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Soil improvement with quicklime – long-time behaviour and carbonation

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In 1979, during the construction of the motorway A3 Regensburg – Passau, southeast Germany, an embankment had to be built. The soil for this embankment was treated with quicklime to accelerate the chemical reaction and shorten the time for earthworks. The treatment results in water reduction, pozzolanic hardening and carbonation of the lime. Previous studies never addressed the scale of these reactions. Here, the degree of carbonation and pozzolanic reaction were determined for the first time to provide evidence for the long-term stability of lime-improved earthworks on a structure with high and long-term stability. In 1990 and 2013, samples from this embankment were taken and examined. The samples were tested using methods for compressive strength and chemical analysis. After 34 years, the results show compressive strengths up to 6 MPa, with 37% of the quicklime being used in carbonation and 47% in pozzolanic reactions. Sixteen per cent free CaO is still available.

Keywords: lime; quicklime-treated soil; long-time behaviour; compressive strength; degree of carbonation; degree of pozzolanic reaction

Introduction

Soil treatment with quicklime or hydrated lime is a well-known and extensively used technique for earthworks to dry up wet soils and to enhance their performance. The embankment reported in these studies has been treated with quicklime. Therefore, the following will only address the use of quicklime, although hydrated lime in different forms is used in other countries for soil treatment.

Quicklime consists primarily of calcium oxide, descriptions and requirements are defined in EN 459-1 (2010). It improves and solidifies most soil types, the subgrade of traffic areas and other earthworks providing clay minerals are present. By using quicklime, unsuitable fine-grained (cohesive) soils or mixed-grained soils can be processed immediately to a condition that allows a smooth and timely production flow of earthwork. This is a result of a short-term reaction which leads to dehydration and clay flocculation. Subsequent long-term reactions can take place over years, during which quicklime hydrates, pH values of the pore water increase and clay minerals become soluble. The consequent release of silica and alumina triggers pozzolanic reactions with lime, followed by an increase in compressive strength (Eades and Grim, 1960). Very wet, non-compressible soils and dry compressible soils are improved by the treatment with lime so that their properties in the long term, even under extreme traffic conditions, weather conditions and water encroachment, retain a high utility value.

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The necessary amount of lime is determined by the Initial Consumption of Lime (ICL), i.e. the quantity of lime the soil needs to reach a pH of 12 (Eades and Grim, 1966) and that ensures an increase in compressive strength.

Lime makes unsuitable soils usable, environmentally beneficial and useful for earthworks. Although the carbon footprint for the quicklime production has to be taken into account, in most cases, soil replacement with all the consequences like additional transportation and materials becomes a sustainable alternative. Soil treatment with lime contributes to the conservation of resources as an extensive study by Celauro, Corriere, Guerrieri, and Lo Casto (2014) on the impact of various construction embodiments of roads showed.

Few studies have been conducted to describe the long-term behaviour of soil improvements and stabilisation with lime and specifically with quicklime. Abricht, Freudenberg, and Hundt (1976) investigated the long-term capacity of lime-improved and lime-stabilised soils to bear loads under practical conditions. Kelly (1977) related his positive experiences with lime stabilisation over a period of 25 years in the Southwest of the United States. The positive results of both reports reflected observations of the behaviour of lime-stabilised soils under the impact of traffic. Neither, however, included an investigation of how the soils mechanical parameters changed over time as a consequence of lime application. Extensive laboratory and field testing by Little (1999) showed a strength improvement in excess of 1.4 MPa. In some soils, ultimate compressive strength values as high as 7.0–10.0 MPa can be reached. Deneele et al. (2013) demonstrated that both pozzolanic reactions and carbonation can lead to an increase in strength under certain conditions.

Ritter and Stahff (1991) investigated an embankment of a motorway 11 years after a quicklime soil improvement had been performed. Based on this study, samples were taken in 2013 from the same spot. The objective in 2013 was to document the changes of the soils mechanical parameters and the mineralogy, as well as the consumption rate of the quicklime 34 years after the quicklime-based soil stabilisation had been carried out.

