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Research Article

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Effect of Sodium Hydroxide on Geotechnical Properties of Soft Soil in Kathmandu Valley

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Abstract

People utilize local soils a lot in building because they are easy to get and cheap, but they don't last long enough for most uses. To overcome this constraint, this study assesses the efficacy of mineral polymerization (MIP) utilizing sodium hydroxide (NaOH) as a stabilizing agent for black organic silt soil. The soil examined, prevalent in the Kathmandu Valley, is of lacustrine origin, distinguished by elevated organic content and diminished strength. testing in the lab included testing for grain size distribution, Atterberg limits, organic content, and pH. We did unconfined compressive strength (UCS) tests on samples that were stabilized with different amounts of NaOH and sand as a filler at the best moisture content. Tests were done on samples in dry, rainy, and wet-dry cycling conditions. The highest UCS values were 77.57 kg/cm² for dry conditions, 38.85 kg/cm² for wet conditions, and 56.30 kg/cm² for cycling conditions. For untreated soil, the highest value was 7.38 kg/cm². The lowest strengths of treated wet and cycling specimens were nevertheless higher than those of the natural soil. The results show that MIP based on NaOH makes soil much stronger and more durable, which suggests that it could be used sustainably in building.

Keywords: soil stabilization technique, Soft soil treatment, Sodium hydroxide, unconfined compressive strength

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Introduction

Creating value is the main aim of engineering (Mishra, 2019). Environmental sustainability orientations (Mishra et al., 2024), green innovation in automotive financial performance (Mishra, 2025), and comparative building performance (Mishra & Rai, 2017) were some innovative approaches researched recently considering environment as a case of cement consumption of Pokhara city of Nepal is only demonstration (Banstola et al., 2021).

Soil stabilization is a crucial process in geotechnical engineering, involving the modification of natural soil properties to enhance its engineering characteristics (Tingle et al. 2007; Firooziet al., 2017). The main objectives of soil stabilization include improving load-bearing capacity, increasing permeability, and resisting weathering and traffic. Mechanical and physical methods of soil stabilization focus on compaction and grain size distribution adjustments to reduce void ratio. Chemical stabilization, on the other hand, is preferred for its ability to yield higher strength and durability (Abid, 2016; Alshaaer 2002). Chemical stabilization involves the reaction between additives and soil particles, creating a strong network that binds the soil grains together (Hausmann, 1990).

Mineral polymerization is a widely used chemical stabilization technique that forms amorphous to semi-crystalline materials at near ambient temperature (Davidovits 1991). These materials consist of cross-linked units of AlO4 and SiO4 tetrahedra, with charge-balancing cations provided by alkali metals (Na+, K+, Li+, Ca2+, Ba2+, H3O+) (Davidovits 1991). Sodium hydroxide, a reactive and non-volatile solution, is known for its vigorous reaction with water and other materials, generating heat. Its key advantage lies in its capacity to react readily with water, acting as a powerful compaction aid that increases density with the same compactive effort. Sodium hydroxide is particularly effective in reacting with aluminum-rich soils (Alshaaer 2002).

Soil conditions play a critical role in the support and longevity of structures, with poor soil often leading to inadequate support and shortened lifespans. Various additives, including lime, Class C fly ash, portland cement, cement kiln dust, and proprietary chemical stabilizers, can improve soil properties by enhancing its strength characteristics. This research focuses on enhancing soil strength using sodium hydroxide. The study aims to evaluate the properties and suitability of local black soil before and after stabilization with sodium hydroxide, investigating mechanical properties such as compressive strength, durability under wet conditions, and water absorption degree. The experiment uses mineral polymerization techniques, which offer a more environmentally friendly alternative to traditional cement stabilization. The study aims to assess the feasibility of using mineral polymerization techniques on black soil commonly found in the northern side of Kathmandu Valley, using different percentages of sodium hydroxide and fillers (sand) to optimize the stabilization process and minimize costs.

Mineral polymerization (MIP) transforms clay minerals into a tectosilicate structure using alkaline reactants (Davidovits, 1991; Huang et al., 2021). When sodium hydroxide is added to suitable soil, it reacts with kaolinite, transforming it into a more stable zeolite or feldspathoid structure. This process creates materials that are stable in water and resistant to high temperatures. Additionally, fine, clean sands can be added to improve granulometry, strength, and durability. The resulting mineral polymers, also known as geopolymers, are formed from chemical reactions between alumino-silicate oxides (Al3+ in fourfold coordination) and alkali polysilicates, forming polymeric Si-O-Al bonds. These structures are amorphous to semi-crystalline, with three-dimensional silico-aluminate structures (Davidovits, 1991). Studies (Abid, 2016; Olaniyan et al., 2011) have shown that adding sodium hydroxide to kaolinite leads to the formation of sodium silicate and sodium aluminate, which precipitate insoluble aluminum oxide hydrates, increasing soil durability. Not all soils are suitable for MIP; they must contain a minimum 20% kaolinite content, avoid swelling clays, and include non-clay minerals like quartz and feldspar, while lacking organic compounds and components unstable in strongly alkaline conditions. MIP has led to the development of new materials with applications in construction, industry, and waste management, with metakaolin and fly ash being used as precursors alongside kaolinite.

