Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0868

XVII European Conference on Soil Mechanics and Geotechnical Engineering
ECSMGE 2019 Reykjavik

Soil improvement with quicklime - quantification of the carbonation rate in an embankment after 34 years

Amélioration des sols à l'aide de la quantification de la chaux vive du taux de carbonatation dans un remblai après trente-quatre ans

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ABSTRACT: In 1979, during the construction of the motorway A3 Regensburg – Passau (Germany) an embankment was built using the technique of soil improvement. The soil was treated with quicklime to accelerate the chemical reaction and shorten the execution time for earthworks. Previous studies were not conclusive to address the scale of chemical reactions taking place after these treatments. In 1990 and 2013, samples from this embankment were taken from the same area and studied chemically and geotechnically. Here, the rate of carbonation and pozzolanic reaction were quantified for the first time to provide evidence for the long-term stability of lime-improved soils for earthworks.
In 2013, samples were collected to investigate the development of compressive strength levels, the rate of pozzolanic reaction, and the rate of carbonation of lime over a 34 years period. The rate of carbonation, calculated from available data of the building phase and chemical analysis lies between 35-40%. The amount of available lime and total CaO content suggest that compressive strength should increase if enough water and clay are available for ongoing pozzolanic reactions in the long-term.

RÉSUMÉ: En 1979, lors de la construction de l'autoroute A3 Regensburg - Passau (Allemagne), un remblai était construit selon la technique d'amélioration des sols. Le sol fût traité avec de la chaux vive pour accélérer la réaction chimique et réduire le temps d'exécution des travaux de terrassement. Les études précédentes n'étaient pas concluantes en ce qui concerne l'ampleur des réactions chimiques se produisant après ces traitements. En 1990 et 2013, des échantillons de ce remblai ont été prélevés dans la même zone et analysés chimiquement et géotechniquement. Ici, le taux de carbonatation et la réaction pouzzolanique ont été quantifiés pour la première fois afin de fournir des preuves de la stabilité à long terme des sols à chaux améliorée.

En 2013, des échantillons ont été collectés pour étudier le développement des niveaux de résistance à la compression, le taux de réaction pouzzolanique et le taux de carbonatation de la chaux sur une période de 34 ans. Le taux de carbonatation, calculé à partir des données disponibles relatives à la phase de construction et à l'analyse chimique, se situe entre 35 et 40%. La quantité de chaux disponible et la teneur en CaO totale suggèrent que la résistance à la compression devrait continuer à augmenter si suffisamment d'eau et d'argiles sont disponibles pour les réactions pouzzolaniques à long terme.

Keywords: Quicklime; Soil treatment; Long-term behaviour; Rate of carbonation; Rate of pozzolanic reaction

1 INTRODUCTION

Soil treatment with quicklime or hydrated lime is a well-known and extensively used technique for earthworks. It is applied to dry up wet soil and to enhance its performance. The use of lime in fine grained cohesive soils providing clay minerals triggers short term and long term reactions which improve and solidify most soil types. The short term reactions which lead to dehydration and clay flocculation have been subject of many research projects and are therefore all well known. Calcium carbonate and Calcium-Alumino-Silicate-Hydrates known as pozzolanic mineral phases are results of the subsequent long term reactions. Few studies have been conducted to describe these reactions. Especially knowledge about the quantification of consumed calcium oxide and the distribution of carbonation and pozzolanic reaction decades after the soil treatment is rare.

The here reported study scales the chemical reactions after three decades. In 1979 an embankment was built during the construction of the motorway A3 between Regensburg and Passau (Germany). The soil was treated with quicklime to accelerate the chemical reaction and shorten the execution time for earthworks. Quicklime consists primarily of calcium oxide as defined and specified in EN 459-1 (2010). In 2013, samples from this embankment were taken and chemically and geotechnically studied (Haas & Ritter, 2018). The results were compared with data gathered from the same area in 1990 (Ritter & Stahff, 1991).

As the studied embankment has been treated with quicklime the following will only address the use of quicklime as it is common in Germany for soil treatment, although hydrated lime in different forms is sometimes used in other countries for this application.

