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

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Abstract. This study aimed to investigate the suitability of some concrete components for producing "high- performance heavy density concrete" using different types of aggregates that could enhances the shielding efficiency against γ- rays. 15 mixes were prepared using barite, magnetite, goethite and serpentine aggregates along with 10% silica fume, 20% fly ash and 30% blast furnace slag to total OPC content for each mix. The mixes were subjected to compressive strength at 7, 28 and 90 days. In some mixes, compressive strengths were also tested up to 90 days upon replacing sand with the fine portions of magnetite, barite and goethite. The mixes containing magnetite along with 10% SF reaches the highest compressive strength exceeding over M60 requirement by 14% after 28 days. Whereas, the compressive strength of concrete containing barite was very close to M60 and exceeds upon continuing for 90 days. Also, the compressive strength of high-performance concrete incorporating magnetite fine aggregate was significantly higher than that containing sand by 23%. On the other hand, concrete made with magnetite fine aggregate had higher physico-mechanical properties than that containing barite and goethite. High-performance concrete incorporating magnetite fine aggregate enhances the shielding efficiency against γ -rays.

Keywords: heavyweight aggregates; high- performance concrete; linear attenuation coefficient (μ); half-value layer (HVL); tenth- value layer (TVL)

1. 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 nuclei of fairly high atomic number Ikraiam *et al*. (2009). The aggregate component of concrete that contains a mixture of many heavy elements plays an important role in improving concrete shielding properties and therefore has good shielding properties for the attenuation of photons and neutrons El-Sayed (2002) and Akkurt *et al*. (2012). 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 (2002).

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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. Minerals like bauxite, hydrous iron ore or serpentine, all slightly heavier than normal weight concrete can be used in case high fixed water content is required. It is essential that heavyweight aggregates are inert with respect to alkalis and free of oil, and 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 and radio therapy rooms and for transporting and storing radioactive wastes. For this purpose, concrete must have high strength and high density. Heavyweight and high strength concrete can be used for shielding purposes if it meets the strength and radiation shielding properties. Such concrete that normally utilizes magnetite aggregates can have a density in the range 3.2 - 4 t/m^3, which is significantly higher than the density of concretes made with normal aggregates Gencel *et al*. (2011) and Gencel *et al*. (2012). Concrete specimens prepared with magnetite, datolite-galena, magnetite-steel, limonite-steel and serpentine were simulated. Başyiğit *et al*. (2011) used heavyweight aggregates of different mineral origin (limonite and siderite) in order to prepare different series of concrete mixtures and investigated the radiation shielding of these concrete specimens. They reported that, the concrete prepared with heavyweight aggregates of different mineral origin 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 enhances the shielding efficiency against γ- rays.

2. Methodology of research

2.1Materials

The starting materials used in this investigation for preparation of the concrete mixes are ordinary Portland cement- OPC- CEM I (42.5 N) complying with (ASTM C-150 2009), obtained from Suez Cement Company, Egypt. Some of the mineral admixtures were used as supplementary cementitious materials; 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. As each country has to make use of its own available raw materials, we had to search for the relevant aggregates that would be suitable for usage as a concrete component and satisfy the needed requirements for the 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 [$(Mg, Fe)_3Si_2O_5(OH)_4$], obtained from El-Sdmin district, Eastern Desert, Egypt.

Fine aggregate was local sand, washed at the site 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 (Egyptian Standard Specification No. 1109 2002) and (ASTM C637 2009). 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 2011). 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 2002). The physical and mechanical properties of coarse aggregates (C), and their fine fractions (F) given in Table 2 were evaluated according to the limits specified by (Egyptian Standard Specification No. 1109 2002), (ASTM C637 2009) and (Egyptian Code of Practice for Reinforced Concrete No. 203 2007). The results showed that, barite coarse aggregate had 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 is 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.

Table1Chemical 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 of coarse aggregates
	Magnetite						Serpentine			
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	-	-	$\le 2.5^a$
Clay and fine materials, (%)	0.1	7.6	0.30	7.6	0.34	-	0.14	13	1.3	$\le 4^a$ $\le 10^c$
Elongation index, (%)	34	-	14.8	-	21.11	-	31	-	-	$\le 25^b$
Flakiness index, (%)	30.3	-	37.1	-	20.05	-	44.5	-	-	$\le 25^b$
Crushing value, (%)	19.87	-	63.3	-	34.3	-	23.8	-	-	$\le 30^b$
Abrasion resistance, (%)	28.1	-	99.20	-	51.1	-	40.1	-	-	$\le 30^a$ $\le 50^c$

[a]According to (Egyptian Standard Specification No. 1109 2002).
[b]According to (Egyptian Code of Practice for Reinforced Concrete No. 203 2007).
[c]According to (ASTM C637 2009).

