ENHANCED RADIATION SHIELDING WITH GALENA CONCRETE

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A new concrete, containing galena mineral, with enhanced shielding properties for gamma sources is developed. To achieve optimized shielding properties, ten types of galena concrete containing different mixing ratios and a reference normal concrete of 2300 kg/m^3 density are studied experimentally and numerically using Monte Carlo and XCOM codes. For building galena concrete, in addition to the main composition, micro-silica and water, galena mineral (containing lead) were used. The built samples have high density of 4470 kg/m^3 to 5623 kg/m^3 and compressive strength of 628 kg/m^2 to 685 kg/m^2. The half and tenth value layers (half value layer and tenth value layers) for the galena concrete, when irradiated with ^{137}Cs gamma source, were found to be 1.45 cm and 4.94 cm, respectively. When irradiated with ^{60}Co gamma source, half value layer was measured to be 2.42 cm. The computation modeling by FLUKA and XCOM shows a good agreement between experimental and computational results.

Key words: galena concrete, shielding, Monte Carlo, FLUKA, XCOM

INTRODUCTION

A shield has been defined as "a physical entity interposed between a source of ionizing radiation and an object to be protected such that the radiation level at the position of that object will be reduced. The object to be protected is most often a human being, but can be anything that is sensitive to ionizing radiation" [1].

With increasing applications of irradiation sources, both in medical and energy industry, radiation shielding and adequate protection remain an important concern. Lead and concrete for their high linear attenuation coefficients, are amongst the most accepted shielding materials. Heavy reinforced concrete with a variety of aggregate additives has also been investigated for radiation shielding improvement.

Using barite ($BaSO_4$) as aggregate to increase linear attenuation coefficient [2, 3] as well as compressive strength [4] has been investigated.

The attenuation coefficients of barium-borate fly ash glasses have been measured for gamma-ray highly collimated photon beam [5]. It is reported that from the shielding point of view, the barium-borate fly ash glasses are better shields for gamma-radiations in comparison to the standard radiation shielding concretes and also to the ordinary barium-borate glasses.

Fiber reinforced concrete with steel fibers, lead fibers and a combination of the two (hybrid fibers) were investigated by Sharma [6] and the effects of the two types of fibers on mechanical and radiation shielding properties of concrete were measured. They have reported up to 36% improvement in radiation shielding compared with ordinary concrete. Kharita [7] used local mineral aggregates to enhance concrete shielding properties for gamma and neutron radiation and reported 10% increase in lowering the half value layer (HVL).

The use of mineral lead sulfate known as galena as a concrete aggregate for radiation shielding enhancement, first suggested by Abulfaraj [8], has been recently investigated by Mortazavi [9, 10]. An improvement in HVL of up to 2.56 cm for galena compared to 5.25 cm of ordinary concrete is reported by Mortazavi.

In this paper we present our result of galena aggregate concrete which has been optimized both in mechanical as well as radiation shielding properties. We prepared six types of galena concrete with composition mixing ratios and an ordinary concrete of 2300 kg/m^3 density as reference. The optimized composition was exposed to ^{137}Cs and ^{60}Co gamma sources to measure its HVL, tenth value layers (TVL), and its linear attenuation. The results of FLUKA [11] Monte Carlo modeling of the radiation dosimetry and XCOM shielding code [12] for assessing our experimental data are also presented in this paper.

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SUBJECTS AND METHODS

Galena mineral from lead mines of Esfahan in central Iran with the specifications given in tab. 1 was used as the main aggregate of our heavy concrete.

The basic aggregate included for the manufacture of concrete for radiation-shielding is specified by ASTM Specification for Aggregates Concrete (C637) [13]. There are referrals within this specification to ASTM C638 [14] for such items as deleterious substances and the grading limits for conventionally placed concrete. ASTM C637 is primarily concerned with radiation-shielding and heavyweight concrete.

Determination of an optimum composition to obtain the lowest HVL as well as highest compressive strength was achieved through experimenting with different ratios of cement, microsilica and water together with galena mineral, fig. 1(a). The prepared samples were tested for their HVL and mechanical strength.

Table 1. Galena mineral specifications

Name	Chemical composition	Molecular weight [g]	Lead inventory	Hardness	Density [gcm^{-3}]	Color
Galena	Lead sulfide (PbS)	239.26	86.59% Pb	2.5	7.0-7.5	Gray--leaden
			13.40% S			

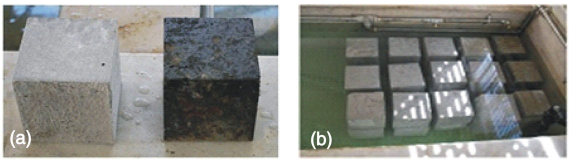

Figure 1. Ordinary and galena concrete (a), curing the concrete samples (b)

Mechanical tests: compressive strength

There is no unique method to come across the optimum composition for our intended application. Many factors influence the rate at which the strength of concrete increases after mixing. Hardening, which is the process of strength growth and may continue for weeks or months after the concrete has been mixed and placed, is due largely to the formation of calcium silicate hydrate as the cement continues to hydrate. Furthermore to enhance the strength of concrete samples, curing them under water has been carried out, fig. 1(b).

