

QUICKLIME (CaO) STABILIZATION OF FINE-GRAINED MARINE SEDIMENTS IN LOW TEMPERATURE AREAS

Peteris Skels

Department of Civil Engineering, Technical University of Riga,
peteris.skels@gmail.com

Thomas Ingeman-Nielsen, Anders Stuhr Jørgensen

Department of Civil Engineering, Technical University of Denmark,
tin@byg.dtu.dk; asj@byg.dtu.dk

Kaspars Bondars, Edmunds Skele

Department of Civil Engineering, Technical University of Riga,
kaspars.bondars@j-a.lv; edmunds.skele@rtu.lv

ABSTRACT

This study presents laboratory testing on quicklime (CaO) stabilization of fine-grained marine sediments in low temperature areas. The soil was sampled on the Fossil Plain in Kangerlussuaq, Greenland, and analyzed in the laboratory at the Technical University of Denmark (DTU). The optimum CaO content in a soil-CaO mixture was determined using a number of laboratory methods, such as pH test, consistency limit analysis, degree of compaction, and short term California Bearing Ratio (CBR) values. The study also numerically demonstrates a long term strength development of the soil-CaO mixture at 1°C and 10°C curing temperatures, comparing stabilization effectiveness between low and normal soil temperature conditions.

Key words: quicklime stabilization, pH test, CBR, soil compaction, temperature

INTRODUCTION

During the construction phase of a civil engineering project, it is of critical importance to ensure the accessibility of the heavy vehicles and equipment used on a construction site. In areas with fine-grained materials, the accessibility may be greatly reduced due to large water contents in the sediments. Furthermore, the ability to compact the material to get an optimal bearing capacity may be reduced as well, with the consequence that one may have to choose between expensive material substitution and higher maintenance costs due to subsequent settlements, structural and pavement damage.

These problems are enhanced in areas with permafrost, especially where the deposits are ice-rich and under warming. The summer thaw layer (the active layer, typically up to 3 m thick) often becomes water logged from the thaw process, and may suffer severe loss in the bearing capacity.

Thick deposits of fine-grained marine sediments exist in large areas of western Greenland. The sediments have been transported by melt-water rivers from the Greenlandic ice sheet to the fiords and sea, where it was deposited in thick sequences of silts and clays. As a consequence of the glacial retreat, the sediments were uplifted due to the isostatic rebound. Today, many of the fine-grained sediments are located above the sea-level, and now complicate construction projects in developing areas.

Most of the housing in Greenland is built directly on the bedrock or founded on point-loaded piles directly to bedrock. However, it is difficult to avoid

the mentioned soil stability problems when roads and other linear infrastructure are constructed. It is therefore of great economic and societal interest to develop methods to improve the stability of fine-grained sediments in Greenland.

There are different soil modification/stabilization methods and modifier/stabilizer types available. Lime is one of the chemical modification/stabilization agents in the form of quicklime (calcium oxide- CaO), hydrated lime (calcium hydroxide- Ca(OH)₂), or lime slurry (a suspension of hydrated lime in water, can be made from either hydrated lime or quicklime). The previous experience has shown that lime reacts with medium-, moderately fine-, and fine-grained soils to produce decreased plasticity, increased workability and strength, and reduced swell.

Lime stabilization, having started as an aid in maintenance work in temperate areas, now covers most fields in construction. This includes highways, farm-to-market roads, shoulders and parking lots as well as non-highway uses such as airport runways, building foundations, and railroad subgrades (Eades et al., 1966). Lime can be used either to modify some of the physical properties and thereby improve the quality of the soil or to transform the soil into a stabilized mass, which increases its strength and durability (*Military Soil Engineering*, 1992). The reaction between lime and soil can be described as a series of chemical reactions. When lime is added to a clayey soil, it must first satisfy the affinity of the soil for lime, i.e., ions are absorbed by clay minerals and are not available to the stabilizing reactions until the affinity is satisfied

(Bell, 1996). Thus, more lime is normally needed for soil stabilization, than for soil modification.

