HBRC Journal (2015) 11, 328–338

Housing and Building National Research Center
HBRC Journal
http://ees.elsevier.com/hbrcj

Development of high-performance heavy density concrete using different aggregates for gamma-ray shielding

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Received 27 March 2014; revised 29 May 2014; accepted 19 June 2014

KEYWORDS

Heavyweight aggregates;
High-performance concrete;
Linear attenuation coefficient (μ);
Half-value layer (HVL);
Tenth-value layer (TVL)

Abstract The performance requirements of the concrete of containment structures are mainly radiological protection, structural integrity, durability, etc. For this purpose, high-performance heavy density concrete can be used. After extensive trials and errors, 15 concrete mixes were prepared by using coarse aggregates of barite, magnetite, goethite and serpentine with an addition of 10% silica fume (SF), 20% fly ash (FA) and 30% ground granulated blast furnace slag (GGBFS) to the total content of OPC. The compressive strength of hardened concrete was determined after 7, 28 and 90 days. In some concrete mixes, compressive strength was also tested up to 90 days upon replacing sand with the fine portions of magnetite, barite and goethite. The results revealed that, the concrete mixes containing magnetite coarse aggregate with 10% SF reaches the highest compressive strength values exceeding over the M60 requirement by 14% after 28 days. Whereas, the compressive strength of concrete containing barite aggregate was very close to M60 concrete and exceeds for 90 days. The results also indicated that, the compressive strength of the high-performance concrete incorporating magnetite as fine aggregate was significantly higher than that containing sand by 23%. Also, concrete made with magnetite fine aggregate has higher physico-mechanical properties than those containing barite and goethite. High-performance concrete incorporating magnetite as fine aggregate enhances the shielding efficiency against γ-rays.

Introduction

Concrete is by far the most widely used material for reactor shielding due to its cheapness and satisfactory mechanical properties. It is usually a mixture of hydrogen and other light nuclei and has a high atomic number [1]. The aggregate of concrete containing many heavy elements plays an important role in improving concrete shielding properties and therefore has good shielding properties for the attenuation of photons and

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http://dx.doi.org/10.1016/j.hbrcj.2014.06.010

neutrons [2,3]. The density of heavyweight concrete is based on the specific gravity of the aggregate and the properties of the other components of concrete. Concretes with specific gravities higher than 2600 kg/m^3 are called heavyweight concrete and aggregates with specific gravities higher than 3000 kg/m^3 are called heavyweight aggregate according to TS EN 206-1 [4]. The aggregates and other components are based upon the exact application of the high density concrete. Some of the natural minerals used as aggregates in high density concrete are hematite, magnetite, limonite, barite and some of the artificial aggregates include materials like steel punchings and iron shot. Bauxite, hydrous iron ore or serpentine, all slightly heavier than normal weight concrete can be used in case of a high fixed water content. It is essential that heavy weight aggregates are inert with respect to alkalis and free of oil as well as foreign coatings which may have undesired effects on bonding of the paste to the aggregate particles or on cement hydration. Presently, heavyweight concrete is extensively used as a shield in nuclear plants, radio therapy rooms and for transporting as well as storing radioactive wastes. For this purpose, concrete must have high strength and density. Heavyweight and high strength concrete can be used for shielding purposes. Such concrete with magnetite aggregates can have a density in the range of 3.2–4 t/m^3, which is significantly higher than that with normal aggregates [5,6]. Concrete specimens prepared with magnetite, datolite-galena, magnetite-steel, limonite-steel and serpentine were simulated. Researchers [7] used heavyweight aggregates of different minerals (limonite and siderite) in order to prepare different series for the radiation shielding of these concretes. It was reported that, the concretes prepared with heavy weight aggregates of different minerals are useful radiation absorbents. The heart of a nuclear power project is the "Calandria" and it is housed in a reactor concrete building typically with a double containment system, a primary (or inner) containment structure (PCS) and a secondary (or outer) containment structure (SCS). This reactor containment structure is the most significant concrete structure in a nuclear power plant.

The main objective of the current research is to investigate the suitability of some concrete components for producing "high-performance heavy density concrete" by using different types of aggregates that could enhance the shielding efficiency against γ-rays.

Methodology of research

Materials

The starting materials used in this investigation are ordinary Portland cement-OPC-CEM I (42.5 N), complying with ASTM C-150 [8], obtained from Suez Cement Company, Egypt. Some of the mineral admixtures were used, including, ground granulated blast-furnace slag (GGBFS), obtained from Suez Cement Company-Tourah Plant (source: Japan); fly ash-class F (FA), obtained from Geos Company, Cairo, Egypt, (source: India) and silica fume (SF), provided from the ferrosilicon alloy Company, Edfo, Aswan, Egypt. It was planned to search for the relevant aggregates that would be suitable for usage as a concrete component and satisfy the requirements for construction of the nuclear power plants (NPP). Consequently, four types of coarse aggregates were used, namely; magnetite (Fe_3O_4), obtained from Wadi Karim, Eastern Desert, Egypt. Goethite [α-FeO(OH)] and barite ($BaSO_4$), obtained from El-Bahariya Oasis, Western Desert, Egypt while, serpentine [$(Mg, Fe)_3Si_2O_5(OH)_4$], from Al-Sdmin area, Eastern Desert, Egypt. Fine aggregate was local sand, washed to remove the deleterious materials and the chloride contamination. The chemical composition of the starting materials was conducted by using XRF Spectrometer PW1400 as shown in Table 1. Coarse aggregates were separated by manual sieving into various fractions of size 5–20 mm according to ESS 1109 [9] and ASTM C637 [10]. The nominal maximum size of coarse aggregates was 20 mm. Effective dispersion has been achieved by adding a superplasticizer admixture (SP-Type G) to the concrete mixes, compatible with ASTM C494 [11]. In some concrete mixes, sand has been replaced by the fine fractions for coarse aggregates of size < 5 mm to produce heavy density concrete according to TS EN 206-1 [4]. The physico-mechanical properties of coarse aggregates and their fine fractions given in Table 2 were evaluated according to the limits specified by [9,10] and ECPRC 203 [12]. The results showed that, barite coarse aggregate had a higher specific gravity than magnetite, goethite and serpentine. Furthermore, water absorption of goethite aggregate was several times higher than that of barite, magnetite and serpentine by 13%, 10%, and 6%, respectively. This may be due to, the microcracks and fissures generated in aggregate; in addition to vesicular surface that forced the introduction of more water into aggregate to compensate its absorption.