In tab. 2, the mixing compositions in 7 samples are shown. The results of 28 day compressive strength test based on ASTM C 39 [15] are presented.

Radiation tests: HVL and TVL

We used both ^{137}Cs and ^{60}Co gamma sources to evaluate the HVL and TVL for different samples. To determine the attenuations of different types of concrete, the tests were carried using blocks of 200 mm 200 mm 200 mm. The schematic of test set-up is shown in fig. 2.

The specimen was subjected to a uniform gamma radiation from the sides providing a dose rate of 3 kGy/h using ^{60}Co as well as ^{137}Cs sources. The dosimetry was carried out with an Eberline RO-20 ionization chamber. The Eberline RO-20 Survey Meter is a self-contained portable survey meter for measurements of exposure rate at medium to high photon radiation levels. The detector is an air-filled ionization chamber, which is sensitive to X-ray and gamma photons in the energy range of approximately 8 keV-1.3 MeV and beta

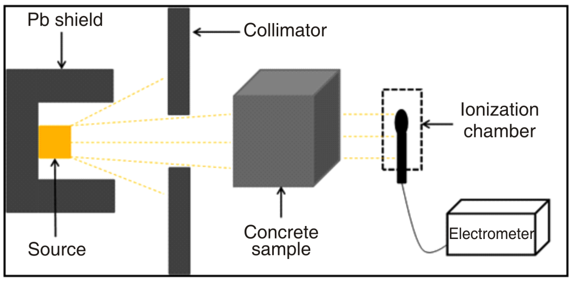

Figure 2. Schematic draw of the setup of the measurements

Table 2. Compositions and mechanical properties of different galena samples

Composition	Ordinary concrete	Sample 1	Sample 2	Sample 3	Sample 4*	Sample 5	Sample 6
Water to cement ratio	0.45	0.38	0.36	0.35	0.30	0.28	0.32
Water (L)	163.00	150.00	142.00	138.00	132.00	127.00	135.00
Cement type 1 [kgm^{-3}]	460.00	430.00	435.00	442.00	447.00	449.00	453.00
Microsilica [kgm^{-3}]	3.50	17.00	19.00	21.00	25.00	24.00	23.00
10 mm grit [kgm^{-3}]	180	1050	930	890	860	870	840
Natural sand [kgm^{-3}]	690.00	600.00	620.00	635.00	658.00	665.00	670.00
Retarders [Lm^{-3}]	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Plasticizers [Lm^{-3}]	14.00	14.00	14.00	14.00	14.00	14.00	14.00
Density [kgm^{-3}]	2350	4470.00	4640	4960	5187	5400	5623
28-day compressive strength [kgcm^{-2}]	300	628	640	659	685	657	653
Galena [%]	0.00	0.40	0.42	0.45	0.47	0.49	0.51

* Sample with the best performance

radiation energy above 70 keV. The survey meter was calibrated for accurate response at the ^{137}Cs gamma energy. Repeated measurements were performed to account for systematic and random errors [16].

Computational modeling by Monte Carlo and XCOM

Using FLUKA Monte Carlo code, the galena concrete irradiated with a ^{137}Cs gamma source was modeled to evaluate the HVL, TVL, and the attenuation coefficients of different samples numerically. FLUKA has been extensively benchmarked against experimental data over a wide energy range of different particles [17].

The agreement between measurement and FLUKA simulation was within 2% in terms of the HVL and 6% for TVL. Therefore the wall thickness can be calculated with a reliable safety margin of less than 1 cm, depending on total attenuation.

Theoretical attenuation coefficient of ordinary and the optimum galena concrete shield composition up to the 105 MeV gamma rays was also obtained by XCOM program.

RESULTS

For our study, ten types of galena concrete with different mixing ratios and containing galena in percentages of 0.40, 0.42, 0.45, 0.47, 0.49, and 0.51, as shown in tab. 2, were produced to investigate the effect of galena ratio on compressive strength, HVL, TVL, and the linear attenuation coefficient of the concrete shield.

Table 3 represents the results of the evaluation of compressive strength, HVL, and TVL of six galena concrete samples and comparison of them with ordinary and the pervious constructed concrete for both ^{137}Cs and ^{60}Co gamma sources. As indicative from tab. 2, increasing galena aggregate content to the mixtures improves the radiation shielding properties, however, it lowers the compressive strength. Due to its highest compressive strength (685 kg/cm^2), as well as low HVL (1.45 cm for ^{137}Cs and 2.42 cm for ^{60}Co), sample 4 is considered to be the optimum galena concrete in this study. The sample provides both mechanical strength and superb radiation shielding to be used in in radiology and radiotherapy clinics.

