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Optimization of reactive powder concrete by means of barite aggregate for both neutrons and gamma rays

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HIGHLIGHTS

- Barite can be used for radiation shielding efficiency of reactive powder concrete.
- In the study, barite significantly improved the linear attenuation of gamma rays.
- Replacement of quartz by barite adversely affected the mechanical properties.
- An optimum barite content was recommended for shielding both neutrons and gamma rays.

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ABSTRACT

High performance concrete has been often preferred in special engineering structures and in challenging composites products. Researchers have recently focused on the radiation shielding characteristics of these type concrete mixtures due to rising nuclear industry in the developing world. In the study, performance of reactive powder concrete was researched with regard to gamma-ray and neutron attenuation when its normal weight aggregate replaced with heavyweight aggregate (barite). For this purpose, reactive powder concrete mixtures were prepared 100% quartz aggregate, 100% barite aggregate and their blending 50–50%, by volume. Some physical and mechanical characteristics such as density, compressive strength, fracture energy, flexural strength and modulus of elasticity of the mixtures were determined. Gamma-ray attenuation coefficients and transmission thickness values were theoretically established for commonly known gamma energies (661.7, 1173.2 and 1332.5 keV). Optimization of the reactive powder mixtures was performed for both neutron and gamma-ray attenuation at 8 MeV. As a result, barite significantly increased the gamma-ray attenuation coefficients of reactive powder concrete. The mechanical performance of reactive powder concrete, however, was markedly reduced as a result of barite substitution. Replacement of quartz by barite aggregate has a more adverse impact on flexural strength than that of compressive strength. A mix that contains 40% barite aggregate of total aggregate volume was found as an optimum RPC mixture for simultaneously shielding neutrons and gamma rays.

1. Introduction

Radiation has recently become one of the most famous research topics in material and physic sciences due to development of nuclear technology and spreading its use in varied industries. Moreover, interest on the alternative energy sources such as solar energy, wind power and nuclear power due to energy crisis in limited fossil fuel resources, and raise in nuclear weapon stockpile have led to irrefutable radioactive contamination in the world.

Designing and resourcing of various concrete types are essential for nuclear and medical centers against numerous applications of gamma–ray sources [1]. Several studies have been performed researching the effects of aggregate type and content, mineral admixtures, waste materials, mix proportions of normal and heavyweight concrete on their gamma-ray attenuation characteristics. Akkurt et al. [2–4] researched the gamma-ray shielding properties of concrete mixtures containing normal and barite aggregates. Researchers have recently focused on the alternative aggregate resources to investigate the shielding characteristics of concrete such as colemanite [5], lead mine waste [6] and lead–zinc mine waste [7]. Moreover, effect of some minor additives on the

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mechanical and shielding efficiency of the concrete has been researched such as boron compounds [8] and bismuth oxide additives [9]. Effect of water to cementitious materials ratio, type of aggregate and binder content on gamma-ray shielding characteristics was presented by Mostefinejad et al. [10]. Gokçe et al. [11] reported the effect of mineral admixtures, water to binder ratio, binder content on the gamma-ray attenuation properties of high consistency barite concrete mixtures. Ouda [12] recently researched the gamma-ray shielding properties of high performance heavyweight concrete by using various aggregates.

Özen et al. [13] studied mechanical and shielding properties of high performance heavyweight concrete having low water to cement ratio (0.28) with barite aggregate and various heavyweight aggregates, and noted that increasing density improved the gamma-ray linear attenuation coefficient of the concrete mixtures. Tufekci and Gokce [14] also researched the shielding performance of heavyweight high performance fiber reinforced cementitious composites containing barite and granulated ferrous waste against X-ray and gamma-ray. Barite, a type of heavy aggregates, is generally used in heavyweight concrete production for against gamma radiation [15]. Heavyweight concrete attenuates both neutron and gamma radiation in neutron research facilities [16]. In addition to heavy elements, neutrons also need shielding materials containing light elements for elastic collisions [17]. Hu et al. [18] stated that inelastic scattering by heavy elements and elastic scattering by hydrogen are quite effective to slow down fast and intermediate-energy neutrons. Thus, the most effective shielding material for nuclear reactors can be obtained by mixing hydrogenous materials, heavy metal elements, and other neutron absorbers [19]. Akkurt and El-Khayatt [20] showed that an optimum barite content of normal performance concrete was more effective for shielding both neutron and gamma-ray.