The optimal lime amount is determined by several measuring procedures such as pH test, degree of plasticity, soil compaction properties. Soil compaction is one of the most critical components in the construction of roads, airfields, embankments, and foundations. The durability and stability of a structure are related to the realization of proper soil compaction, thus the optimal lime amount in this study is also estimated in relation to the compaction optima at natural water content in the field. Additionally, there are well defined the minimal requirements for improved and stabilized soil in EN 14227-11 (EN 14227-11:2006...). However, the choice of the stabilization/modification method is ultimately an economical trade-off.

The objective of this survey is to study the effect of temperature on the optimal CaO content and evaluate the long term strength development, California bearing ratio (CBR), in time for a fine-grained soil from Kangerlussuaq, Greenland.

MATERIALS AND METHODS

A lime stabilization application was tested to the fine-grained soil from Kangerlussuaq, Greenland, at the laboratories of the Arctic Technology Center at the Technical University of Denmark (DTU).

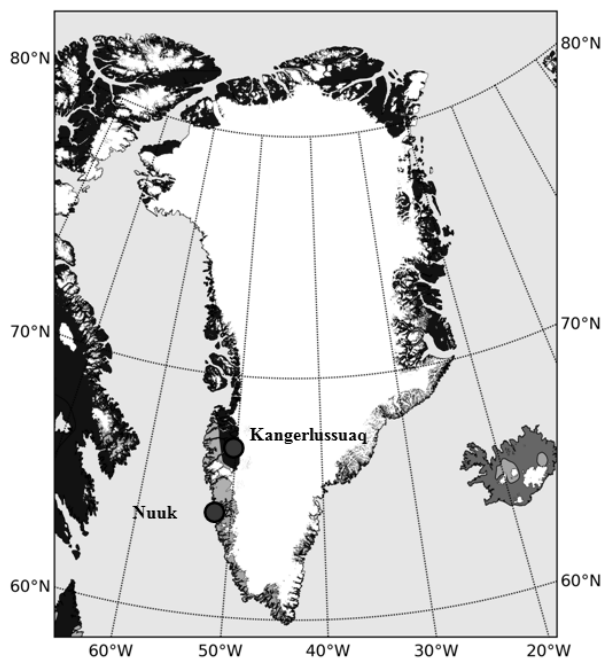


Figure 1. Map of Greenland with the capital, Nuuk, indicated as well as the field site location at Kangerlussuaq. The map also shows the permafrost distribution in Greenland, sporadic (green), discontinuous (orange) and continuous permafrost (blue), according to the classification of (Brown et al., 1998).

The material was sampled close to the Kangerlussuaq International Airport, which is located in an area with continuous permafrost, see Figure 1.

The sieve analysis, hydrometer method (ISO/TS 17892-4:2004...), consistency limits analysis (ISO/TS 17892-12:2004...), pH test, Proctor compaction experiments (EN 13286-2...) and CBR tests (EN 13286-47...) were performed to determine the geotechnical properties of the natural and lime-treated material.

The optimum CaO content was determined in a series of measurements of the soil compaction, pH, and changes in plasticity. In order to achieve the soil compaction optima under the given compaction rate, it is necessary to accomplish the maximum dry density at the natural water content, assuming that extra water is not added. It can be easily evaluated from the Proctor compaction curves for the different soil-lime mixtures. However, it is time consuming to make all these Proctor curves for many different soil-lime mixtures; furthermore, there can be mistakes in the measuring process, because of problems compacting soil properly at very low and very high water contents. Therefore, a new method of determining the optimum lime content for the compaction optima under the given compaction effort and at the natural water content is introduced. The same batch is decided to be reused, adding quicklime (CaO) in portions, mixing it, doing the Proctor compaction test, remolding, and again adding a new portion of CaO. The portions are decided to be small, so that the maximum dry density is expected to match with the 100% dry density or close to that.

The pH of soil-lime mixture is evaluated to be approximately 12.4, the pH of saturated lime water (Eades et al., 1966). The activity of the clay and other minerals in the material mainly affects the plasticity of fine-grained sediments (Bell, 1996). A previous survey by L. Bjerrum on geotechnical properties of Norwegian marine clays showed that the high sensitivity of marine clay is a result of the leaching of salts (Brown et al., 1998), and thus the salinity of the soils should be taken into account as well.