2.2 Mix proportions

To investigate the effect of heavyweight aggregate on the physical and 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 (Bunsell and Renard 2005). The absolute volume method is generally accepted and is considered to be more convenient for heavyweight concrete (Kaplan 1989). Hence, the absolute volume method to obtain denser concrete was used in the calculation of the concrete mixtures. Mix proportions of aggregates per 1 m^3 of the concrete mixture 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 by (Ouda 2013). After extensive trials and errors, 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 of coarse aggregate during mixing and, consequently, 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.

2.3 Mixing, curing and testing specimens

The procedure for mixing heavyweight concrete is similar to that for conventional concrete. In a typical mixing procedure, the materials were placed in the mixer with capacity of 56 dm^3 in the following sequence: for each mix; coarse aggregates and fine aggregates, followed by cement blended with mineral cementing material were initially dry mixed for 2 minutes. Approximately, 80% of the mixing water was added and thereafter the mixer was started. After 1.5 minutes of mixing, 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 minutes. 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 2010). All the concrete specimens were cast in three layers into 100 × 100 × 100 mm cubic steelmoulds; each layer consolidated using a vibrating table. Following casting, concrete specimens were covered with plastic membrane to avoid water evaporation and thereafter kept in

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

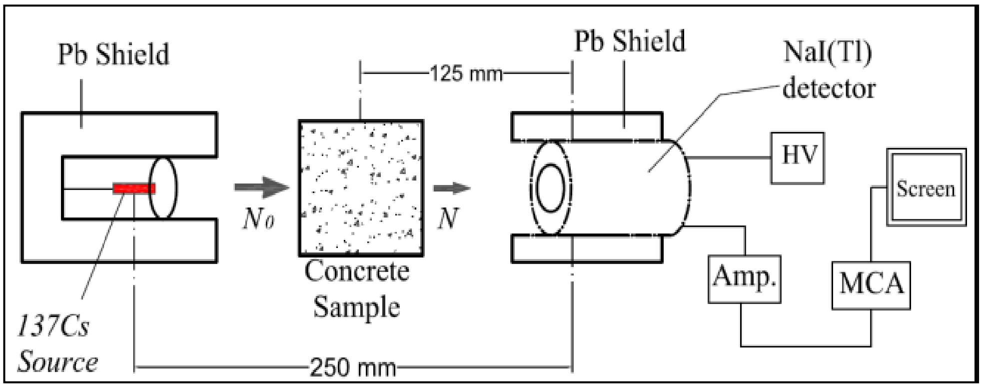

Fig. 1 Experimental setup for gamma radioactive test

the laboratory for 24 hours at ambient temperature. After demoulding, concrete specimens were submerged into water tank until the time of testing. It is well recognized that adequate curing is very important not only to achieve the desired compressive strength but also to make durable concrete. Thus, curing of specimens was performed according to (ASTM C511 2009).

Compressive strength

This test was determined at the curing ages of 7, 28 and 90 days according to (European Standard No. 2390-3 2001). 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 were used to set the compressive strength.

Density of concrete

The density of fresh and hardened concrete was performed according to (Egyptian Code for Design and Construction of Concrete structures- Part VII 2002).

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 taken out and left to oven dry at 105°C prior to the test as recommended by (Yilmaz *et al*. 2011). 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 minutes counting time for each sample. The attenuation coefficient of gamma rays was determined by measuring the fractional radiation intensity Nx passing through the thickness x as compared to the source intensity N0. The linear attenuation coefficient (μ) has been obtained from the solution of the exponential Beer-Lambert's law (Kazjonovs *et al*. 2010).

$$Nx = N0\ e^{-\mu x}\ cm^{-1} \quad (1)$$

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 Eq. (2) and Eq. (3) (Akkurt and Canakci 2011).

$$X1/2 = \ln 2/\mu \quad (2)$$

$$X1/10 = \ln 10/\mu \quad (3)$$

The mean free path (MFP) is defined as the average distance between two successive interactions of photons and it is given from Eq. (4).

$$MFP = 1/\mu \quad (4)$$

3. Results and discussion

3.1 Physico-mechanical properties of concrete

3.1.1 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 in the field for the measurement of workability. The slump of almost all the mixes was in the range of 100 –120 mm. Table 4 depicts the slump values of fresh concrete made with the coarse aggregates of 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 used aggregates; these values are 0.6%, 0.83%, 1.3% and 8.07%