Mix proportions

To investigate the effect of heavyweight aggregate on the physico-mechanical properties of concrete, high-performance heavyweight concrete mixes using the coarse aggregates of magnetite (M), barite (B), goethite (G) and serpentine (S) were designed. Heavyweight concrete mixes can be proportioned using the American Concrete Institute method (ACI) of absolute volumes developed for normal concrete [13]. The absolute volume is generally accepted and considered to be more convenient for heavyweight concrete [14]. Hence, the absolute volume method to obtain dense concrete was used in the calculation of the concrete mixtures. Mix proportions of aggregates per 1 m^3 of the concrete are listed in Table 3. Four series of high-performance concrete mixes with compressive strength in excess of 60 MPa (grade-M60) were prepared by using 10% SF, 20% FA and 30% GGBFS as a partial addition to OPC to study the effect of a supplementary cementing material on the properties of concrete containing heavyweight aggregate. The optimum ratios of supplementary materials were selected on the basis of an earlier research work conducted [15]. The cement content (450 kg/m^3) and sand-to-total aggregate ratio (40%) were adjusted for all concrete mixtures. Coarse aggregates were used in a saturated surface dry condition to avoid the effect of water absorption during mixing to assess the real effect of coarse aggregate on concrete properties. All concrete mixes had constant water to cementitious ratio of 0.35 and a superplasticizer (SP) was used to maintain a constant slump of 10 ± 2 cm.

Table 1 Chemical composition of the starting materials (wt.,%).

Oxides	OPC	SF	FA	GGBFS	Coarse aggregates				Sand
					Magnetite	Barite	Goethite	Serpentine	
SiO_2	21.26	97.14	61.13	24.54	51.56	0.83	1.08	39.51	94.84
Al_2O_3	4.49	0.01	27.68	7.46	0.98	0.96	0.33	0.35	2.12
Fe_2O_3	3.49	1.09	4.15	3.42	43.82	2.54	85.04	5.62	0.82
CaO	63.81	0.02	1.32	55.59	1.24	0.39	0.40	2.04	0.52
MgO	2.02	0.01	0.44	3.36	0.52	–	0.29	35.83	0.1
SO_3^{--}	3.11	0.01	0.28	2.45	0.16	27.95	0.64	0.09	0.11
Cl^-	0.03	–	0.07	0.04	0.08	0.08	0.28	0.06	0.06
Na_2O	0.14	0.20	0.15	0.41	0.13	0.59	0.29	0.01	0.27
K_2O	0.09	0.07	0.85	0.24	0.03	–	–	0.02	0.69
TiO_2	–	–	2.07	0.52	0.08	–	0.06	0.03	0.12
BaO	–	–	0.04	0.08	–	65.65	–	–	–
P_2O_5	–	–	0.61	0.04	0.79	0.06	4.71	0.02	0.04
L.O.I.	1.57	1.36	0.91	1.32	0.24	0.46	6.52	15.59	0.22
Total	99.98	99.91	99.85	99.99	99.74	99.51	99.86	99.54	99.91

Table 2 Physical and mechanical properties of coarse aggregates and its fine portions.

Property	Coarse aggregate and its fine fractions								Sand	Limits for coarse aggregate
	Magnetite		Barite		Goethite		Serpentine			
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine		
Specific gravity, (g/cm^3)	3.48	2.86	4.04	4.00	2.88	2.86	2.79	2.5	2.65	_
Volumetric weight, (t/m^3)	3.03	2.33	2.39	2.94	1.50	2.05	1.99	1.64	1.7	_
Absorption, (%)	0.83	–	0.6	–	8.07	19.4	1.3	–	–	⩽2.5*
Clay and fine materials, (%)	0.1	7.6	0.30	7.6	0.34	–	0.14	13	1.3	⩽4* ⩽10***
Elongation index, (%)	34	–	14.8	–	21.11	–	31	–	–	⩽25**
Flakiness index, (%)	30.3	–	37.1	–	20.05	–	44.5	–	–	⩽25**
Crushing value, (%)	19.87	–	63.3	–	34.3	–	23.8	–	–	⩽30**
Abrasion resistance, (%)	28.1	–	99.20	–	51.1	–	40.1	–	–	⩽30* ⩽50***

* According to ESS 1109 [9].
** According to ECPRC 203 [12].
*** According to ASTM C637 [10].

Table 3 Mix proportions of heavyweight concrete per 1 m^3.