Methodology

In this study a black-colored, fine-grained soil, which is most commonly found in the Kathmandu Valley was utilized. Disturbed soil samples were collected from shallow depths of 1.0 to 1.5 m, carefully placed into plastic bags to prevent contamination, and transported to the laboratory for testing. According to the Unified Soil Classification System (USCS), the natural soil is classified as organic silt of medium to high plasticity (OH). It exhibits a specific gravity of 2.48 and an organic content of 6.2%, categorizing it as medium-organic soil according to the Swedish Classification (Karlsson, & Hansbo, 1989). The soil has measured pH value of 6, indicating acidic soil. It is characterized as fine-grained, with 96.2% of particles smaller than 0.075mm (Figure 1). Some of the properties are shown in Table 1 below.

Figure 1

Grain Size Distribution Curve of Natural Soil and Sand Filler

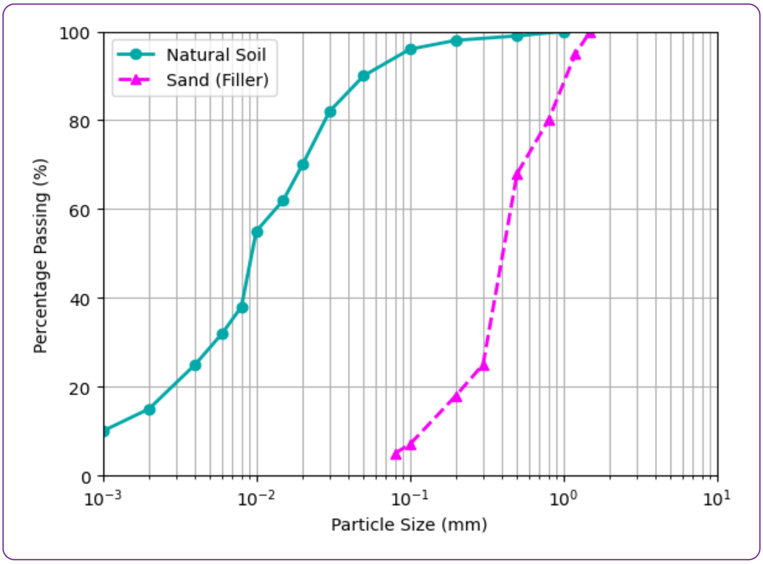


Table 1

Summary of Key Empirical Findings

S.N	Property of the soil	Experimental Value
1	Natural water content (%)	58
2	Specific gravity of soil	2.48
3	Liquid limit (LL) (%)	66
4	Plastic limit (PL) (%)	39.92
5	Plasticity index (PI) (%)	26.1
6	Soil type according to USCS	OH
7	Optimum moisture content (OMC) of natural soil (%)	37.8
8	Maximum dry density (MDD) of natural soil (gm/cc)	1.30
9	Organic content (%)	6.2
10	pH-value	6

Filler Material

The fine-grained sand collected from the same area was used as the filler material in this study. The sand exhibited a specific gravity of 2.67 and a density of 1.447gm/cc. It also contained 3.065% particles smaller than 0.075mm. The grain distribution curve is presented in Figure 1.

Sodium Hydroxide (NaOH)

In this study, sodium hydroxide in the pellet form was brought from the local market and utilized as an additive for the stabilization of the soft soil. Sodium hydroxide, commonly known as caustic soda, is a white, odorless solid that is highly soluble in water.

Specimen Preparation and Testing

The soil sample was air-dried in shade for approximately 10 days at a room temperature ranging from 25˚C to 30˚C. Subsequently, the dried sample was crushed using a wooden hammer. The portion of the sample passing through sieve no. 4 (4.75 mm) ASTM was specifically selected for compaction and unconfined compressive strength testing. Additionally, the sand passing through sieve no. 10 (2.00 mm) ASTM, was uniformly mixed with the natural soil to prepare specimens of the treated soil sample. Index properties, including water content, particle size distribution, specific gravity, liquid limit and plastic limit of the natural soil were determined following ASTM standards. Dry sieving and hydrometer tests were performed to obtain the complete gradation curve of coarse and fine fraction of natural soil. Soil classification in this study was carried out using the Unified Soil Classification System, which considers particle size analysis and Atterberg limits (LL,PI). The classification procedure used was the testing-based procedure, known for its rigorousness compared to the visual-manual procedure. The organic content of the soil was determined through a process involving oven-drying the sample at 60˚C for 24 hours, followed by heating it in a muffle furnace at 440˚C for 12 hours. The weight difference before and after heating provided the organic content measurement. The specific gravity of natural soil and sand filler was determined in the laboratory using a pycnometer. This parameter is essential for evaluating the compaction characteristics of the materials.

Compaction Test

Standard proctor compaction test was conducted for determination of optimum moisture content (OMC) and maximum dry density (MDD) of untreated and treated soil sample. Soil was mixed with varying NaOH: 7,10,13,16 percentages with constant filler sand. Again soil was mixed with varying sand percentage at 50%, 100%, 200%.

