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FULL LENGTH ARTICLE

Physico-mechanical properties of high performance concrete using different aggregates in presence of silica fume

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KEYWORDS

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Abstract Heavy weight high performance concrete (HPC) can be used when particular properties, such as high strength and good radiation shielding are required. Such concrete, using ilmenite and hematite coarse aggregates can significantly have higher specific gravities than those of concrete made with dolomite and air-cooled slag aggregates. Four different concrete mixes with the same cement content and different w/c ratios were designed using normal dolomite aggregate, air-cooled slag by-product and two different types of iron ore aggregates. High performance concrete (grade-M60) can be achieved using superplasticizer to reduce the water/cement ratio; the effect of SF on the performance of concrete was studied by addition of 10% silica fume to the total cement content. The physico-mechanical properties of coarse aggregates and hardened concrete were studied. The results show that, Ilmenite coarse aggregate gives higher physical and mechanical properties than the other aggregates. Also, addition of 10% silica fume developed a stronger and a denser interfacial transition zone (ITZ) between concrete particles and the cement matrix. Crushed air-cooled slag can be used to produce a high-strength concrete with better mechanical properties than corresponding concrete made with crushed hematite and ilmenite. Heavy density concrete made with fine aggregates of ilmenite and air-cooled slag are expected to be suitable as shielding materials to attenuate gamma rays.

Introduction

Concrete is the most commonly used shield material as it is inexpensive and adaptable for any construction design [1,2]. The concrete shielding properties may vary depending on its composition. Different types of special concretes have been developed by changing the aggregate used for preparing concrete, depending on the available natural and artificial local materials [3–6].

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Concrete has been used in the construction of nuclear facilities because of two primary properties: its structural strength and its ability to shield radiation [7]. Aggregates are the largest constituent (about 70 –80% of the total weight) of normal concrete. Different types of natural and artificial aggregates are used to enhance the properties of concrete. Heavy weight concretes have been widely used in building construction especially for critical buildings as it contains a mixture of light and heavy elements, which are ideal materials to shield radiation. Concretes with specific gravities higher than 2600 kg/m^3 are called heavy weight concrete and aggregates with specific gravities higher than 3000 kg/m^3 are called heavy weight aggregate according to TS EN 206-1 [8]. Concrete which is more effective for the attenuation of fast neutrons can be produced by increasing the water content through the use of hydrous aggregates such as limonite. For shields which are required to provide protection mainly against gamma radiations with limitations in regard to thickness, may be desirable to use heavy concretes with densities greater than ordinary concrete. For this purpose special heavy aggregates such as hematite, ilmenite may be used [9–11,5].

To meet such requirements, moderate compressive strength, low shrinkage and high durability are essential. In other words, a particular class of concrete is to be engineered in such a way to satisfy the above properties. HPC according to the definition of ACI [12], is a concrete meeting special combinations of performance and uniformity requirements that cannot be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. HPC distinguishes itself from normal concrete mainly in the following properties: high compressive strength, high durability, high workability and reduced permeability.

The main objective of this investigation is to study the effect of SF on the hydration characteristics of high performance concrete containing iron ore aggregates as indicated from phase formation to produce heavy weight-high performance concrete with different densities and can be used for the attenuation of gamma rays and fast neutrons in nuclear facilities.

Experimental techniques

Starting materials

The materials used in this investigation for the preparation of high performance concrete (grade-M60) are ordinary Portland cement (OPC - CEM I – 42.5N), obtained from Suez Cement Company (Tourah Plant), Egypt and silica fume, provided from the ferrosilicon alloy Company, Edfo, Aswan governorate, Egypt. Two types of iron ores were selected for coarse aggregates, these were hematite (α-Fe_2O_3) and ilmenite ($FeTiO_3$), obtained from El- Bahariya Oasis, western desert of Egypt and Abu-ghosoon area, Red Sea governorate, Egypt, respectively. A third material that has been selected to be used as coarse aggregate was air-cooled slag that is extensively produced as a by-product through iron and steel production at the Egyptian Iron and Steel Company, Helwan, Egypt. Crushed dolomite [($CaMg(CO_3)_2$], obtained from Attaka area, Suez, Egypt has been used as coarse aggregate (reference material). Fine aggregate was local sand with a fineness modulus of 2.8, washed at the site to remove any deleterious materials and chloride contamination. In some concrete mixes, sand has been replaced by the fine aggregates of hematite, ilmenite and air-cooled slag to produce heavy density concrete.

