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COMPARATIVE STUDY ON ENHANCING THE MECHANICAL PROPERTIES OF CLAYEY SAND WITH WASTE PLASTIC FIBERS AND LIME

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Abstract
Introduction. The stabilization of clayey soils remains a dynamic and evolving field, with ongoing research exploring new materials, techniques, and sustainable practices to address the challenges posed by problematic soils in construction and infrastructure development. **The aim of the study** is to investigate the improvement of compaction and mechanical properties of clayey sand by reinforcing its structure with polyvinyl chloride (PVC) plastic fibers of varying sizes and proportions, and/or by applying lime treatment at a minimal dosage. **Methods.** The different mixtures were evaluated through a series of tests, including Proctor compaction tests, California Bearing Ratio (CBR) tests, and direct shear tests conducted under unconsolidated undrained conditions, to assess their mechanical behavior and strength enhancements. **Results** indicated that larger PVC fibers yielded the highest CBR values, even surpassing those achieved through lime treatment alone. Furthermore, the CBR index of the soil increased proportionally with the amount of PVC fibers added. It was also observed that the short-term behavior of clayey sand is significantly improved when reinforced with plastic fibers, whether used independently or in combination with lime treatment. This improvement can be attributed to the combined effects of lime, which strengthens the soil by reducing plasticity and increasing cohesion, and the structural contribution of larger plastic fibers, which promote better interlocking and reinforcement. These findings suggest that stabilizing clayey soils using PVC waste fibers and/or minimal lime treatment offers a technically effective and economically viable solution, while also supporting sustainable development goals.

Keywords: clayey sand; stabilization; PVC plastic waste; lime; mechanical properties.

Introduction

Soil stabilization is a method widely used in geotechnical engineering to enhance the physical and mechanical properties of soil, thereby making it more stable and suitable for various construction applications. This process involves altering soil properties to improve its bearing capacity, shear strength, and resistance to moisture and other environmental factors (Behnood, 2018). Several stabilization methods are employed, including mechanical stabilization, chemical stabilization, and the use of waste materials (Afrin, 2017). Mechanical stabilization involves the physical modification of soil properties through compaction or by blending with such materials as gravel or sand to enhance bearing capacity and reduce settlement potential. Chemical stabilization uses additives like lime, cement, or fly ash, which react with soil particles to form cementitious compounds, thereby increasing strength, reducing plasticity, and improving durability. Recent studies have explored alternative binders such as geopolymers and nanomaterials offering sustainable and effective stabilization solutions (Arora et al., 2019; Ayub and Khan, 2023). Reinforcement techniques involve synthetic or natural fibers (e.g., geotextiles, geogrids, and biochar) to improve the tensile strength and flexibility of the soil matrix (Liu et al., 2020). Recent research indicates that recycled fibers from waste materials — such as plastic bottles and tires — not only enhance soil stability but also contribute to environmental sustainability by diverting waste from landfills (Suthar et al., 2024). The use of waste materials like plastic fibers, tire shreds, and industrial by-products (e.g., slag, construction waste) is gaining traction due to its environmental and economic advantages. For example, recent findings show that incorporating waste plastic fibers into soil improves both compaction characteristics and bearing properties (Amena, 2022). While stabilization techniques are essential for ensuring the stability and longevity of structures built on weak soils, they often raise environmental concerns and may increase construction costs (Amakye and Abbey, 2021). However, by exploring alternative and sustainable

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solutions (Fondjo and Theron, 2021), it is possible to achieve effective soil stabilization without excessive expense (Bekkouche et al., 2022; Gupta et al., 2024; Mishra et al., 2022). Combining multiple stabilizers is a practical approach when a single additive does not yield the desired strength improvement. This strategy leverages synergistic effects between materials such as lime, cement, fly ash, and plastic fibers to enhance both mechanical and physical soil properties (Meddah et al., 2022; Nujid et al., 2022; Thandabani and Letcham, 2023). Incorporating recycled plastic into construction materials and infrastructure provides a multifaceted solution that reduces environmental impact by diverting plastic waste from landfills and oceans. This practice enhances the durability and performance of construction materials, improving their resistance to weathering, cracking, and other forms of degradation. Moreover, the use of recycled plastic promotes sustainable development by reducing reliance on virgin raw materials, conserving natural resources, and lowering greenhouse gas emissions associated with traditional construction practices (Maitlo et al., 2022). Additionally, it offers significant economic benefits by reducing material costs and fostering innovation in green construction technologies, thereby contributing to a more sustainable and circular economy (Zulkernain et al., 2021). The stabilization of clayey soils continues to evolve, driven by ongoing research into innovative materials, advanced techniques, and sustainable practices. Researchers are increasingly exploring unconventional additives such as recycled plastics, industrial by-products, and bio-based stabilizers to improve soil performance while minimizing environmental impacts. This study investigates the enhancement of compaction and bearing capacity of clayey sand through the incorporation of polyvinyl chloride (PVC) plastic fibers of varying sizes and proportions, or through minimal lime treatment. The evaluation was conducted using Proctor compaction and California Bearing Ratio (CBR) tests to assess the effects of these stabilization techniques on the mechanical behavior of the soil and to determine the most effective combinations for improving soil stability.

