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Investigation of gamma radiation attenuation in heavy concrete shields containing hematite and barite aggregates in multi-layered and mixed forms

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HIGHLIGHTS

- Barite and hematite, in separate and mixed forms, increases γ-ray attenuation.
- Hematite had more effect on attenuation of radiations than barite.
- The order of concrete layers had no effect on γ-ray attenuation.
- Integrated and layered concrete shields had similar effect on γ-ray attenuation.

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ABSTRACT

The purpose of this study is to make a concrete shield for gamma rays using barite and hematite gradation in separate, mixed and multi-layered forms. Nuclear and mechanical properties of these concrete shields were measured. The results showed that increasing the barite and hematite aggregates, either in separated or mixed form, increases the linear attenuation coefficient and 28-day compressive strength. It was found that the order of the layers in multi-layered shields has no significant effect on the attenuation of gamma radiations. In equal conditions the integrated mixed concrete shield showed better effects in attenuation of radiations than layered one.

1. Introduction

Different kinds of materials such as lead, iron, graphite, polyethylene and concrete are used to protect against nuclear radiation [1]. Among them, concrete is one of the most appropriate materials that is commonly used for such purposes, and this is due to its suitable structural properties and the varieties of materials used for producing it [2,3]. Usually, ordinary concrete is used to make thick walls to protect against radiations. However, in case of space limitations, heavy concrete is the alternative solution. When the intensity and energy of radiations are high, the thickness of protecting shield needs to be increased. In this case, heavy concrete could reduce the thickness of the protecting shield. According to American concrete institute (ACI), heavyweight concrete has a heavier specific weight compared to concretes made of ordinary aggregates and it could specifically be used as a protecting shield against radiations [4]. Heavyweight concretes are usually made of heavy aggregates. Their density is normally between 2900–6000 kg/m^3 [5]. Mix design of heavyweight concrete is very similar to that of ordinary concrete. Mix design of heavyweight concrete is presented in ACI 304.3R [6] and in the fourth appendix of ACI 211.1 [4]. The best method for mixed designing of heavyweight concrete is the absolute volume method. The use of air-entraining agents and silica fume would significantly help the reduction of bleeding in concrete and also concrete breakaway [7].

Heavyweight aggregates with high densities are used to attenuate gamma radiations [3]. The American Society for Testing and Materials ASTM C33 [8] standard expresses properties of ordinary

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aggregates used in concretes. On the other hand, standards ASTM C637 [9] and ASTM C638 [10] represent required characteristics of aggregates used in concrete shield. Some of these characteristics are density, gradation, and type and features of minerals used in the concrete shield. Barite with chemical formula of $BaSO_4$ and specific gravity of 4–4.4 and hematite with chemical formula of Fe_2O_3 and specific gravity of 4.1–5 are among the commonly-used natural heavy aggregates [3,11].

Production of heavyweight concrete dates back to long times ago. At first, heavyweight concrete was used to strengthen structures against slides. With development of nuclear technology and appearance of gamma and neutron effects, shields made of heavyweight concrete spread [12]. Many efforts have been made all over the world in building shield concretes made of materials with different densities and properties [3,13,14–18].

In 2006, Akkurt et al. [19] investigated the effects of type and amount of barite and normal weight aggregates in concrete on linear attenuation coefficient (LAC). LAC was measured directly on concrete samples and calculated with XCOM code. Results from this experiment showed that in comparison with samples containing ordinary aggregates, samples containing barite revealed higher LAC. During 2010–2012, Akkurt et al. [20–22] investigated the effects of the amount of barite, density, water-cement ratio, and corrosion on the LAC of concrete shield. The studies showed that water-cement ratio and compressive strength did not affect LAC. In addition, LAC of samples decreased as an effect of corrosion.

In 2010, Gencel et al. [23] investigated mechanical and physical properties of concrete containing different percentages of hematite aggregates as nuclear radiation shield. In this study, volume percent of hematite from 10 to 50 was added to the concrete. The water-cement ratio was held constant in all the samples. The results showed that hematite increases the unit weights of concrete that leads to increase the absorption and rays attenuation and decreases thickness of shield as well as costs. Concrete containing hematite showed an acceptable performance. Adding hematite to the concrete mixture leads to a decrement in the drying shrinkage.