FLUKA was used to model the ordinary concrete and the optimum galena concrete samples in the presence of ^{137}Cs gamma source. In figs. 3 and 4, the comparison of HVL and TVL of ordinary concrete and the optimum galena concrete are presented.

Based on comparison and realization, the experimental values of HVL and TVL of the optimum galena concrete in the presence of ^{137}Cs gamma source were determined in figs. 3 and 4 by square point too.

Using FLUKA Monte Carlo code and XCOM program, the theoretical values of attenuation coefficient of ordinary and the optimum galena concrete shield up to the 105 MeV gamma rays was obtained. In fig. 5 the comparison of these results with their experimental values in two special energies are shown.

Table 3. Comparison of HVL (for ^{60}Co and ^{137}Cs sources) and TVL (^{137}Cs) for different concrete samples made with galena aggregate

Concrete type	Compressive strength [kgcm^{-2}]	Density [kgm^{-3}]	HVL (^{60}Co) [cm]	HVL (^{137}Cs) [cm]	TVL (^{137}Cs) [cm]
Sample 1 (this study)	628	4470	2.79	1.86	5.74
Sample 2 (this study)	640	4640	2.758	1.68	5.53
Sample 3 (this study)	659	4960	2.58	1.56	5.17
Sample 4 (best in this study)	685	5178	2.42	1.45	4.94
Sample 5 (in this study)	657	5400	2.36	1.41	4.66
Sample 6 (in this study)	653	5623	2.26	1.339	4.44
Ordinary concrete	300	2350	9.2	6.3	17.2
Barite concrete [3]	140-394	3180-3550	3.6-4.0	NI	NI
Barite concrete [18]	NI*	3490	3.8	NI	NI
Barite concrete [2]	NI	NI	4.4	NI	NI
Super heavy concrete [19]	NI	3800-4200	NI	NI	NI
Datolite-galena concrete [10]	448-522	4420-4650	2.56	NI	NI
Colemanite-galena concrete e [10]	398-464	4100-4650	2.49	NI	NI
Concrete by natural local materials (sample 1) [7]	NI	NI	5.21	4.47	14.86
Concrete by natural local materials (sample 2) [7]	NI	NI	4.33	3.6	12.18
Concrete by natural local materials (sample 3) [7]	NI	NI	4.47	3.77	12.51
Concrete by natural local materials (sample 4) [7]	NI	NI	4.81	3.98	12.51
Concrete by natural local materials (sample 5) [7]	NI	NI	5.59	4.75	15.77
Concrete by natural local materials (sample 6) [7]	NI	NI	5.29	4.75	14.57
Barite concrete [3]	NI	NI	3.21	1.51	4.95

*NI – no information

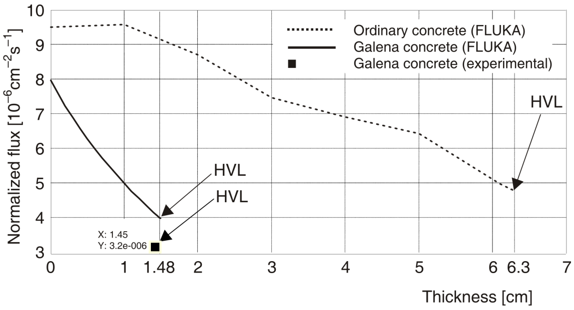

Figure 3. Variation of normalized flux with concrete thickness for determination of HVL in ordinary and galena concretes in the presence of ^{137}Cs gamma source

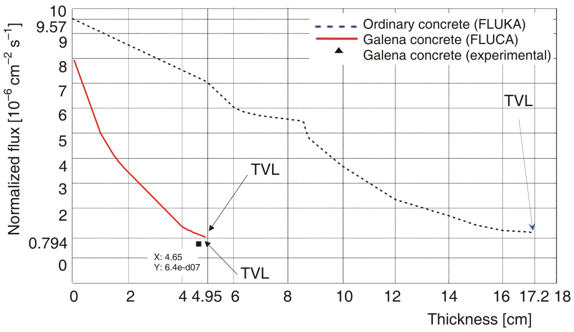

Figure 4. Variation of normalized flux with concrete thickness for determination of TVL in ordinary and galena concretes in the presence of ^{137}Cs gamma source

