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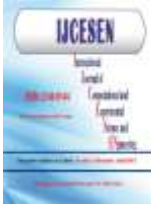

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Research Article

Exploring the Radiation Shielding Efficiency of High-Density Aluminosilicate Glasses and Low-Calcium SCMs

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Abstract:

A lot of work is now going into making low-calcium supplementary cementitious materials (SCMs) and aluminosilicate glasses so that they can be used as radiation shielding materials. These materials demonstrate superior performance in several aspects as compared to conventional concrete. The present investigation focuses on the radiation shielding characteristics of the evaluated materials, specifically their capacity to reduce the intensity of gamma rays and neutrons. Regarded for their exceptional density and ability to include heavy metal oxides, aluminosilicate glasses have remarkable shielding characteristics, especially when designed at the molecular scale. An evaluation of the performance of these materials in comparison to traditional concrete is carried out using Phy-X/PSD software. The goal is to determine the most important shielding properties, such as the mass attenuation coefficient, the linear attenuation coefficient, and the half-value layer. Our study findings suggest that some aluminosilicate glasses, such as GM, consistently demonstrate exceptional photon and neutron attenuation efficiency. The observation that GM performs better than other materials in tests like effective atomic number, rapid neutron removal cross section, and energy absorption accumulation factor supports this claim. There is evidence that using low-calcium glass-crystal materials (SCMs) with aluminosilicate glasses not only improves radiation protection but also makes solutions work better when space or weight are limited. The present investigation validates that these materials exhibit superior performance compared to conventional concrete in challenging environments such as nuclear waste storage, where safety is of utmost significance.

1. Introduction

The ongoing pursuit of advanced materials for radiation shielding has led to the exploration of low-calcium supplementary cementitious materials (SCMs) and aluminosilicate glasses, which have shown significant potential over traditional concrete. In particular, aluminosilicate glasses are becoming more and more known for their high density and capacity to include heavy metal oxides, which improves their ability to attenuate radiation, especially that of gamma rays and neutrons [1-3].

Unlike conventional concrete, which primarily relies on its bulk density, aluminosilicate glasses can be engineered at the molecular level to optimize their shielding properties while maintaining structural integrity. This molecular-level engineering provides a clear benefit in situations where good shielding performance and space efficiency are essential [4-8]. The combination of low-calcium SCMs with aluminosilicate glasses offers the potential to create hybrid shielding materials that surpass the performance of standard concrete. This is particularly relevant in environments where space and weight are critical, and where superior radiation attenuation is required. Prior research by Zheng et al. (2024) examined how temperature affected the dissolution of low-calcium SCMs and aluminosilicate glass in alkaline settings [9], offering important insights into the materials' chemical stability and resilience in harsh settings. This groundbreaking study demonstrated the behavior of these materials in high-stress applications, such as nuclear waste storage, under comparable circumstances. Building upon the findings of Zheng et al. (2024), the current study aims to extend the investigation by evaluating the radiation shielding performance of these materials as standalone entities. The main goal is to determine how well aluminosilicate glass and low-calcium SCMs attenuate neutrons and gamma rays, and to compare their efficacy with traditional concrete. Investigating if these cutting-edge materials may offer better radiation protection and possibly more efficient solutions for situations that need stronger shielding capabilities is the goal of this research [10-12].

2. Material and Methods

2.1 Chemical Composition and Density

Based on their chemical compositions and densities as described in the previous research, the study examines the radiation shielding characteristics of low-calcium supplemental cementitious materials (SCMs) and aluminosilicate glasses. Commercial fly ash (FA) samples as well as five different kinds of aluminosilicate glasses (G2–G6) were utilized. The chemical compositions and densities of these materials are necessary in order to compute the different radiation shielding characteristics.

2.2 Radiation Shielding Calculations

The Phy-X/PSD software was used to calculate several key radiation shielding parameters based on the chemical compositions and densities of the materials [13]. The parameters included the mass attenuation coefficient, linear attenuation coefficient, half value layer, and mean free path. Additionally, the effective atomic number, effective electron density, fast neutron removal cross section, and energy absorption buildup factor were calculated. To compare the performance of the aluminosilicate glasses and SCMs with conventional concrete, the calculated parameters were visualized through various graphs, highlighting the potential advantages of the materials in protection applications.

