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## Research Article

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**Posted Date:** October 22nd, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-11453701/v1>

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**Additional Declarations:** The authors declare no competing interests.

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# Mechanical Performance and High-Energy Photon Attenuation of a Slag-Based Geopolymer Concrete Incorporating Calcined Brezina Dam Sediments

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## Abstract

This study investigates a slag-based geopolymer concrete incorporating calcined sediments collected from the Brezina dam in Algeria, with a focus on mechanical performance and the potential attenuation of high-energy photons. Ground granulated blast-furnace slag (GBFS) was used as the principal precursor, while calcined sediment and silica powder formed the secondary binder fraction. Four mixtures contained 0, 10, 20, or 30% calcined sediment in the secondary binder fraction. The sediment was dried, ground, sieved to 80  $\mu\text{m}$ , and calcined at 750 °C for 5 h. The alkaline activator comprised sodium silicate and 12 M sodium hydroxide, with a reported sodium-silicate-to-sodium-hydroxide mass ratio of 2.5. Specimens received an initial heat treatment at 70 or 80 °C for 6, 8, or 10 h, or at 90 °C for 6 h, followed by maturation at ambient conditions. The reported results indicate that the 10% and 20% sediment mixtures generally exhibited better mechanical performance than the 0% and 30% mixtures. For the 10% mixture, compressive strength increased from 44.74 MPa after 6 h to 58.41 MPa after 10 h at 80 °C; the corresponding values for the 20% mixture were 41.13 and 55.50 MPa. Monte Carlo simulations using GATE/Geant4 for a 6-MV flattening-filter-free photon beam yielded a half-value layer (HVL) of 9.94 cm and a tenth-value layer (TVL) of 27.19 cm for the geopolymer mix. These values were close to those reported for the reference standard concrete (10.11 and 27.69 cm, respectively), while barium-rich concrete showed lower HVL and TVL values. The results support further investigation of calcined dam sediments as a locally available constituent of geopolymer concrete; however, the radiation-shielding findings are simulation-based and require experimental validation.

**Keywords:** geopolymer concrete; ground granulated blast-furnace slag; calcined dam sediment; Brezina dam; compressive strength; photon attenuation; Monte Carlo simulation.

## 1 Introduction

Reducing the environmental burden of construction materials motivates the development of alternative binders based on industrial by-products and locally available mineral resources. Alkali-activated materials and geopolymer binders can incorporate aluminosilicate precursors such as ground granulated blast-furnace slag (GBFS) and calcined clay-like materials [1, 2]. The performance of these binders depends on precursor chemistry, activator composition, curing conditions, and the resulting pore structure.

A further application of interest is radiation shielding in medical and technical facilities. Shielding performance depends on photon energy, elemental composition, density, geometry, and the quality of the material. Heavyweight aggregates or high-atomic-number additives can improve photon attenuation, but may add cost or create workability and segregation challenges [3, 4]. Valorising calcined dam sediments in a slag-based geopolymer could therefore contribute to resource efficiency while providing a material whose mechanical and shielding properties can be assessed.

This paper examines a geopolymer concrete prepared using GBFS, calcined Brezina dam sediment, silica powder, standardised sand, and coarse aggregate. The work has two objectives: (i) to assess the effect of sediment replacement level and initial heat-curing conditions on hardened density and mechanical performance; and (ii) to compare simulated depth-dose attenuation for the geopolymer mix with reference concretes under a 6-MV flattening-filter-free (FFF) photon beam. Because the available shielding results are computational, they are interpreted as a comparative screening study rather than a demonstration of clinical shielding compliance.

## 2 Materials and methods

### 2.1 Raw materials

The principal precursor was ground granulated blast-furnace slag obtained from the El Hadjar steel complex, Annaba, Algeria. The reported Blaine fineness was  $6131 \text{ cm}^2 \text{ g}^{-1}$ , and the absolute density was  $2.723 \text{ g cm}^{-3}$ . Its reported oxide composition included 39.34%  $\text{SiO}_2$ , 9.64%  $\text{Al}_2\text{O}_3$ , 24.93%  $\text{CaO}$ , and 3.64%  $\text{MgO}$ .

Sediments were collected from the Brezina dam, air-dried, oven-dried at  $105^\circ\text{C}$  for 24 h, ground, and sieved through an  $80\text{-}\mu\text{m}$  sieve. They were then calcined at  $750^\circ\text{C}$  for 5 h. The reported absolute density and Blaine fineness of the calcined sediment were  $2.9 \text{ g cm}^{-3}$  and  $13\,000 \text{ cm}^2 \text{ g}^{-1}$ , respectively. Its reported oxide composition was 68.94%  $\text{SiO}_2$ , 8.15%  $\text{Al}_2\text{O}_3$ , 9.73%  $\text{CaO}$ , and 3.33%  $\text{Fe}_2\text{O}_3$ . The silica powder contained more than 95%  $\text{SiO}_2$  and was supplied by TEKNACHEM Algérie. The fine aggregate was standardised sand conforming to EN 196-1; the coarse aggregate was a 3/12.5-mm gravel from the El Bayadh region.