The nominal maximum aggregate size were 19 mm. Both coarse and fine aggregates were graded according to the limits specified by the ESS 1109 [13]. High performance concrete should have low water / binder ratio. Hence, effective dispersion of the mix is necessary to achieve proper workability without increasing the unit water content. This has been achieved using a high range water-reducing superplasticizer (SP) - Type G with specific gravity of 1.195 kg/l compatible with ASTM C494 [14]. The chemical analyses of coarse and fine aggregates are given in Table 1.

Physical and mechanical properties of coarse aggregates and its fine portion carried out according to the limits specified by the ESS 1109 [13] and ASTM C637 [15] are given in Table 2. Results show that ilmenite has higher specific gravity and lower water absorption than hematite, air-cooled slag and natural dolomite.

Coarse aggregates were separated by manual sieving into various size fractions according to [13,15] for coarse aggregate of size 5 – 40 mm. The grading curves of coarse aggregates are shown in Fig. 1.

Casting and Curing

The procedure for mixing heavy 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: Coarse aggregate was first added to the mixer, followed by approximately one third of mixing water and then the mixer was started. Fine aggregate, (cement + SF) and the remaining water were added to the running mixer in a gradual manner. The mixing time for mixtures was continued for 3 min., then followed by 2 min. for final mixing. Fresh mixes were tested for workability by slump test according to ASTM C143 [16], then all concrete specimens were cast into 10 × 10 × 10 cm cubic steel moulds and then subjected to vibration. Following casting, concrete specimens were covered with plastic sheet and kept in the laboratory at room temperature for 24 h. After demolding, specimens were placed in water until time of testing. Curing was done according to ASTM C511 [17]. After curing, the cubes were exposed to compressive strength measurements at 7, 28 and 90 days. The crushed samples at each hydration time were first ground and then subjected to stopping of the hydration process using a mixture of acetone and methanol in the ratio of 1:1 by volume, followed by drying to 80 °C for 24 h to prevent further hydration and the dried samples were kept in a dissiccator for further analysis [18,19]. The density of fresh and hardened concrete was determined according to BS EN 12390-7 [20] as follow:

$$\rho = \mathrm{M/V} \tag{A.1}$$

$$V = \mathrm{Ma} - \mathrm{Mw}/1000 \tag{A.2}$$

where M, weight of specimen; V, volume of specimen; Ma: weight of suspended specimen in air; Mw, weight of suspended specimen in water.

Four different high-performance concrete mixes were prepared from coarse aggregates of dolomite, hematite, ilmenite and air-cooled slag and using sand as fine aggregate in addition

Table 1 Chemical analyses of starting materials (wt.%).

Oxides	OPC	SF	Coarse aggregates				
			Dolomite	Hematite	Ilmenite	Air-cooled slag	Sand
SiO_2	21.26	97.14	2.24	0.27	20.41	32.2	94.84
Al_2O_3	4.49	0.01	0.95	0.24	6.86	9.11	2.12
Fe_2O_3	3.49	1.09	0.61	87.81	35.55	3.15	0.82
CaO	63.81	0.02	37.90	0.29	2.58	37.1	0.52
MgO	2.02	0.01	15.03	0.13	7.44	2.63	0.1
SO_3^{-}	3.11	0.01	0.39	0.73	2.13	3.9	0.11
Cl^-	0.03	–	0.13	0.1	0.05	0.11	0.06
Na_2O	0.14	0.20	0.25	0.12	1.04	1.2	0.27
K_2O	0.09	0.07	0.07	–	0.08	0.12	0.69
TiO_2	–	–	0.13	–	23.08	0.40	0.12
BaO	–	–	–	–	–	7.17	–
P_2O_5	–	–	0.03	5.45	0.30	0.16	0.04
MnO	–	–	–	0.41	0.22	1.68	–
L.O.I	1.57	1.36	42.25	3.91	0.12	0.82	0.22
Total	99.98	99.91	99.98	99.36	99.86	99.75	99.91

Table 2 Physical and mechanical properties of coarse aggregates and their fine portion.