Specimen Preparation

Specimens were prepared achieving the optimum water content and maximum dry density for each mixture of samples, with a constant sand content and varying sodium hydroxide concentrations at 7%, 10%, 13%, and 16%. The sand content also varied at 50%, 100%, and 200%, with sodium hydroxide held constant, using the Harvard miniature apparatus. For each mixture composition, three specimens were prepared. The first specimen was tested for dry compressive strength, the second specimen was used for immersion compressive strength, and the third specimen was subjected to wetting and drying cycles for compressive strength testing. Curing of specimens were done for about 24 hours in an oven at constant temperature of 80˚C, after which they were removed and allowed to cool. Subsequently, the samples were prepared for post-curing, which was conducted under conditions similar to those experienced in natural exposure. From each composition, one specimen was placed in an oven at a constant temperature of 40˚C for a minimum of 7 days. Another specimen from each mixture was immersed in water using a plastic container for at least 7 days. The third specimen from each mixture underwent at least five cycles of drying and wetting, consisting of at least 5 days in the oven set at 40˚C and at least 5 days immersed in water using a plastic container. This third specimen had to be immersed in water for at least 24 hours before the strength test.

Unconfined Compressive Strength Test

Unconfined compressive strength (qu) was determined on the prepared specimens with 24 hours prior immersion and without immersion. Immersed compressive strength virtually represents the worst conditions of the field to which a soil may be subjected. The tests were conducted for both treated and untreated soil for its stress-strain behavior; maximum unconfined compressive strength.

Loss in Compressive Strength

To assess the stability and quality of specimens under different conditions, the compressive strength of specimens subjected to two conditions (dry and wet) was compared. The loss of compressive strength was calculated using the formula:

Loss in compressive strenght (%)

$$= \left(1 - \frac{S_2}{S_1}\right) \times 100$$

Where, S1 and S2 are compressive strength of dry and wet specimens respectively.

Water Absorption

The average percentage of water absorption by the wet specimen was determined using the formula:

$$\text{Water absorption (\%)} = \frac{W_2 - W_1}{W_1} \times 100$$

Where, W1 and W2 are weight of dry and wet specimens respectively.

Results and Discussion

The test results after the soil stabilized with sodium hydroxide as additive and sand as filler material are summarized as follows:

Moisture Density Relationship

The compaction curve of different mixtures of soil, sand and sodium hydroxide are presented in the Figure 2, Figure 3 and Figure 4. The results indicate a substantial reduction in the optimum moisture content and a significant increase in its maximum dry density of the treated soil compared to the untreated soil. The effect of different of sodium hydroxide and sand on the maximum dry density and optimum moisture content of soil are depicted in the Figure 5 and Figure 6 respectively.

Figure 2

Comparison of the Compaction Curve of Different Percentage of Sodium Hydroxide at 50% Sand Content

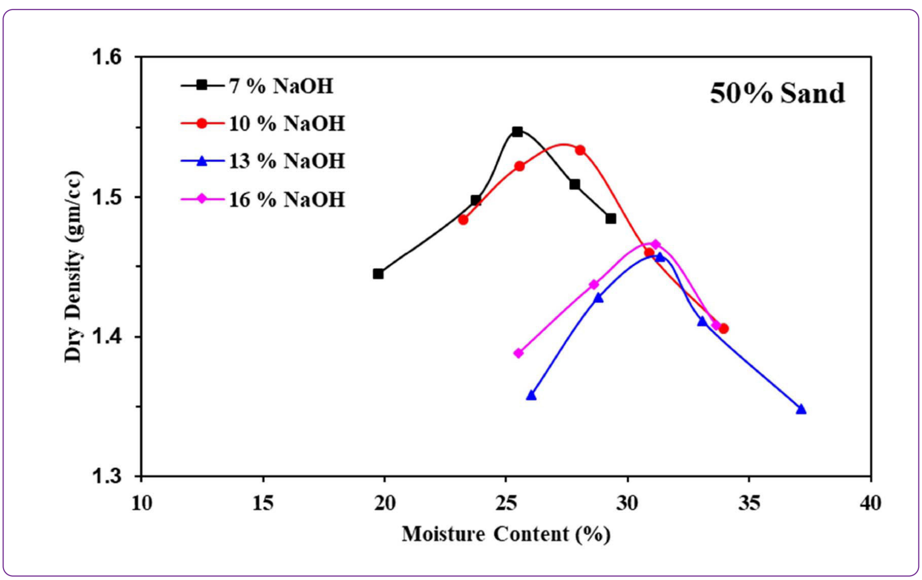


Figure 3

Comparison of the Compaction Curve of Different Percentage of Sodium Hydroxide at 100% Sand Content