Materials and Methods

Materials

In this experimental study, three primary materials — clayey sand, quicklime, and PVC plastic waste — were used to investigate the improvement of geotechnical properties through a combination of chemical and mechanical stabilization techniques.

The clayey sand was sourced from Lardjem located in the Tissemsilt Province of Algeria. Its main characteristics are summarized in Table 1. Particle size analysis of the material enabled the development of its granulometric curve illustrated in Fig. 1. According to the Technical Guide for Road Earthworks (LCPC & SETRA, 2000) and the NF P11-300 standard (AFNOR Editions, 1992), the soil is classified as clayey sand, ranging from plastic to very plastic. Based on the Casagrande plasticity chart, the soil is further classified as low-plastic clay. The granulometric curve (Fig. 1) shows that the material contains both fine and coarse particles reaching up to 4 mm in size. The curve also indicates that the material is poorly graded, meaning that the distribution of particle sizes is neither continuous nor uniform. This non-uniformity can negatively impact the compaction and stability of the material. X-ray diffraction (XRD) analysis was conducted at the Synthesis and Catalysis Laboratory of Ibn Khaldoun University, Tiaret, Algeria. The diffractograms were obtained at room temperature using a Rigaku MiniFlex 600 diffractometer. The XRD results (Fig. 2) revealed the presence of clay minerals such as kaolinite, illite, and chlorite, with traces of montmorillonite. Associated non-clay minerals identified in the soil included quartz and calcite.

Table 1. **Main Characteristics of the Soil**

Symbol	Parameter	Value
Gs (g/cm^3)	Specific Gravity	2.7
% Fines	Sieve Percentage at 80 µm	29
< 2 µm	Sieve Percentage at 2 µm	8
WL (%)	Liquid Limit	40.3
WP (%)	Plastic Limit	23.5
VB	Methylene Blue Value	3.27
% $CaCO_3$	Carbonate Content	22
Wn (%)	Natural Water Content	23.8

The quicklime was sourced from the Lime-Saida Factory in the Saida Province of Algeria.

The PVC plastic waste used in the study was collected from carpentry workshops and subsequently sieved into three distinct size classes: PVC1 (1.0–1.6 mm), PVC2 (1.6–2 mm), and PVC3 (2.0–2.5 mm). This classification enabled a more

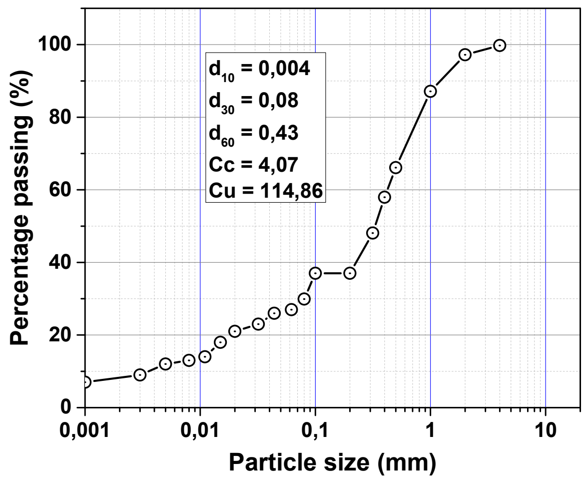

Fig. 1. Particle size distribution of the clayey sand

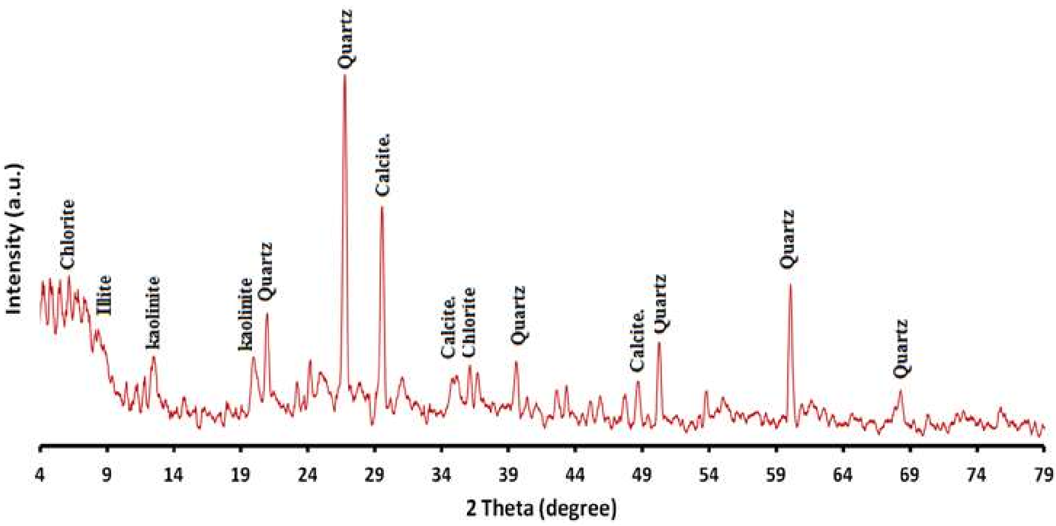

Fig. 2. X-ray diffraction (XRD) diffractogram of the clayey sand

detailed assessment of how varying PVC fiber sizes influence the geotechnical behavior of the stabilized clayey sand.

