Stabilization of Landfills Using Geopolymer-Based Waste Materials to Reduce Permeability under Freeze-Thaw Cycles

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ABSTRACT

The most significant environmental issue associated with waste landfills is the contamination of groundwater resources by toxic and hazardous pollutants. Natural clay is commonly used in landfills to reduce permeability; however, in cold regions, freeze-thaw cycles can significantly increase permeability over time. An optimal solution involves stabilizing and reinforcing the soil at the base of landfills using waste materials already present within the landfill itself. In this study, two types of waste materials were selected as geopolymeric agents for soil stabilization: waste glass powder (0%, 5%, 10%, 15%, and 20%) and calcium carbide residue (0%, 3%, 7%, 10%, and 13%). A comprehensive series of laboratory tests was conducted to evaluate the influence of freeze-thaw cycles on permeability, including unconfined compressive strength, permeability, frost penetration depth, volume change, direct shear, and microstructural analyses. The results indicated that the specimen stabilized with 15% waste glass powder and 7% calcium carbide residue exhibited the lowest permeability and the highest resistance to freeze-thaw cycles. In this optimized stabilized sample, lead adsorption (as a representative heavy and harmful metal in landfills) reached 97% under non-freeze-thaw conditions and remained as high as 83% after 12 freeze-thaw cycles, demonstrating the effectiveness of this method in preventing groundwater contamination. Although freeze-thaw cycles generally led to an increase in soil void volume and consequently higher permeability across all samples, the average pore diameter decreased while the number of pores increased. The findings of this study hold considerable potential for environmental protection and sustainable waste management practices.

KEYWORDS

Landfills, Freeze-thaw cycles, Permeability, Waste materials, Geopolymer.

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1. Introduction

The increasing generation of municipal and industrial waste has intensified the environmental risks associated with landfills. In particular, leachate containing toxic heavy metals such as lead may migrate through landfill liners and contaminate groundwater [1]. Compacted clay is commonly used as a low-permeability barrier; however, its performance may deteriorate in cold regions because repeated freeze–thaw (F–T) cycles cause ice formation, expansion, cracking, and increased hydraulic conductivity [2, 3]. These effects are particularly important in fine-grained soils.

Geopolymer stabilization offers a potentially sustainable approach by reusing waste materials while improving soil performance. Geopolymers generally develop through the alkaline activation of aluminosilicate precursors, producing a binding network that can improve soil strength and may immobilize contaminants [4, 5]. In this study, waste glass powder (WGP), rich in SiO_2, was used as the precursor, while calcium carbide residue (CCR), containing calcium-bearing alkaline compounds, was used as the activator [6, 7]. The study evaluates the combined effects of WGP and CCR on the geotechnical behavior, permeability, volumetric response, and lead retention of clay subjected to repeated F–T cycles. The main contribution is the assessment of this waste-based stabilization system under cold-region conditions.

2. Materials and Methods

Natural clay (NC) was collected from Lalehzar, one of the coldest areas of Kerman Province, Iran, at an elevation of approximately 2,800 m. The soil was classified as low-plasticity clay (CL), with an optimum moisture content of 17.3% and a maximum dry unit mass of approximately 1.78 g/cm³. XRF analysis indicated that the soil contained about 42% SiO_2 and 12% Al_2O_3. WGP was obtained from glass-cutting workshops and contained approximately 71% SiO_2. CCR, a by-product of acetylene production, was rich in CaO (approximately 66%).

The soil, WGP, and CCR were first mixed in the dry state, after which water was added. Preliminary tests indicated that this procedure provided more uniform mixing and allowed the heat released during the reaction of CCR with water to contribute to early activation. All specimens were compacted at the optimum moisture content of the natural clay. WGP contents of 0–20% and CCR contents of 0–13% were investigated; the optimum mixture was identified using unconfined compressive strength (UCS) tests. Specimens were exposed to 0, 3, 6, 9, or 12 closed-system F–T cycles. Each cycle consisted of 12 h at −20 °C followed by 12 h at +20 °C. UCS, direct shear, permeability, and volumetric-change tests were conducted, while SEM, EDX, and BET analyses were used to examine microstructural characteristics. Permeability was measured using the falling-head method in accordance with ASTM D5084. For each condition, three specimens were tested and the mean values were reported.

3. Results and Discussion

The optimum mixture contained 15% WGP and 7% CCR. Its UCS reached 1.54 MPa, approximately 8.5 times that of untreated clay. In contrast, the UCS of natural clay decreased by about 42% after 12 F–T cycles, while its failure strain increased by approximately 36%. The greatest changes occurred during the initial cycles, with the response tending to stabilize after about 9 cycles. The optimized mixture exhibited substantially better resistance to F–T deterioration, which may be associated with the development of a more continuous binding structure around soil particles. Excessive WGP or CCR reduced performance, potentially because of unreacted particles and unfavorable changes in the soil's chemical environment.

