Polypropylene fiber's effect on CBR in lime-stabilized sulfate-contaminated expansive clay

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ABSTRACT

Building on sulfate-contaminated soft soils poses significant geotechnical challenges. Although soil stabilization with fibers has been researched, the specific impact of polypropylene fibers (PF) on lime-stabilized soils in sulfate-rich environments remains unclear. This study explores how PF influences the California Bearing Ratio (CBR) of expansive grey soil (EGS) stabilized with natural pozzolana (NP) and lime, when contaminated with sulfates. In this investigation, EGS was combined with varying amounts of lime, NP, and PF, and exposed to different sulfate concentrations. CBR tests were performed over a range of curing periods (1-120 days), and XRD and SEM analyses were used to observe mineralogical and microstructural changes. Results indicated that adding 8% lime, either alone or with 20% NP, improved the CBR of EGS. The inclusion of PF further increased the CBR up to an optimal 2%, after which it declined. At the 2% PF level, stress transfer from EGS to PF was optimized, enhancing the bonding between PF and EGS particles. The presence of calcium sulfate increased the CBR with higher concentrations and extended curing periods, forming cementitious compounds as observed through XRD and SEM. The combination of 2% PF and 20% NP mitigated the negative impacts of expansive ettringite minerals caused by sodium sulfate contamination in lime-stabilized EGS. The study underscores the effectiveness of PF in enhancing the CBR of EGS, particularly in the presence of calcium sulfates, and supports the use of PF in lime-stabilized expansive clay soils with sulfate contamination. Proper incorporation of PF significantly improves the geotechnical properties of EGS, providing valuable insights for sustainable and effective soil stabilization in sulfate-rich conditions.

Keywords: Expansive grey clayey soil (EGS), additives (lime, natural pozzolana and polypropylene fiber), California Bearing Ratio (CBR), ettringite minerals, sulfates, microstructure, mineralogy, stabilization and reinforcement

1. INTRODUCTION

Globally, soft soils are typically defined by their high compressibility, low bearing capacity, and elevated plasticity index. These characteristics generally stem from the soils' low density, leading to potential fractures and cracks in foundations and structural walls, with the severity depending on the extent of the issues. However, the addition of mineral additives like lime, cement, and fly ash can significantly improve soil strength and stiffness, reduce water content, and enhance overall performance[1]. Harichane et al.[2] observed that the mechanical properties of cohesive soils are markedly improved when treated with lime, either alone or in combination with natural pozzolana (NP), compared to untreated soils.

On the other hand, it is crucial to acknowledge that producing one metric ton of cement results in approximately 0.63 metric tons of CO_2 emissions and requires a significant amount of energy. To reduce CO_2 emissions, which are associated with climate change, flooding, rising temperatures, river depletion, sea level rise, and other environmental issues, the use of alternative mineral additives and fibers in place of cement is essential. Consequently, many researchers recommend the use of volcanic materials and fibers to minimize both CO_2 emissions and energy consumption[1,4-7]. The use of lime, either on its own or mixed with volcanic ash, has become a widely adopted sustainable alternative due to its environmental benefits and effective performance[4].

In Algeria, the high cost of lime compared to natural pozzolana (NP) makes their combination beneficial for reducing construction expenses, CO_2 emissions, and energy consumption. From a mechanical standpoint, the potential decrease in

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geotechnical properties of soil treated with alternative additives instead of cement can be offset by adding polypropylene fibers (PF). These fibers are commercially accessible, offer high tensile strength, and are economically feasible. Previous studies, such as those by Harichane et al.[2] have explored the effects of lime and NP on the engineering properties of cohesive soils.

Extensive research has been conducted on the combined effects of NP and PF on compressibility, swelling, and unconfined compressive strength, both in the presence and absence of sulfates[8,9]. However, their influence on the California Bearing Ratio (CBR) of lime-stabilized clay soils, with or without sulfate contamination, remains underexplored. This study aims to investigate the effect of PF on the CBR of NP-lime-stabilized clay soils that are artificially contaminated with sodium and calcium sulfates. The focus is on CBR as a critical measure of the soil's load-bearing capacity. Moreover, this research will examine the chemical reactions and bonding mechanisms within soil-lime-NP mixtures and soil-lime-NP-sulfate mixtures.