Soil-lime mixtures molded in the large Proctor compaction molds and raw mixtures in sealed plastic bags were stored at 1°C and 10°C curing temperatures for 28-day and 56-day time periods, respectively. The tests were carried out during the curing period after approximately 7, 14, 28 and 56 days. The Proctor tests were performed using a 2.5 kg rammer in the large Proctor mold according to EN 13286-2 point No 7.2 (EN 13286-2...). The Proctor compacted elements were afterwards used in the California bearing ratio (CBR) test, according to EN 13286-47 (EN 13286-47...). pH measurements were conducted at the same time to define how much residual CaO has left for

pozzolanic reactions. The two curing temperatures were chosen in order to compare the soil stabilization effectiveness between low and normal soil temperature conditions.

Raw mixtures were chosen, because it is common that mixing and storing of soil-lime is performed away from the construction field. On the other hand, the molded samples correspond to the mixing, compacting, and curing in situ.

Physical and chemical properties of soil used in the study

The geotechnical properties and semi-quantified mineralogy of the soil used in the study are given in Table 1 and Table 2, respectively.

Table 1
Geotechnical properties of fine-grained sediments

		Marine sediments from Kangerlussuaq
Soil classification		SILT, clayey
Particle size distribution:		
<2µm (%)		57
<5µm (%)		75
<0.01mm (%)		85
<0.1mm (%)		99.8
Average natural water content (%)		24
Average natural salinity (‰)		10
Liquid limit at natural salinity (%)		40.63
Plastic limit at natural salinity (%)		26.50
Plasticity index at natural salinity (%)		14.13
CBR value at average natural water content (%)		3.10
γ (kN/m ³)		1.61
γ _s (kN/m ³)		2.80
pH value		7.4

Table 2
Semi-quantified mineralogy

		Marine sediments from Kangerlussuaq (%)
Quartz		18
Plagioclase (Ca-albite)		36
Amphibole (hornblende)		13
Pyroxene (clinopyroxene)		9
Alkali feldspar (microcline)		17
Chlorite (Clinochlore)		7

The properties of lime used in the study

A/S "Faxe Kalk" quicklime "Proviacal® ST Q" was used for the soil stabilization. The chemical composition, reactivity and fineness of this commercial grade lime material are listed in Table 3.

Table 3
Chemical and physical properties of quicklime

	Mean	Std.dev.
Chemical composition:		
CaO _{total}	95.0%	1.1%
MgO	0.9%	0.1%
SiO ₂	1.6%	0.2%
Al ₂ O ₃	0.25%	0.1%
Fe ₂ O ₃	0.25%	0.1%
P ₂ O ₅	0.15%	0.02%
TiO ₂	0.03%	0.01%
MnO	0.04%	0.01%
CO ₂	1.0%	0.5%
S	0.18%	0.02%
K ₂ O + Na ₂ O	0.07%	0.01%
CaO _{activ}	92.0%	0.7%
Reactivity:		
R (reactivity)	20°C/min	3°C/min
T _{60°C} (time for otaining at temp. 60°C)	2 min	2 min
Fineness of material:		
Material remaining through 1 mm sieve	0%	0%
Material remaining through 0,09 mm sieve	10%	2.5%

RESULTS

Material physical and chemical analysis

The particle size analysis was performed using the hydrometer method according to ISO/TS 17892-4:2004 (*ISO/TS 17892-4:2004...*). 99.8% of the material passed through a 0.063mm sieve, and thus fell in the Silt and Clay fractions. It was estimated, that 57% of the material is in the clay fraction, i.e., the grain size is smaller than 2µm. Additionally, a few gastropod fossils were also present in the soil, but all of them were removed before the particle size analysis. In spite of the observed grain size distribution, the semi-quantitative X-ray diffractometer (XRD) analysis of the bulk sample did not indicate a remarkable clay mineral content. We found mainly silicates (pyroxene, amphibole, and chlorite), quartz and feldspar minerals (microcline, Ca-albite). These minerals, e.g., quartz (mainly consist of SiO₂) in fine state does react with quicklime (Bell, 1996).

Soil compaction

The Proctor compaction experiments according to the previously described method were used for

determining the optimal lime content at the soil natural water content in the field, which in average is 24%. Step by step, the Proctor compaction test was done, the water content was measured, and the dry density was determined for each of the different CaO contents, adding CaO in small portions and reusing the same batch for the next step on the CaO addition.

