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Sustainable stabilization of highly sensitive clay by using recycled crushed concrete

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Abstract. Highly sensitive clays possess a unique metastable structure that can undergo strength loss when subjected to loading or vibration. In regions containing these clays, major challenges to infrastructure development arise, necessitating extensive ground improvement. The conventional applied ground improvement method for these clays is dry deep-mixing of binders like cement and lime, which are highly CO_2 intensive materials. This study investigates the use of recycled crushed concrete (RCC) as a more environmentally friendly alternative for stabilizing highly sensitive clay, in combination with zeolite and quicklime. Zeolite was selected as a pozzolanic material and a source of SiO_2 and Al_2O_3, while quicklime was used to supply Ca^{2+} ions and increase pH to promote pozzolanic reactions. RCC was employed as both a pozzolanic material and a calcium source to reduce the consumption of natural resources. RCC was used in powdered, coarse-grained, and well-graded forms to evaluate the combined effects of chemical and mechanical stabilization. Specimens were tested after 7, 14, and 28 days of curing using unconfined compressive strength tests and X-ray diffraction analysis. The optimum mixture consisted of 50 kg/m^3 of zeolite and quick lime and 25 kg/m^3 of powder RCC. The primary cementitious products identified were calcium-silicate-hydrate and monocarboaluminate.

1 Introduction

Soft soils are characterized by high compressibility, low shear strength, high water content, and low permeability [1, 2]. Infrastructure development in these areas, mainly motivated by the rapid population growth and increasing pressure on land resources, demand the improvement of the soft soil's deformation and strength properties. This challenge becomes even more critical in the case of highly sensitive clays, such as quick clay, which represent a major geotechnical hazard in regions including Scandinavia, Canada, Russia, and Alaska. Due to their unique "house-of-cards" microstructure, quick clays may experience a dramatic loss of shear strength upon disturbance, making extensive ground stabilization necessary prior to construction.

Over the years, various methods have been developed to stabilize highly sensitive clays and transform them into safe foundation materials. These methods include both mechanical and chemical stabilization techniques, such as preloading and surcharging [3], vertical drains [4, 5], stone columns [6], deep soil mixing [7-10], and jet grouting [11, 12]. Among these approaches, dry soil mixing (DSM) is considered one of the most reliable and widely applied ground improvement methods in Norway. In the DSM method, dry binders are mixed with the soil to form stabilized soil columns, resulting in improved strength and deformation properties. A variety of binders can be used in DSM, including lime, cement [13, 14], pozzolanic materials, and industrial waste or by-products [15]. However, lime and cement remain the most used binders in Norway due to their cost-effectiveness and well-documented performance in stabilizing quick clay.

Despite their technical effectiveness, the large-scale use of lime and cement in DSM projects results in significant material consumption and high CO_2 emissions. This environmental impact has become an important concern, highlighting the need for more sustainable and environmentally friendly alternative binders for quick clay stabilization.

One of the alternative materials for reducing the environmental impact of ground improvement is to use waste materials that are no longer suitable for their original purpose and are typically disposed in landfills. Reusing such materials not only reduces the consumption of natural resources but also minimizes waste generation and associated environmental impacts. Among various waste materials, concrete waste represents one of the largest fractions produced worldwide. Recycled concrete can be utilized for clay stabilization in two primary ways. First, crushed concrete can be used in coarse-grained form to enhance mechanical properties, like stone columns, thereby improving the bearing capacity and shear strength of clay. Second, recycled concrete can be finely ground and incorporated into the clay as a source of pozzolanic

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materials and calcium, promoting the formation of cementitious products such as calcium–silicate–hydrate (C–S–H) and enhancing shear strength through chemical stabilization.