Physical/mechanical properties	Dolomite		Hematite		Ilmenite		Air-cooled slag		Sand
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	
Specific gravity	2.61	2.86	3	2.86	4.24	4	2.71	2.5	2.65
Unit weight (t/m^3)	1.49	1.75	1.55	2.12	2.40	1.87	1.61	1.87	1.7
Absorption (%)	0.7	–	10.4	–	0.1	–	1.4	–	–
Clay and fine materials (%)	0.4	16	0.46	15	0.08	17.6	0.44	19.6	1.3
Elongation index (%)	21.4	–	18.5	–	21.7	–	17.6	–	–
Flakiness index (%)	43.7	–	21.6	–	30.8	–	15.7	–	–

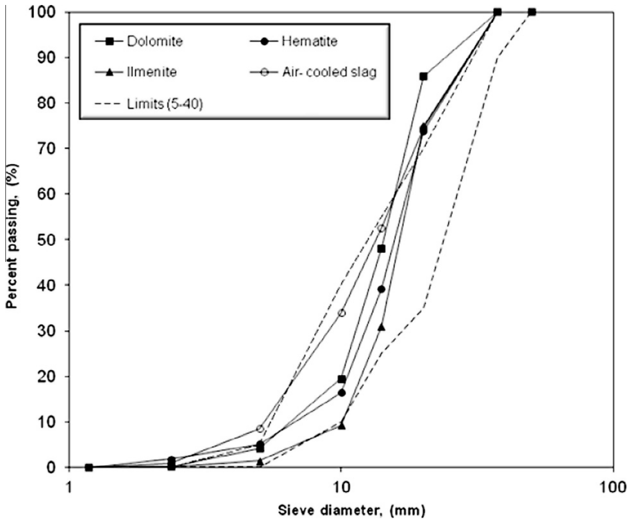

Fig. 1 Sieve analysis of coarse aggregates.

to three other concrete mixes using the fine aggregate of hemartie, ilmenite and air-cooled slag. The mix proportions of various constituents of concrete were designed by following the procedure based on the absolute volume method of mix design [21]. Mix proportions are arrived for grade - M60 after many trials and errors, and by adding of 10% silica fume to the total content of Portland cement. Superplasticizer (SP) was estimated at about 2% from the total content of the binders. The free water content has been limited by about 35% of the total binders in addition to water content absorbed by both coarse and fine aggregates. The material requirements per m^3 of concrete are given in Table 3.

Methods of investigation

Chemical analysis was carried out using XRF Spectrometer PW1400. Compressive strength tests were carried out using a 2000 kN compression testing machine with a loading rate of 0.6 MPa/s according to ES 2390-3 [22]. XRD analysis was carried out using a Philips PW 1050/70 Diffractometer. The data were identified according to the XRD software (pdf-2: database on CD-Release 2005). The microstructure of concrete mixes was studied using SEM Inspect S (FEI Company, Holland) equipped with an energy dispersive X-ray analyzer (EDX).

Results and discussion

Physical properties

The physical properties of the different concrete mixes are shown in Table 4. It can be observed that the differences in slump values are mainly attributed to the differences in water absorption of the used aggregates; these values are 0.7, 10.4, 0.1 and 1.4% for dolomite, hematite, ilmenite and air-cooled slag, respectively (Table 2). Therefore, hematite gives the lowest slump value; this is probably due to the high water content

Table 3 Proportions of concrete mixes.

Mixes	Concrete ingredients (kg/m^3)					
	OPC	SF	Coarse aggregates	Fine aggregates	Sand	SP
D	450	45	951	–	778	10.4
H$_c$	450	45	1081	–	884	10.3
H$_f$	450	45	1114	933	–	12.3
IL$_c$	450	45	1096	–	897	10.3
IL$_f$	450	45	1511	1246	–	11.2
ACS$_c$	450	45	1026	–	840	10.4
ACS$_f$	450	45	966	778	–	10.9

Where D: coarse dolomite, H$_C$: coarse hematite, H$_f$: fine hematite, IL$_C$: coarse ilmenite, IL$_f$: fine ilmenite, ACS$_C$: coarse air-cooled slag and ACS$_f$: fine air-cooled slag.

