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Development of synthetic resin-based mortar for low-activation and neutron shields

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HIGHLIGHTS

- 3 types of synthetic resins-based mortars were investigated especially focusing on the neutron shielding performance.
- A ^{252}Cf spontaneous fission neutron source was used for the neutron irradiation tests.
- The neutron shielding performance increased up to 36.14% compared to the conventional mortar.
- More economical design for neutron shielding can be achieved with a multi-layered system with multiple resin materials.

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ABSTRACT

Concrete that is used in neutron generating facilities, such as fission reactors, becomes radioactive owing to neutron irradiation. Low-activation and neutron shields are critical concerns at the dismantling stage with requirements for radioactive waste management. To enhance these parameters, synthetic resins-based mortar was investigated in this study. The mass of hydrogen is almost the same as that of a neutron, and it effectively retains neutrons by increasing the probability of elastic scattering. It is well known that synthetic resins have numerous hydrogen atoms. Resins containing mortar mixtures were investigated to understand the effect of resin on the mechanical properties of mortar as well as on its neutron-shielding performance. The experimental results showed that the neutron dose equivalent to a resin-based mixture decreased by 63.86% as compared to that of conventional mortar, although the mechanical properties need to be enhanced using suitable special treatments. It indicated significant potential to reduce not only the thickness of the neutron shields but also the amount of radioactive waste.

1. Introduction

Concrete has been used as a radiation shield owing to its mechanical properties, chemical composition, and ease of construction in the nuclear industry [1]. Radiation shields for nuclear power plants (NPPs) are generally designed to capture all primary and secondary radiations emitted by a radiation source. The radiation source emits fast neutrons into its concrete shield. Heavy materials, such as magnetite or steel, contain large nuclei of iron, and thus they are commonly used in concrete shields in order to increase the probability of hitting a neutron. It also slows the neutron because of numerous interactions, which is called inelastic scattering. The intermediate energy of the neutron is retained in the nucleus of the atoms and impacts the receptive nucleus, which has much lower energy, to release another neutron from it. This attenuation is called elastic scattering. The slow, low energy, thermal neutron is finally retained in the nucleus and binding energy is released as secondary gamma radiation [2–3].

Heavy weight concrete with a density higher than 2500 kg/m^3 is generally considered for radiation shields at NPP and other radiation generating facilities [4]. Magnetite aggregates are usually used for producing heavy weight concrete because of their high density, widespread availability, and general acceptability. Special aggregates such as magnetite or recycled steel are well-known heavy materials used for radiation shielding. Unfortunately, radiation shields made of concrete are activated when they are exposed to neutrons for extended periods of time [5]. Ferruginous heavy materials have high potential of radioactivity with radionuclides, especially ^{60}Co, and hence, they are not recommended for the purpose of low-activation [1].

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Considerable amounts of concrete are classified as radioactive waste at the dismantling stage after the shutdown of facilities, and this increases the cost of decommissioning. And there are insufficient radioactive waste disposal facilities which adds to the problem. The International Atomic Energy Agency recommends that both decontamination and decommissioning should be considered at the stage of NPP planning [6].

Therefore, a low activation neutron-shielding technology for the activation of concrete is an important method to reduce radioactive waste from NPP and to prevent social unrest. It will also provide a decisive opportunity to secure a new NPP market in the world. There are two different approaches for low activation radiation shielding of concrete: one is to use shielding constituents that are either less activated through irradiation or not at all, and the other is to use materials, which attenuate radioactive particles quickly through scattering and absorption processes [7]. This study mainly employs the latter with the help of synthetic resins, which have numerous hydrogen atoms. Hydrogen is particularly adept at retaining neutrons of intermediate energy levels and increases the probability of elastic scattering occurring quickly after neutrons attain intermediate energy levels [2–3]. Therefore, the scattering efficiency increases with the increase in the number of hydrogen atoms in the synthetic resin. Though synthetic resins are not directly used in concrete, they are usually used for radiation-shield ing—especially neutron-shielding—composite panels or sheets combined with epoxy resins. This study aims to explore the potential of synthetic resins containing cementitious materials for neutron shields, including their effects on the deterioration of quality, as a step towards developing better neutron-shielding concrete. Three types of synthetic resins were investigated with different replacement levels and basic mechanical properties, and the neutron-shielding performance was analyzed and compared with a normal mortar mixture.