In this study, alternative and waste materials were investigated in the stabilization of highly sensitive clay for DSM method. Zeolite was selected as a pozzolanic material and a source of SiO_2 and Al_2O_3. It is recognized as one of the most effective natural pozzolans [16]. Quicklime was used to supply Ca^{2+} ions and to increase the pH of the system, thereby facilitating pozzolanic reactions. Recycled crushed concrete (RCC) was employed as both a pozzolanic material and a calcium source to further reduce binder consumption. To evaluate the influence of particle size distribution, RCC was used in three different gradations, allowing the combined effects of mechanical and chemical stabilization to be assessed. The present study focuses on reducing lime usage and eliminating cement by utilizing zeolite together with waste materials, while evaluating their potential to improve the geotechnical properties of highly sensitive clay.

2 Materials and methods

2.1 Materials

2.1.1 Soil samples

Sensitive clay samples were collected from central Norway, south of the Trondheim city, at the Tiller-Flotten quick-clay test site established by Norwegian GeoTest Sites (NGTS). The site is approximately 70 m × 100 m and consists of a marine clay deposit exceeding 50 m in thickness. Between 7.5 m and 20 m below the ground surface, the sensitivity of the marine clay is approximately 200 [17]. Therefore, in this study clay samples were obtained from depths ranging between 9 and 11 meters to ensure representation of the highly sensitive layers.

The collected clay was dark gray in color and fully saturated. Immediately after extraction, the soil samples were carefully sealed to prevent moisture loss. The sealed specimens were subsequently stored in a temperature-controlled room at 6 °C that represent ground temperature at these depths, until laboratory testing was conducted.

The collected soil was classified as low plasticity clay (CL) according to the unified soil classification system. The particle size distribution of the clay is shown in Fig. 1 [17]. The quick clay had a water content in the range of 40–45%, a salt content (NaCl) of approximately 2.5 g/L, and a unit weight of about 1.85 t/m³. The plasticity index ranged from 8% to 15%, and the liquid limit varied between 30% and 40% [17]. Quick clay block samples taken from depths of 8–12 meters exhibit unconfined shear strength (Cu) values ranging from 40 to 75 kPa, whereas the remolded clay shows shear strength values below 0.5 kPa [18]. Based on previous studies [7], the chemical composition of the investigated quick clay was determined using X-ray fluorescence (XRF) analysis. The results show that the clay is primarily composed of SiO_2 (51.04%) and Al_2O_3 (16.97%), along with smaller amounts of Fe_2O_3 (9.28%), MgO (5.86%), K_2O (4.05%), CaO (3.22%), Na_2O (2.01%), and SO_3 (0.02%). The loss on ignition (LOI) was measured at 5.6%.

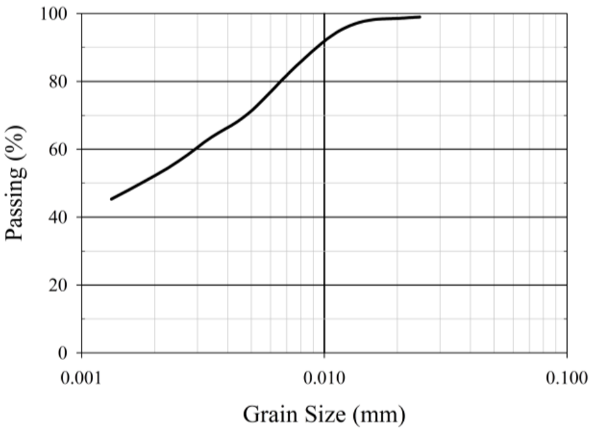

Fig. 1. Particle size distribution of quick clay [17].

According to the XRF results, the major components of the quick clay are silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), indicating that the clay may exhibit pozzolanic characteristics. Consequently, in the presence of calcium hydroxide, clay has the potential to act as a pozzolanic material and react with calcium to form cementitious products. However, the degree of these reactions strongly depends on the reactivity of the clay.

2.1.2 Binders

Three binders were used to stabilize the clay. These binders were selected to provide pozzolanic constituents, namely silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), as well as calcium and a highly alkaline environment necessary for the formation of cementitious products that enhance clay stability.

