RADIATION SHIELDING STRUCTURES: CONCEPTS, BEHAVIOUR AND THE ROLE OF THE HEAVY-WEIGHT CONCRETE AS A SHIELDING MATERIAL - REVIEW



Suha Ismail Ahmed Ali - Éva Lublóy

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The construction of radiation shielding buildings still developed. Application of ionizing radiations became necessary for different reasons, like electricity generation, industry, medical (therapy treatment), agriculture, and scientific research. Different countries all over the world moving toward energy saving, besides growing the demand for using radiation in several aspects. Nuclear power plants, healthcare buildings, industrial buildings, and aerospace are the main neutrons and gamma shielding buildings. Special design and building materials are required to enhance safety and reduce the risk of radiation emission. Radiation shielding, strength, fire resistance, and durability are the most important properties, cost-effective and environmentally friendly are coming next. Heavy-weight concrete (HWC) is used widely in neutron shielding materials due to its cost-effectiveness and worthy physical and mechanical properties. This paper aims to give an overview of nuclear buildings, their application, and behaviour under different radiations. Also to review the heavy-weight concrete and heavy aggregate and their important role in developing the neutrons shielding materials. Conclusions showed there are still some gaps in improving the heavy-weight concrete (HWC) properties.

Keywords: neutron shielding, heavy-weight concrete, heavy aggregates, Gamma rays

1. INTRODUCTION

Radiation is the emission of energy (wave) in space or an object. Radiation can be classified into ionizing radiation and non-ionizing radiation. Non-ionizing radiations are the radio, TV, ultraviolet, infrared, visible light, and power transmission, while ionizing radiation is the X-ray and gamma radiations. The application of ionization radiation is in nuclear power, medical diagnostics, cancer treatment, scientific research, and the aerospace industry. Nevertheless, structure elements of radioactive shielding structures must be shielding against high-energy neutron emission (Outline, 2018).

Application of Gamma/X-ray and neutron sources in nuclear, medical, and industrial sectors still developed. Reports showed there are 449 nuclear reactors in 30 countries and 60 nuclear power plants under construction in 15 countries in addition to more than 10.000 medical therapeutics over the world. Nuclear buildings or nuclear power plants are one of the most complex and dangerous structures. Special construction elements are used for shielding against ionization radiation (Jo, 2019; Kurtis et al., 2017).

Examples of the gamma-emitting radionuclides and their properties of emitted gamma energy and half- lifetime are shown in *Fig. 1*. Radium has the highest energy amount and



Fig. 1: Properties of (Cobalt ⁶⁰Co₂₇, Cesium ₁₃₇Cs⁵⁵, Iridium ₁₉₂Ir⁷⁷, Radium ₂₂₅Ra⁸⁸, and Americium ₂₄₁Am⁹⁵) radionuclides among Based on (Ban et al., 2021) a) Gamma emitted energy and b) Material half-life

a longer half-life. Americium has a lower energy amount and Cesium has a shorter half-life (*Ban et al., 2021*).

1.1 Application of neutron shielding structures with different neutron energy and shielding materials

Application of neutron shielding materials in different sectors are varied with the amount of neutron energy, the weight of the structure, safety, and economic issues. *Fig. 2* illustrates the potential emitted energy in nuclear power plants, nuclear radiotherapy, hospitals, and aerospace. Concrete, metal, and polymers can be used in the construction of the walling elements (Zinkle, Busby, 2009).

In nuclear buildings, the emitted energy neutrons are relatively high that exceeding 2 MeV, so proper shielding is required to ensure the safety of the worker and environment. High density or heavy-weight concrete walls with some additives of moderator and polymers can slow the absorption of the high-energy neutrons. In medical structures, photo energy neutrons range between (25- 10 MeV) are used in the therapy treatment can hazard the patients and staff. Concrete, metalbased, and polymer-based can ensure effective protection for patients and workers (Sukegawa et al., 2014; Walsh, 2013).

Extraordinary shielding materials are required in the aerospace industrial sectors. Cosmic rays in aerospace contain high-energy neutrons and protons (>1 MeV to 1 GeV) and high atomic nuclei, so polymer composites are suitable for their shielding and lightweight properties (Zinkle and Busby, 2009; Sukegawa et al., 2014; Walsh, 2013).