Mixes	Concrete ingredients, kg/m^3										SP
	OPC	Fine aggregates		Coarse aggregates				Pozzolanic materials			
		Sand	Fine portions	M	B	G	S	SF	GGBFS	FA	
M1	450	909	–	1126	–	–	–	45	–	–	9.7
M2	450	905	–	1106	–	–	–	–	–	90	9.7
M3	450	874	–	1068	–	–	–	–	135	–	9.7
M4	450	–	1036	1235	–	–	–	45	–	–	11.2
B1	450	778	–	–	1457	–	–	45	–	–	9.5
B2	450	778	–	–	1457	–	–	–	–	90	10.8
B3	450	778	–	–	1457	–	–	–	135	–	11.3
B4	450	–	1246	–	1457	–	–	45	–	–	10.8
G1	450	700	–	–	–	855	–	45	–	–	10.4
G2	450	682	–	–	–	832	–	–	–	90	10.4
G3	450	673	–	–	–	823	–	–	135	–	10.4
G4	450	–	933	–	–	1072	–	45	–	–	10.4
S1	450	909	–	–	–	–	1126	45	–	–	9.7
S2	450	905	–	–	–	–	1106	–	–	90	9.7
S3	450	874	–	–	–	–	1068	–	135	–	9.7

Mixing, curing and testing specimens

The mixing of heavyweight concrete is similar to that for conventional concrete. The materials were placed in the mixer with a capacity of 56 dm^3 in the following sequence: for each mix; coarse aggregates and fine aggregates, followed by cement blended with mineral cementing materials then initially dry mixed for 2 min. Approximately, 80% of the mixing water was added and mixed for 1.5 min; the rest of the mixing water was added to the running mixer in a gradual manner. All batches were mixed for a total time of 5 min. However, because of the high density of aggregates, potential segregation is a danger. In order to prevent fresh concrete from segregation, the mixing duration was kept as low as possible. After the mixing procedure was completed, slump tests were conducted on the fresh concrete to determine the workability according to ASTM C143 [16]. All the concrete specimens were cast in three layers into 100 × 100 × 100 mm cubic steel molds; each layer consolidated using a vibrating table. Following casting, concrete specimens were covered with a plastic membrane to avoid water evaporation and thereafter kept in a humidity chamber for 24 h. After demoulding, concrete specimens were cured under water until the time of testing. Thus, curing of specimens was performed according to ASTM C511 [17].

Compressive strength

This test was determined at the curing ages of 7, 28 and 90 days according to the European Standard EN 2390-3 [18]. The test was carried out using a 2000 kN compression testing machine and a loading rate of 0.6 MPa/s. A set of three cubic specimens representing the curing time for each mix was used for the compressive strength determination.

Density of concrete

The density of fresh and hardened concrete was performed according to ECCCS – part VII [19].

Radiation attenuation test

The attenuation measurements of gamma rays were performed using sodium iodide NaI (Tl) scintillation detector with a Multi Channel Analyzer (MCA). The arrangements of experimental set up used in the test are shown in Fig. 1. The utilized radiation sources comprised Cs^{137} and Co^{60} radioactive elements with photon energies of 0.662 MeV for Cs^{137} and two energy levels of 1.173 and 1.333 MeV for Co^{60} as standard sources with activities in micro curie (5 mCi) for γ-rays. After 28 days of water curing, specimens were dried at 105 °C prior to the test as recommended [20]. Test samples with different thicknesses of 20–100 mm were arranged in front of a collimated beam emerged from gamma ray sources. The measurements were conducted for 20 min counting time for each sample. The attenuation coefficient of gamma rays was determined by measuring the fractional radiation intensity N_x passing through the thickness x as compared to the source intensity N_o. The linear attenuation coefficient (μ) has been obtained from the solution of the exponential Beer–Lambert's law [21]:

$$N_x = N_o e^{-\mu x}\ \text{cm}^{-1}$$

Half-value layer (HVL) and tenth-value layer (TVL) are the thicknesses of an absorber that will reduce the gamma-radiation to half and to tenth of its intensity, respectively. Those are obtained by using the following equations [22]:

$$X_{1/2} = \ln 2/\mu$$
$$X_{1/10} = \ln 10/\mu$$

The mean free path (MFP) is defined as the average distance between two successive interactions of photons and it is given as:

$$\text{MFP} = 1/\mu$$

Results and discussion

Physico-mechanical properties of concrete

Workability of fresh concrete

The mixability, placeability, mobility, compactability and finishability are collectively known as workability. Slump test is the easiest test that can be used for the measurement of workability. The slump of almost all mixes was in the range of 100–120 mm. Table 4 depicts the slump values of fresh concrete with magnetite, barite, goethite and serpentine. Evidently, the concrete mixes made of barite aggregate (B1, B2 and B3) give the highest slump values; whereas the concrete mixes containing serpentine aggregate (S1, S2 and S3) give the lowest values. The differences in slump values are mainly due to the differences in the rate of water absorption for the aggregates. These values are 0.6%, 0.83%, 1.3% and 8.07% for barite, magnetite, serpentine and goethite, respectively (Table 2). The results showed also that, the slump values decrease by 18%, 33% and 20% upon replacing sand by the fine portions of barite, magnetite and goethite, respectively. This tendency can be attributed to the fact that, the difference in the rate of water absorption between sand and fine aggregate, where

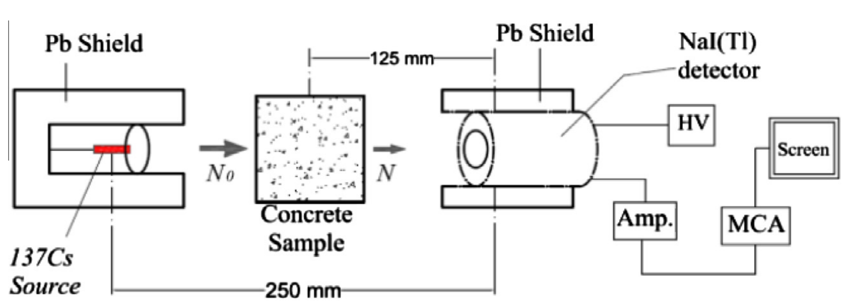

Fig. 1 Experimental setup for gamma radioactive test.

