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The new design of heavy concrete as neutron and gamma shield using galena, B_4C, and nanomaterials

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HIGHLIGHTS

- Designing 11 types of heavy concrete using galena and hematite and limonite iron ore.
- Measurement of neutron and gamma radiation attenuation coefficient.
- Using B_4C and various fibers to improve the quality of heavy concrete.
- Simulations were performed using the MCNP code.
- Very interesting results were obtained in comparison with other professional heavy concrete constructions.

ABSTRACT

Today, with the development of nuclear technology and radiation therapy equipment, radiation protection is important. This study aimed to design heavy concrete with high compressive strength and effective protection against neutron and gamma rays. In this study, 11 types of concrete with different mixing designs including 88 samples were made. In these samples, iron ore aggregates galena, limonite, hematite, polypropylene fibers, nanoparticles, micro-particles of silicon, and B_4C powder have been used. Concrete quality coefficient, compressive strength, gamma, and neutron attenuation coefficients were measured for all samples. Also, the neutron attenuation coefficient for all samples was calculated using the Monte Carlo simulation (MCNPX) code and compared with the experimental values. The density, neutron attenuation coefficient, and compressive strength of concrete samples varied from 2.37 to 3.17 g.cm^{-3}, from 0.0162 to 0.0306 cm^2.g^{-1}, and from 48.0 to 81.3 MPa respectively. The linear gamma attenuation coefficient and gamma-ray tenth value layer (TVL) were obtained from 0.148 to 0.398 cm^{-1} and 15.74 to 5.85 cm respectively. These results showed that the highest neutron and gamma attenuation coefficients were obtained for concrete containing 70% galena iron ore and 20% boron carbide and the highest compressive strength belonged to sample G15 containing 15% galena iron ore and 1.8% boron carbide. G70 was the best concrete regarding the quality factor, defined as the product of multiplying the compressive strength and linear attenuation coefficients of neutron and gamma.

KEYWORDS
Heavy concrete
B_4C
Galena
Limonite aggregates
Hematite aggregates
Gamma and neutron shielding

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1 Introduction

Currently, high-energy ionizing rays are widely used to image and destroy cancerous tumors. When an X-ray machine produces photons with an energy greater than 10 megavolts, many neutrons are also produced in addition to the photons. In this case, adequate protection of workers and other employers against radiation must be ensured. Gamma radiation causes intensive damage to the internal organs of the human body because of high energy and short wavelength (Williams, 1991). In addition, nuclear reactors and nuclear devices produce large amounts of electromagnetic radiation and neutrons that can be very harmful to personnel if not protected. Therefore, adequate shielding must be designed and implemented around the reactor heart and radiation emitting devices so that the radiation level is reduced to an acceptable level. Two types of materials are used to create an effective shield: some light elements to moderate and absorb neutrons, such as hydrogen and boron, and heavy elements to eliminate gamma radiation, such as iron, bismuth, and lead (Hu et al., 2008).

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Table 1: Main Concrete components of samples.

Sample Code	Samples concrete ($5 \times 5 \times 5$ cm^3)											
	Aggregate						W/C=0.44		Cement substitute additives			
	Gravel (g)	Sand (g)	Lime (g)	Galena (g)	Limonite (g)	Hematite (g)	Cement (g)	Water (ml)	Plasticizer (g)	Micro Si (g)	Nano Si (g)	B_4C (g)
O	73.62	136	8.62	-	-	-	54.37	24.37	-	-	-	-
G5	72.43	133.95	9.0	10.86	-	-	54.37	24.37	0.54	5.43	1.35	0.30
G10	70.87	130.60	9.26	22.36	-	-	54.37	24.37	0.54	5.43	1.35	0.65
G15	69.06	127.85	9.60	34.73	-	-	54.37	24.37	0.54	5.43	1.35	0.97
G70	39.18	72.26	15.37	260.01	-	-	54.37	24.37	0.54	5.43	1.35	10.87
G70(P)	-	106.18	22.58	247.73	-	-	54.37	24.37	0.54	5.43	1.35	10.87
L-H5	71.60	132.48	8.90	-	3.77	6.97	54.37	24.37	0.54	5.43	1.35	0.30
L-H10	68.96	127.43	9.03	-	7.66	14.16	54.37	24.37	0.54	5.43	1.35	0.65
L-H15	66.40	122.82	9.22	-	11.72	21.68	54.37	24.37	0.54	5.43	1.35	0.97
L-H70	30.37	56.05	11.92	-	70.87	130.76	54.37	24.37	0.54	5.43	1.35	4.56
H70(P)	32.85	60.83	12.93	-	-	218.55	54.37	24.37	0.54	5.43	1.35	4.56