During earthwork constructions, the treatment of normally unsuitable fine-grained, cohesive soils or mixed-grained soils with quicklime leads to short-term reactions, that improve the in-place conditions immediately and allow a smooth and timely production flow. Long term reactions are defined by increasing pH values of the pore water and dissolving clay minerals. Silica and alumina are released and react with lime to pozzolanic phases that increase the compressive strength (Eades & Grim, 1960).

Pozzolanic reactions help to improve the properties of very wet, non-compressible soils and dry compressible soils to retain a high utility value in the long term, even under extreme traffic conditions, weather conditions and water encroachment.

Various studies showed the positive behaviour of lime-stabilized soils under the impact of traffic (Abricht, Freudenberg & Hundt, 1967, Kelly, 1977). However, previous publications did not address how the soil-mechanical or mineralogical parameters may have changed over time as a consequence of lime application. In extensive laboratory and field testing strength improvement in excess of 1.4 MPa were shown (Little, 1999). Some soils ultimately reached compressive strength values as high as 7.0 to 10.0 MPa. While also caused by pozzolanic reactions, the increase in strength under certain conditions is also triggered by carbonation (Deneele et al., 2013)

In 1991, Ritter & Stahff published the results of the preceding study at the motorway A3 which had demonstrated how soil-mechanical parameters had developed 11 years after soil improvement with quicklime. Based on this study, samples were taken in October 2013 from the same location that was sampled for the 1990 study (Figure 1), with the objective of documenting changes in soil-mechanical parameters and quantifying lime reactions. Calculations based on the total added quicklime content showed a rate of average carbonation between 35 - 40%.

Figure 1. Drilling site 2013

The existing data set is now used for further calculations. The samples had differed significantly regarding their chemistry and physical parameters, as soil treatment and embankment building occurred in layers with varying lime dosages. But also changing boundary conditions with increasing depth may affect the long term reactions.

The distribution of CaO consumed in carbonate and pozzolana have been calculated for every individual sample to quantify varying distributions. Assignment of these variations to boundary conditions was not feasible with existing data and has to be done in subsequent studies.

2 INITIAL SITUATION

The studied building site is an embankment of the motorway A3 in southeast Germany between Regensburg and Passau. It traverses a 600 m long and up to 9 m deep hollow near Waltersdorf. During the construction in 1979, the total of 200.000 m³ excavated material with a mean dry density of 1.77 Mg/m³ was treated with approx. 2.5 % (w/w) quicklime (CL 90 Q), i. e. approximately 8850 t of quicklime was applied (Ritter & Stahff 1991).

The soil was characterised by soft silts in the hollow and critical soil conditions in the embankment's subsoil. Further down, water-bearing layers of sand and Upper Tertiary clay sediments with deposits of coal were discovered. The soil's geotechnical parameters classified it as not suitable for use in the motorway embankment. Tests were conducted to verify the feasibility of a quicklime-based soil improvement. It was shown, that ca. 2 % (w/w) CaO was necessary to improve the Proctor compaction significantly.

Finally a total volume of 2.5 % (w/w) calcium oxide was used for the construction of the embankment. The treatment occurred layered, so the embankment consists of sequences of treated and untreated layers. The Proctor compaction rate of the quicklime treated soils had a mean value of 98.7 %. The proportion of air voids were under 12 % as the permissible maximum required by ZTV E-StB 76 (Forschungsgesellschaft für Straßen- und Verkehrswesen, 1976).

3 SAMPLING

The samples were taken in the years 1990 and 2013 by drilling with a dry core into the hard shoulder of the 10 to 12 m high embankment at km 543.4 in the direction towards Passau. The location is situated slightly to the east of the motorway exit and entrance of Bogen (Figure 1).

It was not possible to get complete cores (Figure 2). At a depth of 10 m geological parameters indicated penetration of untreated in-situ soil. The samples were stored in boxes and additionally wrapped into plastic bags to avoid carbonation reactions after sampling.

Figure 2. Drill core samples

Figure 3 shows the profile recorded in 1990. Quicklime-improved layers are marked with „U vf“ (lime treated silt). Drilling through the improved layers of soil took place and was very difficult both times. The drill core sheared off due to the soil’s strength and brittleness.