Table 4 Slump values of concrete mixtures.

Mixes	Slump values, (mm)
M1	12
M2	9
M3	10
M4	8
B1	12
B2	12
B3	12
B4	9
G1	10
G2	10
G3	10
G4	8
S1	8
S2	12
S3	8

the latter absorbs more water than sand; also, could be due to the rough surface of aggregates requiring finer material to overcome the frictional forces [23].

Density of concrete

The density of fresh and hardened concrete made of magnetite, barite, goethite and serpentine is summarized in Table 5 and graphically represented in Fig. 2. To call the concrete as a high density concrete, it must have unit weight more than 2600 kg/m^3 as stated in TS EN 206-1 [4]. In general, the density of concrete is directly proportional to the specific gravity of coarse aggregates (Table 2); therefore, concrete specimens made of barite coarse aggregate with 10% SF (B1), 20% FA (B2) and 30% GGBFS (B3) as additives to OPC exhibited the highest values of density of fresh or hardened concrete. Whereas, the density of hardened concrete specimens made of magnetite aggregates with 10% SF (M1), 20% FA (M2) and 30% GGBFS (M3) was slightly higher than that of normal concrete by about 1.5%, 0.38% and 2.7%, respectively. It is evident also from Fig. 2 that, the concrete mixes made from the coarse aggregates of goethite and containing 10% SF (G1) and 20% FA (G2) meet the requirements of dense concrete exceeding by about 2% and 1%, respectively; while, the density of concrete was declined by about 2% for the concrete matrix containing 30% GGBFS (G3) as a pozzolanic material. On the other hand, the density values were significantly decreased for all serpentine concrete mixes including 10% SF (S1), 20% FA (S2) and 30% GGBFS (S3) approximately 3%, 6% and 6.5%, respectively. The results revealed also that, the density of concrete increased by about 7%, 14% and 20.6% upon replacing sand with the fine portions of goethite, magnetite and barite with 10% SF (G4, M4 and B4), respectively.

Table 5 Density of fresh and hardened concrete.

Mixes	Density, (ton/m^3)	
	Fresh concrete	Hardened concrete
M1	2.68	2.64
M2	2.69	2.61
M3	2.77	2.67
M4	3.08	3.02
B1	2.92	2.91
B2	2.96	2.95
B3	2.87	2.86
B4	3.54	3.51
G1	2.7	2.65
G2	2.68	2.63
G3	2.59	2.55
G4	2.99	2.84
S1	2.59	2.52
S2	2.48	2.45
S3	2.45	2.43

Compressive strength

The strength development in high-performance concrete systems depends mainly on the pozzolanic activity of mineral admixtures; in addition to the physico-mechanical properties of the aggregates. The compressive strength of concrete mixes made with barite, magnetite, goethite and serpentine coarse aggregates and containing 10% SF, 20% FA and 30% GGBS as additives to OPC cured in water for 7, 28 and 90 days is graphically plotted in Fig. 3. It is found that, the compressive strength increases with curing time for all hardened concretes; this is attributed to the increase of hydration products (especially tobermorite gel) leading to an increase of compressive strength. The results indicated that, the compressive strengths of concrete mixes M1, M2 and M3 (containing magnetite aggregate) are significantly higher than those containing barite, goethite and serpentine at the age of 7 days. Fig. 3 also shows that, the concrete mixes M1 and B1 (incorporating 10% SF) meet the requirements of compressive strength for concrete – grade M60 (i.e. $\geqslant$600 kg/cm^2) after 28 days compared to those of concrete mixes containing 20% FA (M2, B2), and 30% GGBS (M3, B3) whereas, the magnetite concrete reaches the highest compressive strength values exceeding over the M60 requirement by 14%. While, the compressive strength of barite concrete was very close to M60 concrete and increases up to 90 days. This increase of the compressive strength is attributed to the fact that, silica fume with its high surface area and high silica content provides a filler effect and a pozzolanic reaction, thus resulting in a pore refinement by consuming the weaker calcium hydroxide binder with the formation of a stronger binder of calcium silicate hydrate, that results in additional strength improvement compared to FA and GGBS; besides higher physico-mechanical properties of magnetite aggregate than the other mixes; particularly, water absorption (0.83%), crushability value (19.87%) and abrasion resistance (28.1%). On the contrary, the concrete mixes made with goethite and serpentine coarse aggregates with 10% SF, 20% FA and 30% GGBS did not satisfy the requirements of high-performance concrete (grade-M60), whereas the compressive strength could not reach 600 kg/cm^2 even after 90 days. This reduction in the compressive strength is probably due to, the high water absorption content consumed by goethite and serpentine coarse aggregates; these are 8.07% and 1.3%, respectively. This high water content may cause internal bleeding under the aggregate surface leading to the formation of voids in the vicinity of aggregates and thus porous interfacial transition zone (ITZ) will be formed, which generates a weak bond between coarse aggregate and mortar matrix.