Usually, special concrete is used for the construction of shields in nuclear power plants and radiation therapy rooms, which in addition to the effective reduction of nuclear radiation is cost-effective, and has high compressive strength and resistance to thermal stress. That is why concrete has always been the subject of researchers' interest (Gencel et al., 2010; Aygün et al., 2021; Aygün, 2019; Kharita et al., 2008). Concrete has a coherent and integrated structure that can be improved by adding appropriate additives such as coarse sand with various minerals, nanomaterials, and micro particles (Akkurt et al., 2010). Concrete density and gamma attenuation coefficient increased with the addition of galena to concrete (Mortazavi et al., 2007). Other studies have also shown that adding galena to concrete increases density, compressive strength, and gamma ray attenuation factor (Vrijheid et al., 2007). Galena, also called lead glance, is the natural mineral form of lead sulfide (PbS). This aggregate contains significant amounts of lead and iron and is very brittle and has a density of 7.4 to 7.6 $g.cm^{-3}$. Thermal neutrons are absorbed by elements with a large absorption cross-section, and gamma radiation is attenuated through interactions such as Compton scattering, photoelectric absorption, and pair production (Pelowitz et al., 2005). Currently, shielding design requires light materials to slow down fast neutrons, materials with a large cross-section to absorb thermal neutrons, and heavy materials to absorb gamma rays. In this study, the MCNPX code was used to evaluate the mass attenuation coefficient (μ/ρ), linear attenuation coefficient (μ), and decimator layer (TVL). Simulation can be used to avoid additional costs and predict concrete mix design. The results can be compared with experimental values to determine the accuracy of simulation calculations. And finally, one can find the exact input and output files. The work aimed to compare the properties of concrete containing different percentages of available iron ore and other additives on compressive strength and gamma and neutron attenuation coefficients. For the comparison of different concretes, a parameter was proposed as a quality factor including the neutron and gamma attenuation coefficients and the compressive strength of the concretes.

Table 2: Percentage aggregates in the samples.

Code	Aggregate	Percent (%)	Coarse grain	Fine grain					Lime
			Mesh 4 (g)	Mesh 8 (g)	Mesh 16 (g)	Mesh 30 (g)	Mesh 50 (g)	Mesh 100 (g)	Mesh 200 (g)
O	Gravel-Sand	100	73.62	43.37	30.37	31.87	15.87	14.5	8.62
G5	Gravel-Sand	95	72.43	42.75	29.92	31.35	15.67	14.25	9.0
	Galena	5	3.81	2.25	1.57	1.65	0.82	0.75	-
G10	Gravel-Sand	90	70.87	41.67	27.92	30.56	15.28	13.90	9.26
	Galena	10	7.87	4.62	3.25	3.37	1.70	1.53	-
G15	Gravel-Sand	85	69.06	40.80	28.56	29.92	14.96	13.60	9.60
	Galena	15	12.18	7.20	5.03	5.27	2.63	2.40	-
G70	Gravel-Sand	30	39.18	23.06	16.15	16.91	8.45	7.68	15.37
	Galena	70	91.43	53.81	37.67	39.46	19.75	17.93	-
G70(P)	Sand	30	-	33.88	23.72	24.85	12.42	11.30	22.58
	Galena (P)	70	-	79.06	55.35	57.97	29.0	26.35	-
L-H5	Gravel-Sand	95	71.60	42.28	29.60	31.0	15.50	14.10	8.90
	Limonite-Hematite	5	3.77	2.22	1.56	1.63	0.81	0.73	-
L-H10	Gravel-Sand	90	68.96	40.67	28.46	29.82	14.91	13.56	9.03
	Limonite-Hematite	10	7.66	4.51	3.16	3.31	1.66	1.51	-
L-H15	Gravel-Sand	85	66.40	39.20	27.43	28.75	14.37	13.06	9.22
	Limonite-Hematite	15	11.72	6.92	4.83	5.07	2.53	2.31	-
L-H70	Gravel-Sand	30	30.37	17.88	12.52	13.11	6.56	5.96	11.92
	Limonite-Hematite	70	70.87	41.73	29.71	30.60	15.30	13.91	-
H70(P)	Gravel-Sand	30	32.85	19.41	13.58	14.23	7.12	6.47	12.93
	Hematite (P)	70	76.65	45.28	31.70	33.21	16.60	15.10	-