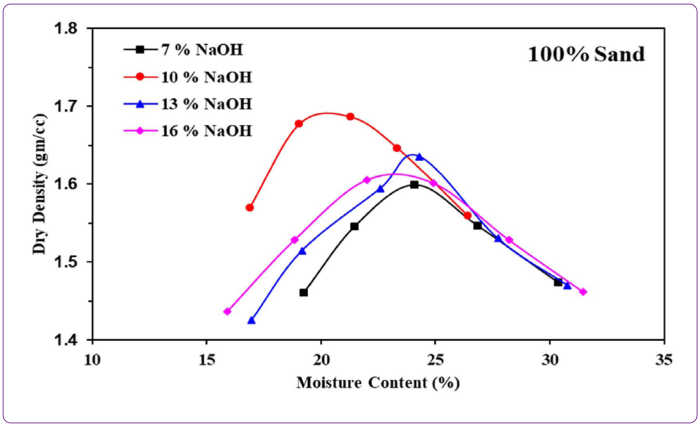


Figure 4

Comparison of the Compaction curve of Different Percentage of SODIUM hydroxide at 200% Sand Content

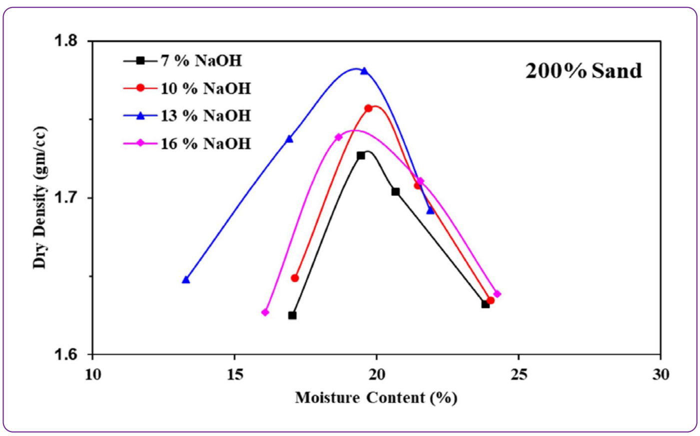


Figure 5

Distribution of OMC with NaOH

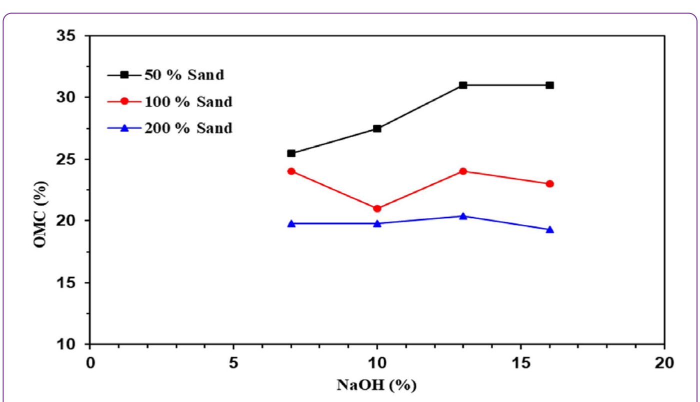


Figure 5 indicates that there is not any usual variation in the optimum moisture content with variation in NaOH percentage. However, an increase in percentage of sand content results in a significant reduction in the OMC.

Figure 6

Distribution of Dry Density With NaOH

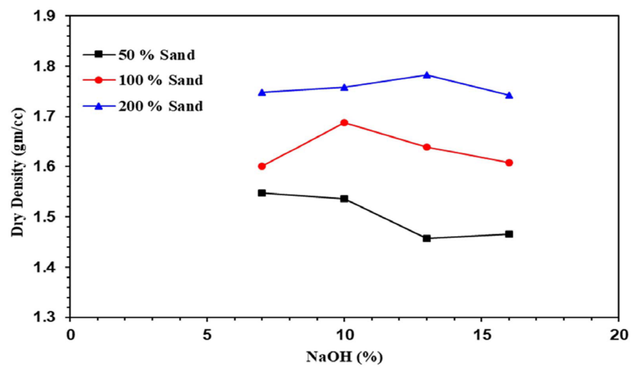


Figure 6 illustrates minimal variation in maximum dry density with alterations in NaOH content for a constant sand content. However, there is significant variation in MDD with sand content. The experimental results indicate that dry densities increase with increasing sand content, reaching a maximum at 200% sand content.

Unconfined Compressive Strength

The unconfined compressive strength of modified soil was determined from the prepared soil specimens. Figure 7 to Figure 15 illustrates the stress-strain curve for dry, wet and cycling specimens varying the percentage of NaOH content and sand content. The distribution of compressive strengths for varying composition of sand and NaOH under different weathering conditions is depicted in the Figure 16, Figure 17 and Figure 18. The results indicate that compressive strength varies significantly with both composition and weathering conditions. Specifically, the compressive strength of the dry specimens were found to be greater than that of the wet and cycling specimens and the wet specimens exhibited lowest strength at the same sand content.