2. MATERIALS, METHODS AND SAMPLES PREPARATION

This study investigated a high plasticity grey clayey soil (EGS) (IP=50.6%, UCS=100 kPa, Gs=2.71, MDD=13.8 kN/m³, OMC=28.3%, CBR=1.35%) sourced from a construction site in Chlef, western Algeria. Natural pozzolana (NP) was obtained from the Beni-Saf region in Oran (western Algeria), and was ground to a specific surface area of 420 m²/kg. The NP was incorporated into the soil at a rate of 20% by dry weight. For stabilization, hydrated lime ($Ca(OH)_2$) was used at 8% by dry weight. Additionally, the study incorporated two types of sulfates: sodium sulfate (Na_2SO_4) and calcium sulfate dihydrate ($CaSO_4{\cdot}2H_2O$), at concentrations of 0%, 2%, and 6% by dry weight. Polypropylene fibers (PF), a commercially available synthetic plastic fiber, were added at proportions of 0% up to 3% by dry weight to assist in soil stabilization and to reduce landfill waste.

CBR tests were conducted on soil samples that were reinforced with PF and stabilized with NP and lime, both with and without sulfate contamination, following the ASTM D1883-21 standard[10]. Mineralogical and microstructural changes in the treated soil samples were analyzed using X-ray diffraction (XRD) and scanning electron microscopy (SEM).

For the CBR tests without sulfates, the soil samples were stabilized using 8% lime, 20% NP, or a combination of both (8% lime and 20% NP), and reinforced with various amounts of PF, resulting in six different sample mixtures. Initially, lime and NP were mixed with the soil in a dry form, sieved through a 1 mm mesh, and then blended with various PF contents. To simulate field conditions and account for the natural variability in fiber distribution, the PF was mixed into the soil in both dry and wet states. This approach aimed to reflect real-world conditions in lime-stabilized soil properties. For the CBR tests involving sulfates, the mixtures were prepared in a similar manner, with different amounts of sulfate added to each mix. Each CBR test was carried out in duplicate on identical samples, and the final values represent the average of the two tests for each sample type.

3. RESULTS

Figure 1 demonstrates how incorporating 20% NP alongside different quantities of PF affects the CBR of EGS stabilized with 8% lime. The results show that adding PF to lime-stabilized EGS improves the CBR, reaching an optimal level at 2% PF, especially with longer curing durations. However, beyond this threshold, the CBR diminishes. The most notable increase occurs when 20% NP is combined with 1% or 2% PF, but exceeding 2% PF results in a reduction in CBR values. In contrast, the use of 20% NP alone or any amount of PF alone in unstabilized EGS leads to only minor changes in CBR. This highlights the importance of PF content in boosting the CBR of PF-reinforced lime-stabilized EGS or NP-lime-stabilized EGS, with improvements observed up to 2% PF and decreases beyond that point.

When PF is introduced to unstabilized EGS samples, regardless of sodium sulfate presence, the CBR shows a slight increase up to 2% PF, but then diminishes with higher PF levels. Sodium sulfate itself exerts a minimal influence on the CBR of NP-stabilized EGS samples across various curing durations. Nevertheless, during brief curing periods (1 day), the introduction of sodium sulfate into EGS samples stabilized with 8% lime, 20% NP, or their combination notably boosts the CBR as the sodium sulfate concentration increases, akin to the impact seen with calcium sulfate. The CBR is more responsive to sodium sulfate than calcium sulfate. After a curing period of 120 days, the CBR of lime-stabilized EGS samples increases considerably with sodium sulfate additions up to 2%, but significantly decreases with higher sodium sulfate concentrations.