Table 3: Percentage of additives material relative to cement for all samples.

Code	Plasticizer (%)	Iron fibers (%)	PP fibers (%)	Micro silicon (%)	Nano silicon (%)	B_4C (%)
O	-	-	-	-	-	-
G5	1	2	0.2	10	2.5	0.6
G10	1	2	0.2	10	2.5	1.2
G15	1	2	0.2	10	2.5	1.8
G70	1	2	0.2	10	2.5	20
G70(P)	1	2	0.2	10	2.5	20
L-H5	1	2	0.2	10	2.5	0.6
L-H10	1	2	0.2	10	2.5	1.2
L-H15	1	2	0.2	10	2.5	1.8
L-H70	1	2	0.2	10	2.5	8.4
H70(P)	1	2	0.2	10	2.5	8.4

2 Materials and Methods

2.1 Experimental method

In the study, 11 types of concrete with different components were produced with dimensions of $5 \times 5 \times 5$ (cm^3) in concrete laboratory of Arak University, including two samples of each type to measure the compressive strength and six samples of each type to measure the gamma and neutron attenuation coefficient. After 24 hours of forming and coding, the samples were placed in a water tank for 7 and 28 days, and then the compressive strength of the samples was measured. Typically, the strength of a 7-day concrete is approximately 75% of the strength of a 28-day sample. The samples were: Ordinary concrete (O), Galena 5% (G5), Galena 10% (G10), Galena 15% (G15), Galena 70% (G70), and Galena 70% powder (G70(P)), Limonite-Hematite 5% (L-H5), Limonite-Hematite 10% (L-H10), Limonite-Hematite 15% (L-H15), Limonite-Hematite 70% (L-H70), Hematite 70% powder (H70(P)). In each sample added 1.08 g iron fiber and 0.1 g polypropylene fiber and other compositions which are presented in Table 1. The percentages of aggregates in the samples and cement additives are presented in Tables 2 and 3, respectively. Given the high percentage of sand in silicon, the purpose of this study was to investigate the effect of iron on gamma flux. The amount of sand was gradually reduced by 5, 10, and 15 percent, and the same percentage of boron and iron ore was added to the concrete. The new density is obtained from Eq. (1):

$$\rho = \frac{1}{100} \sum \rho_i \omega_i \tag{1}$$

where ρ is the new density of the sample, ω_i is the weight percent and ρ_i is the density of each component. The attenuation coefficient can be calculated from Eq. (2). μ (linear) can be obtained using the slope of the $\ln(I/I_0)$ plot for different thicknesses.

