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

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KEYWORDS

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High-performance concrete;
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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.
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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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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 $\pm$ 2 cm.

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