Figure 7

Stress-Strain Curve for Dry Specimen at 50% Sand With Different Percentage of NaOH

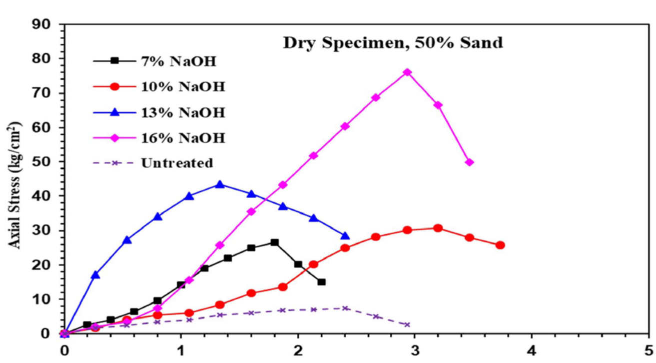


Figure 8

Stress-Strain Curve for Dry Specimen at 100% Sand with Different Percentage of NaOH

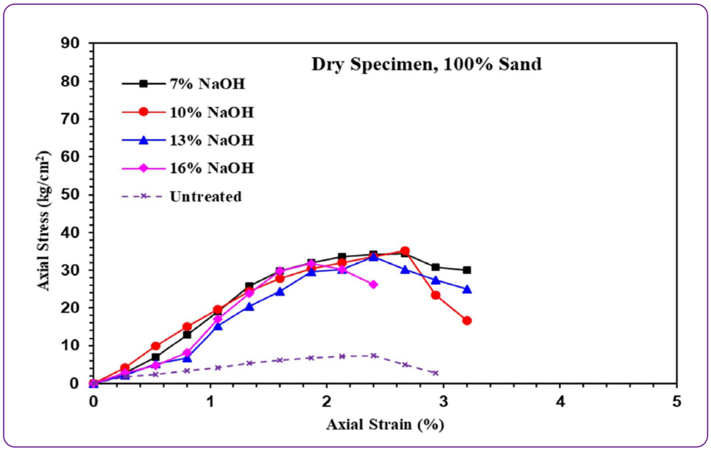


Figure 9

Stress-Strain Curve for Dry Specimen at 200% Sand with Different Percentage of NaOH

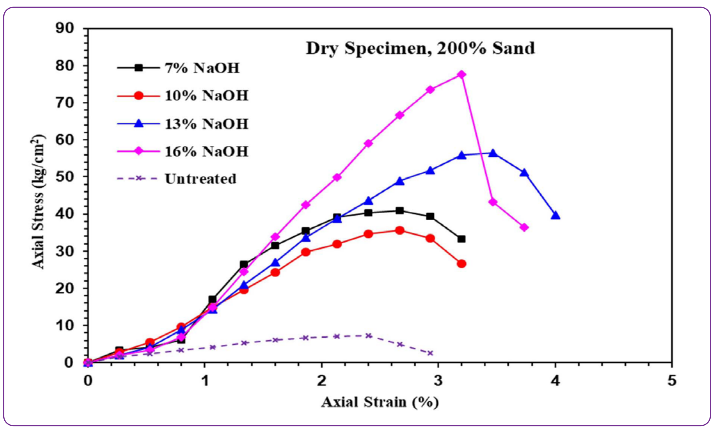


Figure 10

Stress-Strain Curve for Wet Specimen at 50% Sand with Different Percentage of NaOH

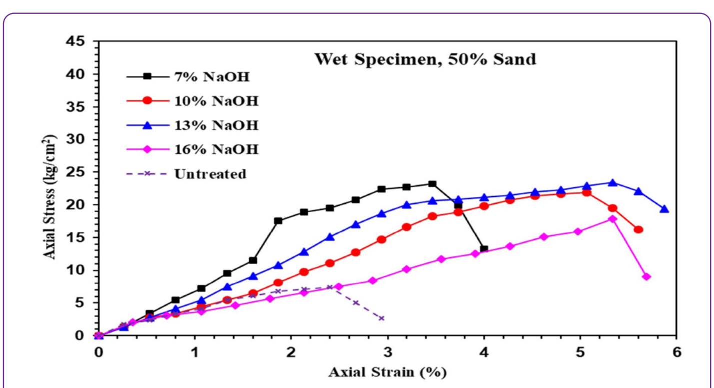


Figure 11

Stress-Strain Curve for Wet Specimen at 100% Sand with Different Percentage of NaOH

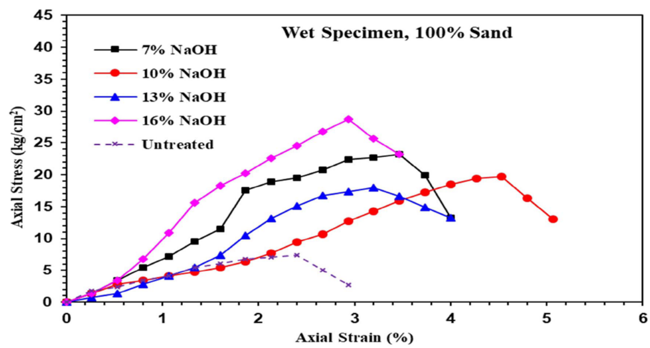


Figure 12

Stress-Strain Curve for Wet Specimen at 200% sand With Different Percentage of NaOH