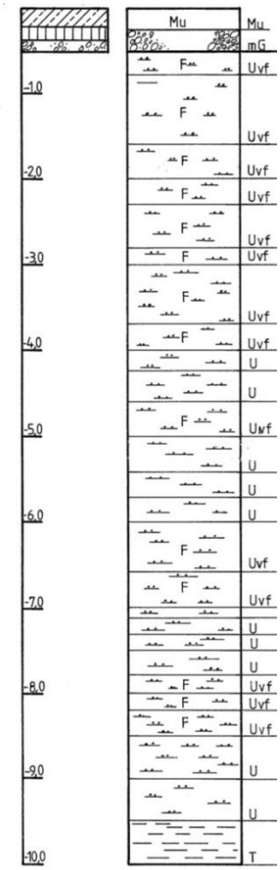

Figure 3. Drilling profile

4 RESULTS

4.1 Methods

The test methods performed are shown in Table 1.

Table 1. Test methods used for the samples collected

Test Method	Study 1990	Study 2013
Compressive strength	DIN 18136	EN 13286-41[1)]
Content of:		
Water	DIN 18121-1	EN 459-2
CaO	DIN 1060-2	EN 459-2
Available lime	Phenolphthalein[2)]	EN 459-2
CO_2	--	EN 459-2

[1)] Slenderness ratio (d/h): 0.8 - 1.05, feed rate: 1 mm/min
[2)] Qualitative test

4.2 Compressive strength

Only few samples were suitable for compressive strength measurement, due to the aforementioned shearing behaviour of the drill. Hence the results in 2013 are from slightly different depths of the embankment and only a descriptive comparison with the 1990 samples is possible.
In 1990, after 11 years, the compressive strength values were situated between 1.3 MPa and 3.4 MPa and therefore above the requirements in aptitude tests for quicklime soil-stabilisation schemes (≥ 0.2 MPa after freezing and thawing). In 2013 results from lime treated layers at nearly similar depths as tested in 1990 showed significantly higher values (Figure 4). The compressive strength of samples from 9.10 m increased from Rc = 0.7 MPa in 1990 to Rc = 1.25 MPa in 2013 due to long-term reactions.

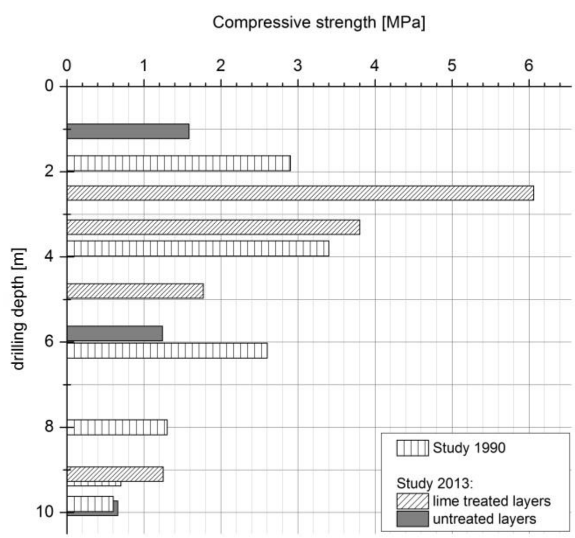

Figure 4. Compressive strength (untreated layers are identified by chemical analysis)

4.3 Chemical analysis

In 1990 quantitative chemical analysis were limited to water and CaO content, while in 2013 wider analysis were conducted to calculate reaction distribution. The samples were analysed for CaO, CO_2, available lime and water content. The carbonate content was calculated from CO_2 values.

The 1990 samples showed an average water content across the entire drilling depth of w_a = 21 % (w/w), i. e. significantly higher compared to w_a = 13.8 % (w/w) for the 2013 samples. The decreased water content implies an advanced dehydration process, probably as a result of continued hydration of reactive lime. The possibility of ongoing hydration was already indicated by the presence of lime and the necessary permeability of the layers cored in 1990.

It was known, that the untreated original soil contained approximately 1.3 % (w/w) of CaO, so with the exclusion of all samples with CaO ≤ 1.3 % (w/w) from further assessment it was secured only lime treated soils were used for calculation. In 2013 analysis showed as lowest CaO values 1.2 % (w/w) and 1.6 % (w/w), so a CaO content of 1.2 % (w/w) was used for this specific dataset as correction parameter regarding the original CaO content of the soil when calculating reaction distributions.