The dry densities obtained from all the tests have been plotted as a function of CaO content (see Figure 2).

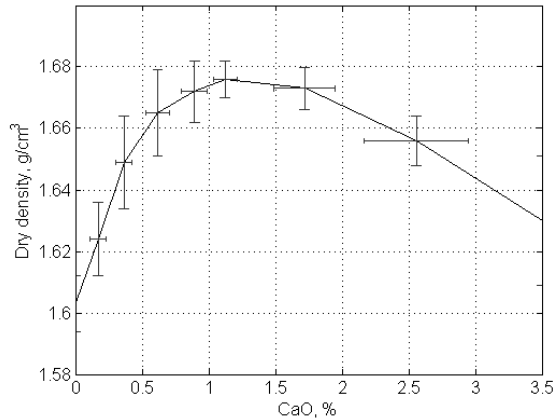


Figure 2. Dry density as a function of CaO content at 24% water content.

Small CaO steps at low CaO contents (from 0%-1.5%), larger CaO steps at higher CaO contents (1.5%-3.5%) account for differences in horizontal errorbars.

Reusing the same material batch, adding CaO in portions, and doing the Proctor compaction testing, the water content is greatly reduced by water evaporation during preparation and testing, especially when there are many measurements and manipulations with the same batch. This results in noticeable dissimilarities in the lime-treated soil dry densities for the same CaO content in vertical direction. Therefore, the soil-lime dry densities are not directly comparable- there are time, reworking, and evaporation factors. Although, the testing procedure described has to be improved, the results presented indicate that the optimal lime amount is 1.2% of CaO for the compaction optima at natural water content.

pH test

The pH values were determined for all the same test samples used in the compaction tests. The soil pH was measured in a suspension of soil and KCl (potassium chloride) of the ratio 1:2.5, determining the pH value with a special pH meter. The pH values from a series of determinations as ordinates against the corresponding CaO as abscissa can be plotted (see Figure 3).

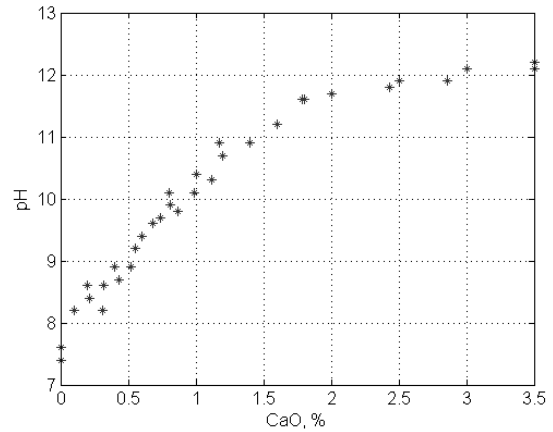


Figure 3 pH values as a function of CaO content.

The pH value is notably rising from 0% to 3% CaO content, after which the increase is slower. Although, the pH for soil solution with 3% CaO content is less than 12.4, it can be estimated as the optimum CaO content, because pH does not increase much more for a higher CaO content.

Changes in plasticity

The soil plasticity properties were measured for 1%; 2%; and 3% lime-treated soil by routine experiments according to ISO/TS 17892-12 (*ISO/TS 17892-12:2004*). The consistency limit values from a series of determinations can be seen in Table 4.

Table 4
Changes in consistency after CaO addition

Lime content (%)	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)
0	26.50	40.63	14.13
1	32.49	52.71	20.22
2	33.25	46.68	13.43
3	33.96	43.94	9.98

The plastic limit sharply rises on addition of 1% CaO, after which it remains more or less steady or rises to a small amount. The liquid limit also rises, but then it slowly decreases. The plasticity index drops below 10% on 3% CaO addition, i.e., corresponding to the plasticity index for a non-plastic soil, so higher CaO content would be illiterate. Therefore, also changes in plasticity indicate that the optimal lime content for the soil stabilization is 3% CaO content.

Determination of optimal lime content

It was proved that the applied methods for determining the optimal soil compaction should be improved in order to get comparable results and to determine the compaction optima and so also to

find the optimal lime amount, however, the method used indicated that the optimal CaO amount is 1.2%. On the other hand, the optimum lime content was assumed to be 3% CaO according to the pH test and changes in plasticity.