1.2 Neutron penetration system

Neutrons interact with the material in three different phenomena, inelastic scattering, elastic scattering, and neutron absorption. Inelastic scattering occurred when a fast neutron exceeding 10 MeV interact with the nucleus. Elastic scattering occurs when neutrons with energy between 1 and 10 MeV lose their high energy neutrons and then the remained energy is kept inside the structure element. Thermal neutrons are slow energy neutrons thermalized by the nucleus during the absorption process, so no emission will occur (*Fig. 3*).

The concept of the process that neutrons work on exciting the nucleus then the liberation of gamma rays and alpha rays



Figure 3. Neutron penetration system, based on (Abdulrahman et al., 2020; Jaeger et al., 1968)

occurred. One of the traditional mechanisms works on decelerating the fast neutron to decrease the energy inside the medium. Slow neutrons need an absorbing element with a large cross-section. However, absorbed neutrons need alternative equal mass such as hydrogen (Abdulrahman et al., 2020; Jaeger et al., 1968).

Gamma (γ) rays, X- rays, and neutrons radiations

Gamma (γ) rays are high-frequency electromagnetic radiation. It has 100 keV energy amount and less than 10 pm wavelength. Gamma-ray is an indirect ionization source and it affects human cells. Gamma rays are weakened by interactions with electrons, hence concrete with high density can be used as a gamma- shielding material. Shielding against Gammaray can be achieved by using materials with a heavy atomic weight such as heavy-weight aggregates (Lessing, 2019).

Neutron radiation governed by the kinetic energy of the neutrons affects the nuclei of atoms. Neutrons are classified into thermal neutrons (lower than 1 eV), epithermal neutrons (between 1 eV and 0.1 MeV) and fast neutrons (above 0.1 MeV). Neutron shielding concrete is design to slow down fast neutrons and thermalize or capture thermal neutrons. It must be thermalized by the hydrogen atom in water and captured



Figure 2. Neutron shielding buildings according to the amount of energy and shielding materials based on (Zinkle and Busby, 2009; Sukegawa et al., 2014; Walsh, 2013)

by a boron atom (Jo, 2019). Concrete can be used as shielding materials for both gamma and neutron radiations. Protection against Gamma radiation depends on the density of materials while protection against neutrons (neutron energy/ speed) depends on the nuclei of the atom. The basic functions of the radiation shielding concrete are strength, durability, attenuation of gamma and neutron radiations, and thermal insulation (Piotrowski, 2020).

1.4 Radiation attenuation coefficient

The Beer-Lambert law is used in the calculation of the intensity of the radiation transmission. The thickness of the shielding material can be determined with an equation (Piotrowski, 2020):

$$I = I_0 e^{-\mu x}$$

where I_0 is the radiation intensity before and after radiation transmission, μ is the linear attenuation coefficient and x is the shielding thickness of the material. Linear attenuation coefficient proportion directly to the density and the atomic number of the material and inversely to the energy of the neutrons.

The effective atomic number can be calculated using the equation:

$$Z_{eff} \frac{\sigma_i f_i A_i \frac{\mu}{\rho}}{\sigma_i f_i \frac{A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i}$$

where is f_i the ratio of the element number to the total element numbers in the material, A_i is the atomic weight and Z_i is the atomic number of the material.

2. HEAVY-WEIGHT CONCRETE (HWC) AS GAMMA/NEUTRON SHIELD

Concrete is one of the most used building materials all over the world. Examples of concrete structures are residential buildings, dams, bridges, power plants, and other infrastructures. Concrete is a mixture of cement, sand, stone (aggregate), and water. Concrete has high compressive strength and low tensile strength, that's why steel bar is added to develop the tensile strength (Brook, 1989). Heavy-weight concrete can be produced using a heavyweight aggregate. Heavyweight concrete represents cost-effective, strength, attenuation radiation, and fire-resistance construction materials; it's useful for the construction of the nuclear building. Concrete with a high hydrogen atom is effective against neutron radiation, while concrete with a high water ratio is effective against both neutron and gamma radiations (Lessing, 2019).