$$\mu = -\frac{1}{x} \ln\left(\frac{I}{I_0}\right) \tag{2}$$

The cylindrical neutron detector BF_3 model 2029 and NaI(Tl) scintillator detector have been used to measure neutron and gamma radiation, respectively. The gas pressure inside the BF_3 detector is 400 tors. It is coated with stainless steel cathode that maximum length is 390.65mm, effective length is 311.15 mm, effective diameter is 24.38 mm and effective volume is 145.23 cm^3. This detector has no sensitive to gamma radiation. The neutron record is limited between 4.4 to 6 volts, to eliminate background radiation and noises. First, the neutron and gamma radiation was measured, with no sample. The neutron radiation has been measured for 300 seconds at the neutron peak range for each sample with thicknesses of 5, 10, 15, 20, 25 and 30 cm. Also, samples are located between the Cs-137 source and NaI(Tl) detector to determine the linear attenuation coefficient and the gamma spectra were recorded for 300 to 1000 seconds for each sample with thicknesses of 5, 10, 15, 20, 25 and 30 cm (distance between the source with detector was fixed for all test steps). The gamma source and the NaI(Tl) detector were 10 cm thick lead shields, and two collimators were placed in front and behind the sample to prevent gamma radiation scattered from the environment from entering the detector. The experiments were done in two separate laboratories. Figures 1 and 2 show the arrangements of the sample, collimator, source, and detector. Finally, the ln(N) diagram was obtained for different concrete thicknesses and the linear attenuations coefficient was calculated. The tenth value layer, TVL, is one of the parameters that determine the degree of reduction of the gamma and neutron flux. TVL is the concrete thickness that reduces the photon and neutron density to 0.1 of the original one.

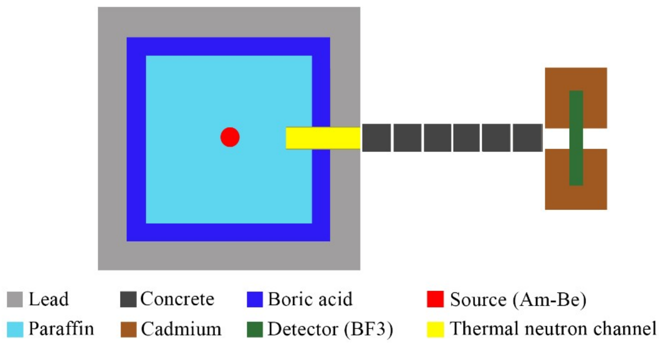

Figure 1: Showing the arrangement of samples for the investigation of neutron attenuation.

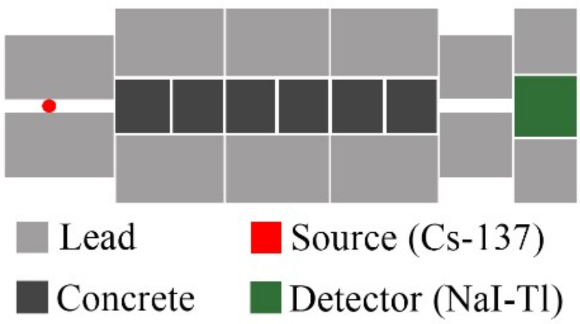

Figure 2: Showing the arrangement of samples for the investigation of gamma attenuation.

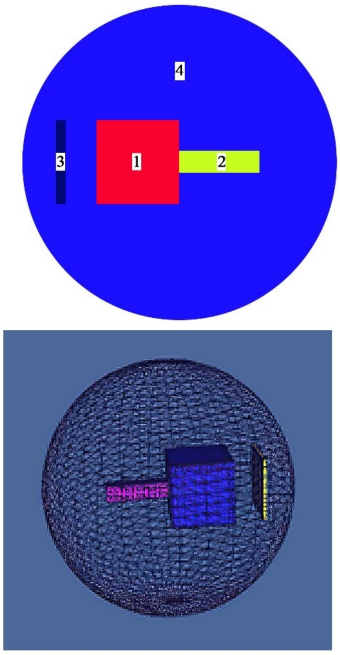

Figure 3: Geometry system for the simulation by MCNP software.

The BF_3 detector is not sensitive to gamma and is used for thermal neutrons, therefore in this experiment, the effect of concrete blocks was only performed on thermal neutrons. In this experiment, due to the use of cadmium coating, only neutrons passing through the sample are measured.

