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Investigating the influence of gamma ray energies and steel fiber on attenuation properties of reactive powder concrete

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Abstract The effect of gamma ray energies and volume ratio of micro steel fiber (1 and 1.5%) on attenuation properties of reactive powder concrete (70 MPa compressive strength) was investigated. Different characteristics have been considered such as linear attenuation coefficient, mass attenuation coefficient, and half-value thickness. Sodium iodide crystal with a gamma ray spectrometer and collimated beam of gamma ray has been implemented to perform the experimental test. Three sources (Cs-137, Co-60, and Bi-207) with energies of (0.662, 1.17 1.33, 0.569, and 1.063) MeV were adopted in the test. The results obtained indicated that mass attenuation coefficient is proportioned inversely with gamma ray energies and directly with a volume ratio of micro steel fiber. The linear attenuation coefficient and half-value thickness of the tested samples have been calculated and discussed. The obtained results showed that increasing the volume ratio of steel fiber has modified the adequacy of the reactive powder concrete as a shielding element since it increases the density and reduces the half-value thickness.

Keywords Radiation shielding · Attenuation properties · Gamma radiation · Density · Reactive powder concrete

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1 Introduction

In nuclear science, radiation protection is considered one of the most essential topics. Shielding from gamma rays can be considered as the most difficult one due to the enormous amount of energy held by gamma photons, and since they have no mass and charge, they can readily penetrate into the matter. Radiation shielding is commonly used to protect medical patients and workers from exposure to direct and secondary radiation during diagnostic imaging in hospitals and radiological facilities. The effectiveness of radiation shielding varies significantly with the attenuation properties of the component materials, material thickness, and radiation energy [1], thus there is always a need to develop materials that can be used as shielding material. In a case of nuclear radiation shielding, a huge amount of shielding materials are required, therefore, it is necessary to investigate the efficiency of the available materials, experimentally, before using them [2]. Generally, it is not fare to consider the concrete as a simple mixture of cement, water, and aggregates. It often contains varies mineral components, chemical admixtures, fibers, etc. These components are usually affecting the characteristics of concrete shielding structures [1]. Also, the cement industry is one of the most common structural materials used in constructions such as home, hospital [3]. For this reason, the type and quantity of aggregates and admixtures are important components for radiation protection properties of concrete and for its physical and mechanical properties. Different researchers in the field of radiation shielding have been published using different construction materials, different geometries, and different nuclear radiation sources. Moreover, a lot of studies are related with linear and mass attenuation coefficients of different materials such as building materials and concrete [4–9]. Mahdy et al. [10] investigated the influence of magnetite on the compressive strength and shielding properties of concrete. Magnetite was implemented as an aggregate material to produce a concrete mixed with three different percentages of silica fume. It was concluded that magnetite and silica fume had improved both the compressive strength and shielding properties. Akkurt et al. [11] used concrete containing different fine and coarse normal aggregates mixed with barite as shielding materials for gamma ray. It was concluded that the type of used aggregate was more important than its proportion in concrete mixed. Wasan et al. [12] investigated the suitability of using reactive powder concrete without steel fiber in shielding structures by measuring linear and mass attenuation coefficient using beta particles and gamma ray with different energies. In the present work, cube samples of reactive powder concrete without and with a different volume ratio of micro steel fiber (1 and 1.5%) have been prepared to investigate the adequacy of using this element as gamma ray shield.

The attenuation of radiation is expressed as

$$I = I_0 \exp(-\mu x), \tag{1}$$

Table 1 Chemical composition of cement

No.	Compound composition	Chemical composition	Weight (%)	Iraqi specification no. 5/1993
1	Silica	SiO_2	21.00	–
2	Alumina	Al_2O_3	5.00	–
3	Iron oxide	Fe_2O_3	3.51	–
4	Lime	CaO	64.10	–
5	Magnesia	MgO	2.30	5 (max)
6	Sulfate	SO_3	2.25	2.8 (max)
7	Insoluble residue	IR	1.27	1.5 (max)
8	Loss on ignition	LOI	3.00	4.0 (max)
9	Tricalcium aluminates	C_3A	0.55	–
10	Lime saturation factor	LSF	0.89	0.66–1.02

All the test were conducted by the National Center of Laboratories and Researches (Baghdad)

