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Durability and Radiation Shielding Performance of Mineral-Admixture Concrete Exposed to Sulfate and Thermal Degradation

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Abstract - The expansion of nuclear energy into dry regions requires concrete structures to endure multiple stress factors, including chemical reactions, thermal conditions, and radiological impacts. This research contributes to a larger study about developing resilient concrete solutions for the Barakah NPPs located in the UAE. The study tested silica fume and GGBS (SG) mortars against ordinary mortars after exposing them to sulfate and chloride-rich solutions at 50°C for four months. The testing results showed that SG mortars maintained good durability and mechanical performance while providing superior radiation shielding compared to standard control mixes. The research demonstrates that mineral admixtures provide both durability benefits and radiation protection, essential for maintaining long-term nuclear infrastructure performance under harsh arid conditions. The current research continues to investigate longer exposure times while developing nano-based additives for performance enhancement.

Keywords: Radiation shielding concrete, sulfate attack, thermal degradation, gamma attenuation, durability, mineral admixtures, arid environments

1. Introduction

Concrete structures located in arid regions of nuclear facilities experience rising degradation rates because of multiple environmental stressors. The combination of high temperatures with sulfate attack and prolonged radiation exposure creates complex degradation mechanisms which threaten the mechanical strength, durability, and shielding properties of concrete components [1,2]. Sulfate attack, particularly when coupled with high temperatures, promotes the formation of expansive phases such as ettringite and gypsum leading to crack formation and loss of structural performance [3]. The exposure of concrete to ionizing radiation produces changes in its microstructure which affects its density, porosity and attenuation properties that are vital for maintaining radiation shielding in nuclear power plants [4].

Based on the literature, traditional Portland cement-based concretes have limited resistance to multi-stressor environments; this drives the need to develop advanced material solutions [5]. Incorporating silica fume with ground granulated blast furnace slag (GGBS) in concrete shows the potential to boost sulfate resistance and strengthen microstructural stability [6]. The effects of chemical degradation, thermal loading and radiation exposure on enhanced concretes need further investigation especially when facilities like the Barakah Nuclear Power Plants (NPPs) in the UAE are considered. This research evaluates the mechanical durability alongside gamma radiation shielding performance and microstructural changes of mortars containing mineral admixtures that experience aggressive sulfate and chloride environments at elevated temperatures for extended periods.

2. Materials and Methods

2.1. Mortar Sample Preparation

Two types of mortar mixes were prepared: a control mix (OA) composed of ordinary Portland cement (OPC) and an enhanced mix (SG) incorporating silica fume (SF) and ground granulated blast furnace slag (GGBS) as supplementary cementitious materials, Table 1 illsutrate the composition, that was casted similar to mix design implemented in BARAKAH NPPs. All mixes were designed with a constant water-to-binder ratio (w/b =0.4) and cured for 28 days under standard laboratory conditions. Mortar samples were prepared for different experimenatl tests: (1) Beams of 160x40x40 mm, for resisitivity and UPV measurments. (2) Small cubes of 50 mm side length, for compressive strength and density measurments. (3) Large cubes of 100 mm side length, for radiation experiment, where it was sliced to 1 cm thick slab after curing.

Table 1: Mix design of the mortar samples in grams.

	Cement type 1	Dune Sand	Crushed Sand	Water	HWRA	GGBS	Silica Fume
O sample	376	230	706	146	4.578	-	-
SG sample	113	230	706	146	4.578	244	19

2.2 Environmental Exposure Regimes

Post-curing, specimens were subjected to four chemical exposure environments representative of field conditions in arid nuclear facilities: (1) Na_2SO_4 solution at 22 °C (S2F), (2) Na_2SO_4 solution at 50 °C (S5F), (3) $MgSO_4$ solution at 50 °C (M5F), (4) $NaCl+Na_2SO_4$ solution at 50 °C (CS5F). The total exposure duration was four months. However, these were accelerated test with high concentration solution of 10 %w/v.

2.3 Evaluation Techniques

To evaluate the mechanical properties, compressive strength tests were done following ASTM C109. Durability parameters, including ultrasonic pulse velocity (UPV), electrical resistivity, and density, were measured after and before exposure. Radiation shielding performance was evaluated by determining the linear attenuation coefficient (μ) by implementing Bear-lambert law. The drop in gamma intensity was measured after placing each slab of concrete using a high-purity germanium detector (HPGe). While the used gamma radiation sources was Co-60.

3. Results and discussion

Following the completion of the exposure period and the application of mechanical, durability, and shielding the resulting data were analyzed. The key findings regarding the performance differences between ordinary and mineral admixture-modified mortars are presented in this section.