The direct-shear results showed that the optimized treatment increased cohesion from 63 to 401 kPa and the internal friction angle from 20° to 35°. After 12 F–T cycles, cohesion decreased by 38% in natural clay, compared with only 15% in the optimized mixture. The corresponding reductions in friction angle were approximately 9.6% and 7%, respectively. These results indicate that the WGP–CCR combination improved both the initial shear strength and its retention during cycling.

The lowest hydraulic conductivity was measured in the optimized mixture. Its permeability was approximately 3.2×10^{-10} cm/s before cycling and 1.6×10^{-10} cm/s after 12 cycles, remaining below that of natural clay (approximately 2.5×10^{-6} cm/s after 12 cycles). The optimized mixture also showed the lowest volumetric deformation; its maximum reported volumetric strain was approximately 2.3%, compared with 9.4% for natural clay. These findings suggest that the combined waste additives limited the development of connected voids and cracks during F–T exposure.

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Lead-retention tests were performed using a $Pb(NO_3)_2$ solution with an initial concentration of 50 mg/L. The solution was in contact with the specimens for 24 h, and the residual lead concentration was measured by atomic absorption spectroscopy. The optimized mixture showed the lowest lead migration and retained approximately 83% of the lead even after 12 F–T cycles. Physical confinement within a denser matrix and chemical interactions are possible contributors; however, their individual contributions were not independently quantified in this study. Accordingly, the term "retention" is used broadly to describe the overall immobilization of lead. The effect of geopolymer on reducing the leaching of heavy metals is shown schematically in Figure 1.

SEM images showed that untreated clay had a loose, heterogeneous structure and developed additional cracks and voids after F–T cycling. The optimized mixture appeared more compact and continuous, with fewer visible defects after 12 cycles. EDX confirmed the presence of O, Si, Ca, and Al and showed an increased Si/Al ratio in the optimized mixture; EDX alone, however, cannot identify specific reaction products. BET results indicated changes in pore-size distribution after cycling, including an increase in micropores and a reduction in the size of larger pores. The microstructural observations were consistent with the measured improvements in strength and permeability.

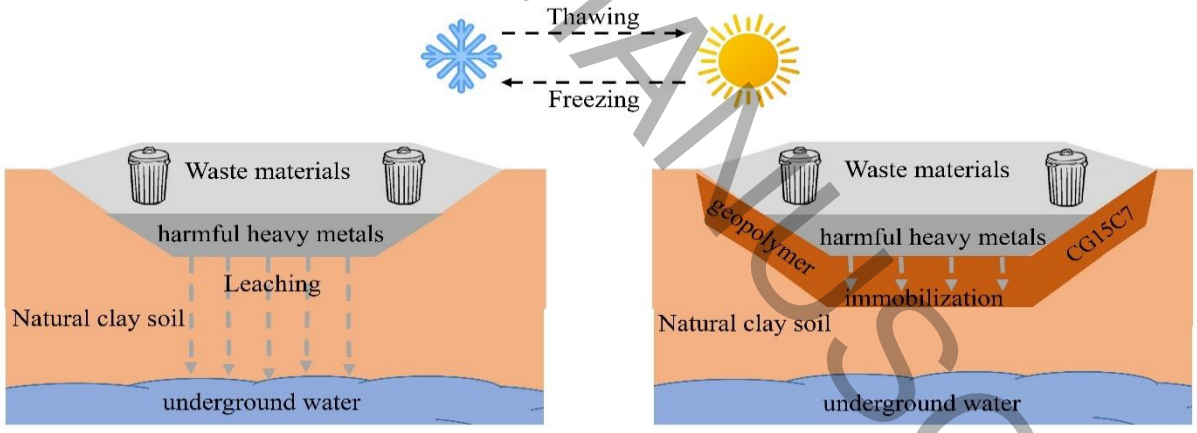

Figure 1. The effect of geopolymer on reducing heavy metal leakage.

4. Conclusions

1. The optimum blend of 15% WGP and 7% CCR substantially improved clay performance. It produced an approximately 8.5-fold increase in UCS, lower permeability and volumetric deformation, and better retention of shear strength after 12 F–T cycles.

2. The optimized geopolymer-treated clay retained approximately 83% of lead after 12 F–T cycles, indicating its potential as a sustainable landfill-barrier material for cold regions. Further long-term testing under realistic leachate and saturation conditions is required.

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