Table 2 Physical properties of cement

No.	Physical properties	Test result	Iraqi specification no. 5/1993
1	Specific surface area (Blaine method) (m^2/kg)	395	230 (min)
2	Setting time (Yicale's method)		
	Initial time setting (h:min)	2:27	00:45 (min)
	Final time setting (h:min)	3:75	10:00 (max)
3	Autoclave expansion (%)	0.08	0.80 (max)
4	Compressive strength (MPa)		
	7 days	21.49	15.00 (min)
	28 days	27.92	23.00 (min)

All the test were conducted by the National Center of Laboratories and Researches (Baghdad)

Table 3 Grading of the fine aggregate

Sieve size (mm)	% Passing by weight	Limit of Iraqi specification no. 45/1993			
		Zone 1	Zone 2	Zone 3	Zone 4
10	100	100	100	100	100
4.75	100	90–100	90–100	90–100	95–100
2.36	100	60–95	75–100	85–100	95–100
1.18	100	60–90	55–90	75–10	90–100
0.60	82.1	30–70	35–59	60–79	80–100
0.30	40.4	5–34	8–30	12–40	15–50
0.15	7.8	5–20	0–10	0–10	0–15
75×10^{-3}	0	5 max			

Table 4 Physical properties of the fine aggregate

No.	Physical properties	Test result	Iraqi specification no. 45/1993
1	Specific gravity	2.63	–
2	Sulfate contained %	0.22	0.5 (max)
3	Absorption	0.6	–

All the test were conducted by the National Center of Laboratories and Researches (Baghdad)

Table 5 Chemical analysis of used water

No.	Chemical test	Standard unit	Results				ASTM C 1602/C 1602M-04
			Tap	Well	River	Drainage	
1	TSS	ppm	<0.1	4	7	15	–
2	TDS	ppm	417	459	386	480	2000
3	Sulfate	ppm	0.2	0.1	0.1	0.2	3000
4	Chloride	ppm	50	125	125	100	1000
5	PH	–	7.2	7.72	7.7	7.4	(4.5–8.5)
6	Turbidity	NTV	4.81	11.6	10.4	4.67	–

All the test were conducted by the Sanitary Laboratory/Civil Engineering Department/Baghdad University

ppm part per million part

Table 6 Chemical composition of silica fume

No.	Compound composition	Chemical composition	Weight (%)
1	Silica	SiO_2	92.03
2	Alumina	Al_2O_3	0.18
3	Lime	CaO	0.70
4	Iron oxide	Fe_2O_3	1.10
5	Magnesia	MgO	2.10
6	Sulfate	SO_3	0.85
7	Loss on ignition	LOI	3.78

All the tests were conducted by the S. C. Geological Survey and Mining

where I_0 is a number of particles of radiation counted during a certain time duration without any absorber, I is number counted during the same time with a thickness x of an absorber between the source of radiation and the detector, μ is linear absorption coefficient.

When discussing the mass attenuation coefficient, Eq. (1) is rewritten as

$$I = I_0 \exp((-\mu/\rho)\rho x), \tag{2}$$

where ρ is the density, (μ/ρ) is mass attenuation coefficient (μ_m), and ρx is area density (mass thickness d_m).

The half-value thickness ($X_{1/2}$) for the samples is calculated according to the following formula

Table 7 Chemical requirements of SF according to ASTM C1240-03

Chemical composition	Test result	Limit of ASTM C 1240-03
Silica (SiO_2), min	92.03	85.00
Loss on ignition (LOI), max	3.78	6.00

Table 8 Technical description of GLENIUM51

Form	Viscous liquid
Color	Light brown
Relative density	1.1
PH	6.6
Viscosity	128 ± 30 CPS
Transport	Not classified as dangerous
Labeling	No hazard label required

Data sheet of the manuscript

Table 9 Details of the adopted mix

Mix proportion (kg/m^3)			SP[a]	SF[b]
Water	Cement	Sand		
360	910	960	160	230

[a] lt/100 kg of cement (max limit is 2.7)