3. Results and Discussions

In this study, we conducted a comprehensive analysis of the radiation shielding properties of various SCM materials, as depicted through several figures. Figure 1 shows that G5 and GM had very close densities, with G5 at 2.647 g/cm³ and GM at 2.644 g/cm³, indicating that higher density often enhances radiation shielding. Moving to Figure 2, we observe a gradual decrease in mass attenuation coefficients (MAC) with increasing photon energy.

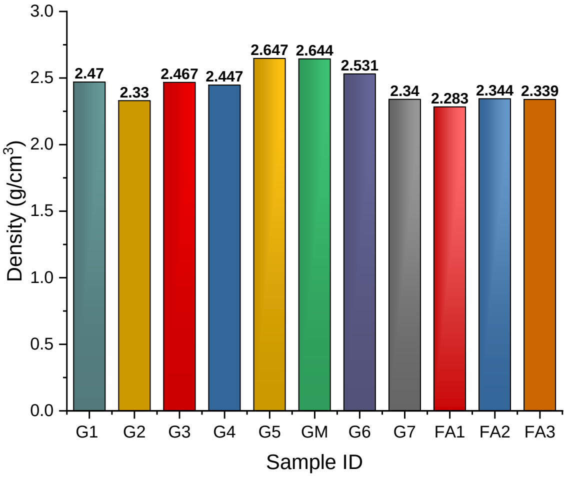


Figure 1: *Density variation for all investigated SCM samples.*

This trend reflects a shift in interaction mechanisms, where higher photon energies result in reduced interaction probabilities [14]. Despite this general trend, G5 and GM consistently exhibited the highest MAC values across energy levels, with G5 at 0.2089 cm²/g and GM at 0.2088 cm²/g at 15 MeV, highlighting their superior photon attenuation capabilities. Correspondingly, Figure 3 confirms GM’s superior performance in linear attenuation coefficients (LAC), which aligns with its high MAC values and underscores its effective photon absorption. In addition, Figure 4 reveals that GM achieved the lowest half-value layers (HVL), indicating that a thinner layer of GM is needed to reduce radiation intensity by half.

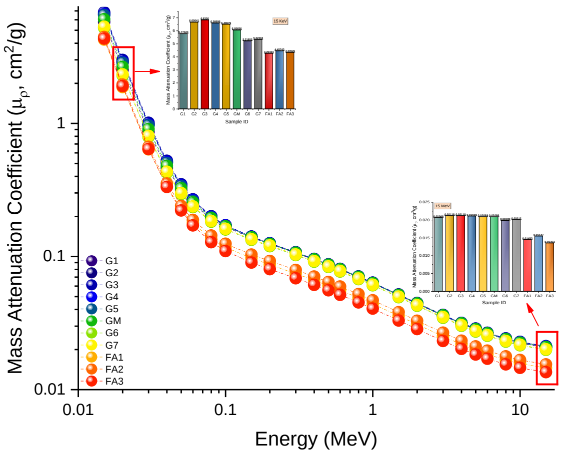


***Figure 2:** Variation of mass attenuation coefficients (cm^2/g) for all investigated SCM samples.*

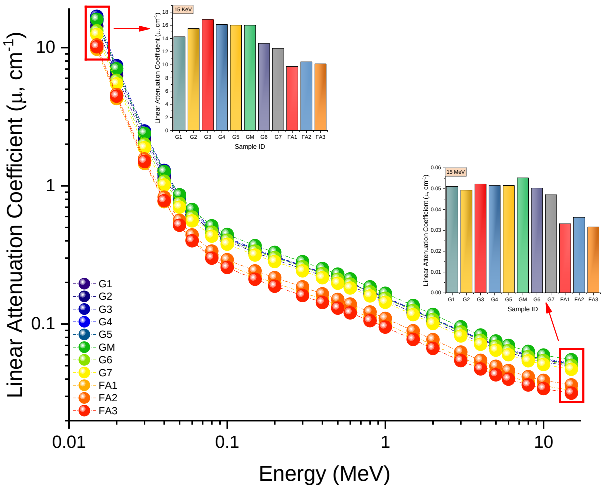


***Figure 3:** Variation of linear attenuation coefficient (cm-1) with photon energy (MeV) for all investigated SCM samples.*