Thanks to its superior mechanical and durability performance, reactive powder concrete (RPC), a type of ultra-high performance concrete, was suggested for industrial and nuclear waste storage facilities by Richard and Cheyrezy [21]. Özen et al. [13] reported that structures accommodating radiation-emitting devices require not only adequate shielding against radiation, but also strength properties. Researchers have recently tried to improve physical and mechanical properties, fire resistance, etc. characteristics of RPC by means of various mix design parameters [22–28]. However, due to high heat of hydration and shrinkage problems [29,30], RPC should be considered in modular precast products rather than massive constructions in-situ applications. Thereby, the products can be evaluated as an alternative shielding material by optimizing its mix components for simultaneously shielding neutrons and gamma rays.

In this study, RPC mixtures were produced by the replacement of its conventional aggregate (quartz) with barite aggregate at 0, 50 and 100%, by volume. Detailed mechanical properties and shielding characteristics of RPC mixtures were determined. In addition to determination of commonly used attenuation coefficients and attenuation thicknesses of the mixtures at 661.7, 1173.2 and 1332.5 keV energies of gamma rays, optimum barite proportion was theoretically found for both neutrons and gamma rays at 8 MeV.

2. Experimental study

2.1. Materials

Some chemical and physical properties of Portland cement (CEM I 42.5 R) and silica fume used in this study are presented in Table 1. To approximate particle size distribution of 0–1 mm barite aggregate, quartz aggregate skeleton was composed by 0–0.4 mm (40%) and 0.5–1 mm (60%) grain sizes. The density and water absorption properties of quartz and barite aggregate are 2.65 kg/dm^3 and 0.12%, and 4.08 kg/dm^3 and 0.54%, in sequence. Oxide composition and grading curve of aggregates are given in Table 2, and Fig. 1, respectively. A polycarboxylate based superplasticizer was used in this study. A straight type, brass coated steel micro-fiber with a 13 mm length, 0.20 mm diameter and an aspect ratio as 65 was used as reinforcing material. The density and tensile strength of steel micro-fiber are 7.17 kg/dm^3 and 2750 MPa, respectively.

To evaluate the effect of replacement of quartz by barite aggregate, three RPC mixtures were prepared. These mixtures were denoted as Q, Q + B, and B depending on the aggregate source. Q and B mixtures were completely composed of quartz and barite aggregate in sequence, whereas Q + B mixture was composed of 50% quartz and 50% barite combination by volume. Note that all RPC mixtures have an aggregate volume of 35%. The aggregate volume of RPC should be limited to ensure ultra-high strength with enough workability.

Table 1
Some chemical and physical properties of cement and silica fume.

Chemical composition (wt.%)	Cement	Silica fume
CaO	61.85	0.49
SiO_2	19.1	92.26
Al_2O_3	4.40	0.89
Fe_2O_3	3.96	1.97
MgO	2.05	0.96
Na_2O	0.27	0.42
K_2O	0.70	1.31
SO_3	3.72	0.33
Cl^-	0.0004	0.09
Loss on ignition	1.82	–
Physical properties		
28-day strength activity index (%)	–	95
Fineness (m^2/kg)*	369	20,000
Specific gravity	3.12	2.2

* Nitrogen absorption method for SF, Blaine method for the others.

Table 2
Oxide composition of aggregates.

Oxides (wt.%)	Barite	Quartz
$BaSO_4$	74.31	–
SiO_2	14.80	92.26
Fe_2O_3	0.53	1.97
Al_2O_3	4.67	0.89
CaO	1.06	0.49
K_2O	0.85	1.31
MgO	0.42	0.96
P_2O_5	0.07	–
MnO	0.25	–
SrO	0.75	–
V_2O_5	1.17	–
Nd_2O_3	0.83	–
Ta_2O_5	0.01	–
Sc_2O_3	0.09	–
Sm_2O_3	0.08	–

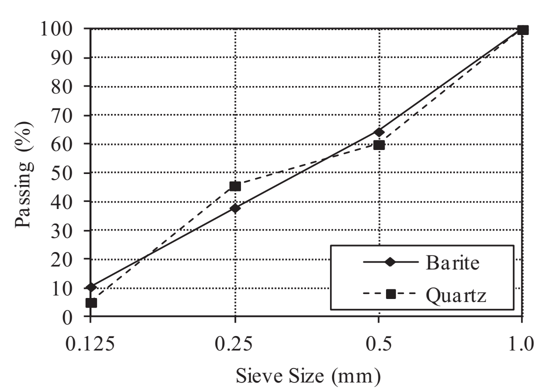

Fig. 1. Grading curve of aggregates.