Sodium silicate and sodium hydroxide were used as alkaline activators. The NaOH solution was reported as 12 M and prepared 24 h before casting. The manuscript source reports a sodium-silicate/NaOH mass ratio of 2.5; this ratio should be checked against the laboratory batch sheets before submission.

### 2.2 Mixture proportions

Four mixtures were reported, with a constant GBFS content of  $750 \text{ kg/m}^3$ , aggregate contents, and activator dosages. The sediment content was varied by changing the balance between calcined sediment and silica powder. The reported proportions are reproduced in Table 1.

### 2.3 Mixing, casting, and curing

The aggregate and solid precursors were first blended. The NaOH solution was then added and mixing continued for 2 min. Sodium silicate was subsequently introduced, followed by a further 5 min of mixing; the reported total mixing duration was approximately 9 min. Fresh mixtures were cast and subjected to a progressive heating regime at  $5^\circ\text{C min}^{-1}$ . Initial heat curing was conducted at  $70$  and  $80^\circ\text{C}$  for 6, 8, or 10 h, and at  $90^\circ\text{C}$  for 6 h. After heating and gradual cooling, specimens

Table 1: Reported mixture proportions (kg/m<sup>3</sup> unless otherwise indicated).

| Constituent                        | M1  | M2  | M3  | M4  |
|------------------------------------|-----|-----|-----|-----|
| GBFS                               | 750 | 750 | 750 | 750 |
| Silica powder                      | 135 | 120 | 105 | 150 |
| Calcined Brezina sediment          | 15  | 30  | 45  | 0   |
| Standardised sand                  | 800 | 800 | 800 | 800 |
| Coarse aggregate                   | 200 | 200 | 200 | 200 |
| Sodium silicate                    | 350 | 350 | 350 | 350 |
| NaOH solution                      | 140 | 140 | 140 | 140 |
| Sediment share of secondary binder | 10% | 20% | 30% | 0%  |

matured under ambient conditions until testing. The source describes measurements after the heat treatment and at 28 days.

## 2.4 Physical and mechanical tests

Dry hardened bulk density was measured on  $40 \times 40 \times 160$ -mm prisms following EN 1015-10. Flexural strength was measured on prismatic specimens, and compressive strength was measured on  $40 \times 40 \times 80$ -mm portions, following the procedures reported in the source as ASTM C348 and ASTM C109, respectively. Each reported mechanical result was calculated as the mean of three specimens. The original study also reports laser particle-size analysis using a CILAS 1180 and X-ray fluorescence analysis of the precursor materials.

## 2.5 Monte Carlo photon-attenuation assessment

Photon attenuation was assessed computationally using GATE based on Geant4. The source was a phase-space file for a Varian TrueBeam linear accelerator with a 6-MV FFF photon beam and a  $20 \times 20$  cm<sup>2</sup> field. The source-to-surface distance was 100 cm. The geopolymer composition was defined using X-ray fluorescence results, and the reported density of the geopolymer mix was 2.35 g cm<sup>-3</sup>. Dose was scored as a function of depth and normalised to the maximum dose:

$$P(z) = 100 \frac{D(z)}{D_{\max}}, \quad (1)$$

where  $D(z)$  is the dose at depth  $z$  and  $D_{\max}$  is the maximum dose recorded in the material. HVL and TVL were estimated from the depths corresponding to 50% and 10% of the maximum dose, respectively. The source document compares the geopolymer mix with standard, WC020, and baryte concretes using their specified elemental compositions and densities. Full simulation settings, statistical uncertainties, and input material definitions should be provided in a final research submission for reproducibility.

# 3 Results and discussion

## 3.1 Hardened density

The reported density decreased as the initial curing duration increased. At 80 °C, the M1 mixture (10% sediment) decreased from 2350 kg/m<sup>3</sup> after 6 h to 2316 kg/m<sup>3</sup> after 10 h. M2 (20% sediment)

decreased from 2312 to 2294 kg/m<sup>3</sup>, M3 (30% sediment) from 2220 to 2193 kg/m<sup>3</sup>, and M4 (0% sediment) from 2198 to 2176 kg/m<sup>3</sup>. The 10% sediment mixture had the highest reported density among these mixtures, while the 30% mixture had the lowest. These trends may reflect differences in packing, pore structure, and moisture loss during heat treatment; further microstructural evidence would be needed to distinguish these mechanisms.

