



## Stabilizing hazardous mine waste in alkali-activated geopolymers for pollution mitigation at abandoned mining sites

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The use of alkali-activated materials presents a sustainable approach to replacing conventional construction resources while promoting waste valorization, in line with the goals of the blue economy for environmentally responsible development. This study explores the innovative use of mine waste (MW) from an abandoned lead-zinc (Pb-Zn) mining site in Northern Tunisia as a cost-effective, high-adsorption additive in the production of metakaolin-based geopolymers. Metakaolin (sourced from Vicente Pereira, Ovar, Portugal) was partially substituted with MW in varying proportions (0%, 5%, 10%, 20%, and 30%). The geopolymer formulations maintained constant molar ratios of  $\text{SiO}_2/\text{Al}_2\text{O}_3$  and  $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$  at 1 to minimize the use of sodium silicate and sodium hydroxide, leading to the development of environmentally friendly geopolymers with a reduced carbon footprint.

The study assessed how the incorporation of MW influences the geopolymers' microstructure, mechanical strength, and ability to adsorb methylene blue dye. Chemical analysis of MW revealed elevated concentrations of hazardous elements, up to 2.23 wt.% Pb and 8.2 wt.% Zn, highlighting the importance of stabilizing these elements to prevent environmental contamination. Scanning Electron Microscopy (SEM) indicated varying degrees of geopolymerization across different formulations, predominantly featuring amorphous phases. After 28 days of curing, samples with 5 wt.% and 10 wt.% MW exhibited the highest compressive strengths of 25 MPa and 30 MPa, respectively.

The adsorption capacity of the developed geopolymers was evaluated using Methylene Blue (MB) dye, with experiments focusing on the effects of adsorbent dosage and contact time. Adsorption kinetics closely followed the pseudo-second-order model, while the Langmuir isotherm model best described the adsorption behavior. Notably, samples with 30 wt.% and 0 wt.% MW achieved the highest adsorption capacities, demonstrating the beneficial role of MW in enhancing the properties of alkali-activated metakaolin geopolymers and its potential to partially substitute metakaolin.

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