3.1 Compressive Strength Results

The compressive strength results of OA and SG mortars before and after four months of exposure to different aggressive environments are presented in Figure 1. The exposure of SG mortars to magnesium sulfate (M5F) resulted in a decrease in compressive strength because Mg^{2+} ions reacted with Calcium Hydrate products and C-S-H to form brucite and gypsum, which weakened the cement matrix. The SG and OA mortars experienced strength increases under sodium sulfate exposure conditions (SSF and S2F) because the ongoing pozzolanic reactions led to denser and more refined matrix structures. After four months, the combined chloride-sulfate exposure (CS5F) resulted in the highest compressive strength values. The chloride ions in the solution reduced excessive ettringite formation which led to less internal expansion and less damage.

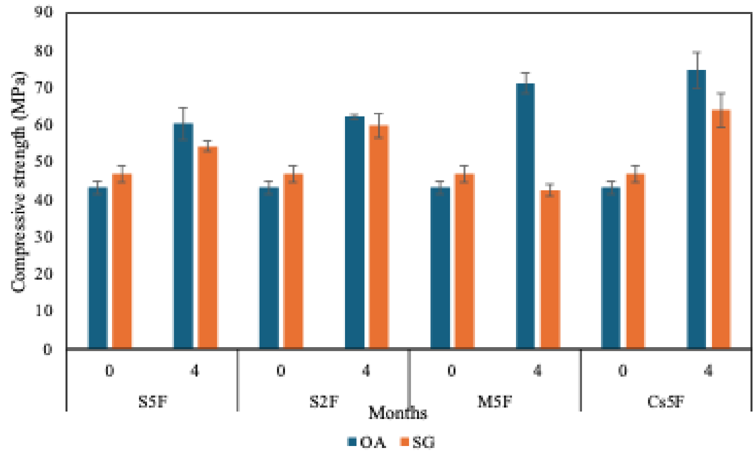

Fig. 1: Compressive strength results before and after 4 months of different exposure conditions.

3.2 Durability Indicators

Durability indicators revealed different behaviors between OA and SG mortars. OA samples exhibited higher UPV values due to faster hydration and denser early microstructure, while SG's finer particles resulted in higher initial porosity, see Figure 2. After exposure to magnesium sulfate SG samples showed reduction in UPV, supporting the observed strength loss. In terms of electrical resistivity as shown in Figure 3, SG mortars initially outperformed OA, attributed to a denser matrix from pozzolanic activity, while OA samples consistently demonstrated lower resistivity, indicating higher ionic permeability and vulnerability to chemical attack. Over time, SG mortars experienced resistivity reductions, particularly under M5F and CS5F conditions, reflecting microstructural damage. Conversely, OA samples exhibited increasing resistivity over exposure time, suggesting ongoing ettringite and gypsum formation that temporarily filled pores before significant cracking developed. Bulk density decreased slightly for both mixes over four months as demonstrated by Figure 4, with greater losses at 50 °C due to accelerated sulfate attack and ettringite-induced microcracking. SG mortars under $MgSO_4$ exposure suffered notable density reduction, aligning with UPV and strength findings, while under CS5F conditions, SG exhibited a slight density increase, likely driven by continued hydration and chloride stabilization effects.