2.1 Ingredients of concrete

Cement is the binding material in concrete; it represents 15 to 25 % of the total weight of the concrete. Water/ water-cement ratio are important parameters at the fresh and hardened phases of the concrete. Fresh concrete should have good workability and consistency properties, while hardened concrete should have sufficient compressive strength and durability. Aggregate represents the major part of concrete (about 70 –

80%). Fresh concrete must satisfy the workability and consistency properties while hardened concrete must have adequate strength, durability. The water to cement ratio is an important factor in the concrete mix, it could enhance the workability and reduce the performance of concrete. Other materials can be added to concrete to improve its performance; these materials are called admixtures (McArthur, Spalding, 2004).

2.2 Aggregates

Aggregate occupies the major part of concrete, (three to fourth) volume of concrete. The specific gravity of aggregates is the factor that controlling the unit weight of concrete. Some advantages of using aggregate are the economy, volume stability, density, and durability. The specific density of aggregate affects the unit weight and the strength of the concrete, while its absorption influences the durability of the concrete (Popovics, 1992).

Aggregates can be natural or manufactured, heavy or lightweight, crushed or naturally processed, inactive or reactive; and fine or coarse aggregates. The dividing line between fine and coarse aggregates is randomly chosen, but usually 4 mm site sieve (opening of 3/16 in (4.75 mm)) separates the two types.

Heavy-weight aggregates or minerals with a high specific gravity greater than 3.5, such as barite, magnetite, ilmenite, limonite, and goethite are mostly used, others are chromite, hematite, taconite, and galena, are not broadly used *(Table 1)*. Ferrophosphorus and ferrosilicon could be used. Otherwise, steel and iron aggregates are available in the forms of shot, punching, and scrap (Popovics, 1992).

Some of the aggregate with high specific gravity, are magnetite, ilmenite, limonite, ferrophosphorus, or of steel shot, etc. The density of the concrete with mineral aggregates is over (200 Ib/ft³) 3200 kg/m³, while the density of concrete with steel fibre aggregates can reach up to (400 Ib/ft³) 6400 kg/m³. Concrete with heavy-weight aggregate can use as a shielding material, due to the combination of radiation absorption and good mechanical properties (*Table 1*).

Chemically bound water content and the specific gravity of aggregates

Hydrogen occurs in different forms in cementitious composition free water or chemically bounded (constitutive water) and embedded in the chemical structure of some aggregates; such as goethite (FeO (OH)) and limonite (2Fe2O3.3H2O). The content of free and embedded water content can be determined by thermogravimetric testing.

There are three types of specific gravity of aggregates (Leung, 2001): Bulk specific gravity, bulk specific gravity (saturated surface dry), and apparent specific gravity. Bulk specific gravity (saturated surface dry) can be determined using the equation:

$$G_{bssd} = \frac{B}{B - C}$$

where

A = weight of oven-dry aggregate sample in air

B = weight of saturated surface-dry sample in air

C = weight of saturated sample in water.

There are two states of moisture in aggregates; total moisture and surface moisture. Total moisture can be less than adsorp-

 Table 1: Physical properties and radiation absorption factors of heavy-weight aggregates

Heavy-weight aggregate	Composition % by weight		Specific gravity (gm/cm ³)		Concrete den- sity lb/ft ³	Radiation absorption factor cm ³ /g	
	Iron	Fixed water	Coarse	Fine		Fast neutrons	Gamma rays (3 MeV)
Limonite	58	9	3.75	3.80			
Goethite (hydrous iron ore)	55	11	3.45	3.70	180 - 200	0.0372	0.0362
Magnetite (iron mineral)	64	1	4.62	4.68	210 - 260	0.0258	0.0359
Barite (barium sulfate)	1-10	0	4.20	4.24	210 - 230		
	1	0	4.28	4.31		0.0236	0.0363
Ferro-phosphorus (slag)	70	0	6.30	6.28	255 - 330	0.0230	0.0359
Steel aggregate	99	0	7.78	-	290-380	0.0214	0.0359
Steel shot	98	0	-	7.50			

From Davis, ACI Journal, American Concrete Institute (Davis, 1962)

tion capacity in (oven and air dry) aggregates, less than or equal to the absorption capacity in (saturated) aggregates, or greater than absorption capacity in (wet) aggregates. The term saturated in aggregates means (surface saturated), because it considered only the quantity of water absorbed during 24- hr. So only the outside part of the aggregate is saturated (Leung, 2001).