Initial situation

Building site

The samples for both studies (1990 and 2013) were collected from an embankment of the motorway A3 at km 543.7 in southeast Germany between Regensburg and Passau. The section from which the samples were taken is situated on a 10- to 12-m high embankment, slightly to the east of the motorway exit and entrance of Bogen. It traverses – after 500 m – a 600 m long and up to 9 m deep hollow near Waltersdorf. During the construction of the motorway in 1979, more than 200,000 m³ of excavated material (354,000 t) from the hollow was improved with approx. 2.5% (w/w) quicklime (CL 90-Q) and used in the build-up of the two embankments. At a mean dry density of 1.77 Mg/m³ for the excavated soil, approx. 8850 t of quicklime was applied in the course of the soil improvement project.

Original soil

The first exploratory drillings in June 1977 pointed to the existence of soft silts (Figure 1) in the hollow and to 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. Table 1 shows a selection of characteristic parameters from the original soils from 1978.

For similar soils to the west of the junction at Bogen, tests had already been conducted to establish the feasibility of a quicklime-based soil improvement. In nearly all cases, these tests had revealed that an addition of 2% (w/w) of CaO would significantly improve the parameters of the Proctor compaction tests.

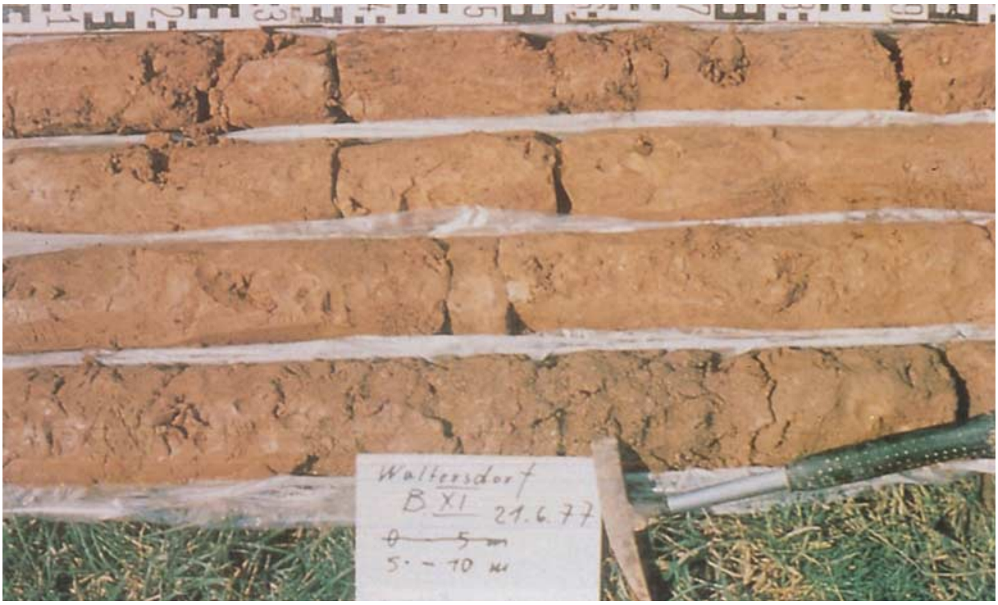

Figure 1. Ground investigation bore 1977 – soft silts in the hollow.

Table 1. Selection of characteristic data of soil indicators of original soils (Ritter & Stahff, 1991).

Soil indicator			Min	Average	Max
Soil types					
DIN 4023				U, fs – U, t, fs	
DIN 18196				Ul – Tl	
Water content	W_n	%	20.0	25.6	29.0
Liquid limit	W_l	%	31.0	33.0	34.2
Plastic limit	W_p	%	16.3	18.6	20.0
Plasticity index	I_p	%	11.0	14.4	17.9
consistency index	I_c		0.55	0.65	0.80
Proctor density	ρ_{pr}	g/cm³	1712	1787	1814
Proctor water content	W_{pr}	%	14.5	16.0	17.8
Total CaO content		%	–	1.26	–
Soil class DIN 18300			2–5		

Construction

As early as August 1979, in the course of the excavation works at the hollow, it became obvious that the excavated soils would not be suitable for further use in the motorway embankment unless quicklime was added.

Ultimately, a total volume of 2.5% (w/w) of CaO was used in the various soil improvement efforts. This value is considered as the calculated average value for the consumption of quicklime after construction was completed. All samples from quicklime-treated soils in the area around the embankment showed a mean Proctor compaction rate of 98.7%. Nearly everywhere, the proportion of air voids was kept under the permissible maximum of 12%, which was required by ZTV E-StB 76 (Forschungsgesellschaft für Straßen- und Verkehrswesen, 1976). Sampling took place in an area with quicklime-improved soils, where the embankment is approx. 10 m high.