Table 4 Physical properties of concrete.

Mixes	Physical properties		
	Slump (mm)	Density (ton/m^3)	
		Fresh concrete	Hardened concrete
D	12	2.39	2.35
H$_c$	8	2.53	2.48
H$_f$	8	2.99	2.83
IL$_c$	12	2.76	2.72
IL$_f$	9	3.32	3.21
ACS$_c$	12	2.66	2.60
ACS$_f$	12	3.05	3.02

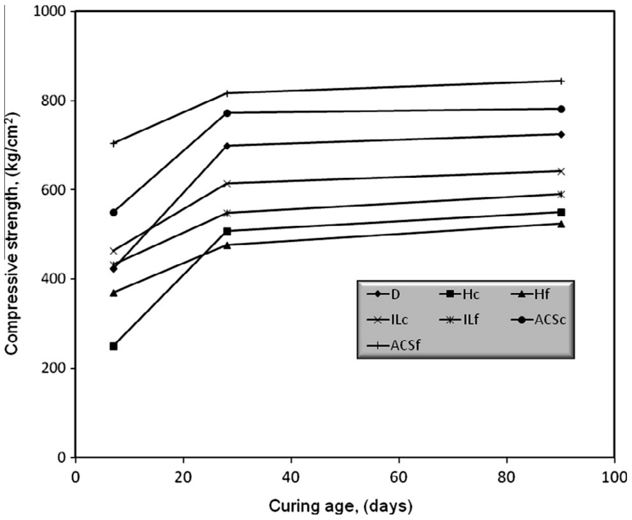

Fig. 2 Compressive strength of concrete made with dolomite, hematite, ilmenite and air-cooled slag aggregates cured in tap water for 90 days.

consumed by hematite aggregate to compensate its high absorption, while, ilmenite gives the highest value. It was also noted that the slump values were decreased upon replacing sand by the fine portion of the raw aggregate, this is also due to the differences in the water absorption between sand and fine aggregate; where the latter absorbs more water than sand.

On the other hand, the differences in the density of concrete mixes are mainly due to the difference in specific gravity of the used aggregates. Consequently, the density of ilmenite concrete is higher than that of dolomite, hematite and air-cooled slag by 16, 10 and 5%, respectively. It was also noted that the density of concrete increases by 18, 14 and 16% upon replacing sand by the fine portion of ilmenite, hematite and air-cooled slag, respectively.

Mechanical properties

The compressive strength of concrete made with dolomite, hematite, ilmenite and air-cooled slag coarse aggregates cured in tap water for 90 days is shown in Fig. 2. In some concrete mixes sand is replaced by the fine portions of raw aggregates. The results show that the compressive strength for all concrete mixes increases with the curing time; this is mainly due to the cement hydration and accumulation of hydration products closing up some of available pore spaces in concrete matrix resulting in improving the mechanical performance. The rate of strength development in high performance concrete systems depends on the pozzolanic activity of silica fume as well as the physical and mechanical properties of the used aggregates. The results indicate that concrete mixes containing air-cooled slag have given higher compressive strength values than those containing dolomite, hematite and ilmenite by about 10, 52 and 20%, respectively. This is due the enhanced interlocking between porous textures of slag and cement paste that leads to improve the transition zone in concrete. Silica fume with high fineness and high silica content provides a filler effect and a pozzolanic reaction, thus resulting in a pore refinement by consumption the weaker calcium hydroxide binder and formation of a stronger binder of calcium silicate hydrate that results in additional strength improvements [23,24]. Thus, silica fume can be utilized beneficially as a supplementary cementing material to improve the mechanical performance of concrete containing heavy density aggregates. The decrease in the compressive strength of hematite concrete is due to the inferior mechanical properties of coarse aggregate as well as the high water content that may cause internal bleeding under the aggregate surface. This result leads to the formation of voids in the vicinity of hematite concrete and thus porous ITZ will be formed in addition to the presence of weak bond areas between coarse aggregate and binding medium as indicated from the microstructure shown in Fig. 4(b).