For this purpose, zeolite was selected as a pozzolanic material due to its high content of SiO_2 and Al_2O_3. The chemical formula of the zeolite used in this study is $Na_{86}[AlO_2]_{86}(SiO_2)_{106}\cdot xH_2O$. In addition, quicklime (CaO) was employed as a calcium source and to increase the pH of the system, thereby enhancing the reactivity of both the zeolite and the clay and promoting their reaction with calcium.

Finally, recycled crushed concrete was used as the third binder, serving both as a pozzolanic material and as a source of calcium for quick clay stabilization. The concrete mix design is presented in Table 1.

Three particle size distributions of crushed concrete were used to investigate the combined effects of mechanical and chemical stabilization of quick clay, with particular emphasis on the influence of particle size distribution. The first crushed concrete fraction consisted of particles smaller than 125 µm, representing a fine powder. The second fraction included coarse particles with sizes ranging from 2000–4000 µm. The third fraction was a well-graded mixture consisting of particles smaller than 125 µm, as well as size ranges of

125–250 µm, 250–500 µm, 500–1000 µm, 1000–2000 µm, and 2000–4000 µm, mixed in equal proportions. The particle size of the zeolite used in this study ranged between 2 and 4 µm, while the quicklime particles were finer than 20 µm.

Table 1. Mix design of the original concrete per laboratory batch.

Material	Amount (kg)
Cement (CEM I 52.5 N)	12.29
Water	5.13
Årdal sand (0-8mm)	36.37
Årdal coarse aggregate (8-16 mm)	28.97
Sika ViscoCrete 5020	0.06
Silica fume	0.64

The experimental design adopted in this study is summarized in Table 2. A mixture of zeolite and quicklime (ZQ), each added at an amount of 50 kg/m³, was considered as the control sample. The remaining mixtures included combinations of zeolite, quicklime, and recycled powdered concrete (ZQPC); zeolite, quicklime, and recycled coarse-grained concrete with particle sizes of 2–4 mm (ZQCG); and zeolite, quicklime, and recycled crushed concrete with a well-graded particle size distribution (ZQWG). The binder contents, expressed in kg/m³, were calculated based on the volume of the clay. For the ZQCG and ZQWG mixtures, approximately half of the mold volume was replaced with waste concrete to evaluate the combined effects of mechanical and chemical stabilization. Based on this replacement ratio and considering a quick clay density of 1850 kg/m³, the amount of concrete substituted for clay was approximately 1000 kg/m³.

Table 2. Experimental design and binder contents for stabilized quick clay samples.

Sample name	Binders content (kg/m^3 of clay volume)			Curing time (days)
	Zeolite	Quick lime	RCC	
ZQ	50	50	0	7, 14, and 28
ZQPC	50	50	25	7, 14, and 28
ZQCG	50	50	1000*	7, 14, and 28
ZQWG	50	50	1000*	7, 14, and 28

*For ZQCG and ZQWG samples, approximately 50% of the clay volume was replaced with recycled crushed concrete.

To crush the concrete, a jaw crusher was used. The crushed material was subsequently passed through a series of sieves and separated into different particle size portions, ranging from finer than 125 µm to 4 mm, as illustrated in Fig. 2.

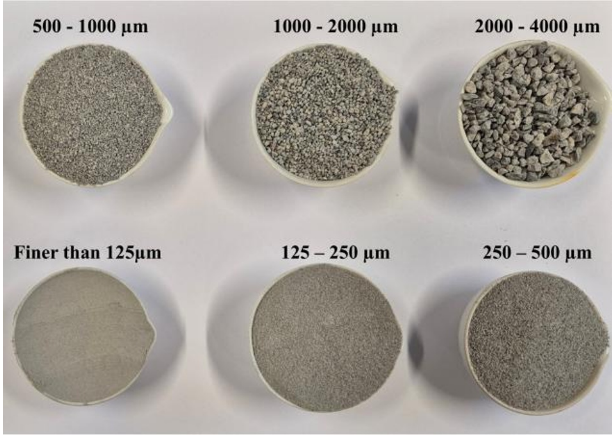

Fig. 2. Particle size fractions of crushed concrete after sieving.