The results of the chemical analysis regarding calcium oxide, calcium carbonate and available lime content of the lime treated layers sampled in 2103 (i. e. 34 years after the application of lime) are shown in Figure 5. Only one sample had no available lime left, all other samples had at least 0.2 % (w/w) available lime with an average value of 0.62 % (w/w). Therefore, even after 34 years there is still reactive lime present. Also the higher levels of available lime correspond with higher levels of total CaO content in the layers.

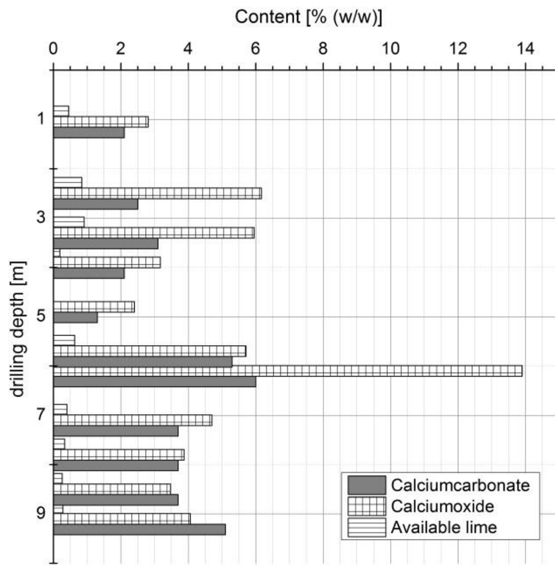

Figure 5. Chemical analysis

4.4 Calculations

Main target was to analyse the percentage of carbonation and pozzolanic reaction plus the resulting available lime 34 years after application. The calculation steps are explained in the following. To facilitate calculation and comparison of the analysed chemical parameters equations were referenced to CaO as standard.

As the lime treatment and construction of the embankment occurred in layers the lime dosage of the samples may differ. Therefore the reaction percentages were calculated separately for every single sample.

4.4.1 CaO content from soil treatment

Calculation of added CaO for soil treatment:

$$\mathrm{CaO}_{add} = \mathrm{CaO}_{sa} - \mathrm{CaO}_{us} \qquad (1)$$

With:

CaO_{add} added CaO for soil treatment (% w/w)

CaO_{sa} CaO in treated soil, analysed (% w/w)

CaO_{us} CaO in untreated soil from literature (1.3 (% w/w))

4.4.2 Chemical bound CaO content

Calculation of chemical bound CaO as % (w/w) after soil treatment:

$$\mathrm{CaO}_{cb} = \mathrm{CaO}_{add} - \mathrm{CaO}_{al} \qquad (2)$$

With:

CaO_{cb} chemical bound CaO (% w/w)

CaO_{al} available lime, analysed (% w/w)

Thereof the percentage of chemical bound CaO can be determined:

$$\mathrm{CaO}_{cb\,\%} = \frac{\mathrm{CaO}_{cb} \cdot 100}{\mathrm{CaO}_{add}} \qquad (3)$$

With:

$\mathrm{CaO}_{cb\,\%}$ percentage chemical bound CaO (%)

4.4.3 Carbonation

The carbonated CaO is calculated from the results of the CO_2 analysis and untreated samples:

$$\mathrm{CaO}_{carb} = \mathrm{CO}_2 \cdot 1.2743 - \mathrm{CaCO}_{3\,us} \qquad (4)$$

With:

CaO_{carb} carbonated CaO (% w/w)

CO_2 CO_2, analysed (% w/w)

1.2743 stoichiometric factor (CO_2 → CaO)

$\mathrm{CaCO}_{3\,us}$ $CaCO_3$ from untreated soil, calculated (% w/w)

The percantage of added CaO wich has been carbonated is named as $\mathrm{CaO}_{carb\,\%}$:

$$\mathrm{CaO}_{carb\,\%} = \frac{\mathrm{CaO}_{carb}}{\mathrm{CaO}_{add}} \cdot 100 \qquad (5)$$

4.4.4 Pozzolanic reaction

The percantage of CaO available for the origin of pozzolana is controlled by the content of carbonated CaO and available lime:

$$CaO_{p\,\%} = \frac{CaO_{add} - CaO_{carb} - CaO_{al}}{CaO_{add}} \cdot 100 \qquad (6)$$

