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Research paper

Investigating the performance of magnetite powder-bentonite mixtures for radiation shielding and gas permeability in wet-dry cycles

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ABSTRACT

Radioactive waste management presents significant environmental and health challenges, requiring barrier materials with strong radiation shielding and low gas permeability. Wet–dry cycles can compromise barrier integrity by inducing microstructural damage, making control of gas migration essential for durable waste isolation. This study investigates the enhancement of bentonite clay by incorporating magnetite powder at concentrations of 15 %, 30 %, and 45 %, focusing on improvements in radiation shielding and gas permeability. Radiation shielding performance was assessed through experimental measurements using a NaI (Tl) Sodium Iodide Scintillation Detectors, complemented by simulations with the MCNP code and data from the XCOM database. The addition of 30 % magnetite significantly improved shielding performance, increasing the linear attenuation coefficient by 38 %, 62 %, and 59 % at photon energies of 662, 1173, and 1332 keV, respectively, while reducing the half-value layer (HVL) and tenth-value layer (TVL). Gas permeability tests under wet–dry cycles showed that magnetite addition initially reduced permeability due to improved compaction. In the wet state, the 30 % magnetite sample (B70-M30) achieved a 73.4 % reduction in gas permeability. Although permeability increased in later cycles due to micro-cracking, B70-M30 consistently exhibited the best performance compared to the 15 % and 45 % magnetite samples. These results highlight the potential of magnetite-enhanced bentonite as a multifunctional barrier material for radioactive waste containment.

1. Introduction

Nuclear science is recognized as one of the most critical and impactful scientific fields, with extensive applications in power generation, industry, medicine, pharmaceuticals, agriculture, and many other areas [1,2]. Ensuring the safe application of nuclear technology, particularly in radioactive waste management, is a primary concern within this field. Low-level radioactive waste (LLRW) includes waste contaminated with radioactive materials or made radioactive through exposure to radiation, which constitutes the majority of this waste [3]. Among the various strategies employed for managing Low-level radioactive waste, disposal has garnered significant attention as one of the most effective methods. Low-level radioactive waste disposal sites are specialized facilities designed for the safe containment and isolation of radioactive waste. The engineered cover layer must exhibit strong resistance to radiation under various environmental conditions while maintaining low permeability to water and gas. In other words, a major challenge in designing these facilities is implementing protective covers to prevent harmful radiation, water, and gas permeability from the landfill, thereby preventing contamination of the surrounding environment, including soil, surface water, groundwater, and air [4,5].

Bentonite, a type of clay known for its high swelling properties, low permeability, self-healing capabilities, and durability, is commonly used to cover landfills [6,7]. Natural bentonite is considered an almost ideal filling material for geological repositories of radioactive waste. Its swelling capacity prevents convective water movement through repository tunnels, and its excellent absorption properties effectively delay radiation release. The presence of ancient bentonites in nature indicates their long-term stability [8]. Recent studies on unsaturated bentonite–sand mixtures have confirmed that these materials maintain low permeability, high swelling capacity, and effective sealing behavior under expansive conditions, highlighting their suitability as engineered barriers [9,10]. Bentonite's ability to swell upon contact with water makes it an excellent sealant, capable of filling voids and preventing

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