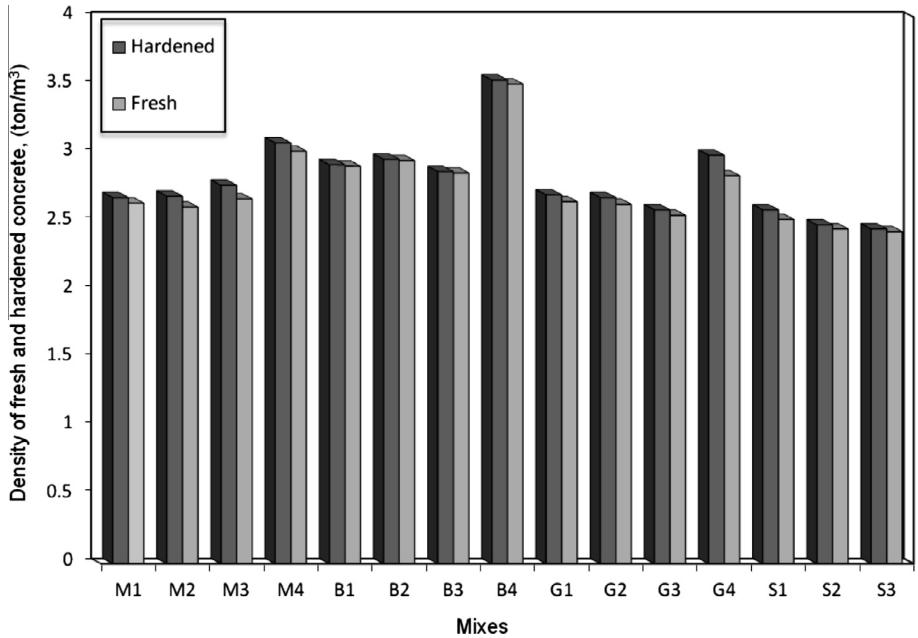

Fig. 2 Density of fresh and hardened concrete.

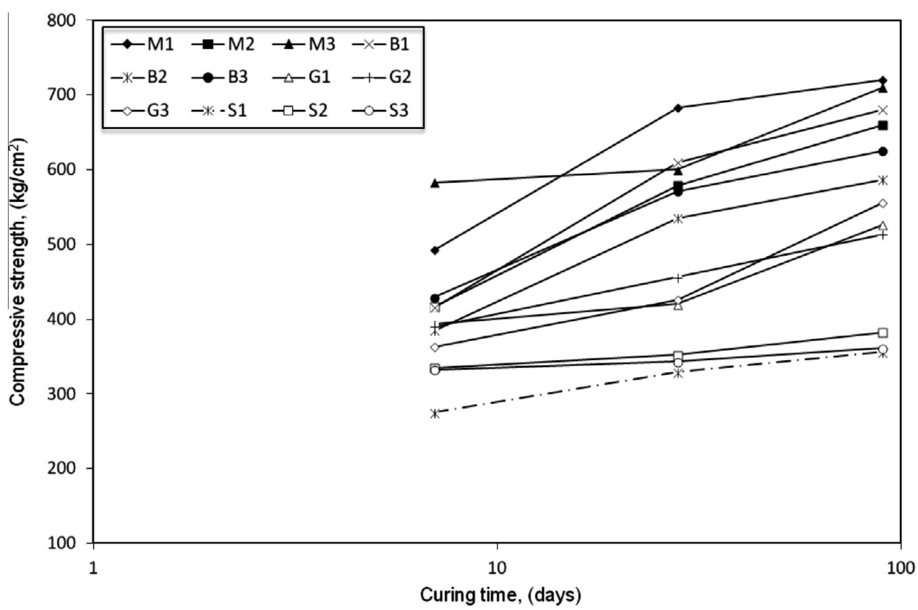

Fig. 3 Compressive strength of concrete made with barite, magnetite, goethite and serpentine coarse aggregates cured in tap water at 7, 28 and 90 days.

From the perspective of compressive strength, heavy density concrete mixes M1 and B1 (containing magnetite and barite coarse aggregates) with addition of 10% SF to OPC meet the requirements of HPC-M60 after 28 days of curing.

Substitution of sand by the aggregate's fine portions

Fig. 4 demonstrates the compressive strength of concrete mixes made with barite and magnetite coarse aggregate with 10% SF upon replacing sand by the fine portions of coarse aggregate (size < 5 mm), cured in tap water for 7, 28 and 90 days. It is clear that, the compressive strength increases with curing time for all hardened concrete mixes. As the hydration proceeds, more hydration products are formed. This leads to an increase in the compressive strength of concrete. Also, the hydration products possess a large specific volume than the unhydrated cement phases; therefore, the accumulation of the hydrated products will fill a part of the originally filled spaces, leads to decrease in the total porosity and increase in the compressive strength [24]. The results indicated also that, the compressive strength of the concrete mix B4 (incorporating barite fine aggregate) is lower than