[b] Replacement by weight of cement

Table 10 Details of sample groups

Group sample	No. of sample	Volume ratio %
A	8	0
B	8	1
C	8	1.5

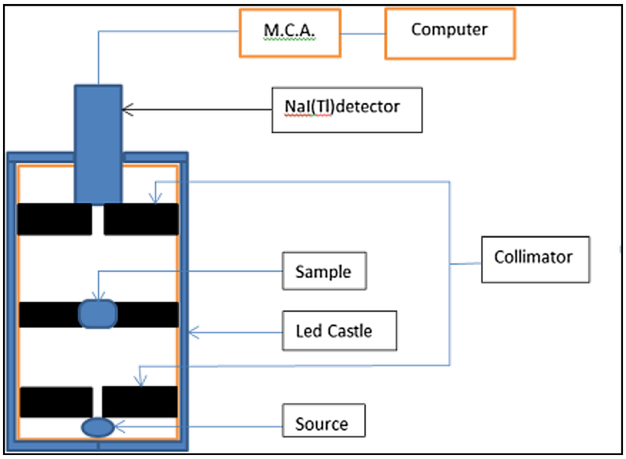


Fig. 1 (Color online) Schematic of experimental setup

$$X_{1/2} = 0.693/\mu, \quad (3)$$

where $X_{1/2}$ is the average amount of material needed to absorb 50% of all radiation.

2 Materials and methods

- Cement

Type I Normal Portland Cement, which is satisfying ASTM C150 requirements, was implemented. It was produced by the Tasloja cement factory. The chemical and physical properties of the cement are presented in the Tables 1 and 2.

- Fine aggregates

Fine aggregate used in concrete mix for all samples was free from clay and other impurities with a maximum size of (600 μm). Table 3 shows both a sieve analysis and limit of Iraq specification No. 45/1993 [13], while Table 4 illustrates the physical properties of the sand. According to the limit of Iraq specification, the used sand can be classified as Zone 4.

- Water

For both mixing and curing processes, tap water was used. Table 5 shows the chemical analysis of the water, which