In this experiment, to check the gamma attenuation, a Cs-137 point source with 3.7 MBq activity and a lead collimator and a scintillation detector NaI(Tl) of 2 inches×2 inches from Ortec company have been used.

2.2 Simulation method

The simulation was performed using the MCNPX code for all types. Using this code, μ (linear) was calculated for all types of concrete containing galena, boron carbide, hematite, and limonite. Samples of different thicknesses are simulated in front of the neutron source (Am-Be). The geometric layout of the simulation is shown in Fig. 3. The flux was calculated once using F4 Tally without a sample (φ_0), and then the flux after different thicknesses of the sample (φ).

In Fig 3, cell number 1 is concrete, cell number 2 is a detector, cell number 3 is a source, and cell number 4 is air.

3 Results and discussion

3.1 Gamma attenuation coefficient

Using the flux values obtained for a particular concrete in the MCNP code, a plot of $\ln(I)$ versus thickness was plotted in Fig. 4. The value of experimental gamma attenuation coefficients for different samples is presented in Table 4. The results show that the linear gamma attenuation coefficient increases with the increase of iron ore content in concrete, which is related to the growth of electron density in concrete. The plots showed linearity for all samples, which means that this type of concrete absorbs gamma rays well. Table 4 shows that the concrete containing 70% iron ore has the highest gamma attenuation coefficient and as a result, the lowest tenth-value layer.

3.2 Neutron attenuation coefficient

Neutron attenuation is exponential in thickness and is highly dependent on the macroscopic cross-section of neutron interactions. The results of neutron measurement using the BF_3 detector for a thickness of 5 to 30 cm for each type of concrete are summarized in Table 5. Figure 5 shows the graph of $\ln(I)$ as a function of thickness for the tested samples. The results show that while increasing the iron content improves the gamma photon absorption coefficient and the quality of the concrete, it is in contrast to the neutrons that are modified by the addition of boron carbide compounds. Compared to the other samples, concrete containing 70% Galena iron ore and 20% boron carbide (B_4C) has the highest attenuation coefficient and lowest TVL (75.3 cm), making it the best type of concrete tested as a protective structure.

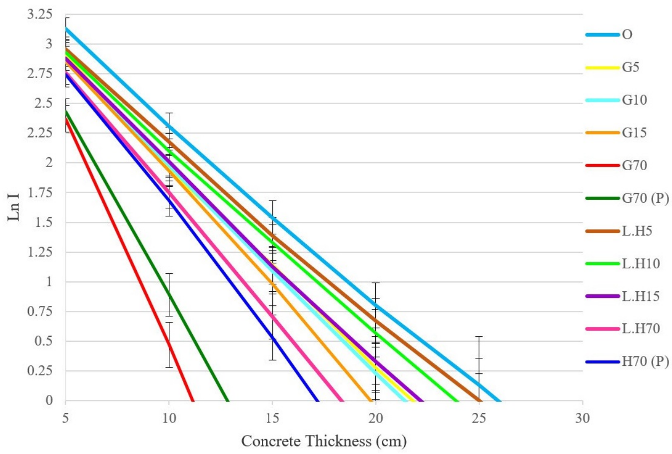

Figure 4: Graph of gamma ray attenuation in terms of concrete thickness for the all samples.

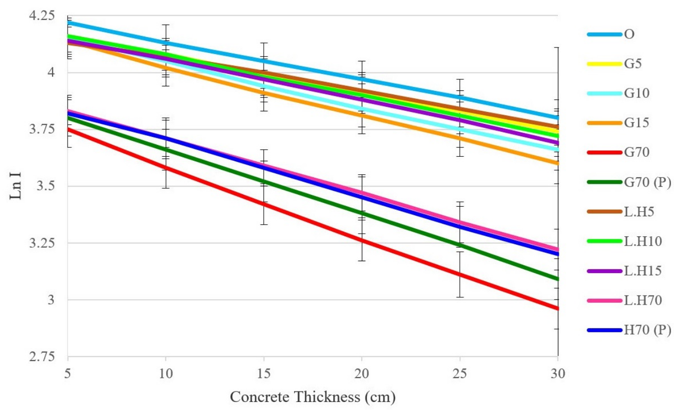

Figure 5: Exprimental graph of neutron attenuation in terms of thickness for the all samples.

