Shielding Properties of Heavy-Weight Concrete Containing Different Amounts of Iron Pellets

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ABSTRACT

With the increase in demand for electricity generation from nuclear energy and the use of radioactive materials for defensive or peaceful purposes, the need for radiation protection from these materials has also increased. One of the most common measures for structural and protective functions is the use of concrete walls as radiation shielding. The use of heavy aggregate in concrete can create a protective shield against harmful rays such as gamma and X-rays. Due to its high atomic number and high density, iron pellets are a suitable aggregate in heavyweight concrete. In this research, 25, 75 and 100% of concrete coarse aggregates were replaced with iron pellets, which had continuous grading and were in the range of coarse aggregate. At 28 days, the compressive strength and gamma-ray shielding properties were evaluated. To improve the mechanical performance of concrete, in some samples micro-silica was added to the amount of 10% of cement weight. The results showed that replacing all aggregates with iron pellets increases the linear attenuation coefficient of concrete by 38%. Although the use of micro-silica has little effect on the shielding properties of heavyweight concrete, it has improved the compressive strength of heavyweight concrete by 35%.

KEYWORDS

Heavyweight concrete, Gamma ray, Iron pellets, compressive strength, shielding

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1. Introduction

Due to its radiation-shielding properties and other functionalities, there is a growing trend toward producing concrete with a higher density than conventional concrete, known as heavyweight concrete. Typically, concrete with a density exceeding 2600 kg/m³ is classified as heavyweight concrete. The classification of concrete into three categories—lightweight, normal, and heavyweight—primarily depends on the type of aggregate used [1]. In addition to density, the radiation-shielding effectiveness of heavyweight concrete is also influenced by the incorporation of metallic elements with high atomic numbers [2]. Consequently, using aggregates with both high density and high atomic numbers can significantly enhance radiation shielding. Otto et al. investigated the impact of magnetite aggregate in concrete on gamma radiation and highlighted its remarkable effectiveness in attenuating neutrons and gamma rays [3]. Similarly, Essen and Dugan assessed the mechanical properties and radiation transmission resistance of concrete by replacing 20% to 100% of its aggregate with limonite, a hydrous iron mineral [4].

Iron pellets, produced from iron ore powder, serve as raw materials in iron smelting furnaces for extracting pure iron. Karami et al. investigated the mechanical properties of heavyweight concrete containing iron pellets and iron powder, where part of the cement was replaced with micro-silica. They reported an increase of up to 30% in compressive strength for this type of concrete [5]. In addition to the use of high-density aggregates, some studies have explored the effects of incorporating nano- and micro-sized materials to enhance radiation shielding properties of concrete [6]. Mesbahi and Ghiasi found that adding micro- and nano-sized powders of materials such as lead dioxide and hematite to conventional concrete resulted in up to 8% higher radiation shielding in samples containing nano-sized particles compared to those with micro-sized particles [7]. Khalaf et al. reported that incorporating a combination of nano materials, including 3% nano silica and 2% nano calcium carbonate, improved the protective properties of concrete against gamma radiation by up to 3.5% [8]. In most studies, the aggregates used were mined and processed for grain size modification. However, limited research has been conducted on the effects of iron aggregates, such as iron pellets, on the properties of heavyweight concrete.

Given the importance of increasing concrete density to enhance radiation protection, this study focuses on preparing heavyweight concrete using iron pellets as an aggregate. Iron pellets not only provide high density but also benefit from the high atomic number of iron, which improves their gamma radiation shielding capabilities. Additionally, micro-silica was incorporated in specific proportions to further increase the density and refine the pore structure of the concrete.

2. Materials and methods

In this study, concrete aggregate was replaced with iron pellets at 25%, 75%, and 100% ratios. The compressive strength of the concrete samples at 28 days of age, as well as their gamma radiation shielding properties, were investigated. As observed in the review of previous research on heavyweight concrete, increasing the proportion of iron aggregate typically enhances the protective properties of concrete but often leads to a reduction in compressive strength. Therefore, this study placed particular emphasis on this effect. To mitigate the reduction in compressive strength caused by the addition of coarse iron particles, micro-silica was incorporated into some of the mix designs. Figure 1 illustrates the iron pellets used in the study, while Table 1 presents the mix design configurations.

Figure 1. Iron pellets and powder used in the mixing design

3. Results and discussion

3-1 Compressive strength and density

Table 2 presents the results of compressive strength and density for the heavyweight concrete specimens. As evident from Table 2, the density of the concrete increased with higher proportions of iron pellets and iron powder. Specifically, the specific gravity of samples containing 25%, 75%, and 100% iron aggregate increased by 11%, 32%, and 48%, respectively, compared to the control sample. The specific gravity of all samples containing iron pellets exceeded 2600

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kg/m³, classifying them as heavyweight concrete according to the ACI code definition. These findings align with the results reported by other researchers [9]. For instance, Tayeh and Saffar observed a 10% increase in density when 30% of the conventional aggregate was replaced with iron chips [10].