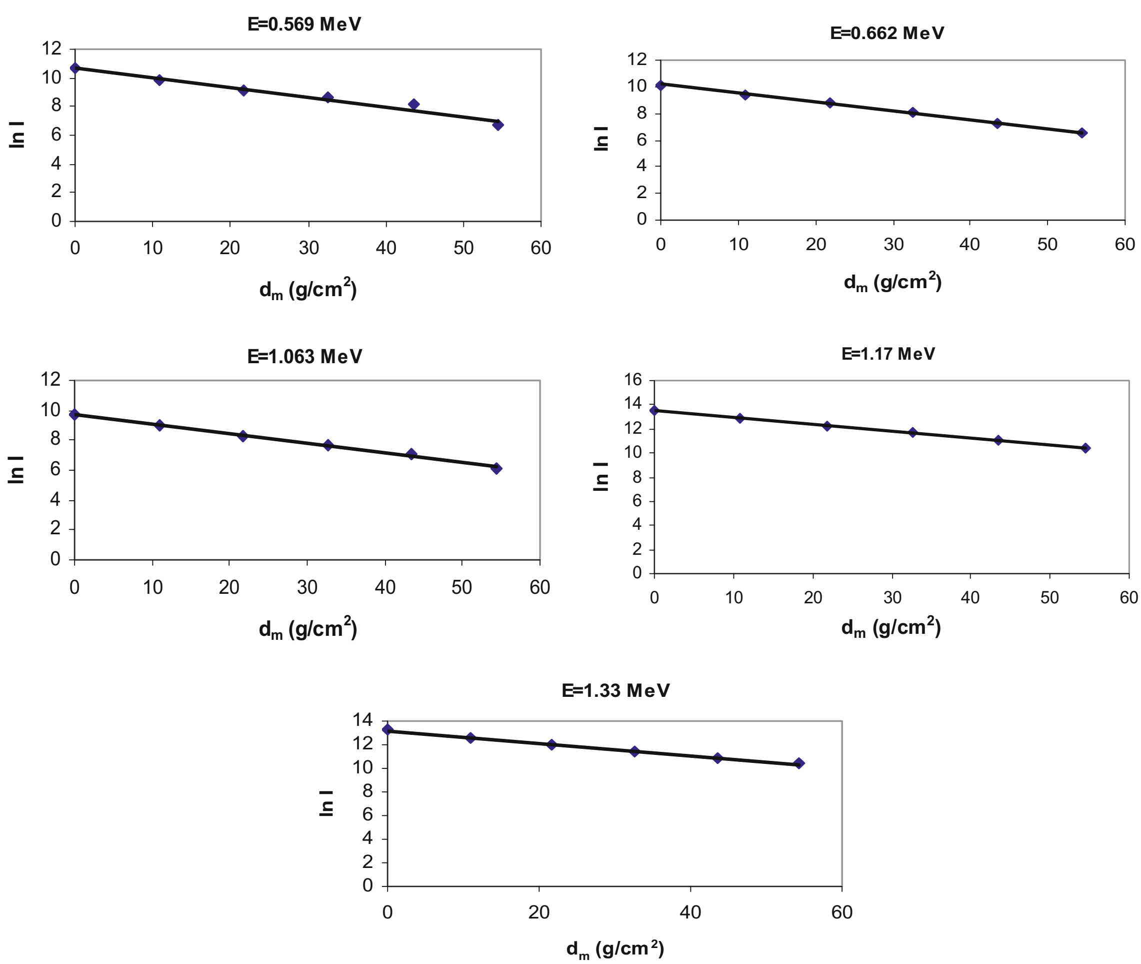


Fig. 2 Logarithmic intensity of a gamma ray as a function of d_m for different energy (sample A)