Table 4: Gamma attenuation coefficient and TVL thickness for samples.

Sample	Counting rate (I) in thickness 30 cm	μ_γ (Linear) (cm^{-1})	ρ (g.cm^{-3})	μ/ρ (cm^2.g^{-1})	TVL (cm)
No sample	50.2	-	-	-	-
O	0.55	0.148	2.37	0.062	15.74
G5	0.3	0.163	2.49	0.065	14.30
G10	0.25	0.171	2.57	0.066	13.62
G15	0.15	0.190	2.64	0.072	12.26
G70	0	0.398	3.60	0.110	5.85
G70(P)	0	0.316	3.17	0.100	7.37
L-H5	0.45	0.147	2.42	0.060	15.66
L-H10	0.4	0.153	2.44	0.062	15.05
L-H15	0.3	0.163	2.60	0.062	14.12
L-H70	0	0.208	2.63	0.079	11.07
H70(P)	0	0.234	2.70	0.086	9.84

Table 5: Experimental neutron attenuation coefficient and TVL thickness for samples.

Sample	Counting rate (I) in thickness 30 cm	μ_γ (Linear) (cm^{-1})	ρ (g.cm^{-3})	μ/ρ (cm^2.g^{-1})	TVL (cm)
No sample	85.5	-	-	-	-
O	44.5	0.0164	2.37	0.0070	140.4
G5	42.5	0.0162	2.49	0.0065	142.2
G10	39.2	0.0195	2.57	0.0075	118.1
G15	36.9	0.0215	2.64	0.0080	107.1
G70	19.3	0.0306	3.6	0.0085	75.3
G70(P)	22.1	0.0256	3.17	0.0080	89.9
L-H5	43.5	0.0167	2.42	0.0069	137.9
L-H10	40.8	0.0185	2.45	0.0075	124.4
L-H15	40.15	0.0185	2.57	0.0071	124.4
L-H70	25.0	0.0249	2.66	0.0093	92.4
H70(P)	24.55	0.0256	2.72	0.0094	89.9

Table 6: Measured compressive strength and QF for all samples.

Sample	Day	Compressive strength (MPa)	Density (g.cm^{-3})	Weight (g)	QF (MPa.cm^{-2})
O	7	48.0	2.37	296.5	0.116
	28	53.8	2.38	297.0	0.130
G5	7	67.6	2.49	310.0	0.178
	28	75.2	2.5	312.0	0.198
G10	7	69.5	2.57	322.2	0.231
	28	79.2	2.58	323.0	0.264
G15	7	72.9	2.63	329.7	0.297
	28	81.3	2.64	330.5	0.332
G70	7	56.8	3.59	448.8	0.691
	28	61.0	3.6	450.0	0.742
G70(P)	7	63.2	3.17	396.0	0.511
	28	67.0	3.17	396.5	0.542
L-H5	7	59.3	2.42	302.0	0.145
	28	69.4	2.42	301.5	0.170
L-H10	7	65.2	2.44	306.0	0.184
	28	73.0	2.46	308.0	0.206
L-H15	7	68.5	2.60	319.5	0.206
	28	76.6	2.53	317.0	0.230
L-H70	7	57.7	2.63	329.0	0.298
	28	62.0	2.66	332.5	0.321
H70(P)	7	62.4	2.70	337.5	0.373
	28	66.1	2.72	340.0	0.395

3.3 Compressive strength of concrete

Compressive strength after 7 and 28 days was measured in concrete laboratory in Arak university. The value of compressive strength, density, and mass of all samples are given in Table 5. The results show that adding 15% galena iron ore to the concrete improves the compressive strength, therefore heavy concrete is much better in this regard. Concrete containing 70% galena iron ore has the highest density compared to other samples.