Methods

In this experimental study, the stabilization of clayey sand involved treating the material with lime and reinforcing it with PVC fibers. A series of tests were conducted to evaluate the effects of these treatments on the geotechnical properties of the material. The testing program included soil identification tests, Proctor compaction tests, California Bearing Ratio (CBR) tests, and direct shear tests. These tests were performed to assess how lime treatment and PVC fiber reinforcement influence the geotechnical properties of the clayey sand. The bearing capacity tests followed the ASTM D-698 standard (ASTM International, 2012) for Proctor compaction and ASTM D1883-21 standard (ASTM International, 2021) for the CBR test. The direct shear test was conducted in accordance with the NF P94-071-1 standard (AFNOR Editions, 1994), using a high shear rate of 1 mm/min to analyze the short-term behavior of the mixtures.

The Eades and Grim method (ASTM D6276-19 (ASTM International, 2019)) was employed to determine the optimal lime dosage required for treating the clayey sand. Lime content was varied from 1 % to 5 % (by total sample mass), and the pH of each mixture was measured. The optimum dosage corresponds to the “fixation point”, indicated by a pH of 12.4. Selecting an appropriate lime content aims to reduce the swelling potential of the clayey sand while maintaining cost efficiency. Optimizing the lime dosage ensures effective soil stabilization, enhances geotechnical properties, and minimizes treatment costs.

Four types of mixtures were prepared for the study:

1. *Soil:* Untreated clayey sand.
2. *Lime-Treated Soil:* Clayey sand stabilized with quicklime to reduce swelling behavior.
3. *Soil–PVC Fiber Mixtures:* Clayey sand reinforced with PVC fibers without lime treatment.
4. *Soil–Lime–PVC Fiber Mixtures:* Clayey sand treated with lime and reinforced with PVC fibers.

The PVC fiber-reinforced mixtures were prepared by adding different percentages (3 %, 4 %, and 5 % by total mass) of distinct PVC waste classes. These mixtures were tested to evaluate the effects of each treatment and reinforcement combination on the compaction and bearing capacity of the material.

Results and Discussion

The histograms in Fig. 3, which display the Methylene Blue Value (MBV) for the soil–lime mixtures, indicate that the clay content (or argillosity)

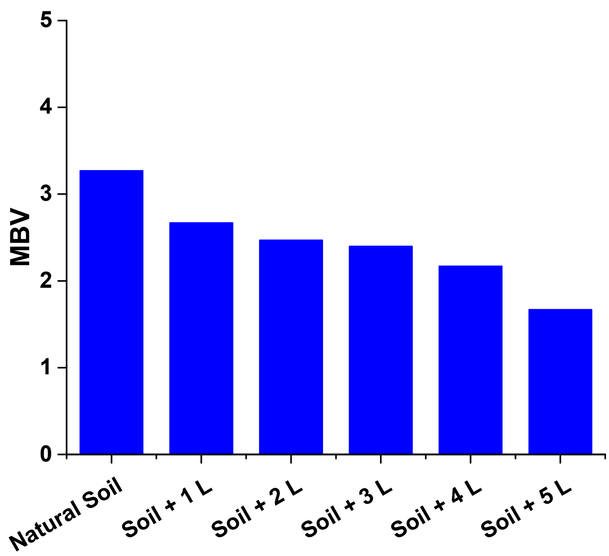

Fig. 3. Methylene Blue values for soil treated with varying lime content

decreases as the percentage of lime added increases. This trend suggests that lime treatment reduces the amount of active clay minerals in the soil.

Fig. 4 presents the Atterberg limit values for the different soil–lime mixtures. These limits — namely the liquid limit (LL), plastic limit (PL), and plasticity index (PI) — offer insights into the changes in plasticity and workability of the clay when treated with varying lime dosages. It is observed that the addition of lime significantly increases the liquid limit, while its effect on the plastic limit is less pronounced. This slight increase in the plastic limit may be attributed to the chemical reactions between lime and the soil, which modify the internal structure of the soil matrix. As a result, the plasticity index (PI), defined as the difference between the LL and PL, also increases. The substantial rise in the liquid limit, combined with a minor increase in the plastic limit, leads to a higher plasticity index. This implies that the treated soil becomes more malleable, thereby improving its workability, which is beneficial in various geotechnical applications.