2.2 Methods

2.2.1 Sample preparation

The raw quick clay was first remolded in a laboratory blender until a homogeneous consistency was achieved. Then, zeolite was added to the remolded clay and mixed for 1 min to ensure uniform distribution. Subsequently, quicklime and crushed concrete were added, and the mixture was further blended for an additional 1 min.

The resulting clay–binder mixture was compacted into cylindrical molds with dimensions of 40 mm in diameter and 80 mm in height. Compaction was carried out using a steel rod, with the clay mixture tamped 30 times per layer to ensure sufficient and uniform densification. To ensure precision and repeatability, three replicate specimens were prepared for each mixture and curing period.

After preparation, the samples were sealed and cured at room temperature for the designated curing durations. Upon completion of the curing period, the specimens were removed from the molds and subjected to the planned laboratory tests.

2.2.2 Unconfined compressive strength tests

To evaluate and compare the effectiveness of waste crushed concrete in the stabilization of quick clay, unconfined compressive strength (UCS) tests were conducted on the stabilized specimens. The tests were performed using an automated uniaxial testing instrument (GDS INSTRUMENT, UNITED KINGDOM), with a constant axial strain rate of 1.5%/min. During testing, the axial stress–strain response was recorded, and the undrained shear strength was determined from the peak compressive stress. All UCS tests were conducted in accordance with ASTM D2166 standard.

2.2.3 X-ray diffraction (XRD) analyses

X-ray diffraction (XRD) analyses were performed on all stabilized samples as well as on the raw quick clay to investigate microstructural changes induced by stabilization and the formation of cementitious products.

For this purpose, specimens were taken from the interior of the samples to avoid surface effects and were oven-dried at 50 °C for 24 h prior to testing.

The XRD measurements were carried out using a Bruker D8 A25 DaVinci X-ray diffractometer (BRUKER, GERMANY) equipped with Cu Kα radiation. Diffraction patterns were collected over a 2θ range of 5° to 80°, with a step size of 0.013°.

3 Results

3.1 UCS Results

Fig. 3 presents the maximum shear strength of quick clay stabilized using four different methods (ZQ, ZQPC, ZQCG, and ZQWG), together with the undisturbed shear strength of untreated clay, as a function of curing time. All mixtures showed a significant increase in shear strength compared to untreated quick clay and exhibited a continuous increase in shear strength with curing time. This trend indicates that chemical reactions occurred throughout the 28-day curing period, leading to the formation of cementitious products and a corresponding increase in strength. Among the investigated mixtures, the highest shear strength was achieved by the ZQWG composition. This mixture exhibited relatively high shear strength after only 7 days of curing and maintained its superiority over the other mixtures up to 28 days. As expected, the control sample (ZQ) exhibited the lowest shear strength throughout the curing period.

A closer examination of the results reveals that, for the control mixture consisting of zeolite and quicklime (ZQ), the shear strength was approximately 240 kPa after 7 days of curing. After 14 days, the shear strength increased by about 45%, and after 28 days, it increased by approximately 90%, reaching an average value of 450 kPa. This trend clearly demonstrates that extended curing promotes the formation of cementitious compounds, resulting in increased shear strength.

For the mixture containing zeolite, quicklime, and recycled powdered concrete (ZQPC), the 7-day shear strength (approximately 255 kPa) showed no significant improvement compared with ZQ. This suggests that, at early curing stages, the recycled concrete powder had not yet significantly dissolved or participated in pozzolanic reactions. However, after 14 days, the shear strength increased by approximately 92%, reaching 492 kPa, exceeding the 28-day strength of the ZQ mixture. After 28 days, the shear strength further increased by about 167%, reaching 680 kPa, confirming the significant contribution of recycled powdered concrete to the stabilization reactions at later curing stages.

In the mixture incorporating recycled coarse-grained concrete with particle sizes of 2–4 mm (ZQCG), the shear strength at 7 days was approximately 320 kPa and increased by about 55% at 14 days and 86% at 28 days. Although the overall trend was like that of the ZQ mixture, ZQCG consistently exhibited higher shear strength, which can be attributed primarily to mechanical stabilization provided by the coarse concrete particles, which enhance load transfer within the clay matrix.