3.4 Concrete quality coefficient

In addition to attenuating gamma rays and neutrons, concrete must also have high strength and be able to withstand structural loads in most cases. For this purpose, we proposed a concrete quality factor to take into account the compressive strength and attenuation coefficients of neutron and gamma radiation in the form of Eq. 3. On this basis, different concretes can be optimized and compared, and then the best one can be selected.

$$QF = CS \times \mu_\gamma(\text{linear}) \times \mu_n(\text{linear}) \tag{3}$$

Table 7: μ_γ (linear) and μ_n (linear) experimental and MCNP code in thickness 30 cm.

Sample	μ_n (Linear) (Experimental)	μ_n (Linear) (MCNP)	μ_γ (Linear) (Experimental)	μ_γ (Linear) (MCNP)
O	0.0164	0.0149	0.148	0.1396
G5	0.0162	0.0160	0.163	0.1499
G10	0.0195	0.0191	0.171	0.1633
G15	0.0215	0.0206	0.190	0.1798
G70	0.0306	0.0300	0.400	0.365
G70(P)	0.0256	0.0238	0.316	0.3087
L-H5	0.0167	0.0153	0.149	0.1361
L-H10	0.0185	0.0182	0.153	0.1453
L-H15	0.0185	0.0181	0.163	0.1489
L-H70	0.0249	0.0244	0.208	0.1827
H70(P)	0.0256	0.0239	0.234	0.2262

Table 8: Comparison of compressive strength of some type of concrete containing different aggregate.

Country	Kind of aggregate	Density (g.cm^{-3})	Compressive strength-28 day (MPa)	Reference
Poland	Basalt from a lead mine	2.49	31 - 39	(Ablewicz and Dubrovskij, 1986)
France	Magnetite	3.58	31 - 47	(Tourasse, 1958)
France	Barytic	3.50 - 4.18	15.5 - 34	(Tourasse, 1958)
Poland	Barytic	3.60 - 3.68	21 - 46	(Komorowskij, 1969)
Poland	Serpentinite	2.28 - 3.27	17.7 - 34.5	(Ablewicz and Dubrovskij, 1986)
Russia	Serpentinite	2.22 - 4.2	8.3 - 23.0	(Komorowskij, 1969)
Poland	Limonite	2.65 - 3.50	18.2 - 32.4	(Komorowskij, 1969)
Germany	Magnetite	3.98	40 - 40	(Manns, 1971)
Iran	Galena	2.49 - 3.59	56.8 - 81.3	This work

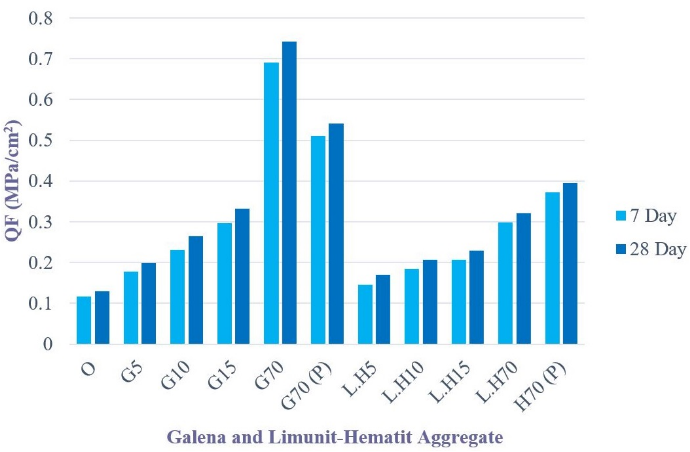

Figure 6: The quality Factors of concrete samples in terms of the percentage of galena and limonite-hematite aggregates.

