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Laboratory Investigation on the Application of Zeolite for Quick Clay Stabilization

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ABSTRACT: Quick clay is a highly sensitive soft soil that poses great risks on the infrastructure development projects as it can suddenly liquefy upon disturbance. In Norway, the deep mixing technology using binders, like quick lime and cement, is the common solution to improve the strength and deformation properties of quick clay. However, the high CO2 emissions associated with the production of lime and cement raises environmental concerns for this approach. The present study aims to eliminate cement from the process while retaining lime as the source of calcium, by investigating the effects of zeolite and hydrated lime on quick clay stabilization in lab-scale. Zeolite, as a pozzolanic material, is a crystalline aluminosilicate rich in active SiO_2 and Al_2O_3. It improves soil strength by reacting with hydrated lime producing C-S-H and other complex compounds like monocarboaluminate. To evaluate their effect on quick clay stabilization, a series of laboratory experiments were conducted, including unconfined compressive strength, and primary wave velocity assessments using the resonant column free-free (RC-ff) technique. These measurements were taken across varying conditions, including zeolite and hydrated lime contents of 10, 30, 50, 70 and 90 kg/m^3 (with a constant total binder content of 100 kg/m^3), and curing times of 1, 7, 14, and 28 days. The results show a significant improvement in the strength and deformation properties of quick clay, confirming the effectiveness of the proposed method. The highest unconfined shear strength values were observed in samples with 50 and 30 kg/m^3 of zeolite, resulting in shear strength values of 400 kPa and 470 kPa, respectively. Considering the higher carbon footprint of lime production compared to zeolite, and the marginal difference in performance between the two, the optimal combination is considered to be 50 kg/m^3 of zeolite and 50 kg/m^3 of hydrated lime.

KEYWORDS: Sustainability, Ground improvement, Zeolite, Soft clay, Pozzolanic materials.

1 INTRODUCTION

Soft soils, such as marine clay, present significant challenges for infrastructure development in many parts of the world. These soils are characterized by their low strength and high compressibility, making them problematic for the construction and development of infrastructure. These challenges are even more severe in the case of sensitive soils like quick clay. Quick clay is a highly sensitive, marine-deposited clay with a unique metastable "house of cards" microstructure. When disturbed, it can experience a dramatic and sudden reduction of shear strength, potentially leading to sudden landslides that may result in loss of life and severe infrastructure damage (Giles, 2020). Therefore, any large infrastructure project in these regions require enormous amounts of ground stabilization.

Various chemical stabilizers have been employed to treat quick clay, such as lime, cement, pozzolanic materials, industrial waste or by-products (Hov, Paniagua, et al., 2023), and salts (Loshelder et al., 2025). Among these, deep mixing with lime and cement, is the most commonly used method in Norway, due to its cost-effectiveness and proven performance in improving the strength and deformation properties of quick clay.

However, the production of these conventional binders for deep mixing technology contributes substantially to global CO_2 emissions. These greenhouse gas emissions increased from 1990 to 2019, limiting the broader application of these otherwise effective stabilization methods.

Given this environmental challenge, the primary goal of this study is to reduce the use of lime and cement and to test sustainable,#eco-friendly, and effective alternative materials for deep mixing stabilization of quick clay. One such material is zeolite, which is pozzolanic material.

Pozzolanic materials are characterized by their composition, primarily consisting of silica (SiO_2) and alumina (Al_2O_3), which react with calcium hydroxide in the presence of water to form cementitious compounds. Zeolite, a crystalline aluminosilicate, stands out due to its high content of reactive silicates and aluminates, making it one of the most effective pozzolanic materials (Mertens et al., 2009).

Previous research has widely highlighted the advantages of using zeolite to enhance the mechanical properties of concrete (Mertens et al., 2009) and sandy soils (Mola-Abasi & Shooshpasha, 2016). However, investigations into the effectiveness of zeolite for stabilizing soft clays remain relatively limited. More notably, the use of zeolite for improving highly sensitive clays, and in particular quick clays, has not yet been investigated. Addressing this significant research gap, the present study evaluates a cement-free binder system composed of zeolite and hydrated lime aiming to assess its potential for improving the geotechnical properties of highly sensitive clay.

2 MATERIALS AND METHODS

2.1 *Materials*

2.1.1 *Soil*

The clay used in this study was collected from one of the Norwegian GeoTest Site (NGTS) located in the Tiller–Flotten region, approximately 10 km south of Trondheim, Norway. The NGTS site is characterized by a 50-meter-thick deposit of marine clay, with highly sensitive clay at the depths between 7.5 and 20 meters below the ground surface, reaching sensitivity values exceeding 200. (L'Heureux et al., 2019). For this study, clay samples were collected from depths of 8 to 11 meters, where the clay exhibits highly sensitive behavior. A clay sample collected from this depth is shown in Figure 1. The clay water content is approximately 45%, the unit weight is around 18 kN/m^3, and the salt content (NaCl) is 2.5 g/l.