The highest shear strength values were observed for the mixture containing zeolite, quicklime, and recycled crushed concrete with a well-graded particle size distribution (ZQWG). After 7 days of curing, the shear strength was approximately 490 kPa, followed by an increase of about 43% after 14 days and approximately 76% after 28 days. While the general trend is similar to that of ZQ and ZQCG mixtures, the superior performance of the ZQWG mixture is attributed to its well-graded particle size distribution, which enhances load transfer and stress distribution within the clay matrix.

Among the investigated mixtures, ZQPC and ZQWG exhibited the best performance, achieving 28-day shear strengths of approximately 680 and 860 kPa, respectively. Both mixtures satisfied the required shear strength criteria for quick clay stabilization. Although the ZQWG mixture exhibited the highest shear strength, it requires the replacement of approximately half of the clay volume with crushed concrete. This approach would necessitate extensive excavation, transportation, and disposal of excess clay, resulting in increased cost and practical challenges in field applications.

In contrast, ZQPC demonstrated the highest rate of strength increase during curing time, indicating effective participation in chemical stabilization reactions and the formation of cementitious products, which significantly enhanced the stiffness and strength of the soft clay. This behaviour demonstrates that recycled concrete is more effective when used in powdered form, acting as a source of both pozzolanic materials and calcium, rather than being applied solely as coarse aggregate for mechanical stabilization. Therefore, ZQPC was chosen as an optimum mixture in this study.

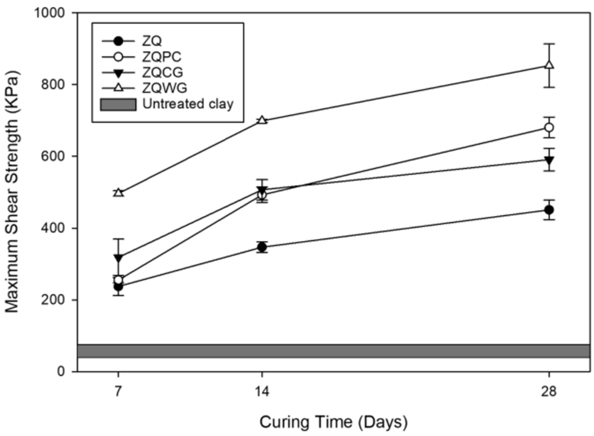

Fig. 3. Variation of maximum shear strength with curing time for different quick clay stabilization methods.

3.2 XRD Results

The X-ray diffraction (XRD) patterns of raw quick clay and stabilized samples after 28 days of curing are presented in Fig. 4. The diffraction pattern of the raw quick clay indicates that the dominant mineralogical constituents are illite–mica, hornblende (amphibole), chlorite, quartz, and plagioclase. These phases are characteristic of natural quick clay and remained identifiable in all stabilized mixtures, although with variations in peak intensity.

For the stabilized samples, the appearance and increased intensity of calcium-bearing phases confirm the formation of cementitious reaction products during curing. In particular, the development of calcium silicate hydrate (C–S–H), although poorly crystalline and therefore not sharply defined in XRD patterns, is evidenced by the broadening of the background hump in the low-angle region. The formation of C–S–H plays a key role in binding clay particles, densifying the soil matrix, and enhancing stiffness and shear strength.

In addition, distinct peaks corresponding to monocarboaluminate ($Ca_4Al_2O_6(CO_3)\cdot 11H_2O$) were identified in the stabilized samples. Monocarboaluminate, also referred to as monocarbonate, is a stable calcium carboaluminate hydrate commonly formed during cement hydration in the presence of carbonate ions [19]. Its presence indicates active chemical interactions between calcium sources, alumina from clay minerals and zeolite, and carbonate groups, contributing to the stabilization process. The formation of both C–S–H and monocarboaluminate phases confirms that chemical stabilization mechanisms dominate in the treated samples, consistent with the observed increase in shear strength.