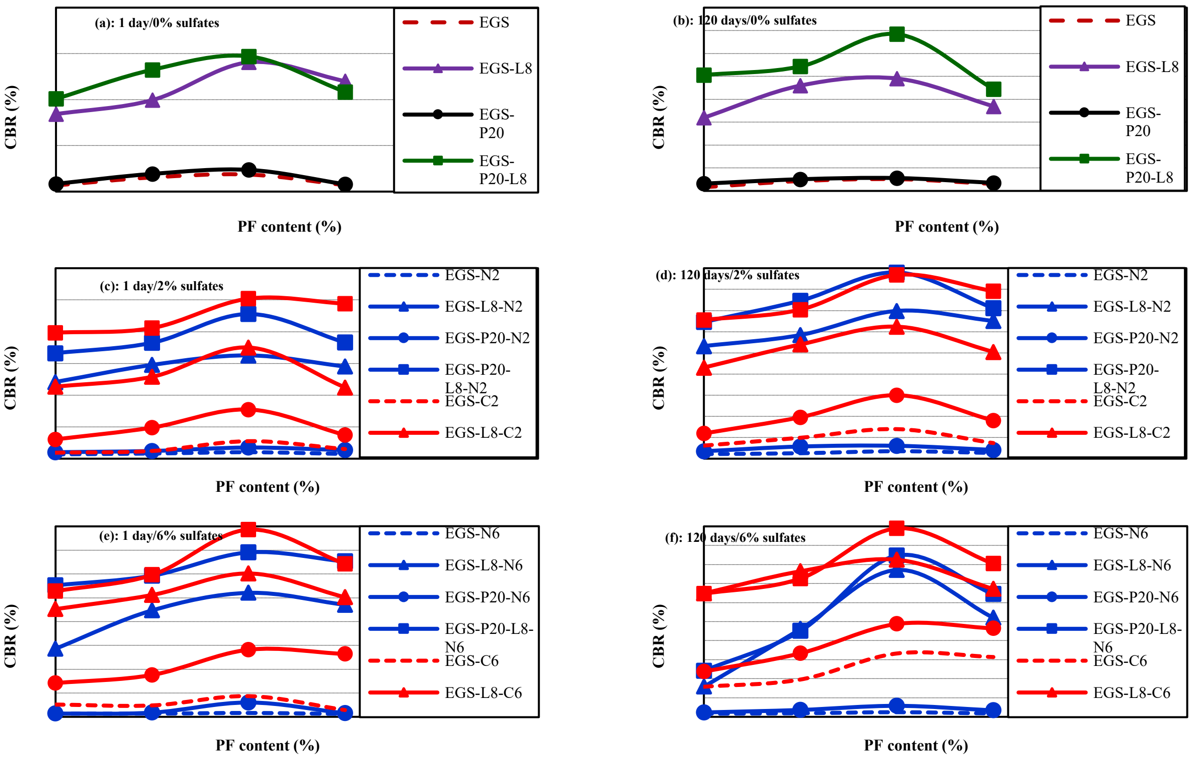

Figure 1. Impact of varying PF contents on the CBR of EGS samples stabilized with 8% L, 20% NP, and their combination (8% L + 20% NP), artificially contaminated with sodium and calcium sulfates, across different curing periods.

4. DISCUSSION

The addition of lime, whether applied independently or in conjunction with NP (without sulfates), induces rapid transformations in the physical characteristics of clay soils owing to their ion exchange capacity. Clay particles possess negative charges, resulting in significant mutual repulsion. Upon dissolution in water, calcium hydroxide releases calcium and hydroxyl ions that attract to the negatively charged surfaces of clay particles. This process mitigates repulsive forces, enhancing adhesion among clay particles, thereby promoting flocculation and agglomeration. This chemical interaction between clay particles and calcium cations promptly modifies the soil's consistency limits[11].

