Construction and Building Materials 172 (2018) 370–377

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Radiation shielding of ultra-high-performance concrete with silica sand, amang and lead glass

N.M. Azreen [a,d,*], Raizal S.M. Rashid [a], M. Haniza [b], Y.L. Voo [c], Y.H. Mugahed Amran [a]

[a] Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia
[b] Jabatan Mineral dan Geosains Malaysia, Mineral Research Centre, Jalan Sultan Azlan Shah, 31400 Ipoh, Perak, Malaysia
[c] DURA Technology Sdn. Bhd., Jalan Chepor 11/8, Pusat Seramik Fasa 2, Ulu Chepor, 31200 Chemor, Perak, Malaysia
[d] Material & Structural Integrity Group, Industrial Technology Department, Malaysia Nuclear Agency, 43000 Kajang, Selangor, Malaysia

HIGHLIGHTS

- Ultra-high performance concrete (UHPC) has rarely been explored for radiation shielding.
- Amang has higher specific gravity than lead glass and silica sand.
- Amang-UHPC is not a suitable material used as γ-rays shield.
- Compression strength of UHPC mixed with lead glass keep on decreasing.

ARTICLE INFO

Article history:
Received 23 June 2017
Received in revised form 15 February 2018
Accepted 26 March 2018

Keywords:
Ultra-high-performance concrete
Amang
Lead glass
Radiation
Attenuation
γ-Rays

ABSTRACT

Barite in Malaysia is limited; therefore, a locally available alternative source must be identified to meet the requirements of high-density concrete for radiation shielding. We selected steel fibre-reinforced ultra-high-performance concrete (UHPC) samples with different inert materials, namely, silica sand, amang and lead glass, as the study object and tested them experimentally for their mechanical properties and radiation absorption capabilities. The UHPC samples showed compressive strength values exceeding 155 MPa at 28 days. Meanwhile, UHPC with lead glass underwent decreased of compression strength in a long period, and UHPC with amang caused an issue related to radiological safety despite that it was effective as a γ-ray shield. Thus, the use of UHPC with silica sand is practical for constructing nuclear facilities because of the abundance and cost-effectiveness of the involved materials.

1. Introduction

Concrete structures in nuclear power plants (NPP), such as containment and reactor buildings, spent fuel pools, cooling towers, water intake structures, hot cells and high-level waste dry casks, are crucial to NPP safety, operation and financial aspects because they help protect the environment from certain external and internal events. External events include seismic activity, potential sabotages and serious climate conditions, such as surges and tornadoes. Meanwhile, internal events include loss-of-coolant accidents and high energy line break (elevated temperatures and radiation). Concrete is a long-lasting material that can be used for NPP facilities and is ideal for radiation shielding against γ-rays or neutrons. History has shown that concrete structures deteriorate commonly because of such factors as improper design, sloppy construction work, use of low-quality materials, high exposure to harsh environments and violation of maximum allowable loads, thereby possible jeopardising the safety of concrete structures and posing risk to people's safety and health [1].

According to [2], heavyweight concrete has specific gravities exceeding 2600 kgm^{-3}. Heavyweight concrete is made of heavyweight aggregates (specific gravities exceeding 3000 kgm^{-3}). For radiation shielding, increasing concrete density also increases the γ-ray attenuation coefficient, thus allowing the concrete to absorb additional radiation for improved environmental safety [3].

Most previous researchers used heavyweight aggregates of various minerals to find the linear attenuation coefficient (μ) theoretically and experimentally in collecting data about concrete mixtures of varying ranges and studying different concrete mixtures used as radiation shields. Scholars have stated that concrete containing magnetite fine aggregates provides better

---

* Corresponding author at: Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia
E-mail address: noorazreen@nuclearmalaysia.gov.my (N.M. Azreen).

https://doi.org/10.1016/j.conbuildmat.2018.03.243
0950-0618/

physio-mechanical properties than concrete made with barite and goethite does [4]. Changes in cement aggregates affect the properties of the concrete in terms of radiation shielding effectiveness and structure. Several studies have investigated the production of high-density concretes that can achieve increased μ while maintaining a small thickness; this goal may be achieved by using special additives instead of changing the aggregate concentration [5–9]. Concretes with additives in the aggregate can provide more efficient γ-ray shielding than ordinary concrete can [10]. In 2015, the shielding parameters of five ores, namely, barite, magnetite, hematite, limonite and serpentine, were investigated. The study found that barite and magnetite are suitable for X-ray shielding [8]. To obtain the μ experimentally, researchers typically select one type of aggregate, such as ilmenite [11], barite [12–16,6], lime/silica [17], zeolite [18], hematite [19], lead glass [20], magnetite [4,21] and lead mine waste [7]. Different photon energies provide varying μ; therefore, numerous experiments are required to obtain only one μ for each photon energy. Hence, μ is calculated theoretically when many minerals are compared; such theoretical calculation has been conducted using such simulation software as XCOM [9,3,5], Monte Carlo simulation [16] and Micro shield [10].