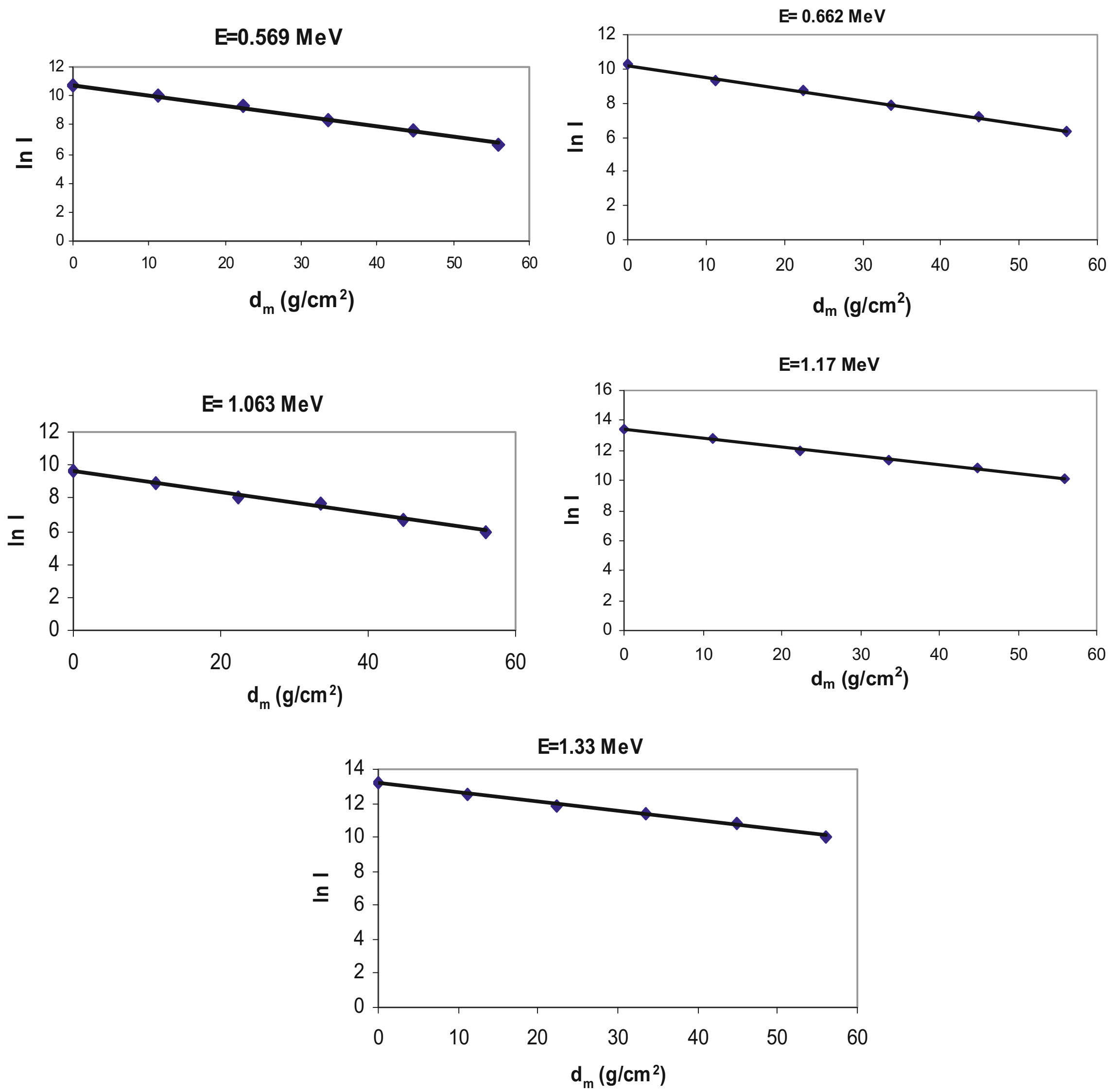


Fig. 3 Logarithmic intensity of a gamma ray as a function of d_m for different energy (sample B)

complies with the limit of ASTM C 1602/C 1602M-04 [14] specification.

- Silica fume

Silica fume conformed to EN 13263, a product of Sika, was used as an additive (pozzolanic material) to produce the RPC for all specimens. The chemical composition and ASTM C1240-03 [15] requirements of silica fume are listed in Tables 6 and 7.

- Superplasticizer

A new generation of modified polycarboxylic ether that complies with ASTM C494-05 [16] types A and F (GLENIUM51) was the superplasticizer used to modify the workability of the reactive powder concrete. Table 8 gives the technical description of GLENIUM51.

- Micro steel fiber

All steel fibers that has a length less than or equal (1.5 in.) are classified as micro steel fiber. Micro high-tensile steel fiber (1000 MPa), used in this work, was one millimeter in diameter and 10 mm in length, i.e., the value of the aspect ratio is 60.

2.1 Casting and curing of the samples

The schedule of the experimental test in this research includes casting three groups of standard cubes (50 mm × 50 mm × 50 mm side length) using the adopted mix of reactive powder concrete as demonstrated in Table 9. The process of mixing was similar to the one recommended by the ACI Committee Report 544. Water curing was used for 28 days after which three cubes were