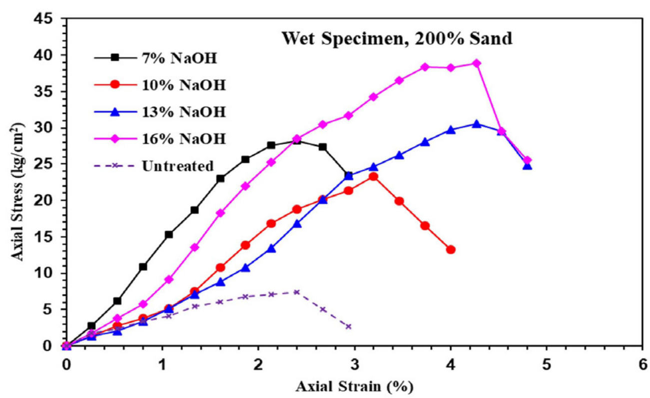


Figure 13

Stress-Strain Curve for Cycling Specimen at 50% Sand with Different Percentage of NaOH

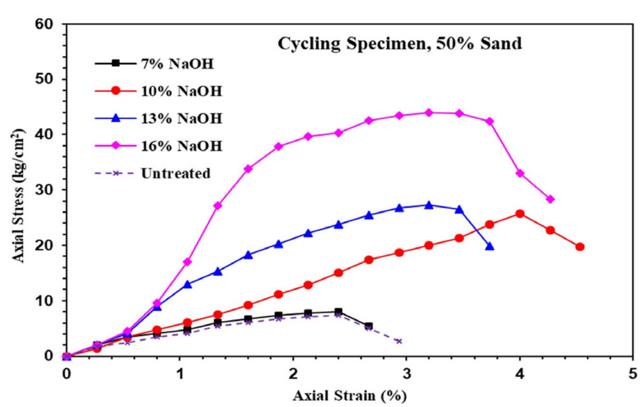


Figure 14

Stress-Strain Curve for Cycling Specimen at 100% Sand With Different Percentage of NaOH

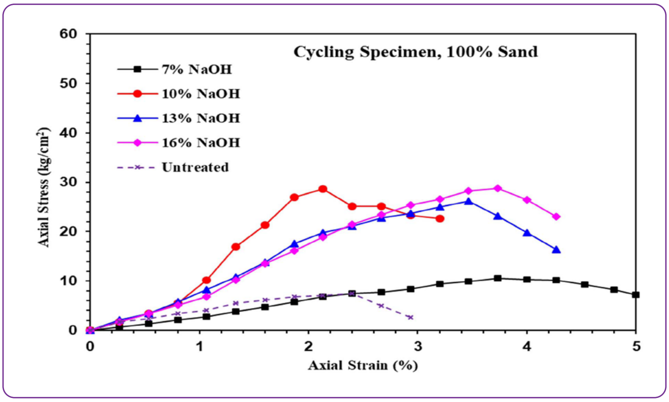


Figure 15

Stress-Strain Curve for Cycling Specimen at 200% Sand with Different Percentage of NaOH

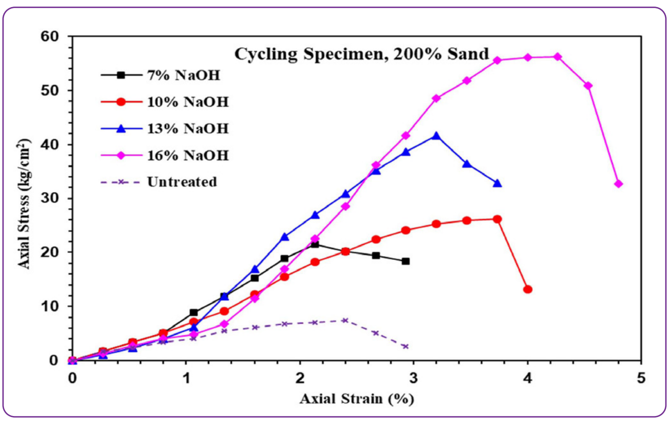


Figure 16

Unconfined Compressive Strength for dry Specimen at Different Percentage of Sand and NaOH

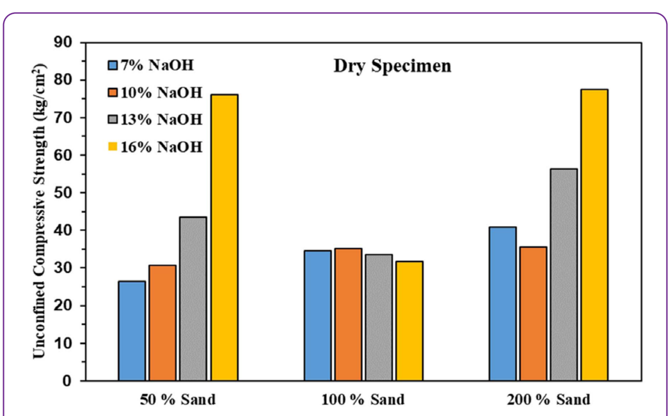


Figure 17

Unconfined Compressive Strength for Wet Specimen at Different Percentage of Sand and NaOH