When sodium and calcium sulfates dissolve in water, they liberate sodium and calcium cations. According to Roy's[12] research, the interaction between sodium sulfate and lime in water results in the formation of sodium hydroxide (NaOH), which generates a more alkaline solution than calcium hydroxide alone. Introducing calcium sulfate into stabilized soil samples aids in reducing particle dispersion by facilitating the exchange of calcium ions between clay particles and calcium sulfate. In contrast, sodium sulfate tends to increase particle dispersion due to sodium cation exchange. The presence of hydrated lime increases the water's pH, accelerating pozzolanic reactions and the dissolution of NP, producing monosilicates $[SiO(OH)_3]^-$ and aluminates $[Al(OH)_4]^-$compounds, as illustrated in Figure 2. According to Shi and Day[13], these interactions result in the formation of binding materials like C-S-H and C-A-H, as depicted in equations (1) and (2).

$$Y[SiO(OH)_3]^- + XCa^{2+} + (Z-X-Y)H_2O + (2X-Y)OH^- \rightarrow C_X - S_Y - H_Z \quad (1)$$

$$2[Al(OH)_4]^- + 4Ca^{2+} + 6H_2O + 6OH^- \rightarrow C_4AH_{13} \quad (2)$$

. The resulting C-S-H and C-A-H compounds in the EGS-lime-NP mixture form a stable protective layer that coats and binds soil particles, effectively sealing voids and reducing the void ratio. This process enhances soil compaction and reduces water permeability[11]. Moreover, the reaction between sodium sulfate and lime or lime-NP blends in water generates NaOH, which is known for its higher alkalinity compared to $Ca(OH)_2$. The elevated pH from NaOH promotes the formation of silica (SiO_2) and alumina (Al_2O_3), which react with remaining lime to form ample cementitious products. These products enhance soil strength and decrease the compression index early on. However, the dissolution of sodium and calcium sulfates increases sulfate ion concentrations, leading to the formation of ettringite minerals, as illustrated in equation (3) and Figure 2.

$$6Ca^{2+} + 2Al(OH)^{-4} + 6H_2O + 4OH^{-} + 3(SO_4)^{-2} \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12}, 26H_2O \quad (3)$$

Initially, the formation of primary ettringite minerals absorbs a substantial amount of water, which increases the CBR. However, over longer curing periods and with 6% sodium sulfate in the EGS-lime mixture, the CBR significantly decreases due to the formation of expansive secondary ettringite minerals[14].