A study of gamma ray transport in materials has shown that photon scattering in the layers with different densities (e.g. water and lead) is different, especially at the layer borders [24]. In order to increase the amount of attenuation of radiations in radiative shield, it is necessary to investigate these effects on heavyweight concretes such as the most-used and most efficient radiative shield. In order to do this, the effects of layering and changing the order of layers on the amount of attenuation of radiations should be measured for concrete shield. In this study, hematite and barite aggregates were used in production of heavyweight concrete as protection against gamma radiations. In most studies [17,19,20,23], these two aggregates were used separately in heavyweight concretes, while in this study, a mixture of hematite and barite aggregates were used as well. Moreover, the multi-layered concrete samples were produced by putting different concrete layers together. The effect of aforementioned aggregates, layering and changing the order of layers on the amount of attenuation of radiations and also their compatibility in concrete environment were investigated.

2. Material and mix design

In this study, in order to build concrete samples, materials with the following properties were used:

- Cement:

Portland cement type I with specific gravity of 3.15 and chemical components described in Table 1 was used.

- Water:

In this study, drinking water was used in mix design. According to the ACI 304.3R, water used in heavyweight concrete mix should be as in ASTM C94 [25] or ACI 302 [26] and should be free of any contamination and external materials.

- Superplasticizer:

Bleeding and aggregate segregation are two common issues in heavyweight concrete mix design. Therefore, the use of superplasticizer is necessary in the mix design procedure [7]. In this study, polycarboxylate-ether based GHRYSO was used as superplasticizer.

- Coarse aggregate:

According to the ASTM C637 standard [9], grading of heavyweight aggregates (coarse and fine aggregates) is similar to that of ordinary aggregates and matches the ASTM C33 [8] standard. Considering these facts and limitation of dimensions of casts, coarse aggregates were of size 4.75–9.5 mm and consisted of ordinary gravel with specific gravity of 2.86, hematite coarse aggregate with specific gravity of 4.1 and barite coarse aggregate with specific gravity of 4.

- Fine aggregate:

Concrete fine aggregates are materials that 95–100% of them can pass through sieve No. 4 (4.75 mm) [8]. The fine aggregates fill up spaces between coarse aggregates. In this study, fine aggregates were of sizes less than 4.75 mm and consisted of ordinary sand with specific gravity of 2.64, hematite fine aggregates with specific gravity of 4.1 and barite fine aggregates with specific gravity of 4.

The selection of water-to-cement ratio was made based on the resistance and environmental conditions of concrete and type of superplasticizer. This ratio was set to 0.33 in all the mix designs. Moreover, as the aggregates humidity changed during different days and in laboratory environment, the humidity of consumed aggregates was measured at the time of sample production. Also, necessary corrections were made to weights of aggregates and to the amount of water as well. In this study, plasticizer with 1% of volume percentage of cement was used to achieve an identical slump.

In order to achieve the goals defined in this study, eight concrete samples were produced by using seven mix design as showed in Tables 2 and 3 described in the following:

- **Ordinary concrete**: one mix design for ordinary concrete was produced. This mix design included two different samples, one wet ordinary concrete (WOC) and one dry ordinary concrete (DOC). These samples were tested in wet and dry conditions, respectively. In dry condition, the samples were kept in an oven at 100 °C until the weight became constant. In wet condition, the samples were kept in water for one week and tested afterwards.
- **Barite concrete**: two mix designs for concrete containing barite aggregates including barite concrete 50% (B50) and barite concrete 100% (B100), which were produced, respectively, by replacing 50 and 100 volume percentages of ordinary aggregates with barite aggregates.
- **Hematite concrete**: two mix designs for concrete containing hematite aggregates including hematite concrete 50% (H50) and hematite concrete 100% (H100), which were produced, respectively, by replacing 50 and 100 vol% of ordinary aggregates with hematite aggregates.
- **Mixed concrete**: two mix designs for concrete containing a mixture of barite and hematite aggregates including barite-hematite 50% (BH50) and barite-hematite 100% (BH100), which were produced, respectively, by replacing 50 and 100 vol% of ordinary aggregates with barite and hematite aggregates, both with the same ratio.

The concrete samples of the aforementioned mix designs with different thicknesses ranging from 20 mm to 180 mm, were tested after preparation, casting and curing under standard conditions [27] for a period of 28 days. In this study, the multi-layered concrete was produced by putting together layers of barite, hematite, and mixed concrete. Multi-layered concrete were made as follows:

- Two-layered concrete consisting of one layer of B100 and one layer of H100 (B100-H100).
- Three-layered concrete consisting of one layer of B50, one layer of H50 and one layer of DOC (B50-H50-DOC).
- Two-layered concrete consisting of one layer of H50 and one layer of BH50 (H50-BH50).
- Two-layered concrete consisting of one layer of H100 and one layer of DOC (H100-DOC).

The amount of materials used in the mix designs of this study, is presented in Table 3. It is calculated based on the absolute volume method which is in accordance with the fourth appendix of ACI-211 [4].