2.3 Admixtures

Admixture can be added to the cement, water, and aggregate mixture to improve the workability, mechanical and shielding properties, and durability of the concrete. Admixtures can be categorized into chemical and mineral admixtures.

Chemical admixtures can be divided into surfactants, and set-controlling admixtures. Surfactants are long-chain organic molecules and they must be added in a small amount (< 1wt. %). Air- entraining agent, water-reducing admixture, and superplasticizer are some of the surfactants. The function of the air-entraining is to add small bubbles, so the defrost resistance can be improved. Water reducing surfactant work on releasing the inside captured water after diffusing charges into the cement and water paste. Superplasticizer is most effective on the water reduction prospect, and applicable on the production of high-strength and high-workability concrete. Set controlling admixtures are used for the purpose of retard or accelerate the hydration reaction on the cement and water mixture. It could be useful in reducing the degradation of concrete.

Minerals admixture are available in nature and can be added in a large amount compared to the chemical admixture about (> 10 wt. %). Some of the minerals admixtures are fly ash, blast furnace slag, and silica fume. Mineral admixtures have cementitious properties. It can be added to replace part of the cement in concrete. Consequently, the thermal behavior, ultimate strength, and durability will be developed in addition to the cost-effective benefit (Leung, 2001).

3. REVIEW AND ANALYSIS OF THE PAST FINDINGS

A review on the (Modern heavyweight concrete shielding: Principles, industrial applications, and future challenges) was handled by (Ban et al., 2021). The study introduced the future challenges and current limitations of research on the HWC as radioactive shielding material and the development of its shielding capabilities. Recent studies showed that there is a direct proportion between the attenuation of gamma and neutrons radiation and the atomic (mass) number of the shielding material. There is some shortage of research on improving heavy-weight concrete by using natural or artificial heavy-weight aggregates or using more than one type of aggregates. No research on the effect of reducing the water/cement ratio on the attenuation coefficient, the lower reported ratio was 0.35. There is a scarcity of research on using the combination of using (nanoparticles, crack control, and elevating Z the atomic number to improve the resistance of the (HWC). No enough prior research on the shielding capabilities of the (HWC) on the elevated temperature up to 800 °C as well as the correlation between the thermal conductivity of the materials with the other shielding properties.

Akkurt et al. (2010) investigated the radiation shielding of the normal, Pumice, and barite aggregates, using the image processing techniques (IPT). The final results were compared to the calculated values using XCOM. Results showed that the linear attenuation coefficients increase with the density of the material. A good correlation was found to the calculated results, so (IPT) can be used as an alternative method for radiation shielding investigations. Aslani et al. analyzed the mechanical properties of the fibre-reinforced heavy-weight selfcompacting concrete. Hooked end steel and polypropylene (PP) fiber (60, 65mm length and 0.75, 0.85 mm Dia.) were added as fibre, while magnetite was used as heavy aggregate (75-100 %). The final results demonstrated the possibility of the production of heavyweight self-compacting concrete (HWSCC) with steel and (PP) fibres. Magnetite aggregates have higher water absorption than the normal aggregates, however, substitute the (NWA) with the (HWA) will reduce the compressive strength due to the crystallized microstructure of (HWA), high water absorption, and segregation. Adding 0.75 steel fibre and 0.25 (PP) will improve the compressive strength.

Aygün et al. (2021) developed new heavyweight (chromium ore) concrete for nuclear shielding radiations, based on the different type of minerals of (chromium ore, hematite (Fe₂O₃), titanium oxide (TiO₂), limonite (FeO (OH) nH₂O), and siderite (FeCO₃) and compounds (galena (PbS), chromium oxide (Cr₂O₃) and manganese oxide (MnO₂). Experiments were used to investigate the mechanical and temperature resistance properties, while GEANT4 were used in the simulation of the mass attenuation coefficient and the effective atomic number . Results showed the developing of the compressive strength up to 30 MPa, and resistance under