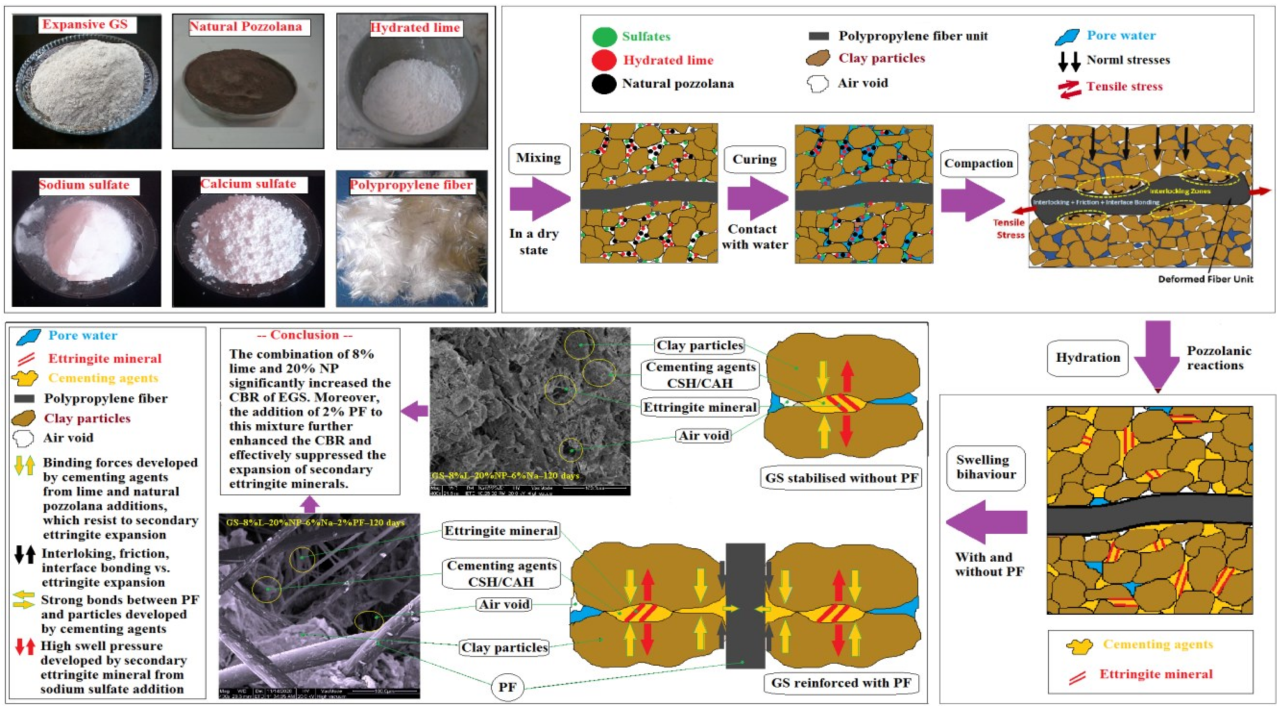

Figure 2. Mechanism of CBR enhancement using 20% NP + 2% PF in lime-stabilized EGS contaminated with sodium and calcium sulfates.

However, when sodium sulfate concentrations are low (below 2%), the formation of secondary ettringite can actually enhance the CBR of stabilized EGS. In PF-reinforced lime-stabilized EGS, the interaction between PF and soil particles becomes especially significant, particularly in the presence of cementitious agents produced from pozzolanic reactions. Increased PF content enhances this interaction, improving surface friction between PF and soil particles and thereby enhancing the CBR. However, if PF content exceeds 2%, there could be a decline in CBR due to PF aggregation, which hampers the interlocking and friction between PF and soil particles.

Remarkably, the adverse effects of sodium sulfate on lime-stabilized EGS can be completely neutralized by using an optimal treatment of 2% PF+20% NP, as illustrated in Figure 2. Overall, changes in the CBR are influenced not only by the type and amount of sulfate but also by PF content and curing duration.

5. CONCLUSION

Upon meticulous examination of the experimental data, several pivotal conclusions come to light:

- In scenarios where sulfates are absent, introducing a modest 2% infusion of PF into NP-lime-stabilized EGS yields a notable surge in CBR, marking an optimal augmentation level.
- In the presence of sulfates, incorporating varying concentrations of calcium sulfate showcases no deleterious impacts

on the treatment process. Instead, it distinctly diminishes the CBR of the investigated EGS, owing to the introduction of non-expansive materials like calcium sulfate alongside a concurrent reduction in clay content.

- The addition of 20% NP to lime-stabilized EGS samples notably mitigates the adverse effects induced by sodium sulfate, effectively remedying compressibility issues by bolstering CBR. Furthermore, the inclusion of 2% PF into sodium sulfate-rich lime-stabilized EGS samples showcases commendable efficacy, enhancing CBR by addressing secondary ettringite mineral formation, as evidenced by SEM imaging. However, it's imperative to note that lime treatment of EGS with elevated sodium sulfate content may not consistently provide an optimal remedy for low bearing capacity issues. Elevated levels of sodium sulfate in clay soil or groundwater should be recognized as detrimental to soil stabilization due to their adverse impacts on the stabilization process. Additionally, lime stabilization in isolation may exacerbate low bearing capacity by fostering the development of expansive ettringite minerals in soils abundant in sodium sulfate. Hence, prudence is advised when utilizing lime as a stabilizer in sulfate-rich soils, mandating a thorough assessment of sulfate levels prior to on-site application. Conversely, the utilization of NP-PF blends in lime-stabilized clay soils is strongly recommended for their efficacy in bolstering soil bearing capacity.

- Ultimately, the triumph of soil stabilization hinges upon various factors, encompassing the nature and quantity of additives utilized, sulfate composition and concentration, PF proportion, and duration of curing. Moreover, reinforcing NP-lime-stabilized expansive clay soil with PF emerges as a particularly potent approach.

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