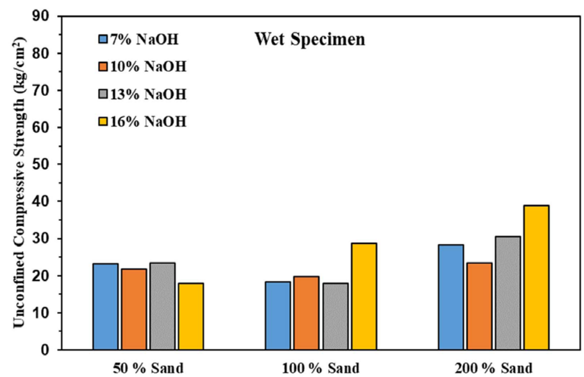
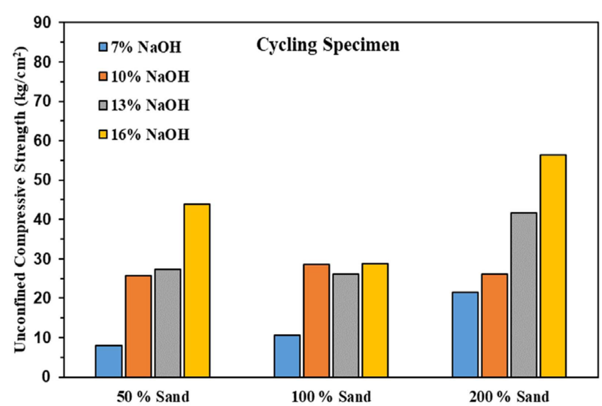


Figure 18

Unconfined Compressive Strength for Cycling Specimen at Different Percentage of Sand and NaOH



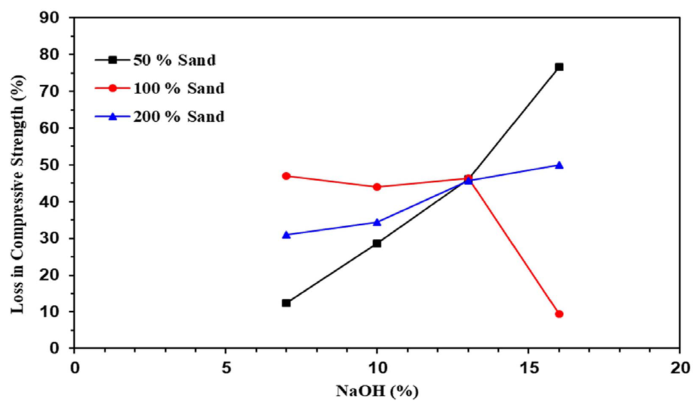
Furthermore, as the sand content increased, the compressive strength of all specimens increased, with the highest compressive strength observed at 200% sand content across all specimen types (dry, wet, cycling). With the variation of NaOH concentration from 7% to 16%, an increase in unconfined compressive strength was observed, reaching the maximum at 16% NaOH. This trend was consistent for all specimens except the dry specimen with 100% sand content and the wet specimen with 50% sand content. Although the UCS increased compared to untreated soil, the strength increment trend for varying NaOH percentages remained constant. This consistent trend may be attributed to the differences in accuracy levels during the preparation and testing of specimens across different NaOH concentrations.

Loss in Compressive Strength

The compressive strength of the specimens was lost due to immersion in water. The distribution of compressive strength loss for various sodium hydroxide (NaOH) content is depicted in Figure 19. It was observed that the loss of compressive strength increases with higher NaOH content for specimens containing 50% and 200% sand. However, for specimens with 100% sand content, the loss in compressive strength decreases as the NaOH content increases. This result is favorable for the 100% sand content specimens, as the loss in compressive strength is minimal with increasing NaOH content.

Figure 19

Distribution of Loss in CS with NaOH



The values of unconfined compressive strength and their losses in strength for different amounts of sodium hydroxide and sand content in the dry, wet, and cycling specimens are tabulated on Table 2.

Table 1

Unconfined Compressive Strength and Loss in Different Conditions

Specimen No.	% of Sand	% of NaOH	Unconfined Compressive Strength (kg/cm^2)			Loss in UCS	% Loss in UCS
			Dry Specimen	Wet Specimen	Cycling Specimen		
217	50	7	26.517	23.239	8.056	3.278	12.36
2110		10	30.628	21.875	25.752	8.753	28.58
2113		13	43.434	23.440	27.298	19.994	46.03
2116		16	76.113	17.856	43.944	58.257	76.54
117	100	7	34.478	18.259	10.594	16.219	47.04
1110		10	35.148	19.699	28.609	15.449	43.95
1113		13	33.568	17.977	26.220	15.591	46.45
1116		16	31.725	28.709	28.800	3.016	9.51
127	200	7	40.839	28.195	21.540	12.644	30.96
1210		10	35.560	23.304	26.154	12.256	34.47
1213		13	56.439	30.619	41.613	25.820	45.75
1216			77.568	38.850	56.300	38.718	49.91