	TypeofMethods and TestedaggregatesParameters			Strength (MPa)	Behaviors on elevated		Linear attenuation	
			e	Compressive	Flexural	tempe	ature Density	coefficient (cm ⁻ ¹)/ Mass
Autl			βĄ			np (⁰ C)	kg/m ³	attenuation coefficient
						Ten		(cm²/g)
(Azreen <i>et al.</i> , 2018)	Steel fibre reinforced with different inner materials (silica sand, amang, and lead glass)	Experiments Mechanical properties, and Radiation absorption capabilities	28 days	(165.7, 157.5, and 170.1) at 28 days age	(30.7, 28.8, and 28.3) at 28 days age			Linear ¹³⁷ Cs (0.155, 0.182, 0.175) at 0.662 MeV ⁶⁰ Co (0.096, 0.112, 0.106) at 1.173 and 1.333 MeV
(ftor for the second se	Experiments - Mechanical Properties. - Radiological absorption capabilities	28 days	C (51.8), B (47.8), P (47.3) and S (51.3)	C (7.1), B (6.9), P (6.8) and S (7.3)			Linear C (0.08), B (0.25), P (0.1), and S (0.06) at 59.60 keV	
		180 days	C (63.9), B (59.7), P (58.3) and S (64.4)	C (8.4), B (8.3), P (7.7) and S (8.4)				
(Demir et al., 2011)	Barite (B), colemanite (K), and normal aggregate (N) 13 Mixtures Selected (B100, B85K15, N85K15, and N 100)	Experiments - Radiation transmission - Linear and mass attenuation coefficient				Room Temperature	(3451, 3208, 2157, and 2310)	Linear ¹³⁷ Cs (0.261, 0.248, 0.185, and 0.187) at 0.663 MeV Mass (0.076, 0.077, 0.086 and 0.081) at 0.663 MeV
(Rasoul Abdar Esfahani <i>et</i> al., 2021)	Ground granulated blast furnace slag (GGBFS) and copper slag (CS) with percentages of GGBFS (0– 60%) and CS (0–100%) G30C50 and G60C100	Experiments Mechanical properties and Radiation absorption capabilities	28 days	43.2 and 32.4		Room temperature	2555 and 2845	¹³⁷ Cs (0.296 and 0.333) ⁶⁰ Co (0.141 and 0.156)
								Thermal Conductivity (W.m ⁻¹)
Dolomite (NWA) as reference concrete (REF), Barite aggregate fill BAR), and Electric Arc Furnace (EAF) steel slag	Dolomite (NWA) as reference concrete (REF),	Experiments Behaviour at high temperature (TGA/DSC),		49, 47, and 65 MPa		20 ⁰ C	2401, 2766, and 2805	2.05, 1.34 and 1.51
	Thermal stability, thermal conductivity during heating, and mechanical properties	90 days	35, 40, and 49 MPa		150 °C	2600	1.75, 1.4, and 1.3	
			36, 30, and 40 MPa		0 C	2600	1.3, 1.0, and 0.9	
(F				10, 25, and 39 MPa		450 °C	2500	1.5, 1.25, and 1.1



Figure 4. Values of the linear attenuation coefficient and the compressive strength of the reviewed literature

temperatures are up to the desired level. The study verified that concrete with aggregates and additives are better gamma and neutron shielding than the standard (HWC).

Azreen et al. (2018) tested the mechanical properties and the radiation absorption capabilities of the steel fibre-reinforced as ultra-high-performance concrete (UHPC) and the effect of adding, silica sand, amang, and lead glass. The tested samples showed compressive strength values higher than 155 MPa at 28 days. The compressive strength of the lead glass sample decrease for a long time. Amang is effective against Gamma rays due to its high density, but it has a radiological effect on the surroundings. Silica sand is most practical for nuclear buildings and cost-efficiency (Table 2).

Binici et al. (2014) investigated the mechanical and radioactivity shielding performance of mortars made with colemanite, barite, ground basaltic pumice, and ground blast furnace slag as additives to create special mortars. The final results showed that barite, colemanite, and blast furnace slag wastes are effective in gamma-ray shielding. The linear absorption coefficient decreased with increasing the colemanite percentage in the sample. Samples with blast furnace slag have low radioactive permeability (Table 2).

Demir et al. (2011) measured the radiation transmission of concrete with barite, colemanite, and normal aggregates using the beam transmission method for 0.663 MeV X-rays energy of ¹³⁷Cs radioactive isotope. Results showed the decrement of the linear attenuation coefficients with increasing the energy source. Barite is effective on 0.663 keV, while colemanite is effective for neutrons shielding because it contains boron (Table 2).