On the other hand, upon replacing sand with the fine portion of raw aggregates, air-cooled slag concrete shows a further increase in compressive strength of up to 6%, this is due to the concave holes and micro-pores on the surface of crushed aggregate are filled with mortar and hydrated cement paste which increases

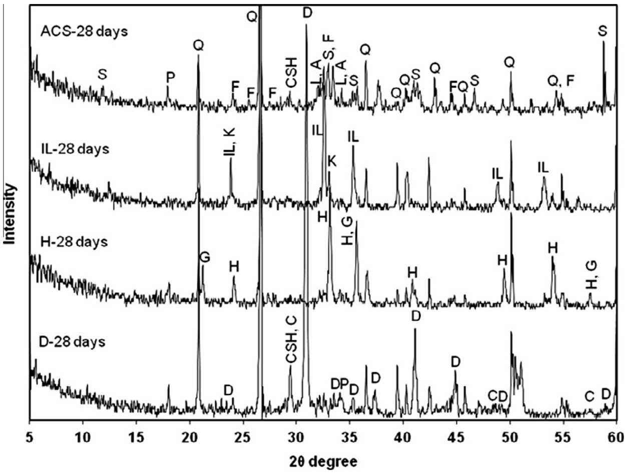

Fig. 3 XRD patterns of concrete containing dolomite, hematite, ilmenite and air-cooled slag aggregates cured in tap water for 28 days.

the interlocking and the mechanical bond between aggregate particles and cement matrix in concrete [25]. While, concrete mixes containing hematite and ilmenite show a further decrease in compressive strength of up to 6 and 11%, respectively upon replacing sand with the fine aggregate.

XRD analysis

The XRD patterns of concrete made with dolomite, hematite, ilmenite and air-cooled slag aggregates cured in tap water for 28 days are shown in Fig. 3. The patterns for all concrete mixes show the presence of cement hydration phases such as portlandite (P), calcium silicate hydrate (CSH) and calcite (C), unhydrated cement phases [larnite (β-C_2S) and alite (C_3S)] as well as the presence of the main peaks characteristic for dolomite (D), hematite (H), ilmenite (IL) and the main minerals of air-cooled slag such as srebrodolskite ($Ca_2Fe_2^{3+}O_5$) and feldspars (F) in addition to some traces from goethite (G) and kaolinite (K) minerals overlapping with hematite and ilmenite ores, respectively. The patterns indicate also that, the intensity of the main portlandite peaks at 2θ (17.97, 28.75 and 34.13) decreases for all concrete mixes at 28 days. This is mainly due to the consumption of liberated lime and formation of additional amounts of C-S-H that improves the mechanical performance of concrete matrix as well as it strengthens the interfacial structures between coarse particles and cement matrix. Also, the formation of poorly crystallized C-S-H proves the progress of pozzolanic reaction in the silica fume-$Ca(OH)_2$ system. The peaks featured for β-C_2S phases are still detected at 28 days; this is due to the rate of hydration of belite phases is slower than those of alite. Quartz (Q) peaks have almost the same intensities at 28 days for all concrete mixes.

Microstructure by SEM

The morphology and microstructure of concrete made with dolomite, hematite, ilmenite and air-cooled slag aggregates cured in tap water for 28 days are shown in Fig. 4. The SEM micrographs for all concrete specimens displayed the existence of a two-phase material consisting of aggregate particles of varying sizes and shapes dispersed in a binding medium which