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

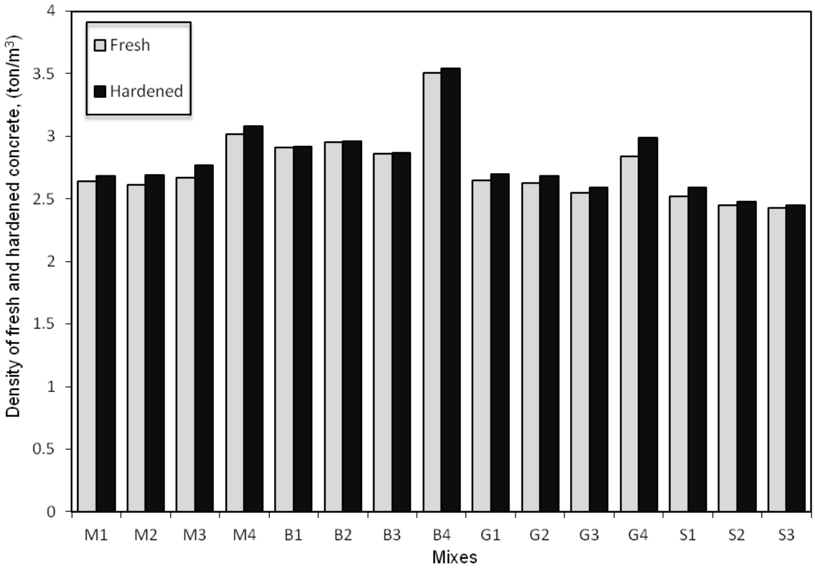

Fig. 2 Density of fresh and hardened concrete

for barite, magnetite, serpentine and goethite, respectively (Table 2). The test results showed also that, there is a decrease in slump values 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 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 (Nadeem and Pofale 2012).

3.1.2 Density of concrete

The density of fresh and hardened concrete mixes made of magnetite, barite, goethite and serpentine coarse aggregates is graphically represented in Fig. 2. To call the concrete as high density concrete, it must have unit weight more than 2600 kg/m^3 as stated in (TS EN 206-1 2002). 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 along with 10 % SF (B1), 20% FA (B2) and 30% GGBFS (B3) as additives to OPC exhibited the highest values of density whether in the case of fresh or hardened. Whereas, the density of hardened concrete mixes made of magnetite aggregates along with 10% SF (M1), 20% FA (M2) and 30% GGBFS (M3) was found to be slightly higher than that normal concrete by about 1.5%, 0.38% and 2.7%, respectively. It is evident also from Fig.1 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; whilst, 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 included 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 along with 10% SF (G4, M4 and B4), respectively.

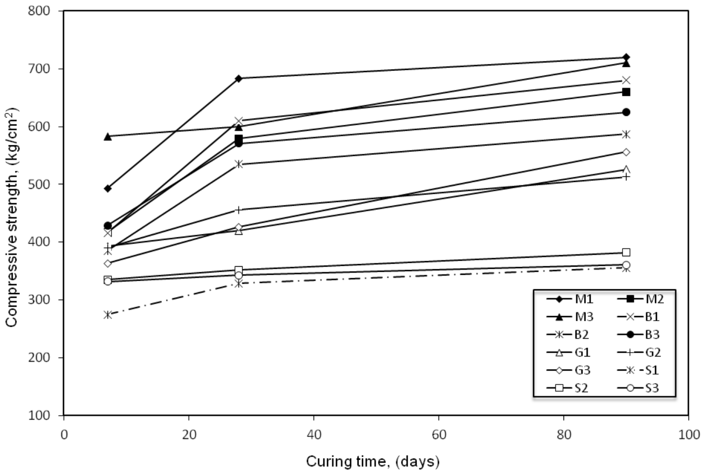

Fig. 3 Compressive strength of concrete made with barite, magnetite, goethite and serpentinecoarse aggregates cured in tap water at 7, 28 and 90 days

3.2 Compressive strength

The rate of strength development in high- performance concrete systems depends mainly on the pozzolanic activity of mineral admixtures; in addition to the physical and mechanical properties of the used aggregates. The compressive strength results 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 are graphically plotted in Fig. 3. It is found that, the compressive strength increases with curing time for all hardened concrete mixes; this is attributed to the increased content of hydration products (especially tobermorite gel) leading to an increase of compressive strength.