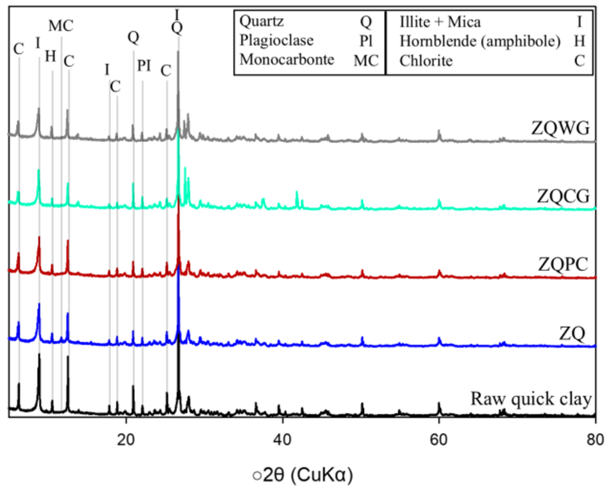

Fig. 4. XRD patterns of raw and stabilized quick clay after 28 days of curing.

4 Conclusion

This study investigated the potential of recycled crushed concrete (RCC) as a sustainable alternative to conventional cement- and lime-based binders for the stabilization of highly sensitive quick clay using the deep soil mixing method, in combination with zeolite and quicklime. The primary goal was to reduce the lime and cement consumption and associated CO_2 emissions while maintaining sufficient mechanical performance.

Unconfined compressive strength (UCS) results demonstrated that all stabilized mixtures exhibited a significant increase in shear strength compared to untreated quick clay, with strength increasing consistently with curing time, indicating ongoing pozzolanic and cementitious reactions. Among the investigated mixtures, ZQPC (zeolite–quicklime–recycled concrete powder) and ZQWG (zeolite–quicklime–well-graded recycled crushed concrete) exhibited the highest strength performance after 28 days of curing. Although ZQWG achieved the highest shear strength, its application requires the replacement of approximately half of the clay volume with crushed concrete, which may pose practical and economic challenges in field applications. In contrast, the ZQPC mixture demonstrated a high rate of shear strength development while requiring significantly lower material addition to the clay.

The XRD analysis confirmed the formation of cementitious phases, with monocarboaluminate and calcium–silicate–hydrate identified as the main reaction products, supporting the observed mechanical improvements. These results indicate that recycled concrete powder actively participates in pozzolanic reactions and effectively enhances clay stiffness and strength through chemical stabilization.

Overall, the findings suggest that recycled crushed concrete is most effective when used in powdered form as a combined source of calcium and pozzolanic materials. The ZQPC mixture, consisting of 50 kg/m³ of zeolite, 50 kg/m³ of quicklime, and 25 kg/m³ of recycled concrete powder, is therefore identified as the optimum stabilization method among those studied. This approach provides a promising pathway for reducing cement and lime consumption while improving the geotechnical properties of highly sensitive clays, contributing to more sustainable ground improvement practices. However, the present study was limited to laboratory-scale testing, short-term curing periods, and a specific combination of quick clay and binders. Therefore, further research is recommended to evaluate long-term durability, large-scale mixing efficiency, and field-scale performance. In addition, the applicability of the proposed binder system should be examined for other clay types. Despite these limitations, the present study provides valuable evidence that waste concrete powder can be successfully reused in clay stabilization, offering both geotechnical and environmental benefits.