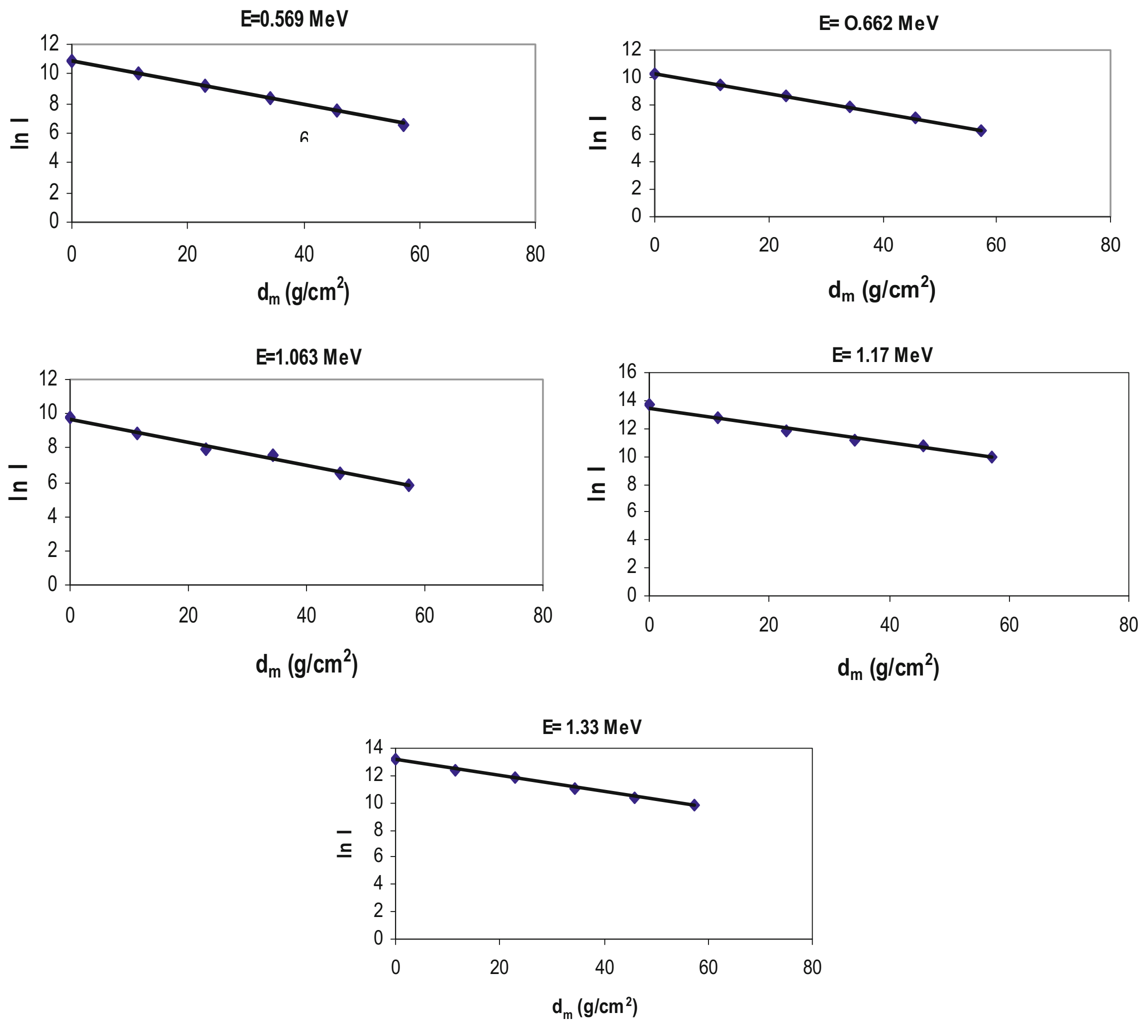
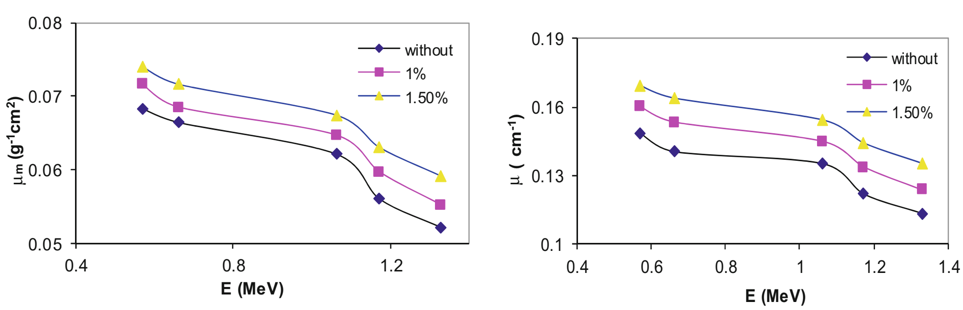


Fig. 4 Logarithmic intensity of a gamma ray as a function of d_m for different energy (sample C)

Fig. 5 (Color online) Attenuation coefficient of reactive powder concrete without and with a volume ratio of (1 and 1.5%) as a function of energy



(a) Mass attenuation coefficient **(b)** Linear attenuation coefficient

tested (dry surface) to evaluate the compressive strength. Each group of the castellated samples contains eight cubes, as presented in Table 10. Three of them were tested to evaluate the compressive strength of reactive powder concrete at an age of 28 days and the other five cubes were tested after being attenuated with a gamma ray.

2.2 Experimental setup

The planning of the experimental program with the electronic configuration is schematically shown in Fig. 1.

The assembly was placed in a lead castle. Two collimators with a diameter of 5 mm were used as shown in Fig. 1. The distance between source and detector was

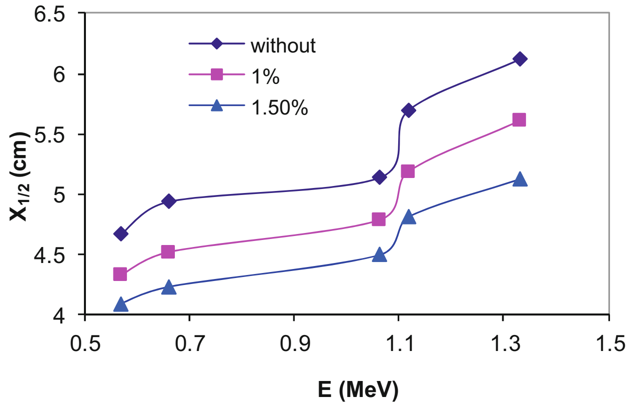


Fig. 6 (Color online) Half-value thickness of reactive powder concrete without and with a volume ratio of (1 and 1.5%) as a function of energy