The results indicated that, the compressive strength of concrete mixes M1, M2 and M3 (containing magnetite aggregate) are significantly higher than the other concretes (containing barite, goethite and serpentine) at the age of 7 days. Fig. 2 showed also that, the concrete mixes M1 and B1 (incorporating 10% SF) meet the requirements of compressive strength for concrete – grade M60 (i.e., $\geq$ 600 kg/cm^2) after 28 days of curing compared to the compressive strength 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 exceeds upon continuing up to 90 days. This enhancement in the compressive strength is attributed to, silica fume with its high fineness 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 aggregates; 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 along 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/cm2 even after

90 days of curing. This reduction in compressive strength is probably due to, the high water content consumed by goethite and serpentine coarse aggregates; these are 8.07% and 1.3%, respectively. High water content may causes 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.

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.

3.3 Substitution of sand by the aggregate's fine portions

Fig. 4 demonstrates the compressive strength results of concrete mixes made with barite and magnetite coarse aggregate along 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, resulting in decrease the total porosity and increase the compressive strength (El-Didamony *et al*. 2011). The results indicated also that, the compressive strength values of the concrete mix B4 (incorporating barite fine aggregate) are lower than those 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. That is why, the decrease of compressive strength of concrete containing fine aggregate of barite may be related to 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 mix containing fine aggregate of magnetite M4 was significantly higher than that containing sand by 23%, 15% and 20% at ages of 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.

3.4 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 photon energy of 0.662 MeV for Cs^{137} and two photon energies of 1.173 and 1.333 MeV for Co^{60}. The measured results are summarized in Table 5. 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 are graphically plotted in Figs. 5 and 6, respectively. As shown in two Figs., the linear attenuation coefficients for both Cs^{137} and Co^{60} increase with shield concrete thickness. The linear attenuation coefficients of concrete sample made with magnetite fine aggregate (M4) are higher than the concrete made with sand (M1) at photon energy of 0.662 MeV (Fig. 5). Also, linear attenuation coefficients for the two concrete mixes decrease with the increase of gamma ray

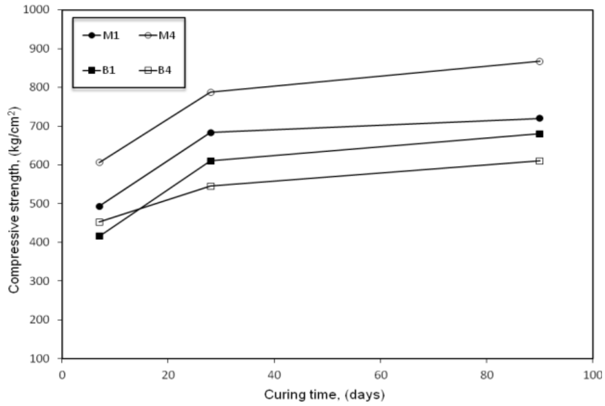

Fig. 4 Compressive strength of concrete made with magnetite and barite upon replacing sand withthe fine portions of aggregates cured in tap water at 7, 28 and 90 days

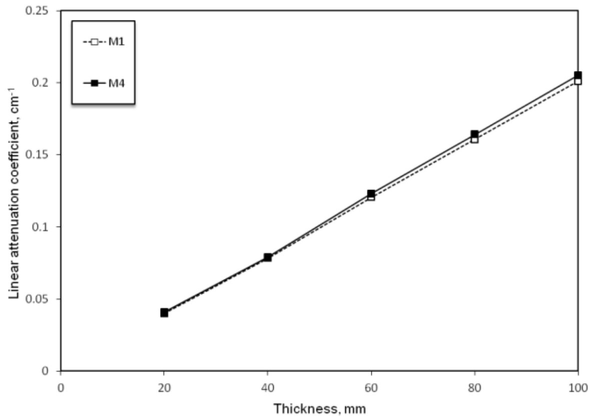

Fig. 5 The variation of linear attenuation coefficients with shield concrete thickness made withmagnetite aggregate for Cs^{137} with photon energy of 0.662 MeV

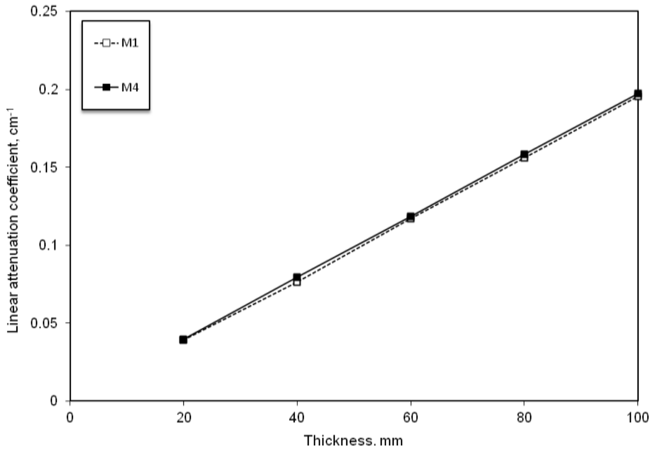

Fig. 6 The variation of linear attenuation coefficients with shield concrete thickness made withmagnetite aggregate for Co^{60} with photon energies of 1.173 and 1.333 MeV

energy. Therefore, at two photon energy of 1.173 and 1.333 MeV, the attenuation values of concrete containing fine magnetite are greater than that 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 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 (Akkurt *et al*. 2010).