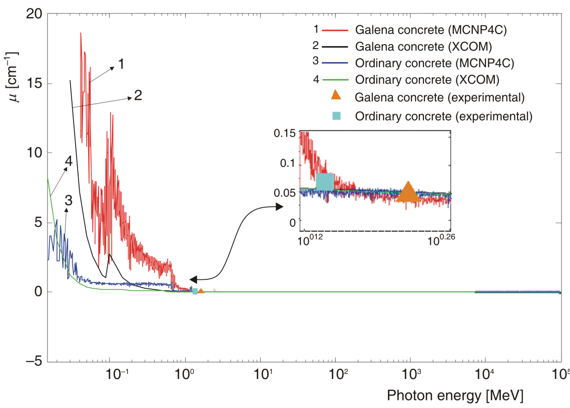

Figure 5. The comparison of numerical (FLUKA and XCOM) and experimental variations of attenuation coefficients with incident photon energy for ordinary and the optimum galena concretes

DISCUSSIONS

As presented in tab. 3, compressive strength of the galena concrete samples (628-685 kg/m^2) have increased compared to ordinary concrete (300 kg/m^2) and previous studies such as barite concrete (140-394 kg/m^2), colemanite-galena concrete (398-464 kg/m^2) and datolite-galena concrete (448-522 kg/m^2). Addition of galena mineral have had resulted an increase in density (4470-5623 kg/m^3) in comparison with ordinary concrete (2350 kg/m^3) and previously studied concrete including barite concrete (3180-3550 kg/m^3), super heavy concrete (3800-4200 kg/m^3), and datolite-galena concrete (4420-4650 kg/m^3).

When the samples have been placed in the field of gamma radiation of ^{60}Co, a reduction of about 69-75% in HVL in comparison with ordinary concrete, 23-49% with barite concrete, 12% with datolite-galena concrete, and 9% with colemanite-galena concrete has been obtained. Also a reduction of 70-79% in HVL and 67-74% in TVL, in the field of gamma emitted by ^{137}Cs, compared with ordinary concrete has been observed.

Based on the results obtained in this study, the optimum galena concrete whose mixing composition represented in tab. 2 has the half and tenth value layers (HVL and TVL) of 1.45 cm and 4.94 cm when irradiated with ^{137}Cs gamma source and compressive strength of 685 kg/m^2. This represents a low HVL as well as highest compressive strength when compared with the previous studies.

Since the most common material for radiation shielding is concrete, this composition could be a highly suitable option where high-density concrete is required in nuclear industry and radio-medical centers like megavoltage radiotherapy rooms, and nuclear reactors.

The difference between XCOM and Monte Carlo simulation results presented in fig. 5 is due to the fact that the XCOM program is not appropriate for inhomogeneous media and its results are considered as an estimation of attenuation coefficient of inhomogeneous media. As seen in fig. 5, because of the accuracy of Monte Carlo simulation, there is a good agreement between Monte Carlo simulation results and experimental data.

CONCLUSION

In this paper a new galena concrete containing galena mineral, with enhanced shielding properties for gamma sources has been introduced. Concrete samples made of galena showed a significantly better performance in radiation shielding, as well as compressive strength compared to ordinary concrete. A reduction of about 69-75% in HVL in the field of ^{60}Co and 70-79% in HVL and 67-74% in TVL in the field of ^{137}Cs in comparison with ordinary concrete has been observed experimentally. These experimental results are in good agreement with computational modeling by FLUKA and XCOM codes.

AUTHOR CONTRIBUTIONS

Computational modeling by Monte Carlo and XCOM was carried out by H. Majidi and S.

Sarshough, and experiments were carried out by K. Hadad. All authors analyzed and discussed the results. The manuscript was written by S. Sarshough and K. Hadad, and the figures were prepared by K. Hadad.

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УНАПРЕЂЕНА ЗАШТИТА ОД ЗРАЧЕЊА УПОТРЕБОМ БЕТОНА СА ГАЛЕНА МИНЕРАЛОМ

Развијена је нова врста бетона који садржи минерал галена и има побољшана заштитна својства за примену код гама извора зрачења. Како би се постигла оптимална заштитна својства, испитано је десет врста бетона са галена минералом различитог састава и референтни стандардни бетон густине 2300 kg/m^3. Истраживања су обављена експериментално и нумерички – употребом програмских кодова Монте Карло и XCOM. Поред основних састојака воде и микро-силиката, испитивани бетон садржи минерал галена (који укључује олово). Начињени узорци бетона су високе густине, од 4470 kg/m^3 до 5623 kg/m^3, и чврстоће на притисак од 628 kg/m^2 до 685 kg/m^2. Утврђене HVL и TVL вредности, при озрачивању цезијумом (^{137}Cs), износе 1.45 cm и 4.94 cm, респективно, док при озрачивању кобалтом (^{60}Co), HVL износи 2.42 cm. Рачунарско моделовање употребом програма FLUKA и XCOM даје добро слагање између експерименталних и нумеричких резултата.

Кључне речи: бетон са галена минералом, заштита од зрачења, Монте Карло, FLUKA, XCOM