Comparative Study of Soil Injection Materials: Shear Strength of granular soils with Polymer, Cement Slurry, and Nano-Silica

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***Abstract*—In geotechnical engineering, injecting materials into soil is essential for improving soil properties, stabilizing foundations, and preventing ground collapse. This study explores the shear strength of calcareous and silica sands when treated with various injection materials, including Polyurethane Foam Adhesive (PFA), cement slurry, and nano-silica. The findings reveal that increasing the quantity of PFA and cement slurry enhances shear strength. For PFA content between 0 and 5%, calcareous sand exhibits greater shear strength compared to silica sand, but this trend reverses when PFA content exceeds 5%. Curing time is crucial, with PFA-injected samples reaching a similar shear strength in 1 hour to that of cement slurry-injected samples in 7 days, due to PFA's rapid reaction. Cement slurry-injected samples display slightly more brittleness than those injected with PFA. These results highlight the potential of PFA and nano-silica as effective soil stabilization agents, presenting viable alternatives to traditional materials like cement in civil engineering.**

***Index Terms*—soil stabilization, Polymer, Cement, Nanomaterial, Injection**

I. INTRODUCTION

Weak soils pose significant challenges in civil engineering due to compromised stability and load-bearing capacity [1–6]. Fine silica sand, in particular, suffers from low shear strength, poor bearing capacity, and weak compaction characteristics [7,8]. Conversely, calcareous sand faces issues with particle breakage and high volume changes, affecting overall material strength and soil structure stability [9–11]. Addressing these issues necessitates effective soil improvement techniques, with soil injection being a prominent method.

Soil injection enhances weak soils by injecting stabilizing agents to improve mechanical properties and overall stability [12,13]. This technique mitigates settlement issues and boosts soil bearing capacity, crucial for the long-term safety of structures [14,15]. However, traditional injection slurries, like cement, face limitations such as brittle fracture, environmental toxicity, and potential vegetation damage. Optimizing factors like the water-to-cement ratio, injection pressure, and soil properties is essential for effective soil injection.

The drawbacks of cement slurry injection, including environmental impact, extended curing time, and limited penetration in fine-grained soils, drive the search for alternative materials like Polyurethane Foam Adhesive (PFA) [16,17]. PFA offers faster curing times, lightweight composition, strong adhesive properties, flexibility, durability, and chemical resistance. Research highlights its effectiveness in enhancing cohesion in rockfill materials and improving the strength of gravelly and silty soils.

Recent studies demonstrate PFA's potential in soil improvement, enhancing mobilized shear strength at sand-steel interfaces, reducing liquefaction-induced settlement, and improving the durability of roadbed rehabilitation materials [18–24]. Civil engineering is also embracing nanomaterials for their unique properties, which enhance construction materials' strength and durability [8,25,26]. Despite individual studies on PFA and nanomaterials, their combined application in soil injection remains understudied.

This paper explores the novel use of PFA and nano-silica injections in enhancing the shear strength of silica and calcareous sands, addressing a gap in current research. The study provides a comparative analysis with conventional cement-injected samples, highlighting the advantages of these innovative materials in soil stabilization.

II. MATERIALS AND METHODS

In this study, silica and calcareous sands were used as the primary materials. Figure 1 shows the grading curves of both types of sand. The calcareous sand particles are angular, while the silica sand particles are more rounded.

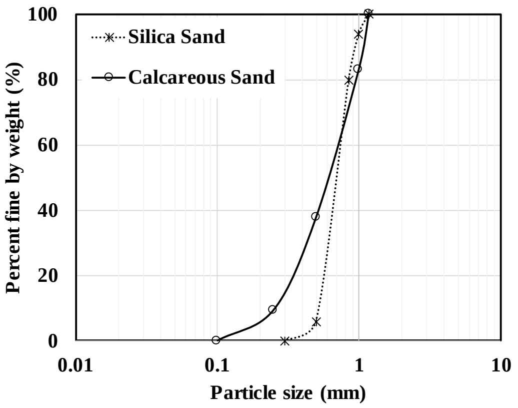

Figure 1. Particle size distribution curves of silica and calcareous sand

The PFA used in this study is a two-component rigid foam system, comprising liquid-A (Isocyanate) and liquid-B (Polyol). These components are mixed in a 1:1 volume ratio, initiating a polymerization reaction that forms a three-dimensional network of polymer chains. This reaction quickly transforms the mixture from a liquid to a solid foam, significantly increasing its volume. The resulting structure provides the adhesive and cohesive properties needed for soil stabilization, establishing strong connections among soil particles.

Ordinary Portland Cement (OPC) is a widely used construction material in civil engineering due to its versatility and strong binding properties, which enhance the strength and durability of soil structures. It is commonly employed in projects such as road construction and foundation stabilization. In the experiments conducted for this study, OPC classified as P.O.42.5 was used, following the Chinese standard GB175-2007.

In the current study, nano-silica has been used to enhance the effect of PFA for soil stabilization.