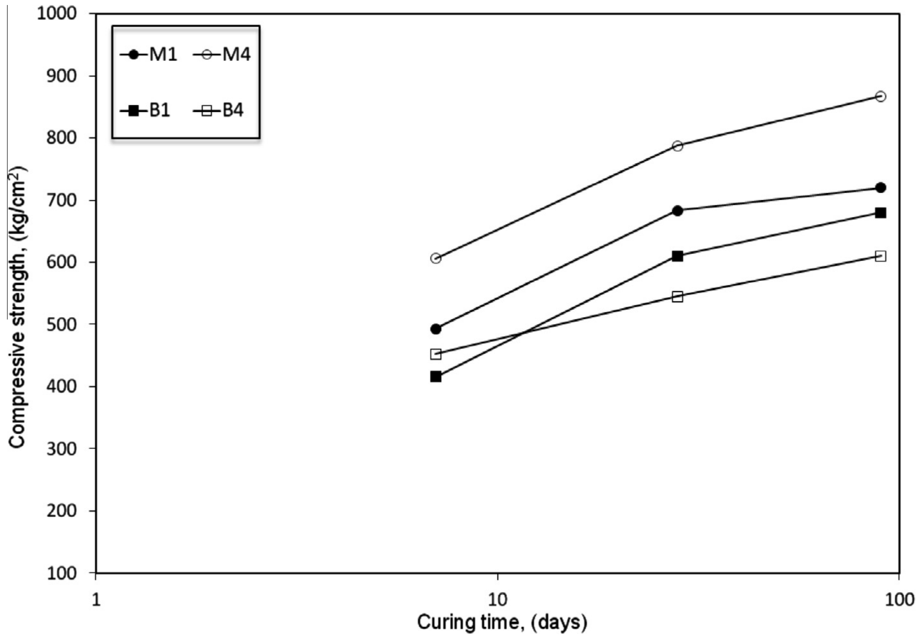

Fig. 4 Compressive strength of concrete made with magnetite and barite upon replacing sand with the fine portions of coarse aggregate cured in tap water at 7, 28 and 90 days.

Table 6 Relationship between the attenuation coefficients (μ), the half-value layer (HVL) and the tenth-value layer (TVL) of concrete mixes made with the coarse aggregates of magnetite.

Mix notation	γ-Sources	Thickness, mm	μ, cm^{-1}	HVL (cm)	TVL (cm)	MFP (cm)
M1	Cs^{137}	20	0.04	17.32	57.50	25
		40	0.0783	8.85	29.37	12.77
		60	0.1205	5.75	19.08	8.29
		80	0.1607	4.31	14.31	6.22
		100	0.2009	3.44	11.44	4.97
M1	Co^{60}	20	0.039	17.77	59.02	25.64
		40	0.0762	9.09	30.21	13.12
		60	0.1172	5.91	19.64	8.53
		80	0.1561	4.44	14.75	6.41
		100	0.1954	3.55	11.78	5.12
M4	Cs^{137}	20	0.041	16.90	56.15	24.39
		40	0.0791	8.76	29.10	12.64
		60	0.123	5.63	18.72	8.13
		80	0.164	4.22	14.04	6.10
		100	0.205	3.38	11.23	4.88
M4	Co^{60}	20	0.0395	17.54	58.28	25.31
		40	0.0793	8.74	29.03	12.61
		60	0.1184	5.85	19.44	8.44
		80	0.1582	4.38	14.55	6.32
		100	0.1975	3.51	11.65	5.06

that containing sand by about 10.7% and 10.3% at curing ages of 7 and 28 days, respectively. The interfacial zone is generally weaker than either of the two main components of concrete. Thus, it has a significant effect on the performance of concrete. This is due to the fact that, the decrease of compressive strength of concrete containing fine aggregate of barite may be related to the vulnerable nature of barite either coarse or fine; particularly, crushing value and abrasion resistance (Table 2). Also, this tendency is probably due to the formation of a weak ITZ between coarse aggregate and mortar matrix. On the contrary, the compressive strength of concrete containing fine aggregate of magnetite M4 was significantly higher than that containing sand by 23%, 15% and 20% at 7, 28 and 90 days, respectively. Angular particles of magnetite aggregate either coarse or fine increase the compressive strength, since they have larger surface area, and, therefore, greater adhesive forces develop between aggregate particles and the cement matrix.

Gamma-ray radiation shielding

The linear attenuation coefficient (μ), half-value layer (HVL) and tenth-value layer (TVL) of concrete mixes prepared with magnetite coarse aggregate were measured at a photon energy of 0.662 MeV for Cs^{137} and two photon energies of 1.173 and 1.333 MeV for Co^{60}. The results are summarized in Table 6. The variation of linear attenuation coefficients as a function of different shield thickness for concrete mixes (M1 and M4) in the field of gamma-ray emitted by Cs^{137} and Co^{60} sources is graphically plotted in Figs. 5 and 6. It was found that, the linear attenuation coefficients for both Cs^{137} and Co^{60} increase with shield concrete thickness. The linear attenuation coefficients of concrete made with magnetite fine aggregate (M4) are higher than those with sand (M1) at photon energy of 0.662 MeV (Fig. 5). Also, linear attenuation

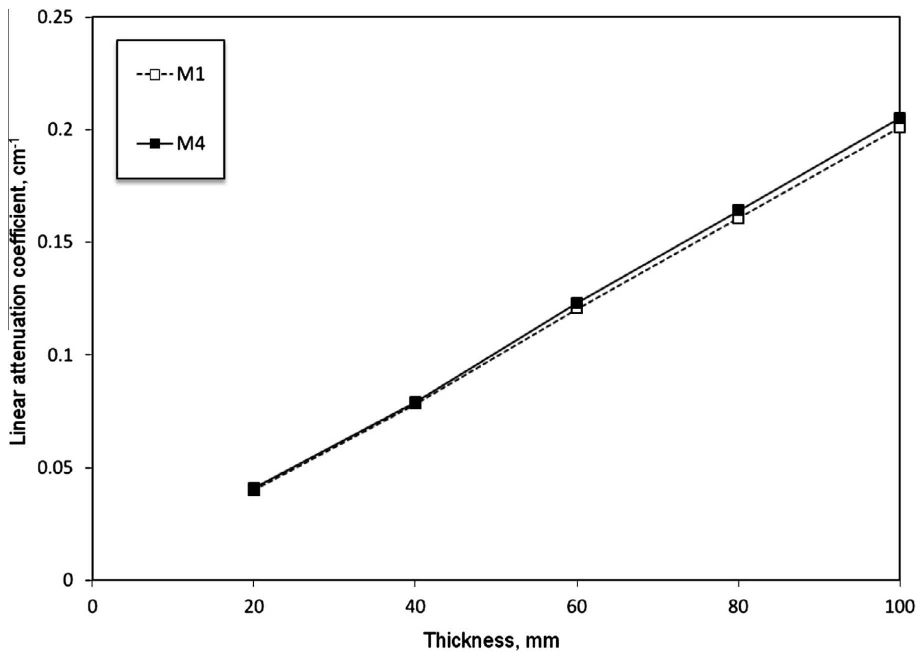

Fig. 5 Variation of linear attenuation coefficients with shield concrete thickness made with magnetite aggregate for Cs^{137} with photon energy of 0.662 MeV.