To reduce lime-related costs, pH measurements were conducted for soil–lime mixtures with lime contents ranging from 1 % to 5 %. The goal was to determine the fixation point, which corresponds to a pH of 12.4. As shown in Fig. 5, the optimal lime dosage for treating the clayey sand is approximately 1 %.

Fig. 6 illustrates the Atterberg limit values for different mixtures of clayey sand and PVC fibers. Minor variations in these limits are observed, likely due to differences in sample preparation and handling. However, these variations are minimal, indicating that the addition of PVC fibers does not significantly alter the internal structure of the soil. While the fibers may slightly influence the workability of the mixture,

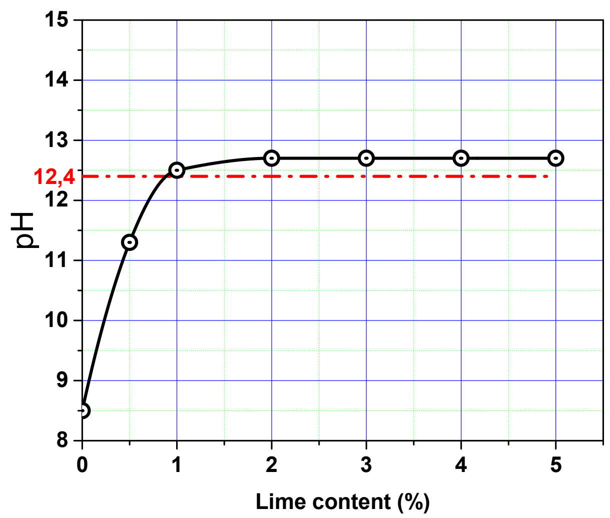

Fig. 5. pH measurements for different soil–lime mixtures

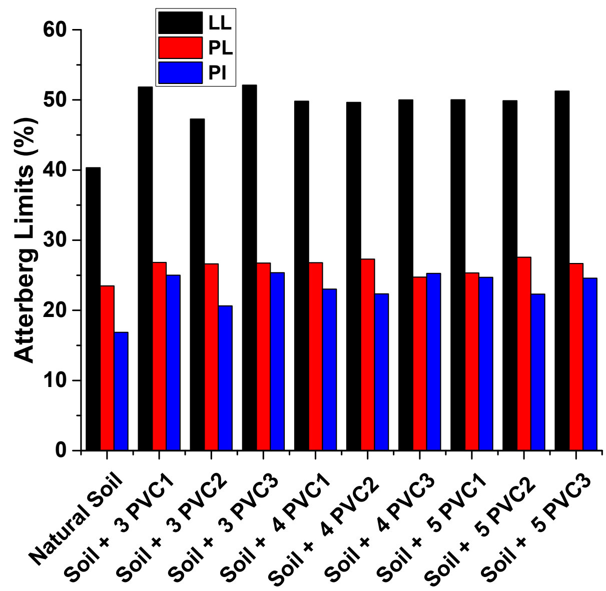

Fig. 6. Atterberg limits for mixtures of soil and PVC fibers

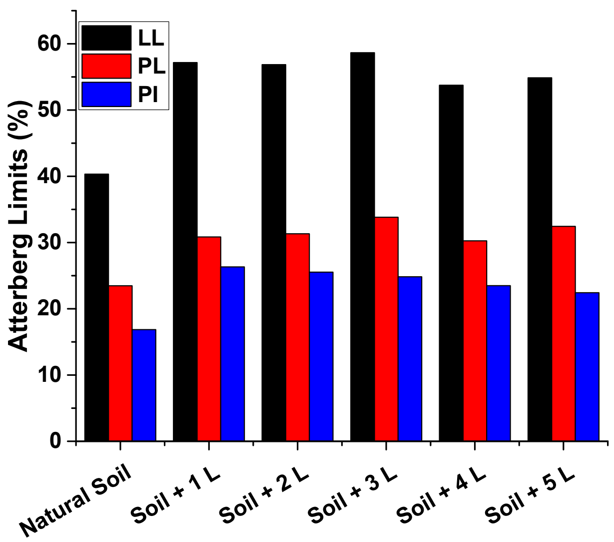

Fig. 4. Atterberg limits vs. lime content for treated soil

the fundamental properties of the soil — reflected in the Atterberg limits — remain largely unchanged. This suggests that the primary structure of the soil is preserved despite the incorporation of PVC fibers.

