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Investigation of gamma ray shielding efficiency and mechanical performances of concrete shields containing bismuth oxide as an environmentally friendly additive

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HIGHLIGHTS

- Environmentally friendly Bi_2O_3 can be added in concrete for shielding γ-rays.
- γ-ray shielding properties improve with both the Bi_2O_3 and PbO additives.
- Bi_2O_3-loaded concretes own superior attenuation at 0.01–1 MeV γ-rays.
- 25% Bi_2O_3-loaded concrete provided the best shielding and structural capability.

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ABSTRACT

Concrete has a proven ability to attenuate gamma rays and neutrons without compromising structural property; therefore, it is widely used as the primary shielding material in many nuclear facilities. Recently, there is a tendency toward using various additives to enhance the shielding properties of these concrete mixtures. However, most of these additives being used either pose hygiene hazards or require special handling processes. It would be ideal if environmentally friendly additives were available for use. The bismuth oxide (Bi_2O_3) additive shows promise in various shielding applications due to its proven radiation attenuation ability and environmentally friendly nature. To the best of our knowledge, however, Bi_2O_3 has never been used in concrete mixtures. Therefore, for this research, we fabricated the Bi_2O_3-based concrete mixtures by adding Bi_2O_3 powder in the ordinary concrete mixture. Concrete mixtures with lead oxide (PbO) additives were used for comparison. Radiation shielding parameters like the linear attenuation coefficients (LAC) of all these concrete mixtures showing the effects of the Bi_2O_3 additions are presented. The mechanical performances of concrete mixtures incorporated with Bi_2O_3 additive were also investigated. It suggested that the concrete mixture containing 25% Bi_2O_3 powder (B5 in this study) provided the best shielding capacity and mechanical performance among other mixes. It has a significant potential for application as a structural concrete where radiological protection capability is required.

1. Introduction

Gamma radiation is commonly generated in a wide range of nuclear facilities such as nuclear reactors, nuclear research laboratories, high-level storage casks, and medical diagnostic centers. To guarantee the safety of the public and employees, maintaining control of the gamma radiation intensity is of great importance. Hence, it is essential to ensure the attenuation property of any intended shielding material. Concrete has a proven ability to attenuate gamma rays and neutrons without compromising structural integrity; therefore, it is widely used as the primary shielding material in many nuclear facilities. In recent years, an increased interest in radiation shielding concrete mixtures has motivated the development and testing of different experimental concrete mixtures. Many of these researches in the shielding concrete field have been limited to the use of different aggregates (Akkurt et al., 2010; Akkurt and Canakci, 2011; Gencel et al., 2011; Mostofinejad et al., 2012; Ouda, 2015; Singh et al., 2015; Topçu, 2003). However, recent research efforts have considered the use of different additives to enhance the shielding properties of concrete (González-Ortega et al., 2014; Mostofinejad et al., 2012; Oto et al., 2013; Ouda, 2015; Rezaei-Ochbelagh and Azimkhani, 2012;

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Rezaei-Ochbelagh et al., 2012; Singh et al., 2015; Waly and Bourham, 2015; Yaltay et al., 2015). Rezaei-Ochbelagh and Azimkhani (2012) studied whether a lead powder additive could affect the shielding properties of concrete (Rezaei-Ochbelagh and Azimkhani, 2012). Oto et al.(2013) investigated the use of barite powder additives as means to improve the ability of concrete to shield against gamma rays (Oto et al., 2013). These experiments confirmed that these additives do provide advantages in attenuating gamma radiation when compared with the concrete mixture without additives. Although these heavyweight additives are capable of enhancing the shielding ability of concrete, they also require crushing that creates dusts and/or results in potential exposure to toxic compounds. Thus, these additives are often less desirable especially when the environmental effects are considered.

Environmentally friendly additives show promise in various applications because they can reduce or eliminate the hygiene concerns, and can reduce the cost of workers' training. Bismuth is one such environmentally friendly additive. With a high density and atomic number, bismuth has been previously identified as a superior additive to radiation shielding materials when compared to lead because of its potential for enhanced safety and cost savings (Martinez and Cournoyer, 2001). However, bismuth is too expensive to use directly in concrete mixtures. Instead, bismuth oxide (Bi_2O_3) is commonly used as an additive; Bi_2O_3 is far less expensive and the Bi component comprises 89% of Bi_2O_3 by weight making it an advantageous additive candidate. Bismuth oxide has already been used in various gamma ray and X-ray shielding material in a diverse set of products including glass, polymer-bismuth, fabrics, and hand cream (Kaewkhao et al., 2010; Maghrabi et al., 2015; Plionis et al., 2009; Shah et al., 2012; Singh et al., 2014a). For instance, J. Kaewkhao and coworkers studied whether Bi-addition could make improvement on the shielding efficiency of various types of glass systems (Chanthima and Kaewkhao, 2013; Chanthima et al., 2012; Kaewkhao and Limsuwan, 2010; Kaewkhao et al., 2010; Kirdsiri et al., 2011; Ruengsri et al., 2015; Yasaka et al., 2014). From these investigations, it was learned that Bi_2O_3 is a promising substitute for PbO in radiation shielding glasses. To the best of our knowledge, however, bismuth (in its more cost-effective Bi_2O_3 form) has never been used in concrete mixtures.