### 3.2 Compressive and flexural strength

The reported compressive strength increased with longer heat-curing duration. At 70 °C, M1 increased from 43.14 MPa after 6 h to 48.33 MPa after 8 h and 53.52 MPa after 10 h. At 80 °C, M1 reached 44.74, 50.13, and 58.41 MPa after 6, 8, and 10 h, respectively. For M2, the corresponding values at 80 °C were 41.13, 49.77, and 55.50 MPa. After 6 h at 90 °C, the reported compressive strengths were 47.75, 46.50, 45.10, and 45.10 MPa for M1, M2, M3, and M4, respectively.

The source reports that all mixtures gained compressive strength by 28 days, consistent with continued reaction and maturation after the initial thermal treatment. It also identifies the 10% and 20% sediment mixtures as the better-performing compositions under the investigated conditions. A complete numerical table of every curing condition, uncertainty estimates, and individual replicate values is not available in the source summary used to prepare this manuscript and should be added before submission. The reported flexural-strength discussion notes that M1 increased from 4.86 to 8.22 MPa between the initial thermal-treatment measurement and 28 days; the exact corresponding curing condition should be specified from the original laboratory records.

### 3.3 Simulated photon attenuation

The depth-dose profiles decreased with increasing depth after the build-up region. The geopolymer mix (GPM) and standard concrete showed similar simulated attenuation, whereas the WC020 and baryte reference concretes showed more rapid dose reduction. Table 2 summarises the reported HVL and TVL values.

Table 2: Reported half-value layer (HVL) and tenth-value layer (TVL) from the Monte Carlo depth-dose profiles.

| Material           | HVL (cm)          | TVL (cm) |
|--------------------|-------------------|----------|
| Geopower mix (GPM) | 9.94              | 27.19    |
| Standard concrete  | 10.11             | 27.69    |
| WC020              | 6.62 <sup>a</sup> | 24.49    |
| Baryte concrete    | 7.35              | 20.69    |

<sup>a</sup>The source document contains an inconsistency: the table reports 6.62 cm for WC020, while the discussion text reports 8.65 cm. This value must be checked against the simulation output before the manuscript is submitted.

The reported GPM HVL and TVL were approximately 1.7% and 1.8% lower than those of standard concrete, respectively, indicating similar attenuation in the simulated configuration. However, the GPM did not outperform the baryte reference, which had a TVL of 20.69 cm. The data therefore support a cautious conclusion: the investigated geopolymer may provide attenuation comparable to the specified standard-concrete model, but the results do not establish equivalence for all beam qualities, geometries, or clinical shielding applications. Independent experimental measurements and uncertainty analysis are needed before practical use can be recommended.

## 4 Limitations

Several limitations should be addressed in a revised version. First, the radiation-shielding results are simulation-based and should be validated experimentally. Second, complete dose-depth data, Monte Carlo statistical uncertainties, physics lists, production cuts, scoring voxel dimensions, and detailed material definitions are needed to enable reproduction. Third, the reported WC020 HVL is inconsistent between the results table and the accompanying discussion. Fourth, the mix-design activator ratio and all batch quantities should be checked against laboratory records, and the full strength dataset should be presented with replicate variability. Finally, environmental benefits are discussed as motivation only; no life-cycle assessment or measured carbon footprint was conducted in this study.

## 5 Conclusions

A slag-based geopolymer concrete incorporating calcined Brezina dam sediments was investigated for mechanical performance and simulated high-energy photon attenuation. The reported results indicate that sediment replacement level and initial heat-curing conditions affect hardened density and strength. The 10% sediment mixture reached a compressive strength of 58.41 MPa after 10 h at 80 °C, while the 20% mixture reached 55.50 MPa under the same condition. Mixtures containing 10% and 20% sediment were reported to perform better mechanically than those containing 0% and 30%.

For the simulated 6-MV FFF beam, the geopolymer mix had reported HVL and TVL values of 9.94 and 27.19 cm, close to those of the modelled standard concrete. These results are preliminary and should not be interpreted as proof of clinical shielding adequacy. Future work should provide complete strength data and uncertainty estimates, resolve inconsistencies in the reported shielding values, document simulation settings, validate the attenuation experimentally, and assess durability and environmental impacts.

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Author contributions

**Hind Sallai** : Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Elhadj Dahi**: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – review & editing (equal). **Aya Ouali**: Data curation (equal); Formal analysis (equal); Visualization (equal). **Abd El Djailil Hamidi**: Data curation (equal); Formal analysis (equal); Visualization (equal). **Asma Idrici**: Data curation (equal); Formal analysis (equal); Visualization (equal)

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