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. As shown in two Figs., the HVL and TVL values of mixes (M1 and M4) decrease with the increase of concrete thickness for Cs^{137} and Co^{60}, respectively. The lower are the values of HVL and TVL, the better are the radiation shielding materials in term of the thickness

Table 5 The 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	C^{s137}	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

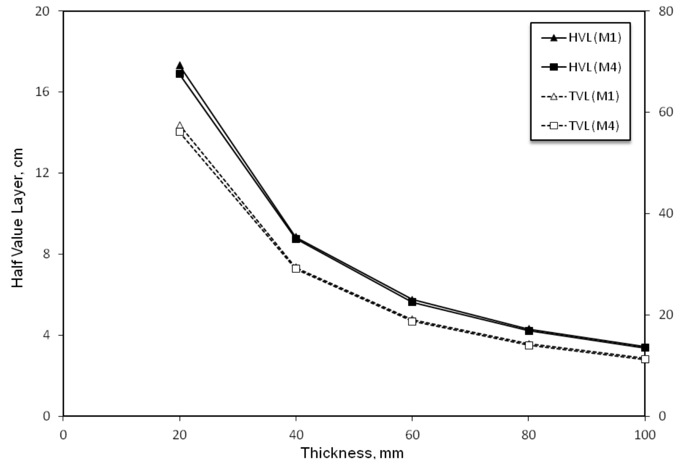

Fig. 7 Half-value layer (HVL) and tenth-value layer (TVL) as a function of concrete thickness formagnetite concrete using Cs^{137} source at photon energy of 0.662 MeV

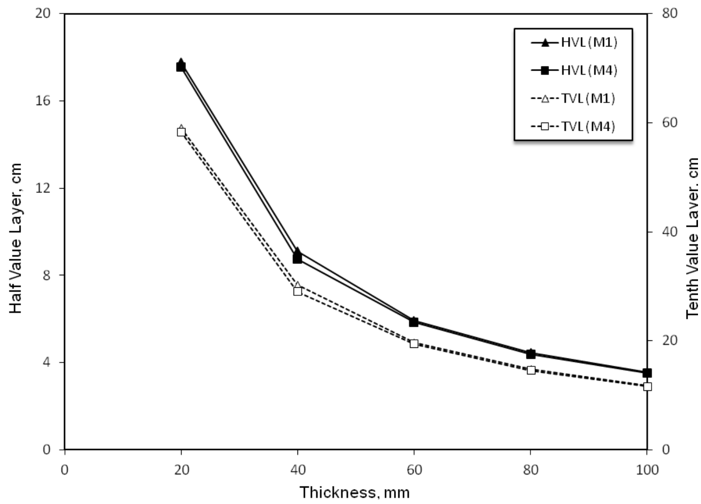

Fig. 8 Half-value layer (HVL) and tenth-value layer (TVL) as a function of concrete for thicknessmagnetite concrete using Co^{60} source at photon energies of 1.173 and 1.333 MeV

requirements. At 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 shown in two Figs. 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 that obtained for Cs^{137} (Fig. 7); where the HVL and TVL of sample (M4) decrease with increasing the density of concrete. Therefore, sample (M4) could be considered the best for gamma radiation shielding.

4. Conclusions

From the preceding discussions, the following conclusions can be summarized.

- Barite aggregate has 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.
- High-performance heavy density concrete made with magnetite coarse aggregate along with 10% SF reaches the highest compressive strength values exceeding over the M60 requirement by 14% after 28 days of curing. Whereas, the compressive strength of concrete containing barite aggregate was very close to M60 and exceeds upon continuing for 90 days. On the contrary, the concrete mixes made with goethite and serpentine coarse aggregates along 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 of curing.
- Concrete made with magnetite fine aggregate showed higher physico-mechanical properties than the corresponding concrete containing barite and goethite.
- High- performance heavy density concrete made with the fine portions of magnetite aggregate enhances the shielding efficiency against γ-rays for Cs^{137} at photon energy of 0.662 MeV and for Co^{60} at photon energies of 1.173 and 1.333 MeV.

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