With:

$CaO_{p\,\%}$ percentage of CaO available for pozzolanic reaction (%)

4.4.5 *Available lime*

The percentage of available lime in the reaction distribution can be calculated simmilary:

$$CaO_{al\,\%} = \frac{CaO_{al}}{CaO_{add}} \cdot 100 \qquad (7)$$

With:

$CaO_{al\,\%}$ percentage of available lime in the reaction distribution (%)

4.4.6 *Degree of reaction parameters*

The results of all calculations for every lime treated sample are shown in Figure 6. The average values are:

- Degree of carbonation: 40 %
- Degree of pozzolanic reaction: 46 %
- Degree of available lime: 14 %

All results are based on added CaO values, individually calculated for every single sample. The wide variaton on the degree of reaction parameters reflect the layered treatment with varying lime dosages.

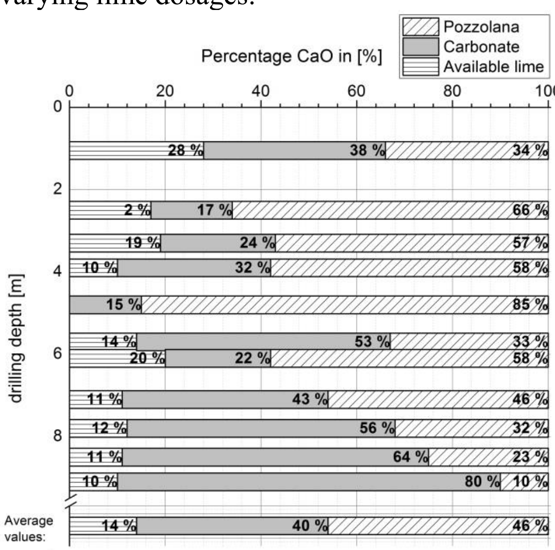

Figure 6. Reaction distribution of added CaO in percentage in lime treated samples

5 CONCLUSIONS

This study aimed on the quantification of calcium oxide consumed in the long term reaction of soil treatment, the distribution of carbonation, pozzolana and available lime and the development of the compressive strength after more than three decades.

Samples were taken from a lime treated embankment of the motorway A3 in southeast Germany which has been built in 1979 by approximately 200,000 m³ / 354,000 t excavated soil and 8,850 t Quicklime (CL 90 Q).

In 1990 and 2013 drilling was performed in the same area of the embankment. Both times compressive strength was tested on samples from different layers. After 11 years the values of the lime treated samples were situated between 1.3 MPa and 3.4 MPa and increased up to a maximum of 6.1 MPa with a mean value of 3.2 MPa after 34 years. The increase of compressive strength proves an ongoing pozzolanic reaction.

The percentage of carbonation and pozzolanic reaction plus the resulting available lime after 34 years has been calculated for every individual sample. Details are shown in Figure 6. On average 40 % of CaO were carbonated, 46 % reacted pozzolanic and 14 % are still available as free lime.

The results show detailed and varying reaction distribution for different layers. The available lime suggests further hardening of the soil if enough water and clay fraction are available for pozzolanic reactions, both which can be expected at the studied building site. Hardening can be affected through an integration of available lime in the pozzolanic reaction and by further carbonation.

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7 DATA SET

Table 2. Data set

drilling depth (m)	**Compressive strength (MPa)** Study 1990	Study 2013	**CaO (% w/w)** Study 2013	**Available Lime (% w/w)** Study 2013	**$CaCO_3$ (% w/w)** Study 2013
0.7			1.23	0.14	1.0
1.1		1.56	2.81	0.45	2.1
2.5	2.9		6.17	0.84	2.5
3.3		6.06	5.95	0.91	3.1
3.9		3.8	3.17	0.19	2.1
4.8	3.4		2.40	0	1.3
5.8		1.24	1.22	0.16	1.1
5.7		1.77	5.71	0.63	5.3
6.1			13.9	2.59	6.0
7.1			4.70	0.40	3.7
7.8			3.87	0.33	3.7
8.5	2.6		3.47	0.26	3.7
9.1			4.06	0.28	5.1
9.9		0.66	0.61	0	4.2