This study used a submarine sediment shear system to analyze the shear strength of injected samples. The shear box measures 100 mm × 100 mm × 80 mm and consists of an upper and lower section. The normal load is applied to the fixed upper box, while the movable lower box is adjustable for different tests. The apparatus includes a container, pressure gauge, regulator, and a modified upper mold with two injection holes near the sample's shear line.

This study examines the shear behavior of injected silica and calcareous sand using direct shear tests. Samples were prepared using the dry funnel deposition method, then transferred to the direct shear device where normal stress was applied. Samples with a relative density deviation beyond ±5% were discarded and re-tested. Normal stress levels of 100, 200, and 400 kPa were used to determine shear strength parameters according to Mohr-Coulomb criteria.

For injection, a syringe delivered a precise volume of liquid. PFA injection involved mixing its components (liquid-A and liquid-B) with nano-silica, where only one PFA component was mixed with nano-silica to ensure a homogeneous solution. Each PFA component was injected separately, with liquid-B followed by liquid-A. Nano-silica was added based on its weight relative to the PFA components. Air pressure of 75 kPa was used for PFA injections, while 150 kPa was necessary for cement injections due to higher resistance encountered during injection. Cement injections required higher pressure to avoid issues like pipe blockages.

Curing time was calculated post-injection, followed by incremental application of shear stress at 0.01 mm/s to evaluate the shear behavior of the samples.

Given the fine nature of the sand particles and challenges observed in preliminary tests, a deliberate decision was made to establish a water-to-cement (w/c) ratio of 1 in this study. This aimed to refine and optimize the injection process.

III. RESULTS AND DISCUSSION

The variation in shear strength of samples with different PFA content is shown in Figure 2. The curing time for theses samples was 1 hour after injection of PFA. As PFA content increases from 0 to 20%, the shear strength of both silica and calcareous sands rises gradually. However, the trend differs between the two sand types, analyzed across three zones:

1. Zone 1 (0-5% PFA): Calcareous sand exhibits higher shear strength than silica sand due to its angular particles compared to the round particles of silica sand.
2. Zone 2 (5-15% PFA): Shear strength values of both sands become nearly equal, indicating a transition zone.
3. Zone 3 (15-20% PFA): Silica sand surpasses calcareous sand in shear strength, as the angular shape of calcareous sand loses its influence due to a more complete PFA cover.

At low PFA content, the higher shear strength of calcareous sand is due to its angular shape and thin PFA covers. At high PFA content, silica sand outperforms calcareous sand, likely due to the lower permeability coefficient (*k*) of calcareous sand, and its greater porosity. The higher *k* value in silica sand allows better PFA penetration during injection, especially at high PFA volumes. In contrast, the high porosity and distinct shape of calcareous sand particles require more PFA to fill spaces, resulting in less surface coverage. The differences in shear strength between silica and calcareous sands are due to particle shape, permeability, porosity, and their interaction during the PFA injection process.

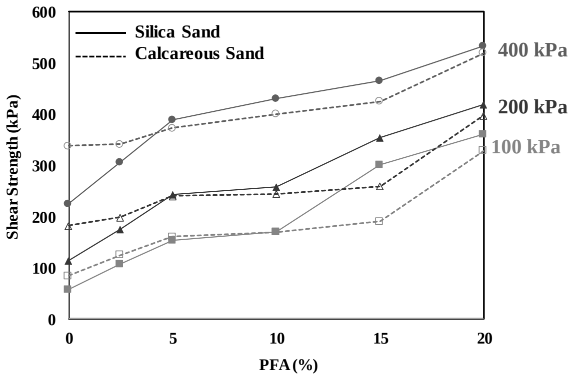

Figure 2. Variation of shear strength versus PFA content

Figure 3 illustrates the shear strength variation of silica and calcareous sand samples after injecting cement slurry and curing for 7 days. Both sands show a gradual increase in shear strength with higher cement slurry content. Initially, calcareous sand has higher shear strength than silica sand at lower cement slurry levels, but this reverses at higher cement slurry levels. The transition point of this trend shifts to higher cement slurry percentages as normal stress increases from 100 to 400 kPa.

While cement slurry-injected samples were cured for 7 days, PFA-injected samples were cured for only 1 hour. In some cases, PFA-injected samples exhibit the highest shear strength, while in others, cement slurry-injected samples do. There is no consistent trend for either sand type. Generally, the differences in shear strength between the two types of injected samples are modest, usually less than 24%.

Comparatively, silica samples consistently exhibit higher shear strength than calcareous sand samples, with the difference increasing with higher cement slurry content.