Regarding the 4th category of mixtures (clayey sand–lime–PVC) prepared with 1 % lime, it is observed that the plastic fibers influence the between lime and soil (Fig. 7). The presence of plastic fibers introduces an additional variable that affects the overall behavior of the mixture. Specifically, these fibers can influence the plasticity index by modifying the consistency and plasticity of the mixture. While lime typically increases the plasticity index by enhancing the workability of the soil, the inclusion of PVC fibers alters this effect. The fibers may disrupt the uniform interaction between lime and soil particles, changing the consistency

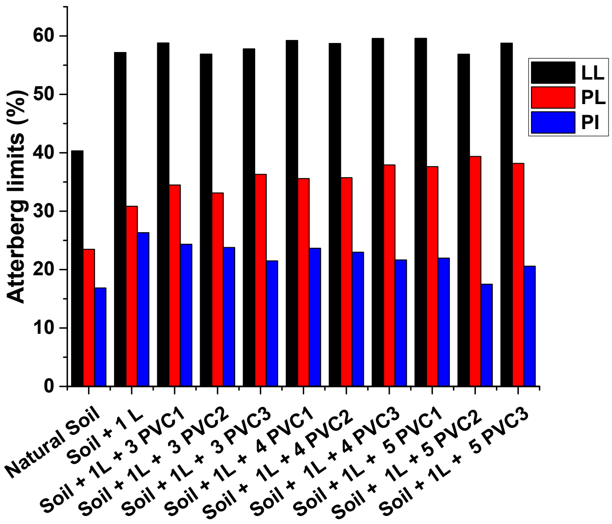

Fig. 7. Atterberg limits for mixtures of soil, lime, and PVC fibers

of the mixture. This suggests that the combination of lime and PVC fibers produces a more complex interaction, where the effectiveness of stabilization may be enhanced or limited depending on the fiber content and distribution within the mixture.

From Fig. 8, it is observed that plastic fibers alter the mechanical properties of the soil during compaction, which impacts the shape of the Proctor curve. This modification affects both the maximum dry density and the optimum water content. The reduction in maximum dry density can be attributed to the lower density of plastic fibers compared to soil particles. Variations in water content are influenced by the dimensions and proportions of the plastic fibers, which play a crucial role in determining the optimum water content for each mixture. Additional water is necessary for better handling, especially when plastic fibers are incorporated. It can be noted that the bell-shaped curve is maintained even after adding plastic fibers to the soil, indicating that the mixtures retain their sensitivity to water. This suggests that while the inclusion of PVC fibers may improve certain mechanical properties, it does not significantly alter the fundamental water sensitivity of the soil. This retained sensitivity could be due to the fact that the plastic fibers, although affecting compaction and density, do not fully mitigate the behavior of the clay particles.

For soil mixtures containing 1 % lime and PVC fibers of various percentages and dimensions, Fig. 9 shows a notable decrease in dry densities. This decrease can be attributed to two main factors: (1) the addition of lime initiates a chemical reaction with clay minerals, causing flocculation and agglomeration, which increases the overall volume of the mixture; and (2) the incorporation of low-density PVC fibers further reduces the dry density by replacing denser soil particles. Notably, the Proctor curves for soil stabilized with lime and plastic fibers tend to flatten, indicating reduced sensitivity to water.

For the California Bearing Ratio (CBR) tests, samples were prepared using different compaction energies: 10, 25, and 56 blows per layer (B/L). After preparation, the samples were immediately subjected to penetration testing to determine the immediate CBR value. Fig. 10 presents the immediate CBR values for various mixtures composed of soil, PVC fibers and/or lime, compacted using a low compaction energy of 10 B/L. It was observed that the CBR values increase with the size of the PVC fibers at each dosage level. For example, at a 5 % dosage, the CBR values increased with increasing fiber dimensions, with the maximum values obtained for the 3rd class fibers (2–2.5 mm). This trend suggests that larger fiber sizes more effectively enhance the bearing capacity of the soil under compaction. The increased surface area and interlocking effect of larger fibers likely improve the soil structure, providing better resistance to deformation and enhancing the