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References

1. A. Md Zahri, and A. Zainorabidin, An overview of traditional and non traditional stabilizer for soft soil. IOP Conf. Ser. Mater. Sci. Eng. **527**, 012015 (2019)
2. X. Wang, S. Kim, Y. Wu, Y. Liu, T. Liu, and Y. Wang, Study on the optimization and performance of GFC soil stabilizer based on response surface methodology in soft soil stabilization. Soil Found. **63**, 101278 (2023)
3. E. Oh, A. Balasubramaniam, M. Bolton, G. Chai, M. Braund, V. Wijeyakulasuriya, R. Nithiraj, and D. Bergado, Soft Clay Properties and Their Influence in

Preloading with PVD and Sur-charge. 15SEAGC. In Proceedings of 15th Southeast Asian Geotechnical Engineering Conference, Bangkok, Thailand (2004)

4. Y.-M. Chen, X.-W. Tang, and N. Jia, Consolidation of sensitive clay with vertical drain. Int. J. Numer. Anal. Meth. Geomech. **31**, 1695 (2007)
5. B. Indraratna, A. S. Balasubramaniam, and P. Ratnayake, Performance of Embankment Stabilized with Vertical Drains on Soft Clay. J. Geotech. Engrg. **120**, 257 (1994)
6. P. M. Deshpande, Interactive Encased Stone-Column Foundation - Synopsis. DFI, **96**, 1 (1996)
7. S. Hov, P. Paniagua, C. Sætre, M. Long, G. Cornelissen, and S. Ritter, Stabilisation of Soft Clay, Quick Clay and Peat by Industrial By-Products and Biochars. Appl. Sci. **13**, 9048 (2023)
8. S. Hov, P. Paniagua, C. Sætre, H. Rueslåtten, I. Størdal, M. Mengede, and C. Mevik, "Lime-cement stabilisation of Trondheim clays and its impact on carbon dioxide emissions. Soil Found. **62**, 101162 (2022)
9. P. Paniagua, B. K. Bache, K. Karlsrud, and A. K. Lund, Strength and stiffness of laboratory-mixed specimens of stabilised Norwegian clays. Proc. Inst. Civ. Eng.-Ground Improv. **175**, 150 (2020)
10. P. Paniagua, S. Ritter, M. Moseid, and G. Okkenhaug, Bioashes and Steel Slag as Alternative Binders in Ground Improvement of Quick Clays. Geo-Congress 2023, Los Angeles, CA, USA, March 26–29 (2023)
11. E. Ho Chu, H. Lim Ching, and G. Tan Chin, Jet Grouting Applications for Large-Scale Basement Construction in Soft Clay. Innovations in Grouting and Soil Improvement, Austin, TX, USA, January 24-26 (2005)
12. T. Y. Poh, and I. H. Wong, A field trial of jet-grouting in marine clay. Can. Geotech. J. **38**, 338 (2001)
13. V. Q. Nguyen, T. N. Phan, and S. Likitlersuang, Influence of in-situ Soil Properties on the Mechanical Properties of Cement Treated Soft Clay: A Case Study in Vietnam. Transp. Infrastruct. Geotechnol. **13**, 29 (2026)
14. T. D. Nguyen, T. N. Phan, and S. Likitlersuang, Evaluating the Applicability of Large-Diameter Cement Deep Mixing Method for Soft Ground Improvement: A Landmark Case Study in Vietnam. Int. J. Geosy. Ground Eng. **11**, 19 (2025)
15. T. D. Nguyen, T. N. Phan, and S. Likitlersuang, Strength and Stiffness Characteristics of Clays Stabilised with Cement and Granulated Blast Furnace Slag in the Red River Delta, Vietnam. Int. J. Geosy. Ground Eng. **11**, 58 (2025)
16. G. Mertens, R. Snellings, K. Van Balen, B. Bicer-Simsir, P. Verlooy, and J. Elsen, Pozzolanic reactions of common natural zeolites with lime and parameters affecting their reactivity. Cem. Concr. Res. **39**, 233 (2009)
17. J.-S. L'Heureux, L. Anders, and E. Arnfinn, The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. AIMS Geosci. **5**, 831 (2019)
18. S. Ritter, P. Paniagua, and G. Cornelissen, Biochar in Quick Clay Stabilization: Reducing Carbon Footprint and Improving Shear Strength. Geo-Congress 2023, Los Angeles, CA, USA, March 26–29 (2023)
19. T. Matschei, B. Lothenbach, and F. P. Glasser, The AFm phase in Portland cement. Cem. Concr. Res. **37**, 118 (2007)