The results also indicate that in heavyweight concrete, as the percentage of iron pellets and flakes increases, the compressive strength remains relatively unchanged or even decreases slightly unless micro-silica is added to the mix design.

Table 1. Mixes design and material compositions in one cubic meter of concrete samples

Mixes	water (kg)	cement (kg)	Iron powder (%)	Iron pelts (%)	Iron powder (kg)	Iron pelts (kg)	Fine aggregates (kg)	Coarse aggregates (kg)	Micro-silica(kg)
C	180	400	-	-	-	-	960	860	-
CM	180	360	-	-	-	-	960	860	40
H25	180	400	25	25	336	336	720	645	-
H25M	180	360	25	25	336	336	720	645	40
H75	180	400	75	75	1050	1050	240	215	-
H75M	180	360	75	75	1050	1050	240	215	40
H100	180	400	75	100	1050	1350	240	-	-
H100M	180	360	75	100	1050	1350	240	-	40

Figure 2. Gamma source, detector, and the condition of the specimen

Table 2. Compressive strength and specific mass of concrete samples

Mixes	Density (kg/m^3)	Compressive strength (MPa)
C	2403	40
CM	2407	44
H25	2657	41
H25M	2653	43
H75	3165	41
H75M	3169	50
H100	3554	38
H100M	3589	54

3-1 Gamma ray radiation shielding

For gamma radiation protection testing, a cesium source was used, as shown in Figure 2. Figure 3 shows the percentage of radiation transmitted through different samples compared to the reference sample. One of the important parameters for evaluating the radiation shielding is the linear attenuation coefficient (μ). This coefficient represents the fraction of photons that are attenuated when passing through one centimeter of material. This coefficient is calculated based on the Beer-Lambert law as follows:

$$\mu = \frac{1}{x}\ln\left(\frac{I_0}{I_x}\right) \qquad (1)$$

which, μ represents the linear attenuation coefficient, expressed in cm^{-1}, x is the thickness of the material (cm), and I_0 and I_x denote the initial radiation intensity and the radiation intensity after passing through a material thickness of x, respectively. The values obtained for the linear attenuation coefficient of the specimens, based on the amount of iron pellets, are shown in Figure 3. As evident from the figure, the inclusion of micro-silica has slightly increased the linear attenuation coefficient of heavyweight concrete, thereby improving its radiation-shielding properties to a small extent. With an increase in the amount of iron aggregate, the μ coefficient has risen significantly. For instance, the value of μ increased from 0.156 for the control sample to 0.215 for the sample containing 100% iron pellets, representing a 38% increase in the μ coefficient.

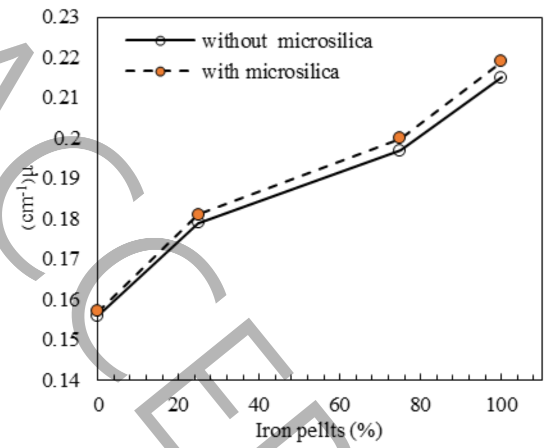

Figure 3. Effect of iron pellet and micro-silica on linear attenuation coefficient

4. Conclusions

In this study, the density, compressive strength, and gamma-ray shielding properties of heavyweight concrete were evaluated. The concrete mixtures contained varying percentages of iron pellets and 10% micro-silica. The following general results were obtained:

As the percentage of iron pellet aggregate in concrete increased, the compressive strength remained nearly constant. However, when all aggregates were replaced with iron pellets, the compressive strength experienced a slight decrease. In contrast, the compressive strength of concrete containing micro-silica increased with higher proportions of iron pellets.

The inclusion of micro-silica did not significantly enhance the radiation-shielding properties of concrete. However, by improving the compressive strength of the concrete, it counteracted the reduction in strength caused by the iron pellet aggregate. Consequently, the simultaneous use of iron pellets and micro-silica can enhance both the mechanical performance and radiation protection properties of heavyweight concrete.

5. References

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