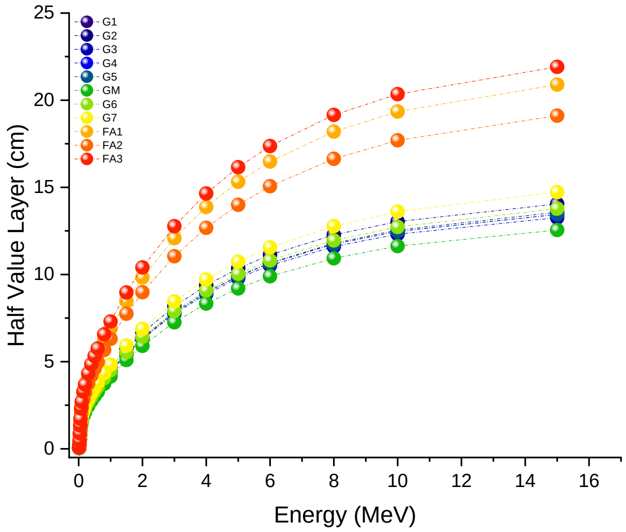


***Figure 4:** Variation of the half-value layer (cm) for all investigated SCM samples.*

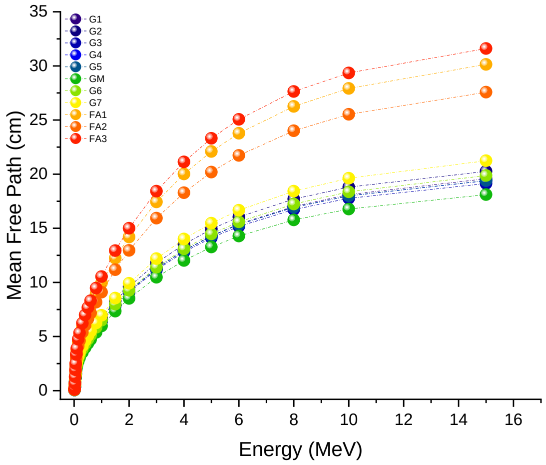


***Figure 5:** Variation of mean free path (cm) with photon energy (MeV) for all investigated SCM samples.*

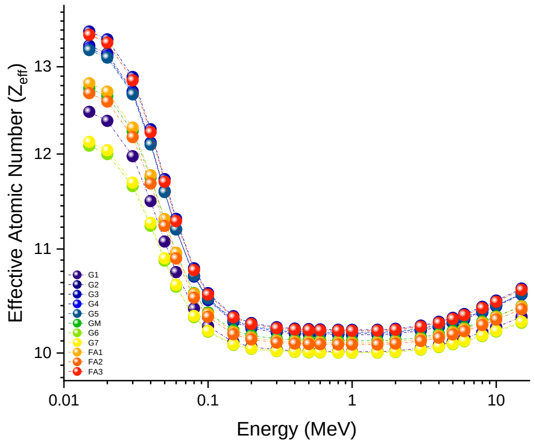


***Figure 6:** Variation of effective atomic number (Z_{eff}) with photon energy (MeV) for all investigated SCM samples.*

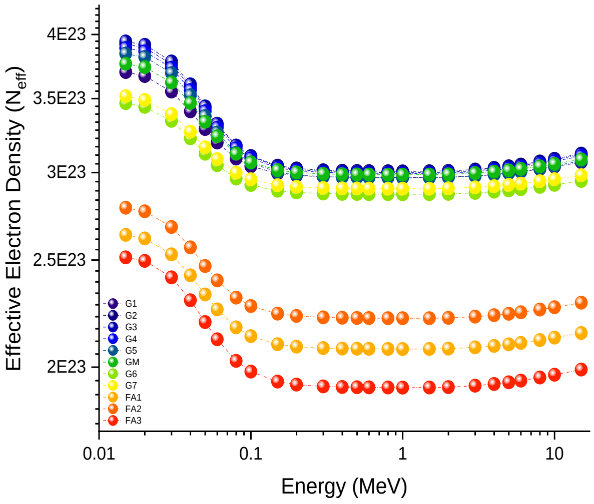


***Figure 7:** Variation of effective electron density (N_{eff}, electrons/g) with photon energy (MeV) for all investigated SCM samples.*