Figure 20

Distribution of Water Absorption With NaOH

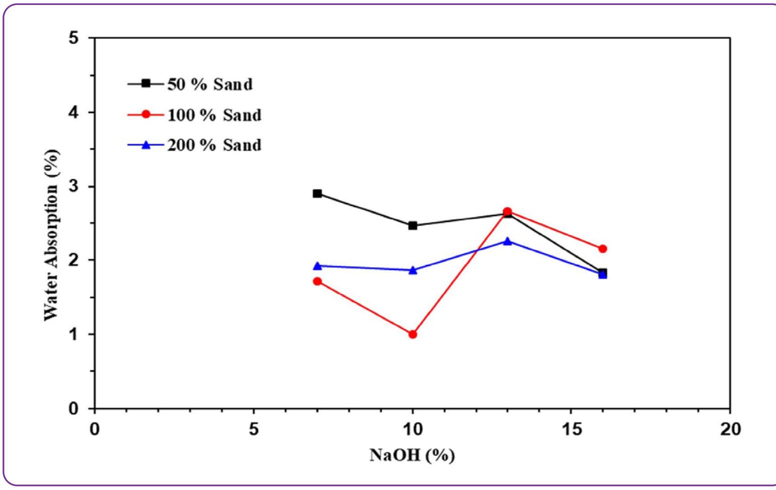


Figure 20 illustrates the relationship between water absorption and NaOH content. The plot indicates a decrease in the water absorption rate as the percentage of NaOH increases. Specimens with 50% sand content exhibit greater water absorption compared to those with other sand contents.

Suggested Research Areas

- **Cement Additives for Soil-Cement Stabilization:** Explore cost-effective Nepalese cement brands (e.g., Shivam OPC, Brij PPC) as stabilizers for soft soils, assessing strength gains and economic viability for foundations, linking to Mishra & Chaudhary (2018) on supermarket site cement handling.
- **Lightweight Blocks on Stabilized Soils:** Evaluate autoclaved aerated concrete (AAC) blocks' performance on treated soft soils for earthquake-resistant walls, building on Khanal et al. (2020) findings of AAC's suitability in Nepal amid rising construction demands.
- **Safety in Soil Treatment Operations:** Investigate occupational hazards during chemical soil stabilization (e.g., alkali handling) in cement-related processes, extending Sah et al. (2019) analysis of accidents in Nepal's cement industries to geotechnical sites.
- **Cost Analysis of Stabilized Foundations:** Quantify cost implications for earthquake-resistant load-bearing buildings using treated soft soils, referencing Mishra (2019) cost estimates (Rs. 401k–2.1M) for models in Ramechhap, adaptable to Kathmandu.
- **Quality Management in Stabilization Projects:** Develop quality systems for soil improvement in bridges/roads on soft soils, drawing from Mishra (2018) practices like Total Quality Management in Kathmandu bridge projects emphasizing time, cost, and safety.

Conclusion

In this research, we evaluated the effectiveness of the MIP technique with NaOH as an additive to improve the geotechnical properties of soft soil. We conducted a series of compaction tests and unconfined compressive strength (UCS) tests to assess the suitability of this approach. Our findings and conclusions from this experimental study are outlined below:

- The addition of NaOH results in a significant increase in the dry density and a substantial reduction in the OMC of the treated soil. However, variations in NaOH content do not lead to significant changes in the dry density and OMC of the soil composition. This suggests that the variation in sodium hydroxide for a constant sand content has a minimal impact on the soil's compaction characteristics.

- The dry density increased with an increase in the percentage of sand, accompanied by a decrease in the optimum moisture content. This suggests that the addition of sand can improve the compaction characteristics of the soil, requiring less moisture for optimal compaction.
- The unconfined compressive strength of the improved soil increased with increasing sodium hydroxide content and sand content. Specifically, a sand content of 200% yielded greater compressive strength compared to 100% and 50% content. This implies that the combination of sodium hydroxide and sand can significantly enhance the strength of soft soil.
- The study also found that the compressive strength loss was more significant at 50% sand content, and the loss increased with increasing sodium hydroxide content for 50% and 200% sand content. However, at 100% sand content, the loss decreased with increasing sodium hydroxide content. This suggests that higher sand content can mitigate the adverse effects of sodium hydroxide on the soil strength.
- Furthermore, as the sand content increased, water absorption decreased, with greater absorption observed at 50% sand content. Additionally, an increase in sodium hydroxide resulted in a decrease in water absorption. This indicates that the combination of sodium hydroxide and higher sand content can improve the soil resistance to water absorption, which is beneficial for durability and stability.

The findings of this study provide valuable insights into the potential use of sodium hydroxide and sand for improving the geotechnical properties of soft soil in the Kathmandu Valley. The use of sodium hydroxide as an additive has shown promising results in enhancing soil strength and reducing water absorption, which are crucial factors in geotechnical engineering. This study is significant in the geotechnical field as it offers a sustainable and cost-effective solution for improving the properties of soft soil, which is prevalent in many regions around the world. Additionally, the treatment work using sodium hydroxide and sand has significant implications in the construction field, where soil stabilization is often required for building foundations, roads, and other infrastructure. Further research could explore the long-term effects and environmental impacts of these soil improvements, providing a more comprehensive understanding of their potential benefits and drawbacks.

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