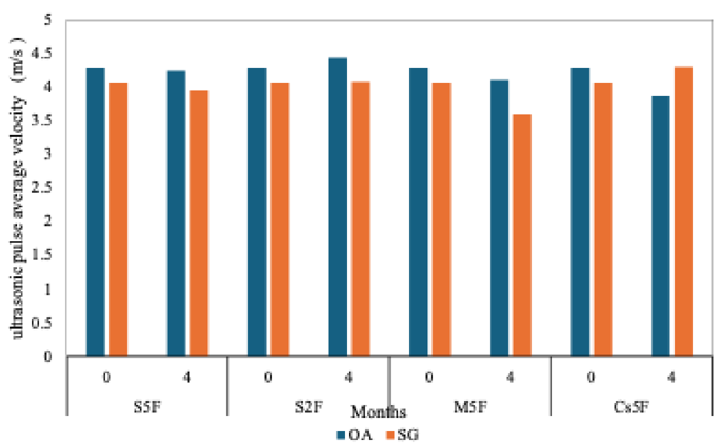

Fig. 2: UPV results before and after 4 months of different exposure conditions

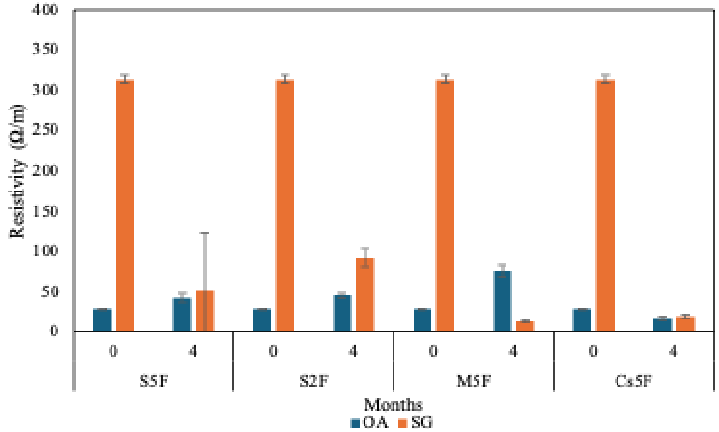

Fig. 3: Resistivity results before and after 4 months of different exposure conditions

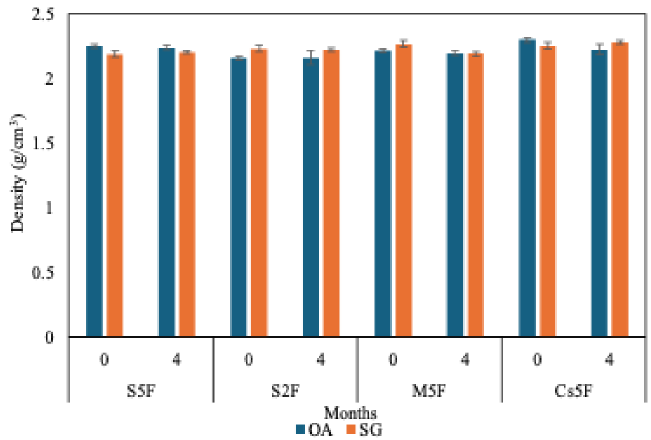

Fig. 4: Density results before and after 4 months of different exposure conditions.

3.3 Gamma Radiation Shielding Performance

Figure 5 illustrate the influence of sulfate-induced degradation at elevated temperatures on gamma radiation shielding over four months for both OA and SG mortars. SG samples consistently maintained higher attenuation values, attributed to their denser microstructure and lower porosity. In contrast, OA samples exhibited reduced shielding performance after exposure, likely due to microcracking and phase changes disrupting mass density. These findings confirm that chemical degradation affects shielding capacity. However, mineral admixtures help preserve radiological integrity. As expected, attenuation decreased with increasing photon energy, reflecting deeper penetration of higher-energy gamma rays.

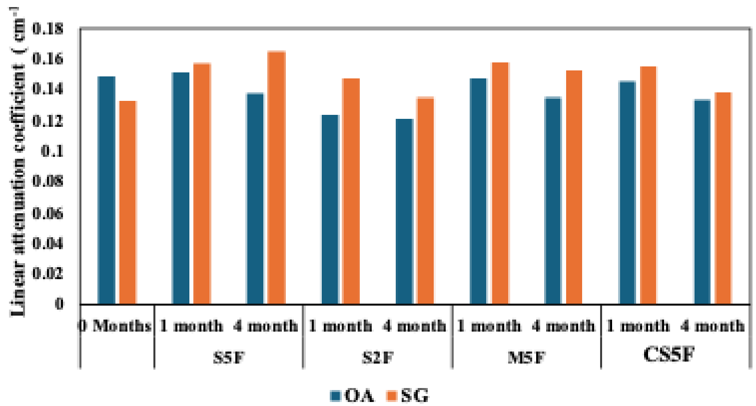

Fig. 5: Gamma attenuation coefficient results before and after 4 months of different exposure conditions.

4. Conclusion

The incorporation of mineral admixtures silica fume and GGBS improved the mechanical durability and radiation shielding capacity of mortars under aggressive chemical and thermal exposures. SG mortars showed superior strength retention and durability, effectively preserving shielding integrity despite chemical degradation. Magnesium sulfate exposure caused the most severe deterioration, consistent with literature findings, while combined chloride-sulfate attack at elevated temperature resulted in less damage than pure sulfate exposure. These results confirm that mineral admixtures enhance concrete resilience in nuclear infrastructure applications under harsh arid conditions. Future work will extend exposure durations to assess long-term degradation behavior, expand testing conditions to include irradiation environments, and incorporate nano-additive modifications to further optimize mechanical and shielding performance. SEM, EDS, and XRD will be used to perform advanced microstructural analyses to study chemical transformations, crack development, and phase stability under coupled chemical, thermal, and radiological stressors.

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