2. Significance of research

Synthetic resins are very effective commercial materials for neutron shields, but researchers have maintained their focus on the development of epoxy-based neutron-shielding resins with boron for radiation shields, which minimizes secondary gamma rays [8–10]. A majority of the researchers employed flexible panel and sheet types to aid in neutron shielding. Very little technical research on the fabrication of shielding concrete by incorporating synthetic resins (not synthetic fibers) is available. This study investigates cementitious materials containing synthetic resins for low-activation radiation shielding. The influence of the amount and type of synthetic resin on the basic mechanical properties and shielding performance of the mortar is experimentally determined. Furthermore, additional issues that may arise in the production process, which should be considered and overcome are listed for further research.

3. Material and methods

3.1. Material

The main materials considered in this study were type I ordinary Portland cement (type I OPC), fine aggregate, water, and synthetic resins. Their properties were summarized in Tables 1–3. Three types of commonly used synthetic resins were considered for this study, they are: high density polyethylene (PE), polypropylene (PP), and ultra-high molecular weight polyethylene (UHMW-PE). For PE, 7000F (Lotte Chemical Corp.) was used, which has a bi-modal design of molecular composition and offers both excellent processability and mechanical properties. For PP, B-110 (Lotte Chemical Corp.) was used, which is a homo polymer resin produced by the polymerization of propylene and processed by sheet extrusion. For UPMW-PE, Celanese GUR 4120 (Celanese Corp.) was used, which is a linear polyolefin resin in powder form with a molecular weight of approximately 5.0 MM g·mol, calculated using Margolies' equation. The UHMW-PE is well-known to have excellent wear and chemical resistance. It should be noted that the physical properties of synthetic resins are much lower than those of natural aggregates-except in the case of flexural modulus-as shown in Table 3. Therefore, this would decrease the overall mechanical performance of the mortar-e.g., a reduction in compressive strength may be observed.

A total of ten mortar mixtures were prepared as summarized in Table 4, and classified into 4 groups, depending on the type of resin: PE, PP, and UHMW-PE. The important parameters were the type of resin and replacement levels of 20, 40, and 60 vol% of fine aggregates by resins. In addition, conventional mortar (MOR in Table 4) was regarded as a control specimen. For consistency, the water cement ratio (w/c ratio), unit cement content, and unit water content were fixed at 48.5%, 568.35 g, 275.65 g, respectively.

The specimens were manufactured to test for compressive strengths and neutron-shielding performance. Three specimens per mixture were prepared to measure the compressive strength and their sizes were $5 \times 5 \times 5$ cm as described in ASTM C109/109M:2013 [11]. For the neutron irradiation test, four specimens per mixture were prepared with a cross-section of 15×15 cm and a thickness of 5 cm on considering the size of the shadow cone in neutron irradiation test equipment.

Aggregates were prepared in a saturated surface-dry state and dry-mixed with OPC in a mixer pan for two minutes. If the mixture was to include resins, the resins were added last; water was added, and the mixing continued for another three minutes to prevent segregation in the fresh mortar. The slump flow of fresh mortar was measured in accordance with ASTM C143 [12], and then it was poured into various types of steel molds, consolidated, and cured in the water maintaining a constant temperature of 23 ± 2 °C until their compressive strengths were measured. All steel molds were removed at an age of 1 day.

3.2. Methods

Compressive strengths were recorded at the age of 28 days in accordance with the ASTM C109/C109M:2013 [11]. At the same age, the neutron irradiation (transmission) test was also performed using a ^{252}Cf spontaneous fission neutron source with a half-life of 2.65 years, which is one of the traditional standard neutron sources [13], a dosimeter, and instrument calibrations. A warhead-shaped neutron source had a diameter of 3.4 mm and a height of 8 mm, and its emission rate was 2.360×10^{8} s^{-1} with a neutron mean dose equivalent of 385 pSv cm^2. The energy spectrum of ^{252}Cf is displayed in Fig. 1, which is very similar to the biological shielding concrete wall of a reactor at NPP in Korea [14]. This source mainly

Table 1
Properties of Type I Portland cement used in the preparation of mortars.

Type of cement	Main components (%)						Density (g/cm^3)	Blaine fineness (m^2·kg^{-1})
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3		
OPC	21.01	61.33	6.40	3.12	3.02	2.14	3.15	341.3