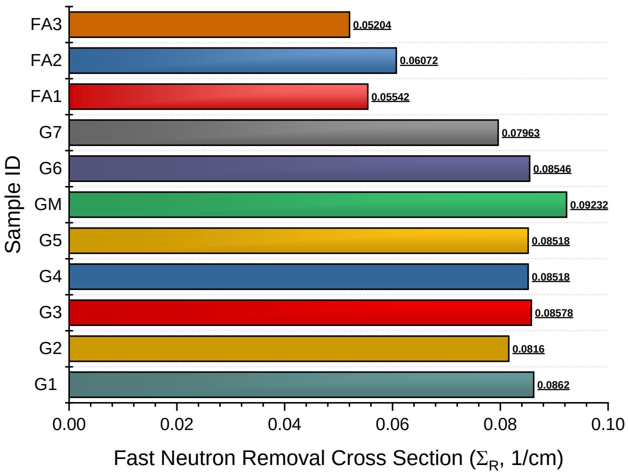
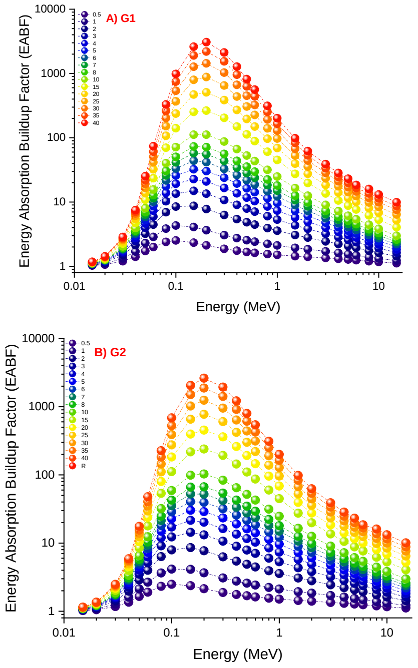
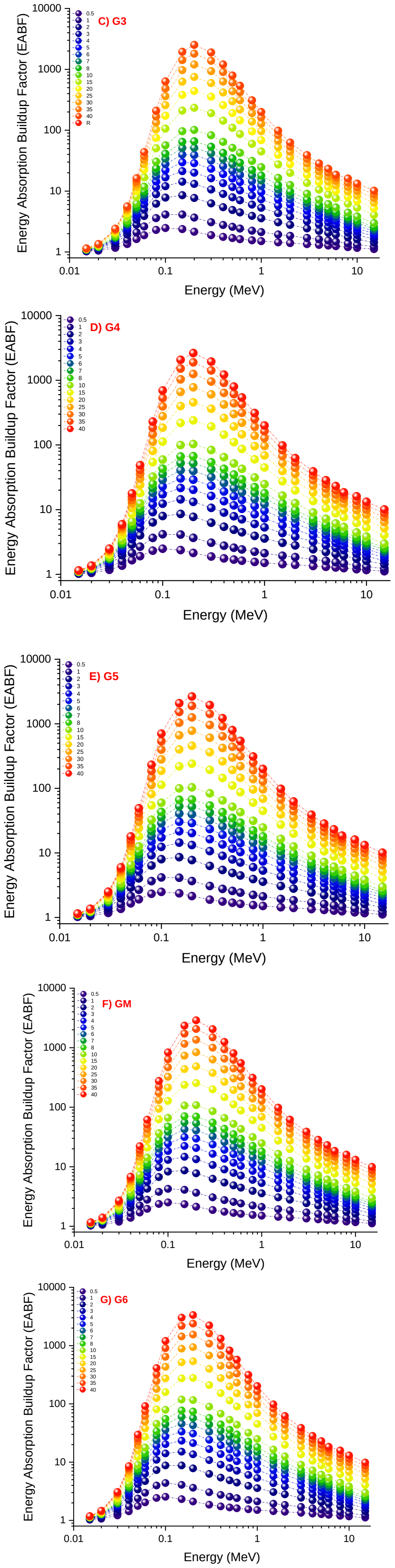


Figure 8: *Variation of fast neutron removal cross section (∑R, 1/cm) values of all investigated SCM samples.*

This finding further supports GM's effectiveness as a shielding material. Similarly, Figure 5 shows GM's lowest mean free path (MFP) values, suggesting that gamma rays travel shorter distances before interacting with the material. These results reinforce GM's superior attenuation capabilities observed in both HVL and LAC. Moving to Figures 6 and 7, we note that effective atomic number (Zeff) and effective electron density (Neff) generally decrease with increasing photon energy. This trend reflects the reduced likelihood of interactions as photon energy rises. Despite some variations, these parameters support the overall findings of the study regarding gamma-ray attenuation. Furthermore, Figure 8 highlights GM's highest fast neutron removal cross-section (FNRCS), demonstrating its exceptional ability to shield against fast neutrons.