2.1.2 *Binders*

The binders used in this study were Zeolite ($Na_{86}[AlO_2)_{86}(SiO_2)_{106}]\cdot xH_2O$), with an average particle size of 2 µm, and hydrated lime ($Ca(OH)_2$), with particles size smaller than 20 µm. The mixtures were prepared using various proportions of the two binders: 10, 30, 50, and 70 kg/m³ of each binder, while maintaining a constant total binder content of 100 kg/m³.

Figure 1. Quick clay sample collected from a depth of 8,2 meters at the NGTS site.

2.2 *Methods*

2.2.1 *Sample preparation*

The collected quick clay was remolded in the laboratory using a blender until it became homogeneous and uniform in appearance. The desired amount of zeolite was then added to the clay and mixed for 1 minute. After that, the specified amount of hydrated lime was added to the clay–zeolite mixture and thoroughly mixed for an additional 2 to 3 minutes, ensuring uniformity. Note that during the mixing process, cation exchange and flocculation reactions were normally observed.

The resulting clay–binder mixtures were compacted into cylindrical molds measuring 40 mm in diameter and 80 mm in height using a rodding technique. This involved tamping the mixture with a steel rod approximately 30 times per layer to ensure proper compaction (Kitazume et al., 2015).

To ensure precision and consistency, three replicate samples were prepared for each combination and curing times. The samples were cured at ambient temperature (18.9 – 21.4 °C) for 1, 7, 14, and 28 days. After the curing periods, experimental tests were performed on the samples.

2.2.2 *Resonant column free-free (RC-FF) technique*

The Resonant Column – Free-Free (RC-FF) method was employed to determine the dynamic properties of the stabilized clay samples (Lindh & Lemenkova, 2022). In this procedure, specimens were positioned horizontally on a soft foam base to simulate free-free boundary conditions, minimizing external restraint at both ends. Ten light mechanical impacts were applied to one end of the specimen to initiate longitudinal compression waves (P-waves), while the response was measured at the opposite end using an accelerometer. This setup allowed the sample to vibrate in its natural mode, and the resulting signal was transformed into the frequency domain using a Fast Fourier Transform (FFT) to identify the fundamental resonant frequency. The dynamic modulus was then calculated based on the measured resonant frequency, the length of the specimen, and its density (Hov, Kitazume, et al., 2023).

2.2.3 *UCS experiments*

Unconfined compressive strength (UCS) tests were conducted on the stabilized quick clay specimens using a GDS automated uniaxial testing device, with an axial strain rate set to 1.5 %/min. The test was conducted in accordance with the ASTM D2166 standard. During the tests, stress–strain behavior and undrained shear strength were recorded.

2.2.4 *Microstructural Analysis*

To investigate the mineralogical changes resulting from the addition of zeolite and hydrated lime during the stabilization process, X-ray diffraction (XRD) analysis was performed. The analysis was performed on samples oven-dried at 50ºC as well as on untreated clay using Bruker D8 A25 DaVinci X-ray diffractometer with CuKα radiation. Scans were conducted over a 2θ range of 5° to 80°, with a step size of 0.013°.

3 RESULTS

All experiments were conducted on five different zeolite–hydrated lime compositions, using 10, 30, 50, 70, and 90 kg/m³ of zeolite while keeping the total binder content constant at 100 kg/m³. The remaining portion in each mix was composed of hydrated lime.

3.1 *RC-FF results*

Based on the compression wave velocity (V_c) found using the RC-FF method, the small-strain Young's modulus (E_{max}) was calculated using : $E_{max}=\rho V_c^2$, where ρ is the bulk density of the sample (Kim et al., 1997; Verástegui-Flores et al., 2015). Note that the mixture containing 90 kg/m³ of zeolite did not exhibit significant stabilization. The specimens prepared with this composition lacked sufficient strength to be placed horizontally for RC-FF testing. Thus, the E_{max} values for this composition were not included in the analysis.

The results of E_{max} over the curing time for each composition are presented in Figure 2. A clear and consistent increase in E_{max} was observed with increasing curing time, except for the composition containing 70 kg/m³ of zeolite, which remained nearly constant after 7 days. This trend indicates that the stiffness of quick clay improves over time when stabilized with appropriate combinations of zeolite and hydrated lime.

Compositions containing 30 kg/m³ and 50 kg/m³ of zeolite demonstrate a significant increase in E_{max}. This indicates a rapid stabilization process and shows that these two compositions are the most effective in terms of stiffness development over time.