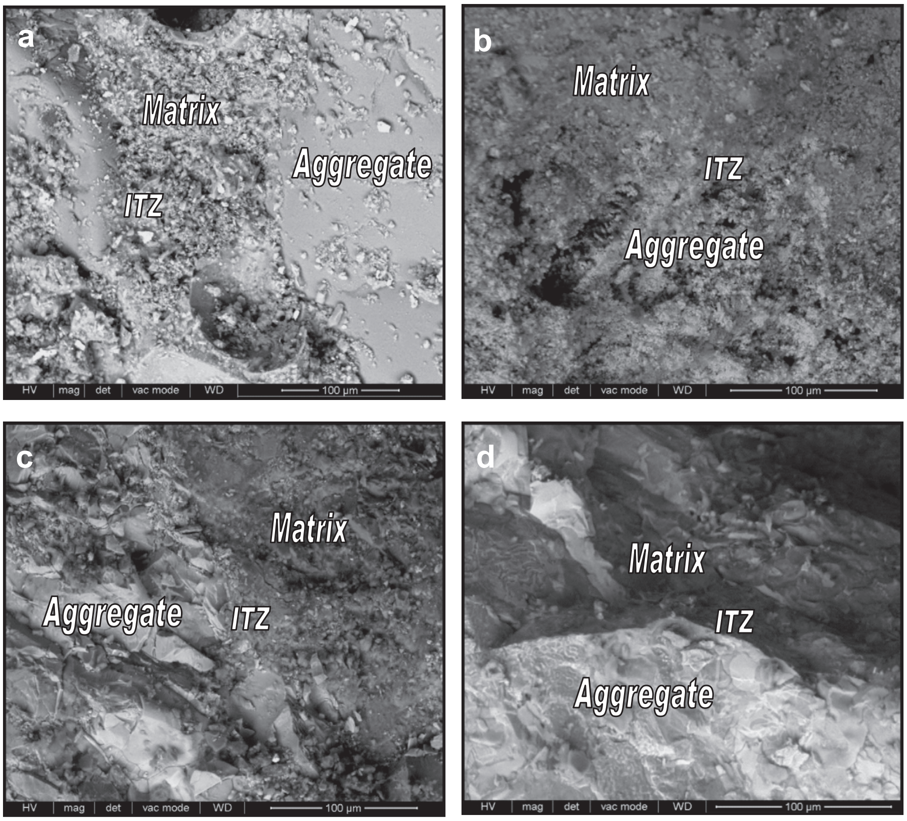

Fig. 4 SEM micrographs of concrete cured in tap water for 28 days; (a) dolomite, (b) hematite, (c) ilmenite and (d) air-cooled slag.

consists of an incoherent mass of the hydrated cement paste. A third phase could also be distinguished in the structure; this represents the interfacial transition zone (ITZ) between the particles of coarse aggregate and the cement matrix. 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 [26].

Evidently, the microstructure of the reference dolomite concrete shows that the hydration products are formed and distributed heterogeneously around aggregate particles that existed mainly in the form of crystal-like C–S–H; while, the micrograph of hematite concrete indicated a relatively permeable structure, due to the formation of a weak bond between coarse aggregate and binding medium, since hematite ore consumes high water content to compensate its high absorption; which may causes internal bleeding under the aggregate surface leading to the formation of voids in the vicinity of hematite particles and thus porous ITZ will be formed.

On the other hand, the micrograph for both ilmenite and air-cooled slag specimens showed a relatively dense and compact microstructure, where the addition of silica fume developed a stronger and a denser ITZ between concrete particles. This is due to filler effect and pozzolanic activity of silica fume as it acts as a microfiller, filling the ITZ and the microcracks formed on the concrete surface, followed by the pozzolanic reaction to form additional amounts of C-S-H that improves the aggregate-matrix bonds associated with the formation of a strengthened and less porous transition zone.

Conclusions

From this study, it can be concluded that:

(1) Ilmenite coarse aggregate shows higher physical and mechanical properties than the other aggregates.
(2) The microstructure of concrete made with air-cooled slag and ilmenite aggregates exhibit a homogeneous and a compact microstructure compared with hematite and dolomite.
(3) Crushed air-cooled slag can be used to produce a high-strength concrete with better mechanical properties than corresponding concrete made with crushed hematite and ilmenite.
(4) Addition of 10% silica fume to the cement content developed a stronger and a denser interfacial transition zone (ITZ) between concrete coarse particles and the cement matrix.
(5) Upon replacing sand with the fine aggregates of ilmenite and air-cooled slag, recommend their utilization for the production of heavy density concrete suitable for the attenuation of gamma rays than conventional concrete.

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