Developing such an environmentally friendly additive loaded concrete mixture requires a better understanding of Bi_2O_3 effects on concrete mixtures properties. Therefore, for this research, we produced a variety of concrete mixtures with different concentrations of Bi_2O_3 ranging from 0% to 25% based on 5% increments. Concrete mixtures with a lead oxide (PbO) additive were used for comparison. The shielding ability of Bi_2O_3-loaded concrete mixture against gamma rays from a ^{137}Cs (662 keV) radioactive source was investigated and compared with theoretical values calculated using the XCOM program. Additionally, the mechanical properties of the Bi_2O_3-loaded concrete mixtures were also tested to verify their structural capacity.

2. Research methodology

2.1. Materials and mix proportions

Concrete mixtures contain essential constituents, including cement, aggregates, water, and occasionally additives based on characteristic ratios. These constituents, as well as their ratios, may differ systematically among different types of concrete mixtures. We produced standard concrete mixtures (O0) using ordinary Portland cement (32.5 N), limestone-based aggregates (gravel), local sand, and tap water. The chemical compositions of the cement, gravel, and sand, as shown in Table 1, were determined using an X-ray fluorescence (XRF) spectrometer (Model PW 4400). Unlike the O0 mixture, a primary feature of radiation shielding concrete is the inclusion of heavyweight fillers such as barite, magnetite, lead, etc. For our research, Bi_2O_3 and PbO powders served as the fillers and were regarded as additives for the cement; therefore, acting as part of the cementitious material.

Once we selected the ingredients, their ratios were determined using the generally accepted absolute volume method; a special mix proportion method for radiation shielding concrete does not currently exist. Table 2 summarizes our concrete mix proportions. In Table 2 and throughout this paper, the mixtures characteristics are denoted using letter/number codes: the first letter indicates the type of additive (i.e. O = non additive, B = Bi_2O_3, and P = PbO) and the number indicates the percentage of additive (i.e. 0 = 0%, 1 = 5%, 2 = 10%, 3 = 15%, 4 = 20%, and 5 = 25%). Different percentages of Bi_2O_3 and PbO additives were used to examine the effects of additives on the shielding properties of these concretes. To minimize the number of variables, the cement content (488 kg/m^3) and aggregate content (i.e., sand 512 kg/m^3 and gravel 1141 kg/m^3) were constant among the mixtures. Because of the high concentration of Bi_2O_3 and PbO, segregation was a concern. To prevent segregation, we maintained the water-to-cementitious material ratio rather than the water-to-cement ratio at a constant of 0.42.

2.2. Sample preparation

According to our designed mix proportion, each ingredient was mixed sequentially as follows: gravel, sand, cement, Bi_2O_3 or PbO powder, and finally the water. After the mixture was verified as uniform, the concrete specimens were cast in three layers into the 70.7 mm × 70.7 mm × 70.7 mm steel molds. Following casting, a plastic membrane was covered on the molds to prevent water evaporation at ambient temperatures. After 24 h, the specimens were demoulded and then cured under water for 28 days prior to testing.

2.3. Concrete properties

2.3.1. Radiation attenuation properties

Of all radiation shielding parameters, the LAC is the most widely used indicator of the shielding ability of concrete against gamma rays. Additionally, the half-value layer (HVL) and the tenth-value layer (TVL) are also important radiation shielding parameters which often used to determine the thickness requirement for gamma radiation shielding. In this paper, we used

Table 1
Compositions of cement, gravel and sand (wt%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl^-	Na_2O	K_2O	TiO_2	P_2O_5	MnO	NiO	L. O. I
Cement	20.61	6.35	3.42	63.25	2.32	2.31	0.02	0.14	0.29	0	0	0	0	1.09
Gravel	4.03	0.69	0.48	50.69	27.87	0.08	1.86	1.11	0.17	0.07	0.01	12.78	0.02	0.14
Sand	87.47	5.09	2.19	0.70	0.71	0.04	0.82	0.72	1.89	0.14	0.06	0.10	0.01	0.06