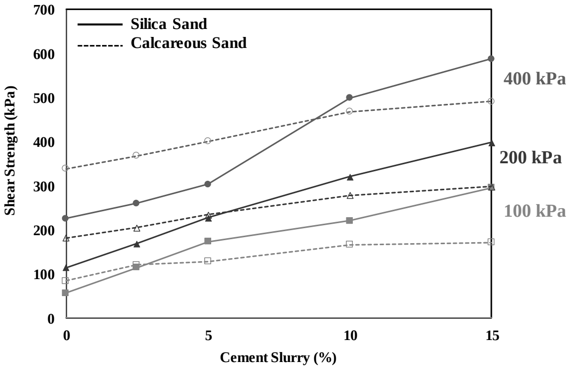

Figure 3. Variation of shear strength versus cement slurry content

In this series of tests, nano-silica was added to the PFA component before injection to enhance the effectiveness of PFA. The tests utilized three weight percentages of nano-silica (0.875%, 1.75%, and 3.5%) relative to the weight of the PFA components, with the PFA content kept constant at 10%. The relative density (Dr) of the samples was maintained at 30%, and testing was conducted after a 7-day curing period. Figure 4 shows the effect of nano-silica content on the shear strength of PFA and nano-silica-injected samples.

The results indicate a significant increase in shear strength as nano-silica content rises from 0% to 1.75%, but further increases beyond 1.75% lead to a decline in shear strength. The peak shear strength for both sand types is achieved at a nano-silica content of 1.75%. Two main factors may explain the decrease in shear strength with higher nano-silica content:

1. Excess nano-silica can significantly alter the viscosity of the injected fluid, compromising penetration and overall injection quality.

2. The abundance of nanoparticles, while helpful in filling void spaces, may also occupy intergranular spaces within the sand, reducing interparticle friction.

Comparatively, nano-silica has a more pronounced strengthening effect on silica sand than on calcareous sand.

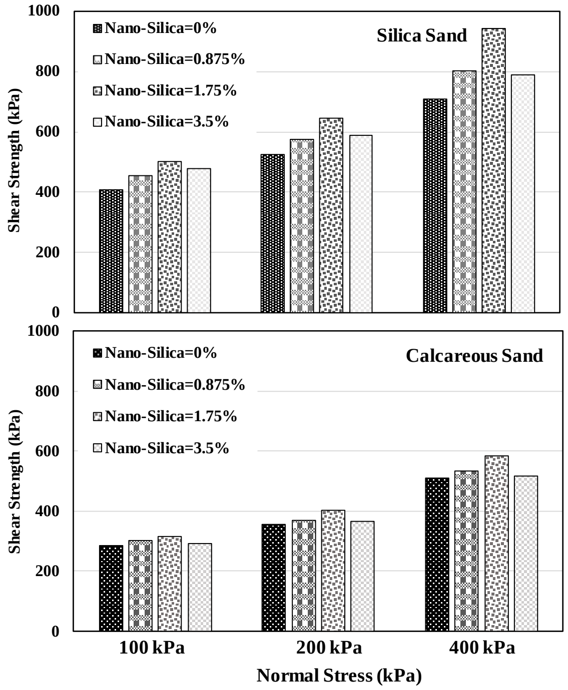

Figure 4. Variation of shear strength for various nano-silica contents

IV. CONCLUSIONS

This research presents an innovative approach by utilizing PFA injection to enhance the shear strength of silica and calcareous sands. The rapid reactivity of PFA is advantageous for time-sensitive projects. We systematically examined the effects of various parameters, including the type of injection materials (PFA, cement slurry, and a blend of PFA and nano-silica) and the content of injected materials (0% to 20%). The key conclusions are as follows:

1. Shear Strength Increase with PFA Content:

- Shear strength gradually increases with rising PFA content (0-20%) for both sand types, though trends differ slightly.

- For silica sand with 10% PFA injected after 1 hour, shear strength increased by 202%, 128%, and 91% under normal stresses of 100, 200, and 400 kPa, respectively. For calcareous sand under the same conditions, increases were 101%, 35%, and 18%.

- Calcareous sand shows higher shear strength than silica sand up to 5% PFA due to its angular particle shape. Between 5-15% PFA, shear strengths are nearly equal, indicating a transition zone. For 15-20% PFA, silica sand surpasses calcareous sand, possibly due to more complete PFA coverage.

2. Comparison with Cement Slurry:

- PFA-injected samples cured in 1 hour exhibit shear strength similar to cement slurry-injected samples cured in 7 days, due to PFA's faster reaction.

- For a given curing time, PFA-injected samples show significantly higher shear strength than cement slurry-injected samples.

3. Impact of Nano-Silica:

- Adding nano-silica to PFA injection boosts shear strength for both sand types, with a more pronounced effect on silica sand.
- The optimal nano-silica content in PFA is 1.75%.
- The addition of 1.75% nano-silica increased shear strength by 23%, 22%, and 32% for silica sand, and 10%, 13%, and 15% for calcareous sand, after a 7-day curing period under normal stresses of 100, 200, and 400 kPa, respectively.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

AUTHOR CONTRIBUTIONS

Meysam Bayat: Conceptualization, Methodology, Investigation, Writing - Original Draft Preparation.

Zohreh Mousavi: Formal Analysis, Writing - Review & Editing, Visualization.

Wei-Qiang Feng: Formal Analysis, Writing - Review & Editing, Visualization.

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