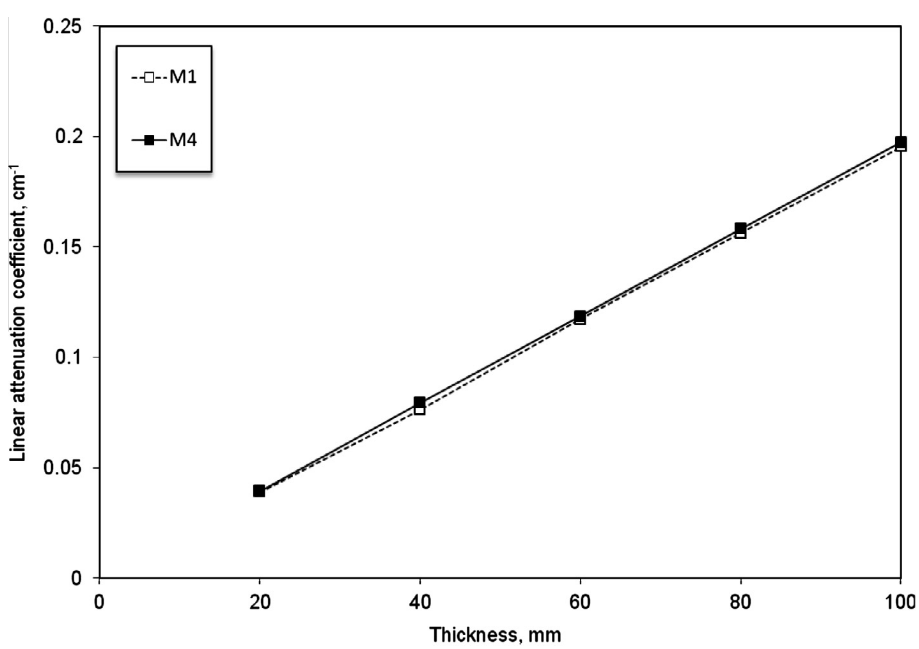

Fig. 6 Variation of linear attenuation coefficients with shield concrete thickness made with magnetite aggregate for Co^{60} with photon energies of 1.173 and 1.333 MeV.

coefficients for the two concrete mixes decrease with the gamma ray energy. Therefore, at two photon energies of 1.173 and 1.333 MeV, the attenuation values of concrete containing fine magnetite are greater than those containing sand (Fig. 6). With regard to gamma-ray shielding, fine magnetite in sample M4 (ρ = 3.02 ton/m^3) increases the density of concrete by 14% compared to M1 (ρ = 2.64 ton/m^3) containing sand. It is clearly seen that, the linear attenuation coefficients depend on the photon energy and the density of the shielding material; accordingly, the concrete samples containing fine

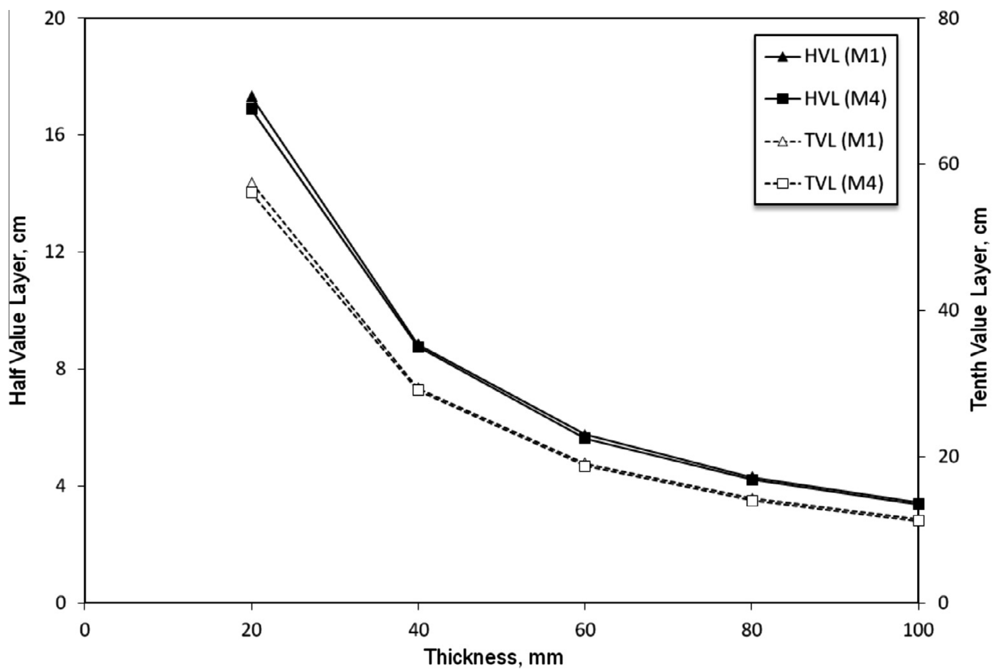

Fig. 7 Half-value layer (HVL) and tenth-value layer (TVL) as a function of concrete thickness for magnetite concrete using Cs^{137} source at photon energy of 0.662 MeV.