Rasoul Abdar Esfahani et al. (2021) which are mostly discarded in landfills. Alternatively, they can be used in concrete production to reduce the consumption of cement and natural aggregates. One of the applications that can benefit from heavy-weight aggregates such as CS, is concrete tailored for radiation shielding purposes. However, there was no prior study on effect of combined use of CS and GGBFS on radiation shielding capability of concrete. This study is aimed to address the effect of GGBFS and CS content on gamma-ray shielding and mechanical performance of high-density concrete. For this purpose, concrete mixes were prepared with different percentages of GGBFS (0-60% investigated the

mechanical and gamma-ray shielding properties and the environmental benefit of using the industrial waste of ground granulated blast furnace slag (GGBFS) and copper slag (CS) as aggregate for production (HWC). The concrete mix was designed with a combination of (GGBFS) and (CS) by a replacement of (0-60%) and (0-100%) respectively. Results verified that (GGBFS) and (CS) are suitable for the radiation shielding of structures. The optimum compressive strength was obtained by 30% (GGBFS) and 50% (CS), while the best radiation shielding capability was obtained with 60% (GG-BFS) and 100% (CS) amount (Table 2).

Beaucour et al. (2020) studied the use of Electric Arc Furnace (EAF) and steel slag as heavyweight aggregates that could be suitable for radiation shielding. Likewise, his study compared the thermal behaviour of EAF to (barite and normal aggregates). Thermal stability of the three different aggregates was found in addition to the thermal conductivity. The final results showed the reduction of EAF strength under high temperatures. EAF slag aggregates have better thermal behaviour than barite aggregates (Table 2).

There is a strong correlation between the different parameters of the compressive strength, attenuation coefficient, density, and thermal conductivity/fire resistance. However, developing these parameters can ensure the best radiation shielding of the structure. Fig. 4 summarizes values of the compressive strength and attenuation coefficient for different testing materials. The steel fibre has a direct effect on improving the mechanical properties and it has less effective in increasing the linear attenuation while adding a replacement amount of mineral additives (mineral aggregates and steel aggregates) more effective on increasing the attenuation coefficient of the concrete.

4. CONCLUSIONS

The application of radiation shielding structures is developed all over the world. X-Rays and Gamma rays are utilized for different purposes in the nuclear, health, agriculture, and aerospace sectors. Proper design of radiation shielding structures is necessary to ensure safety for the people and the surroundings. Concrete, metal, and polymers are the main neutron shielding materials. Concrete with special properties

is a good solution for economic and sustainability purposes.

Previous research illustrated the shortage in the information and the development of heavy-weight concrete to be more applicable as a radiation shielding material. Heavy-weight aggregates and additives are two important key factors, because of their high density and their high atomic number in addition to their role in developing the strength and the linear attenuation coefficient of the concrete. Using heavyweight or natural/ artificial aggregates can decrease the thickness of the wall (cost-effectiveness). There are still gaps in improving the HWC by using natural or artificial heavyweight aggregate through improving the HWC mix design by the absolute volume approach (use more than one type of aggregate or even fiber). The literature reported some scarcity of research on the reduction of water/cement ratio to achieve high-density concrete, as well as the combination of using nano-particle, crack control, and elevating Z (atomic number) value to improve the resistance of the harmful radiation.

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Suha Ismail Ahmed Ali

(Dec 1988), Ph.D. student (BME University, Hungary), MSc in architecture for health-healthcare design- (Sapienza University of Rome, Italy). P.G diploma in business administration (International University of Africa). BSc in civil engineering (University of Juba). Experience as a civil engineer, and lecturer (Sudan). Her main research field is healthcare (Hospitals) design, structure, construction cost estimation, and energy simulation modelling.

Assoc. Prof. Éva Lublóy

Éva Lublóy (1976), Dr.-habil, PhD, Senior lecturer in structural engineering, at the Budapest University of Technology and Economics. Her main fields of interest are: fire design, behaviour of constructions materials at elevated temperature. Member of the Hungarian Group of *fib*. <u>lubloy.eva@</u> <u>epito.bme.hu</u>