3.2 *UCS results*

Figure 3 illustrates the UCS results of five different compositions at various curing times. For zeolite contents of 10, 30, and 50 kg/m³, the peak shear strength gradually increased with curing time, which aligns well with the RC-FF results.

The samples containing 90 and 70 kg/m³ of zeolite did not gain sufficient strength. The samples containing 30 and 50 kg/m³ of zeolite showed significantly improved strength and stiffness, indicating that these amounts of zeolite and hydrated lime are sufficient to effectively enhance the shear resistance of quick clay.

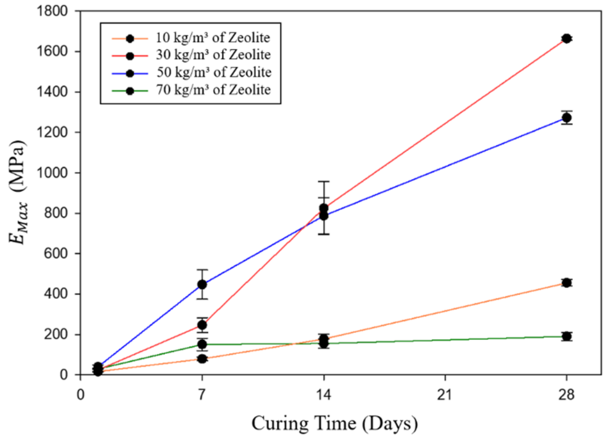

Figure 2. Small-strain Young's modulus (E_{max}) versus curing time

Figure 4 shows the development of shear strength over 28 days of curing. The sample containing 50 kg/m^3 of zeolite exhibited performance closely comparable to that of the 30 kg/m^3 zeolite. At 28 days, the strength of the 50 kg/m^3 of zeolite composition was only approximately 17% lower than the maximum strength achieved by the 30 kg/m^3 of zeolite mixture. From an optimization perspective, the 50 kg/m^3 of zeolite mixture uses approximately 28.6% less lime, which is beneficial from an environmental standpoint due to the intensive carbon footprint involved in lime production. Thus, this composition is considered as the optimum composition for quick clay stabilization.

3.3 *Microstructural analysis*

Figure 5 presents the XRD patterns of untreated quick clay and quick clay stabilized with the optimum composition after 28 days of curing. The analysis identifies the presence of illite and mica, chlorite, hornblende, quartz, and plagioclase in the untreated quick clay. The main production mineral in the stabilized quick clay was monocarboaluminate. Indeed, indications of the presence of calcium silicate hydrate (C–S–H) were observed. Therefore, it may be concluded that the strength gain is primarily attributed to the formation of monocarboaluminate. Monocarboaluminate, also known as monocarbonate, with the chemical formula $Ca_4Al_2(CO_3)(OH)_{12}\cdot 5H_2O$, is the most stable form of calcium carboaluminate hydrates that is usually produced during cement hydration. It forms through the reaction of the aluminate phase with limestone in cement hydration. This stable mineral forms with approximately 7.7% carbonate content, which is considered a relatively small amount of carbonate or CO_2 (Matschei et al., 2007).

In the case of quick clay in this study, monocarbonate formed as a result of the pozzolanic reaction, where the alkaline environment created by the hydrated lime facilitated the dissolution of zeolite. The released aluminum then reacted with the calcium ions from the hydrated lime, leading to the precipitation of monocarbonate.

