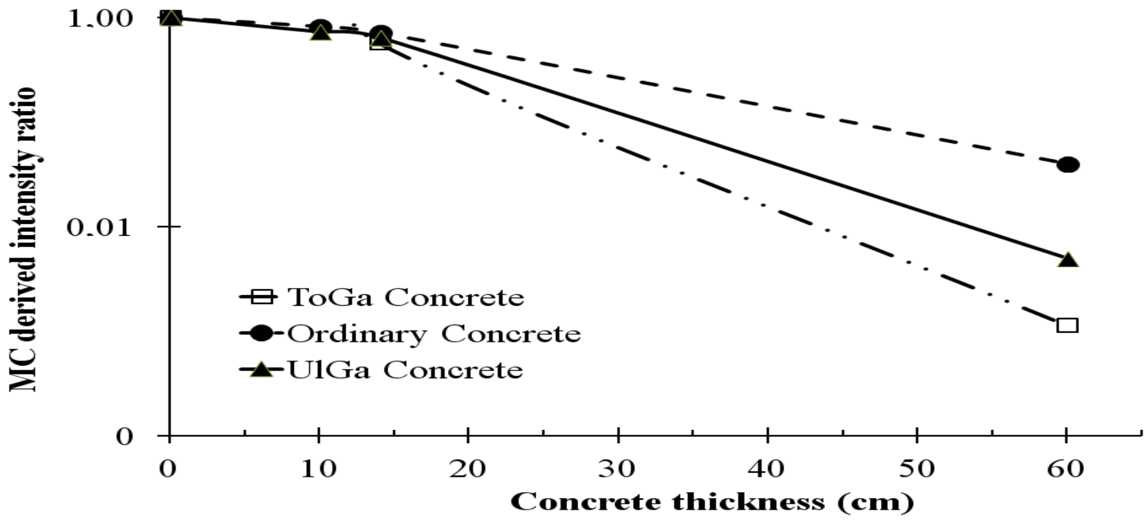

Figure 3. Comparison among the ratios of the intensities for Tourmalin-Galena (ToGa), UlGa and ordinary concretes to the intensity for an unattenuated neutron beam (MC-derived intensity is plotted in a logarithmic scale).

DISCUSSION

Based on the results obtained in this study, the calculated value for HVL of the ToGa concrete samples for ^{60}Co gamma rays was 2.72 cm which is much less than that of ordinary concrete (6.0cm). The MC-derived HVL for photons with the same energy was 2.77 cm, showing good agreement with the experimental data. Moreover, ToGa concrete had up to 10 times greater neutron absorption compared to reference concrete.

As illustrated in figure 1, the tourmaline content in the concrete sample is directly proportional to its density and compressive strength, i.e., by increasing tourmaline content in the concrete sample, its density and compressive strength increased significantly. The increase in concrete compressive strength is because of the high compatibility of tourmaline with other components such as cement and micro siliceous materials in the mixture. This compatibility helps with the suitable adhesion and uniformity of To Ga concrete [21]. As it was previously reported that using high-density concrete may cause higher neutron doses in the maze entrance door of a radiation therapy bunker [22], this type of concrete can be used for construction of bunkers for high-energy photon radiation therapy. As the neutron transmission of the concrete primarily depends on the hydrogen content (which does not significantly depend on the density), the neutron transmission of high-density concretes can be reasonably and conservatively estimated by using the linear tenth-value layer of normal concrete [23].

Currently, our research group is in the process of finding the optimum level of constituents and mix design for best shielding and mechanical properties. Furthermore, the authors are in the process of adding the optimum level of different boron-containing minerals such as tourmaline for constructing an efficient shield against neutrons in a nuclear reactor. Also, some experiments are being conducted on finding the optimum water/cement ratio. It is believed that this part of the research not only opens a new horizon in finding economic and efficient gamma/neutron shielding in high-energy radiotherapy bunkers and nuclear power plants, but also helps prevent radiation leakage from radioactive sources.

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