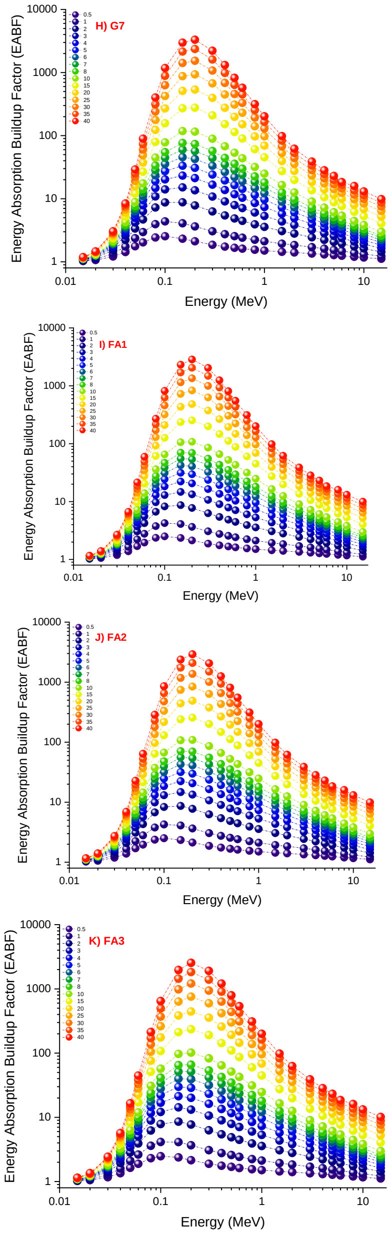


Figure 9(a-k). *Variation of energy absorption buildup factors (EABF) of all investigated SCM samples at different mean free path values.*

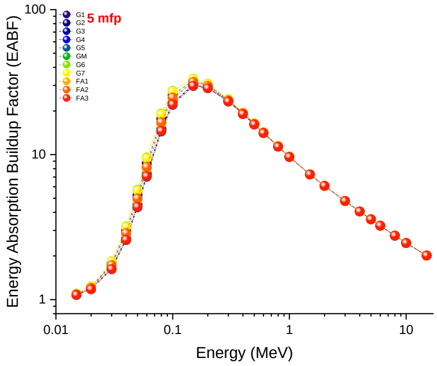


Figure 10: *Benchmarking of Energy absorption buildup factor all investigated SCM samples at 5 mfp.*

Finally, Figure 9(a-k) presents the energy absorption buildup factor (EABF) for each sample. The values were closely clustered, but further analysis at a fixed mean free path of 5 mfp indicated that G3 had the lowest EABF values in this region (Figure 10). This suggests that, while all materials exhibited comparable performance, G3 showed marginally superior absorption of radiation at this distance. This result is significant for assessing the practical effectiveness of shielding materials, as it highlights G3's potential for slightly better performance in real-world applications where energy absorption is a critical factor. Overall, as photon energy increases, the shift in interaction dominance impacts shielding performance [15,16]. GM's consistent superiority across various parameters underscores its effectiveness in providing comprehensive radiation shielding, aligning with the study's objective to evaluate and identify optimal shielding materials.

4. Conclusions

This study builds on our earlier work, "Experimental Investigation of the Temperature-Dependent Dissolution Process of Aluminosilicate Glass and Low-Calcium Supplementary Cementitious Materials Under Alkaline Conditions", which focused on the chemical stability of aluminosilicate glasses and low-calcium SCMs, this study extends our understanding by evaluating their radiation shielding efficiency [17-18]. According to our results, denser materials—like G5 and GM—have better shielding characteristics, which is consistent with the material properties found in the previous study. Notably, GM showed exceptional performance in a variety of radiation shielding parameters, including both neutron shielding and photon attenuation, demonstrating its usefulness in real-world scenarios. Building on the findings of our earlier research on chemical stability, this study's trends include the effect of material density on shielding performance. This relationship emphasizes how crucial material composition is in defining stability and shielding effectiveness. All things considered, this research validates that the characteristics mentioned in the previous studies [19-25] are essential for improving radiation shielding materials, and GM stands out as a particularly potent choice for complete radiation protection.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.

- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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