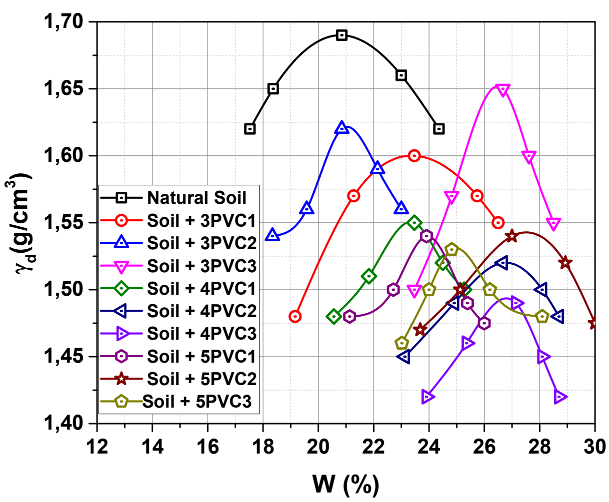

Fig. 8. Proctor curves for mixtures of soil and PVC fibers

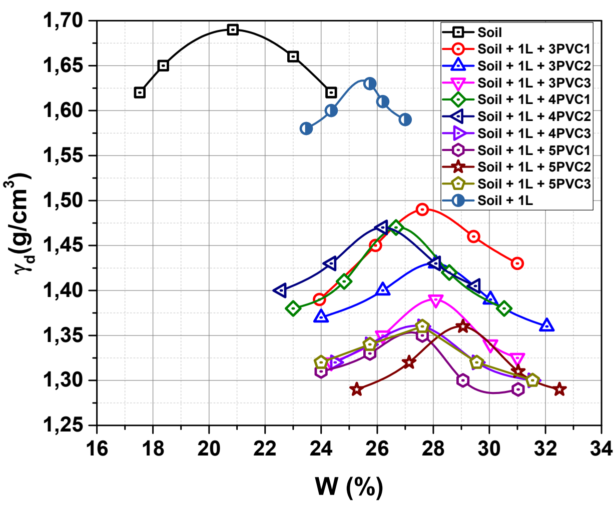

Fig. 9. Proctor curves for mixtures of soil, lime and PVC fibers

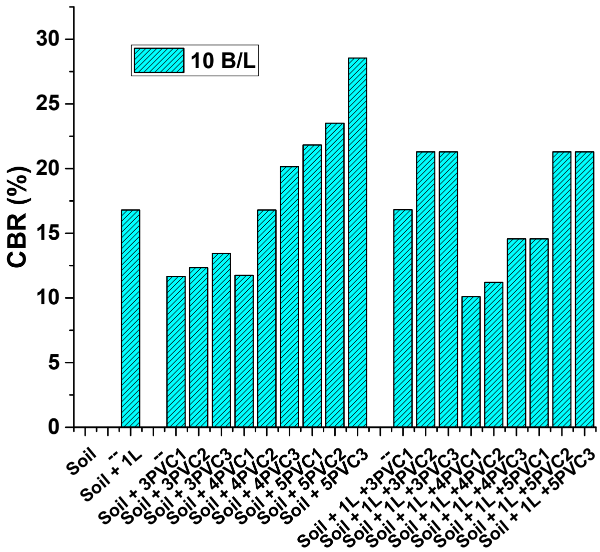

Fig. 10. CBR values for mixtures prepared at low compaction energy (10 B/L)

overall stability of the mixture. A similar trend was observed for samples prepared with medium and high compaction energies, as shown in Figs. 11 and 12. The CBR values consistently increased with fiber size, regardless of the applied compaction energy. This indicates that larger fibers (such as PVC class 3 with dimensions of 2–2.5 mm) significantly improve the bearing capacity of the soil across different compaction levels. Amena (2022) found that CBR values increase with higher percentages of plastic fiber addition when reinforcing expansive subgrade soils. The effectiveness of larger fibers in reinforcing the soil remains evident, as they contribute to better interlocking and load distribution, thereby improving the mechanical properties of the soil under varying compaction conditions. Notably, the CBR values obtained for mixtures containing 5 % plastic fibers of the 2nd (1.6–2 mm) and 3rd classes (2–2.5 mm), either alone or in combination with lime, were superior to those achieved with lime treatment alone. This enhancement is likely due to the synergistic effect between lime treatment, which improves soil cohesion and reduces plasticity, and the reinforcement provided by the larger plastic fibers, which improve interlocking and structural integrity. These combined effects contribute to a more stable and robust soil matrix, enhancing the overall bearing capacity of the mixtures. However, achieving these results requires high compaction energy.

It should be noted that Berrahou and Bendjilali (2023) found that stabilizing fine clay with small plastic fibers produced better results, which contrasts with the findings of this study. Here, larger plastic fibers yielded superior performance. This discrepancy suggests that the optimal fiber size for stabilizing clay materials shall closely match the grain size in the treated material. By ensuring that the fiber size aligns with the soil grain size, better interlocking and distribution within the soil matrix can be achieved, leading to more effective reinforcement and enhanced soil properties.

The short-term behavior of the soil was evaluated through direct shear tests conducted under unconsolidated, undrained conditions. The results are shown in the Mohr's stress diagram in Fig. 13. Mixtures of soil treated with lime and reinforced with plastic fibers exhibited significantly higher shear strengths than untreated soil. This improvement is attributed to increased shear resistance from lime stabilization and the stress-distributing and crack-bridging effects of PVC fibers. Reinforcing the soil

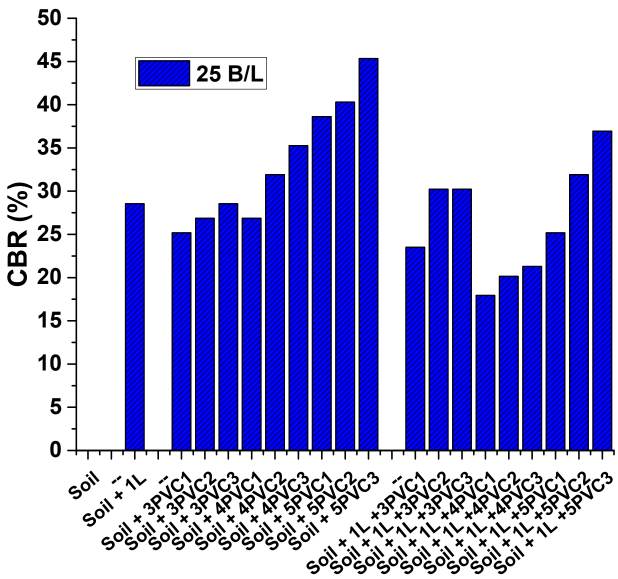

Fig. 11. CBR values for mixtures prepared at medium compaction energy (25 B/L)