In order to evaluate and compare the strength gain in time, the long term measurements were done for both 1.2% and 3% CaO content.

Long term measurements

Strength development at 10°C curing temperature

In the first stage of the long term measurements 1.2% and 3% CaO soil-treated samples were stored at 10°C. The CBR values from this measurement series is plotted as ordinates against the corresponding time step in days in Figure 4.

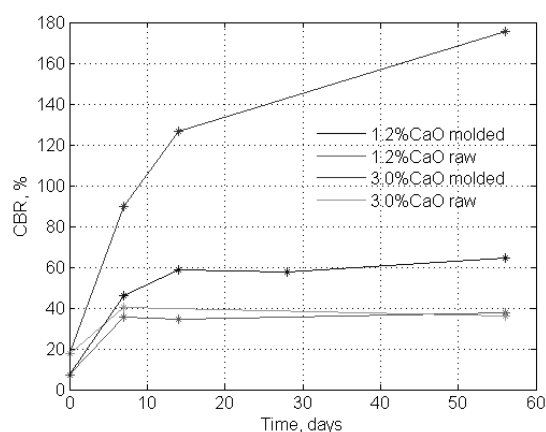


Figure 4 CBR values as a function of time at 10°C curing temperature.

The CBR value after 14 days storing at $t^{\circ}=10^{\circ}\text{C}$ for 3% CaO soil-lime molded samples is 126.83%, while for 1.2% CaO soil-lime molded samples it is 58.49%. After 56 days storing at $t^{\circ}=10^{\circ}\text{C}$ for 3% CaO soil-lime molded samples the CBR value is 175.39%, while for 1.2% CaO soil-lime molded samples it is 64.73%. In general, these results indicate that for 3% CaO content the CBR value increase is greater than for 1.2% CaO content for molded material samples.

Raw soil-lime samples showed similar results both for 3% CaO content and for 1.2% CaO content. It can be seen that the CBR value after 7 days storing at $t^{\circ}=10^{\circ}\text{C}$ for 3% CaO soil-lime raw samples is 40.24%, while for 1.2% CaO soil-lime raw samples it is 35.68%. After 56 days storing at $t^{\circ}=10^{\circ}\text{C}$ for 3% CaO soil-lime raw samples the CBR value is 36.24%, while for 1.2% CaO soil-lime raw samples it is 37.38%.

Strength development at 1°C curing temperature

In the second stage of the long term measurements 1.2% and 3% CaO soil-treated samples were stored

at 1°C. The CBR values from a series of determinations as ordinates against the corresponding time step in days as abscissas are plotted in Figure 5.

The plot shows a great increase in the CBR values for 3% CaO soil-lime molded sample, while the CBR value for 1.2% CaO lime-soil molded sample has increased after 7 days and then the increase has been small. After 28 days storing at $t^{\circ}=1^{\circ}\text{C}$ for 3% CaO soil-lime molded samples the CBR value is 77.00%, while for 1.2% CaO soil-lime molded samples it is 43.53%. In general, these results indicate that for 3% CaO content the CBR value increase is greater than for 1.2% CaO content also at 1°C curing temperature for molded material samples. Raw soil-lime samples showed similar results both for 3% CaO content and for 1.2% CaO content.

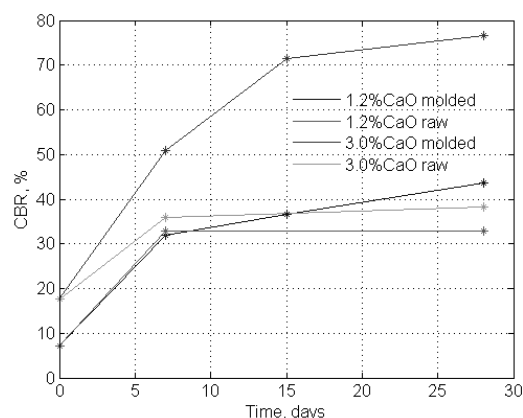


Figure 5 CBR values as a function of time at 1°C curing temperature.

Furthermore, the CBR value after 28 days storing at $t^{\circ}=1^{\circ}\text{C}$ for 3% CaO soil-lime raw samples is 38.22%, while for 1.2% CaO soil-lime raw samples it is 32.80%.