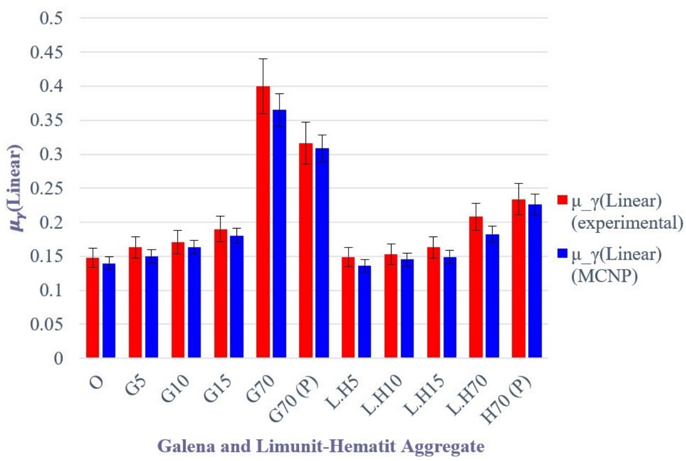

Figure 8: MCNP calculations and measured experimental μ_γ (linear) for Galena and Limunit-Hematit aggregate.

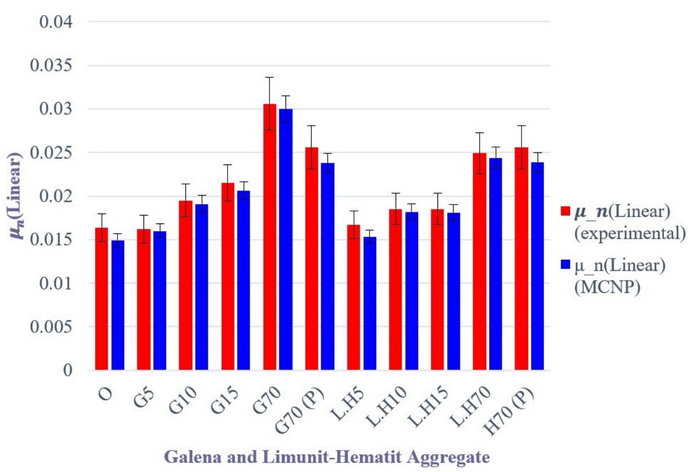

Figure 7: MCNP calculations and measured experimental μ_n (linear) for Galena and Limunit-Hematit aggregate.

We proposed this formula considering three basic parameters for comparison and optimization to compare concrete. In this equation, CS is the compressive strength in MPa, and μ_γ (linear) and μ_n (linear) are the gamma and neutron attenuation factors in cm^{-1}, respectively. The results are summarized in Table 6 and show that G70 concrete containing 70% galena iron ore and 20% boron carbide has the best quality among other samples. Figure 6 shows the QF changes for different types of concrete after 7 and 28 days.

3.5 The necessity of using MCNP code

As computer science evolves, problem solving by simulation is widely used in various sciences. Simulation can be used to solve particle transport problems in the environment and obtain useful and close data to laboratory results that are costly to do. In this study, the experimental data were in agreement with the simulation data; therefore, can be said laboratory data were being accurate and almost error free. In Figs. 7 and 8, the results of simulation calculations with MCNP code and experimental measurements are shown in the form of histograms. Simulation results can be used for concrete mix designing without additively costs.

3.6 Comparison of results with other important works

Table 8 compares the results of this study with some reported results from some countries. The compressive strength of concretes in this study was definitely higher than in other countries, while the density was approximately in the same range.

A comparison of Tables 6 and 8 shows that all concrete samples in this work were better than samples from other countries, and the results of this study can be used for nuclear power plants and radiotherapy facilities.

4 Conclusions

These studies were carried out to improve the quality of the concrete in terms of compressive strength and attenuation coefficients so that it can be used in smaller thicknesses for radiation protection. In this study, 11 types of concrete were designed. For all samples, the quality factor was calculated, which shows that the best concrete was G70, and the best compressive strength was obtained by G15 after 28 days of immersion in water. The measured data were compared with simulation data and experimental values given in some countries, where our results were significantly higher than in other countries.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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