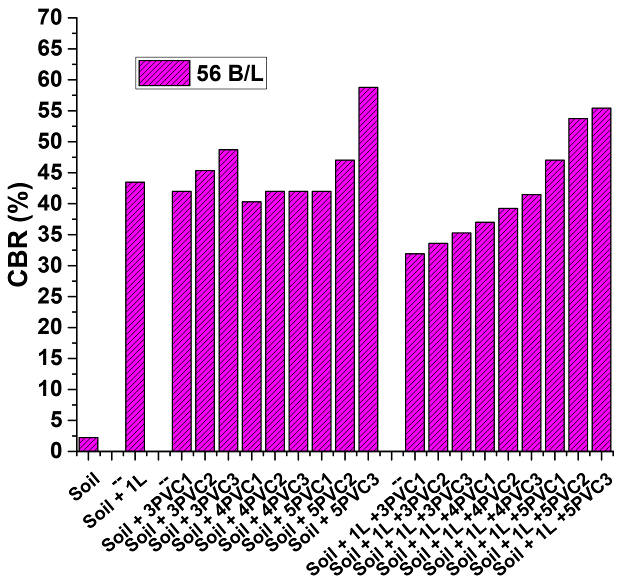

Fig. 12. CBR values for mixtures prepared at high compaction energy (56 B/L)

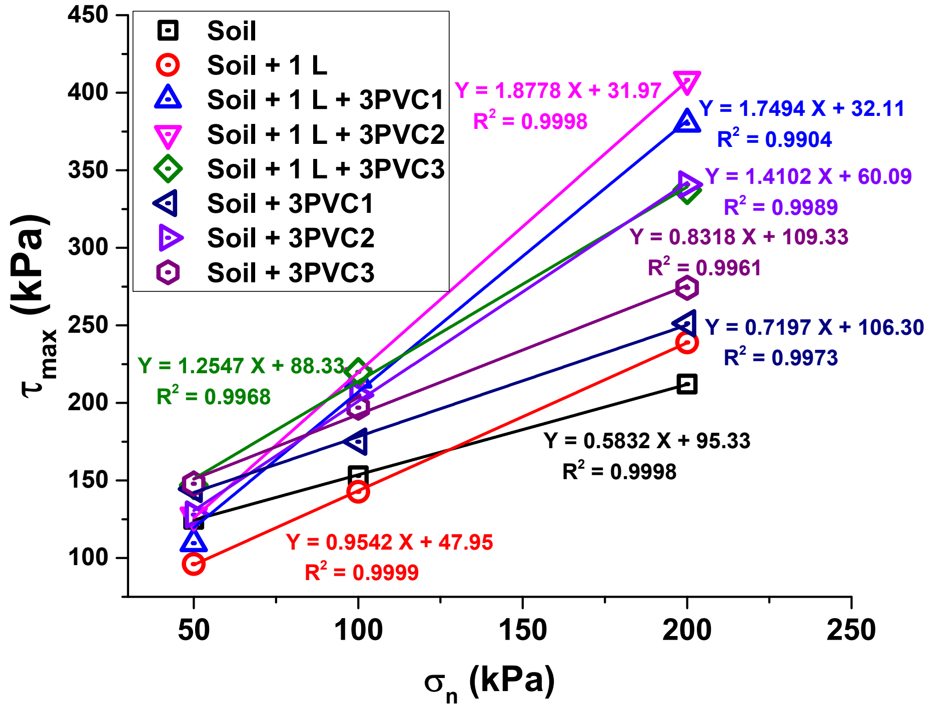

Fig. 13. Failure stresses for the different mixtures

with PVC fibers alone also led to notable gains in shear strength. The undrained cohesion values, plotted in Fig. 14, show that the large plastic fibers (PVC 3) yield the highest cohesion, confirming their superior reinforcing effect. These results align with the CBR findings and highlight the potential of plastic waste as a sustainable and effective reinforcement for enhancing the mechanical properties of clayey sand soils.