Comparing the CBR values between $t^{\circ}=1^{\circ}\text{C}$ and $t^{\circ}=10^{\circ}\text{C}$ curing temperatures, we observe that the strength increase is greater at $t^{\circ}=10^{\circ}\text{C}$ curing temperatures for the molded material samples, but for the raw material samples it is almost the same.

pH measurements

As it was expected, the pH values decreased in long term soil-lime reactions for both $t^{\circ}=1^{\circ}\text{C}$ and $t^{\circ}=10^{\circ}\text{C}$ curing temperatures. Our measurements showed that the pH values after 14 days curing at $t^{\circ}=10^{\circ}\text{C}$ decreased faster than at $t^{\circ}=1^{\circ}\text{C}$. That means the pozzolanic reactions are retarded at $t^{\circ}=1^{\circ}\text{C}$, which is in agreement with the long term strength development measurements.

Relatively low strength increase for 1.2% CaO soil-lime molded samples after 7 days could be explained by the fact that the pH values decreased below the value of 10.5 at $t^{\circ}=1^{\circ}\text{C}$ or even below the value of 10.0 at $t^{\circ}=10^{\circ}\text{C}$, which are pH values when

solubility of silica and alumina are reduced. For 3% CaO soil-lime molded samples the pH value after 7 days curing is still high enough to maintain solubility of silica and alumina, and ensure the pozzolanic reactions to continue and increase the sample CBR value.

CONCLUSIONS

1. The optimal lime amount was well estimated with the pH test. A CaO content of 3% was evaluated as the optimal lime amount for soil stabilization. The plasticity for 3% soil-CaO mixture dropped below 10%, a value typical of non-plastic material. Therefore, these two methods can be used together for the optimal CaO content evaluation.

In this survey the optimal CaO content was also determined for the compaction optima at the natural water content in the field. We found that 1.2% of CaO is the optimum lime amount for the compaction optima at the natural water content in the field.

2. The CBR values for 1.2% and 3% soil-lime mixtures in time can be seen in Figure 4 and Figure 5.

The long term analysis showed that for 3% of CaO content the CBR value increase is greater than for 1.2% of CaO content at both 10°C and 1°C curing temperatures; therefore, even if the compaction optima is not reached for 3% of CaO content, the strength gain in the soil more than compensate for the changes in the compaction optima, and they should not be regarded as disadvantageous.

The CBR value from 3.10% for natural non-treated soil is increased to 175.39% for 3% lime-treated molded sample after 56 day curing at 10°C temperature and to 77.00% after 28 day curing at 1°C temperature, while it is increased to 64.73% for 1.2% lime-treated molded sample

after 56 day curing at 10°C temperature and to 43.53% after 28 day curing at 1°C temperature. The CBR value increases are remarkable for both 1.2% and 3% lime-soil moulded samples. However, the immediate bearing index (immediate CBR test) for 1.2% of CaO content was only 7.16% while for 3% of CaO content it was 17.63%; therefore, according to EN 14227-11 lime-soil mixture of 1.2% does not fulfil the immediate bearing index value of at least 10% for soil stabilization. Therefore, also according to EN 14227-11 recommendations 3% CaO content is regarded as sufficient for soil stabilization, while 1.2% CaO content is not.

3. The CBR values for raw soil-lime mixture cured in sealed plastic bags remained almost constant after the first time step for both 1.2% and 3% CaO contents curing at 1°C and 10°C temperatures. We consider this effect to be caused by the long term pozzolanic reactions not occurring among particles, as in the case of molded samples; moreover, compaction is less optimal, because of reduced water content in the cured material. In the field it could mean that the greatest compaction and strength effect would be achieved in the case where the material is treated and compacted in situ.

The initial swelling tests showed that the test material does not exhibit notable swelling behaviour. It was therefore decided to exclude swelling from the measuring procedure.

4. All in all, application of the CaO stabilization of the fine-grained marine sediments from Kangerlussuaq, Greenland, is useful both in normal and low temperature soil temperature conditions, although, the stabilization effect is greatly reduced at 1°C temperature. For the future work, it would be essential to evaluate the CaO stabilization effectiveness in the field.

ACKNOWLEDGEMENTS

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