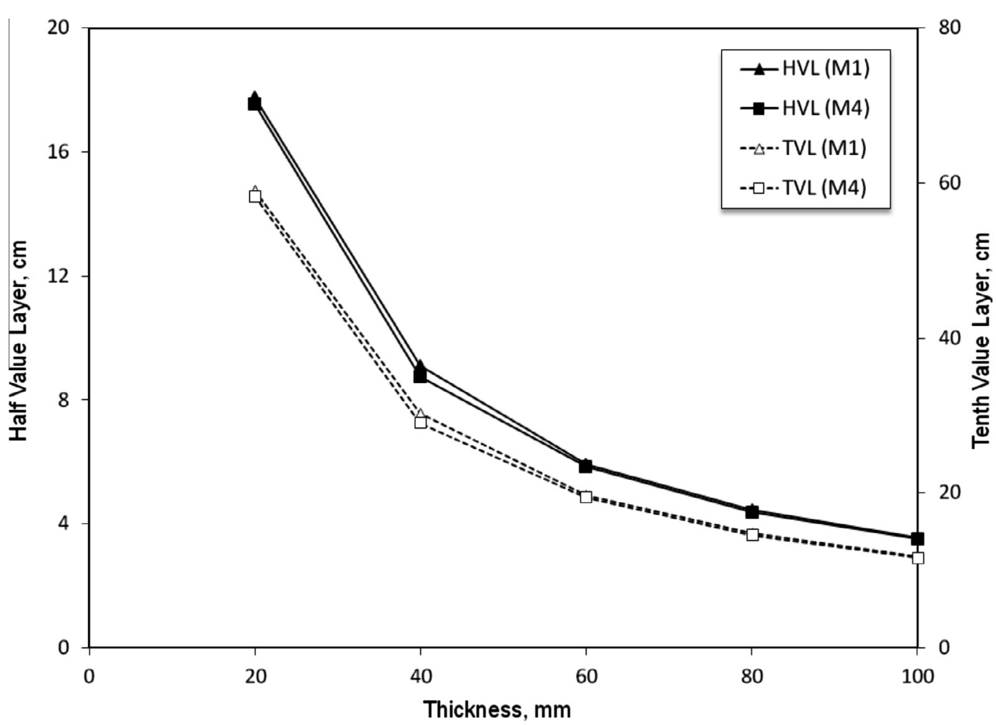

Fig. 8 Half-value layer (HVL) and tenth-value layer (TVL) as a function of concrete thickness for magnetite concrete using Co^{60} source at photon energies of 1.173 and 1.333 MeV.

magnetite (M4) are remarkably effective for shielding of gamma rays.

The effectiveness of gamma-ray shielding is described in terms of the HVL or the TVL of a material. The HVL is the thickness at which an absorber will reduce the radiation to half, and the TVL is the thickness at which an absorber will reduce the radiation to one tenth of its original intensity [25].

Figs. 7 and 8 show the HVL and TVL values of concrete mixes M1 and M4 (incorporating magnetite aggregate) for different gamma energies emitted by Cs^{137} and Co^{60} sources as a function of concrete thickness. It is shown that, the HVL and TVL values of mixes (M1 and M4) decrease with the concrete thickness for Cs^{137} and Co^{60}, respectively. The lower the values of HVL and TVL, the better are the radiation shielding materials in terms of the thickness requirements. At a photon energy of 0.662 MeV for Cs^{137} source, the values of HVL and TVL for mix M4 (incorporating magnetite fine aggregate) are lower as compared to the mix M1 (incorporating sand) at the same energy (Fig. 7). The results indicated also that, the values of HVL and TVL are inversely proportional to the concrete density; therefore, sample M4 (ρ = 3.02 ton/m^3) showed lower HVL and TVL values than sample M1 (ρ = 2.64 ton/m^3) for different gamma energies. At photon energies of 1.173 and 1.333 MeV for Co^{60} (Fig. 8), the results are in a good agreement with those obtained for Cs^{137} (Fig. 7); where the HVL and TVL of sample (M4) decrease with the density of concrete. Therefore, sample (M4) could be considered the best for gamma radiation shielding.

Conclusions

From the previous findings, the following conclusions can be summarized:

1. Barite aggregate had a higher specific gravity than magnetite, goethite and serpentine aggregates. Furthermore, water absorption of goethite aggregate was several times higher than that of barite, magnetite and serpentine aggregates by 13%, 10% and 6%, respectively.
2. High-performance heavy density concrete made with magnetite coarse aggregate with 10% SF reaches the highest compressive strength exceeding over the M60 requirement by 14% after 28 days. Whereas, the compressive strength of concrete containing barite aggregate was very close to M60 and increases up to 90 days. On the contrary, the concrete with goethite and serpentine coarse aggregates with 10% SF, 20% FA and 30% GGBS did not satisfy the requirements of high-performance concrete (grade-M60), since the compressive strength could not reach 600 kg/cm^2 even after 90 days.
3. Concrete made with magnetite fine aggregate showed higher physico-mechanical properties than that containing barite and goethite.
4. High-performance heavy density concrete made with the fine portions of magnetite aggregate enhances the shielding efficiency against γ-rays for Cs^{137} at a photon energy of 0.662 MeV and for Co^{60} at photon energies of 1.173 and 1.333 MeV.

Conflict of interest

None declared.

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