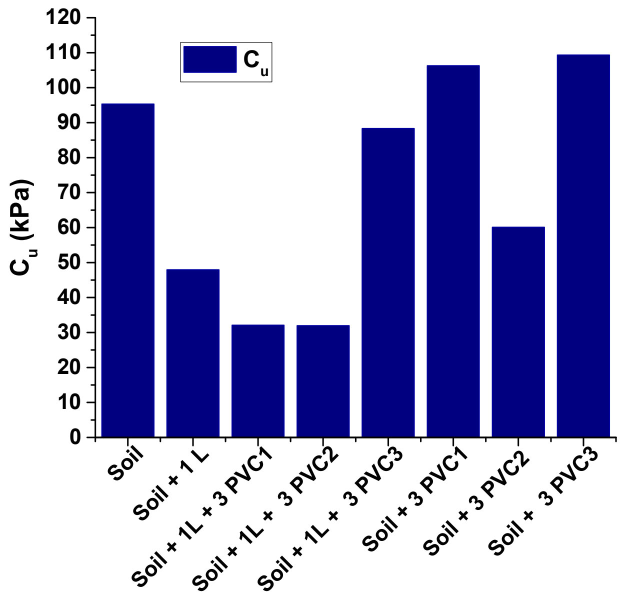

Fig. 14. Undrained cohesion for the different mixtures

Conclusions

The aim of the study was to examine the effect of adding plastic fibers of various sizes and proportions, with or without lime treatment, on the compaction and bearing properties of clayey sand. Based on the results obtained, the following conclusions can be drawn:

- The presence of plastic fibers affects the overall behavior of the mixture by altering its consistency and plasticity, thereby influencing the plasticity index and modifying the workability and deformability of the soil.
- The Proctor curves of soils stabilized with lime and plastic fibers tend to flatten, indicating reduced water sensitivity, in contrast to mixtures containing only plastic fibers, which retain a bell-shaped curve.
- Immediate CBR tests revealed that the bearing capacity of clayey sand mixtures containing plastic fibers improves with increasing fiber size and proportion. The best results were achieved using the largest fibers (2–2.5 mm), which closely match the particle size of the treated soil. This suggests that incorporating plastic fibers into clayey sand can notably improve its bearing capacity, as evidenced by the increased CBR values with larger fibers. However, to maintain these improvements, it is essential to protect the material from water exposure.
- The short-term behavior of clayey sand is significantly improved by reinforcing its structure with plastic fibers, either independently or in combination with lime treatment. The results indicated that larger plastic fibers, specifically PVC 2 and PVC 3, provided the best shear resistance, demonstrating their effectiveness in reinforcing the clayey sand matrix.

- The combined stabilization approach using 1 % lime and plastic fibers presents a promising solution, as the mixtures become less sensitive to water, indicating enhanced stability and reduced susceptibility to moisture-induced changes. However, achieving optimal performance with this method requires the application of higher compaction energy.

Overall, the results show that the combined stabilization approach using lime treatment and plastic fiber reinforcement is an effective technical solution in terms of both performance and cost. However, in-situ testing and additional durability assessments are necessary to further validate the effectiveness and reliability of this technique for broader geotechnical applications.

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СРАВНИТЕЛЬНОЕ ИССЛЕДОВАНИЕ ПО УЛУЧШЕНИЮ МЕХАНИЧЕСКИХ СВОЙСТВ ГЛИНИСТОГО ПЕСКА С ИСПОЛЬЗОВАНИЕМ ОТХОДОВ ПЛАСТИКОВЫХ ВОЛОКОН И ИЗВЕСТИ

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Аннотация
Введение. Укрепление глинистых грунтов — развивающаяся область, в которой продолжаются исследования по применению новых материалов, технологий и рациональных практик для решения проблем, связанных с нестабильными грунтами в строительстве и создании инфраструктуры. **Цель исследования** — рассмотреть улучшение уплотнения и механических свойств глинистого песка путем армирования его структуры пластиковыми волокнами из поливинилхлорида (ПВХ) различных размеров и пропорций и/или за счет обработки известью в минимальной дозировке. **Методы.** Различные комбинации смесей оценивались с помощью ряда испытаний, включая определение плотности грунта методом Проктора, определение несущей способности грунта калифорнийским методом, а также испытания на прямой сдвиг неконсолидированных недренированных образцов, для оценки их механических и прочностных характеристик. **Результаты** показали, что наиболее высокие значения калифорнийского числа несущей способности грунта были достигнуты при использовании крупных волокон ПВХ, при этом они превышали значения, полученные при применении извести в отсутствие армирования. Кроме того, эти значения возрастали пропорционально количеству добавленных ПВХ-волокон. Также было отмечено, что в краткосрочной перспективе характеристики глинистого песка значительно улучшаются при армировании пластиковыми волокнами, как с обработкой известью, так и без нее. Это улучшение объясняется совокупным действием извести, которая укрепляет грунт за счет снижения пластичности и увеличения сцепления, и крупных пластиковых волокон, которые способствуют лучшей связности и армированию структуры. Полученные результаты свидетельствуют о том, что укрепление глинистых грунтов с использованием волокон из отходов ПВХ и/или извести в минимальной дозировке представляет собой технически эффективное и экономически целесообразное решение, способствующее в том числе достижению целей устойчивого развития.

Ключевые слова: глинистый песок; укрепление; отходы ПВХ; известь; механические свойства.