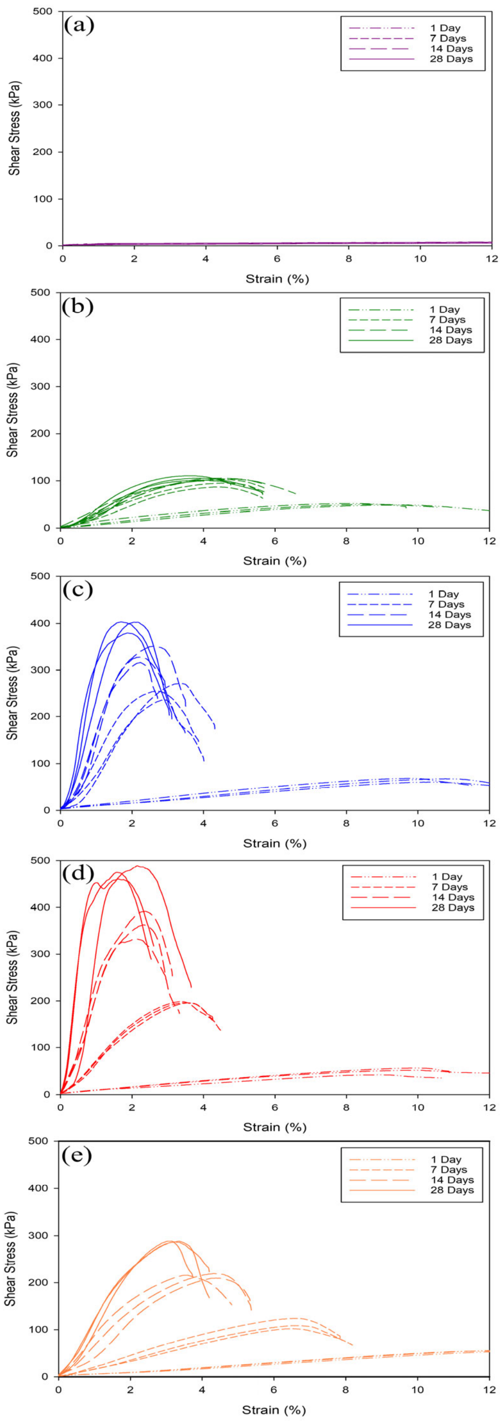

Figure 3. Shear stress-strain curves of (a) 90 kg/m^3 of zeolite, (b) 70 kg/m^3 of zeolite, (c) 50 kg/m^3 of zeolite, (d) 30 kg/m^3 of zeolite, and (e) 10 kg/m^3 of zeolite, at different curing times

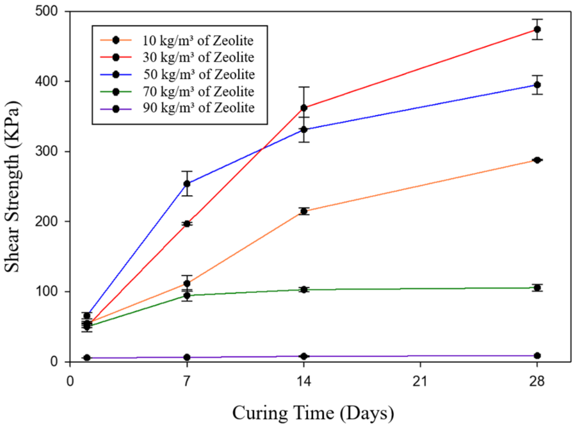

Figure 4. Shear strength versus curing time

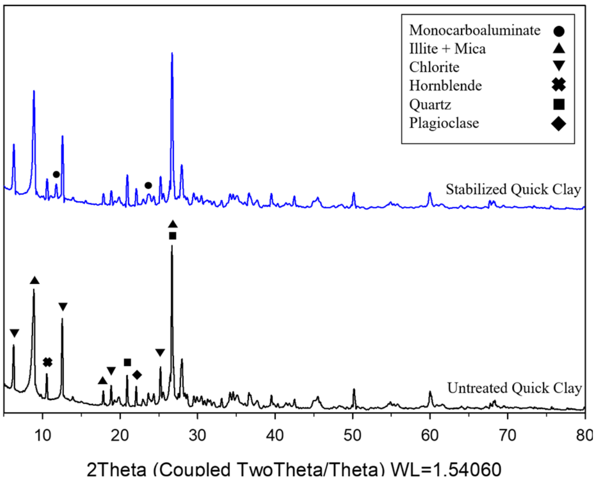

Figure 5. XRD spectra of untreated and stabilized quick clay

4 CONCLUSIONS

While cement-lime deep mixing is a common method for stabilizing quick clay, it is associated with significant greenhouse gas emissions. To address this issue, this study explores an eco-friendly alternative material to replace cement and reduce the amount of lime. Zeolite, a high-quality pozzolanic material, was chosen to stabilize quick clay in combination with hydrated lime.

To evaluate the effectiveness of zeolite in quick clay stabilization, various proportions of zeolite (10, 30, 50, 70, and 90 kg/m³) were added while keeping the total binder content constant at 100 kg/m³. Tests were conducted after curing time of 1, 7, 14, and 28 days.

Unconfined compressive strength (UCS) tests and resonant column free-free (RC-FF) tests were performed to assess improvements in mechanical properties. Additionally, X-ray diffraction (XRD) analysis was performed to investigate mineralogical changes during stabilization.

The results showed that the mixtures containing 30 and 50 kg/m³ of zeolite were the most effective in improving strength and stiffness, as indicated by higher UCS and E_{max} values. Considering the higher carbon footprint associated with lime production compared to zeolite, and the relatively 17% shear strength difference between these two compositions, the mixture with 50 kg/m³ of zeolite is identified as the optimal combination.

XRD analysis revealed that the main production in the optimal mixture was monocarboaluminate, the most stable form of calcium carboaluminate hydrate. This suggests that the strength gain is primarily due to the formation of monocarboaluminate.

In conclusion, zeolite, as an eco-friendly material, proves to be an effective alternative for stabilizing quick clay when combined with hydrated lime.

5 ACKNOWLEDGEMENTS

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