Ultra-high-performance concrete (UHPC), a cementitious composite that can achieve compressive and flexural strengths exceeding 200 and 20 MPa, respectively, is one of the most advanced concrete technologies today [22]. In 1977, the first high-performance cement was the hot-pressed cement [23], followed by macro-defect-free cement [24], slurry-infiltrated fibre concrete [25] and similar materials. Reactive powder concrete (RPC), which was used by researchers to increase compression strength from 200 MPa to 800 MPa through improved fineness and reactivity, was subsequently introduced [22]. However, RPC is too costly and therefore is not favoured for use in the industry. In 1994, De Larrard [26] proposed the UHPC, which shows high compressive strength due to high density. Researchers immediately started using UHPC in their studies. M.M. Reda [27] reported that the UHPC mixture has higher density than ordinary concrete due to the highly dense microstructure of the former. Z. Wu [28] and Amin [29] researched the flow capability, pore structure and hydration of nanomaterials, whereas Sukhoon [30] studied the speed of crack propagation of UHPC. Ambily [31] and Zhao [32] explored the combinations of copper slag and iron ore with UHPC. Finally, Tina [33] researched the hydration process of amorphous silica on UHPC.

The main principles in UHPC design are porosity reduction and microstructure, homogeneity and toughness improvement [34]. The use of UHPC for NPP structures will enhance the collection of periodic imaging data using non-destructive testing methods because of the abovementioned main principles. In this research, lead glass and amang are mixed with UHPC, and these mixtures are compared with UHPC containing silica sand.

The lead glasses used for this research come from a CRT TV funnel and are non-biodegradable waste glasses. This waste material can cause serious environmental pollution, especially to soil, water and air. This pollution issue must be addressed by reusing waste materials. By recycling such items, one not only helps save the environment by minimising landfill spaces and conserving natural resources but also saving energy and money [35].

Amang (tin-tailing) is a by-product of a rough concentration of casserite (tin dioxide), which can be obtained in tin mining. Amang is processed to produce valuable minerals, such as ilmenite, zircon, monazite, xenotime, columbite and struverite. These minerals contain naturally occurring radioactive materials (NORMs) and are improved to process amang and thus yield technologically enhanced NORMs [36].

Previous studies have used only concrete containing high-density coarse aggregates. UHPC has rarely been explored. Therefore, the current research mixes high-density materials in place of silica sand with UHPC. This work aims to investigate the use of various concrete components, namely, lead glass and amang, to create high-performance, high-density concrete that can improve shielding efficiency better than silica sand can against emitted radiation rays, that is, γ-rays.

2. Materials

The cement used in this research was ordinary Portland cement (OPC) type I (manufactured for [37] by Tasek Corporation Berhad). The fine aggregates used were amang (Minerals and Geoscience Department Malaysia), silica sand (Dura Technology Sdn. Bhd) and lead glass (Nippon Glass (M) Berhad). The fine aggregates measured less than 1.35 mm and thus met the general specification requirement in producing UHPC [38]. To produce high-strength concrete, densified silica fume was added to the mix in powder form, which contained 97% silica dioxide (SiO_2) with a particle size range of 0.1 μm–1 μm. To adjust the workability of the concrete, a polycarboxylic ether-based admixture was used as superplasticiser. Two types of steel fibres were utilised, namely, 0.5% by volume straight steel fibre with a total fibre length of 20 mm and fibre ø of 0.2 mm and 0.5% by volume end hooked steel fibre with a total fibre length of 25 mm and fibre ø of 0.3 mm. All steel fibres were fabricated with a minimum tensile strength of 2500 MPa. The chemical components in the material (except loss of ignition) were tested using an X-ray fluorescence spectrometer, as shown in Table 1.

3. Mix design and sample preparation

Three series of UHPC with three types of fine aggregates were prepared on the basis of the study by R. Yu [38]. The optimum ratio for each mixture was based on normal UHPC, as shown in [34] using only silica sand (SS-UHPC). To obtain a water-to-binder ratio that was less than 0.2 to maintain workability (180–220 mm), extensive trial-and-error was conducted on the trial mix of amang (A-UHPC) and lead glass (LG-UHPC); the mix proportion was adjusted by changing the masses of the fine aggregates, water and superplasticiser. The adjusted mix proportion selected is presented in Table 2.

The dry binder powder (cement and silica fume) was poured into a mixer machine (300 kg capacity) and dry mixed for 2 min at low speed. Then, the fine aggregates were poured and mixed for 4–6 min until properly blended. By weight, 70% water and 50% superplasticiser were added to the mixer machine at medium speed for 2–3 min. The remaining water and superplasticiser were added after achieving a flowable mix. Finally, all the materials were thoroughly mixed for 1 min before workability was determined using the flow table test as per [39].

The mix was then cast in three layers, and each layer was compacted using a vibrating table. The specimens were sprayed with a curing compound to avoid water evaporation, demoulded after 24 h at ambient temperature and then placed in a hot-water tank (with temperature reaching 90 °C) for accelerated curing for 3 days according to [40].

3.1. Tests on UHPC

To measure compression strength, 12,100 mm cubes were made for each mix and three specimen were tested after 1, 7, 28 and 56 days. Three 75 mm ø × 150 mm-long cylinders were prepared for each mix to determine the modulus of elasticity at 28 days. To measure the flexural strength (modulus of rupture) of each mix, three 100 mm × 100 mm × 500 mm prisms were cast