Table 11 Details of compressive strength for the sample groups

Group sample	No. of sample	Average compressive strength MPa
A	3	70 (no gamma effect)
	5	68.5 (including gamma effect)
B	3	76 (no gamma effect)
	5	74.8 (including gamma effect)
C	3	83 (no gamma effect)
	5	82.3 (including gamma effect)

approximately 35 cm. Energy calibration was performed using a set of standard gamma sources. Measurements have been carried out using a collimated beam of ^{137}Cs, ^{60}Co, and ^{207}Bi gamma sources with energies (0.662, 1.17, 1.33, 0.569, and 1.063) MeV. The leakage gamma ray intensities behind the samples have been captured by using a sodium iodide crystal NaI(TI) scintillation detector with a dimension of 2″ × 2″. The incident and transmitted intensities were determined for a fixed preset time at 1000 s in each measurement.

3 Results and discussion

In order to test the radiation shielding of reactive powder concrete without and with steel fiber, linear attenuation coefficient, mass attenuation coefficient, and half-value thickness are studied. Figure 2 shows the intensity of radiation emitted from ^{137}Cs, ^{60}Co, and ^{207}Bi gamma sources with energies (0.662, 1.17, 1.33, 0.569, and 1.063) MeV, respectively, as a function of d_m (g/cm^2) without micro steel fiber (sample A). The different component of concrete and the percentage of these components have played an important role in attenuation properties.

The addition of micro steel fiber to the reactive powder concrete showed an obvious increase in density.

Figure 3 shows the intensity of radiation with a micro steel fiber volume ratio of 1% (sample B) at different gamma ray energies in MeV (0.569, 0.662, 1.063, 1.17, and 1.33) as a function of d_m (g/cm^2). Also, the results of the sample with a volume ratio of 1.5% (sample C) are shown in Fig. 4. It can be detected that the intensity is inversely proportioned to the thickness of the samples. The slope of the absorption graph gives the experimental gamma ray mass attenuation coefficient (μ_m) of the absorber reactive powder concrete in terms of (cm^2/g). This is shown in Fig. 5a. This figure shows the variation of mass attenuation with the gamma ray energies in MeV for different samples of reactive powder concrete without and with steel fiber. It is shown that the mass attenuation coefficient decrease with increasing gamma ray energies, and the higher values of μ_m were found at sample C with 1.5% steel fiber, while the lowest values were found for sample A without steel fiber. These results give the conclusion that the mass attenuation coefficient increases with increasing the steel fiber percentages by volume (1 and 1.5%).

Figure 5b shows the effect of gamma ray energies in MeV on linear attenuation coefficient (μ) for different samples of reactive powder concrete without and with micro steel fiber. It is shown that the linear attenuation coefficient decreases with increasing the gamma ray energies. At the same time, the linear attenuation coefficient increases with increasing the volume ratio of micro steel fiber. The behavior of the linear attenuation coefficient curve is opposite to that of the $X_{1/2}$ curve, as shown in Fig. 6. This demonstrates that as the percentage of micro steel fiber increased, the properties of the reactive powder concrete attenuations improved and give better shielding for the reactive powder concrete. It is clear from Fig. 6 that larger thickness of materials is needed to stop higher energy photons.

The compressive strength for all the tested samples was compared with those of no gamma effect, and it was found that there is no significant reduction in the compressive strength of the reactive powder concrete samples shown in Table 11.

4 Conclusion

In this work, linear attenuation coefficient, mass attenuation coefficient, and half-value thickness of reactive powder concrete without and with different volume ratios of steel fiber (1 and 1.5%) were investigated. It was detected that the density of the sample can be modified by increasing the steel fiber volume ratio. This inevitably increases the attenuation of gamma radiation hence the half-value thickness of the sample reduces. Depending on these results, reactive powder concrete can be used in radiation shielding since it exhibits a positive photon attenuator at different energies (0.569, 0.662, 1.063, 1.17, and 1.33) MeV. The gamma radiation shielding capabilities can be enhanced by using steel fiber volume ratio of 1.5%. In addition, the compressive strength of the tested samples has no significant changes in its compressive strength after being affected by gamma radiation.

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