Sampling and preparation methods

Sampling

First study in 1990

Soil samples were collected by drilling with a dry core into the hard shoulder of the A3 motorway (in the direction towards Passau) at km 543.7 (Figure 2). Figure 3 shows the drilling profile. The quicklime-improved layers have been highlighted (U vf = lime-treated silt).

Second study in 2013

Thirty-four years after the quicklime-based soil improvement scheme had been completed; new samples were extracted from the embankment in November 2013. The focus was on assessing

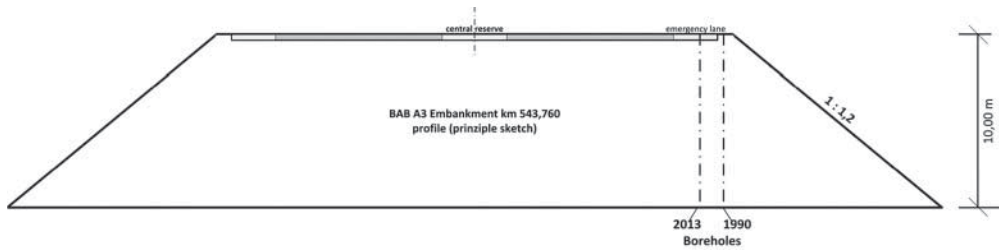

Figure 2. Principle of the embankment profile at km 543.7.

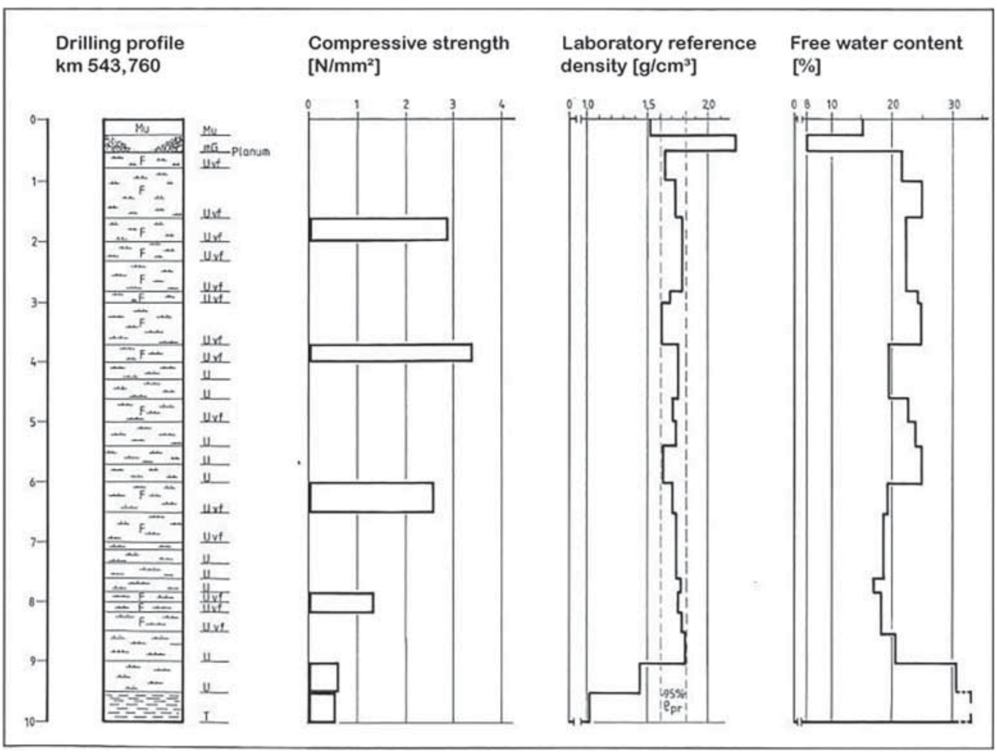

Figure 3. Drilling profile, compressive strength, dry densities and water content of the drilling in 1990 (Ritter & Stahff, 1991).

the percentages of pozzolanic reaction, carbonation and as a result the available free lime of the added quicklime content after 34 years.

The drilling site – the emergency lane of the motorway at km 543.7 – was in the immediate vicinity of the drilling site of the 1990 study (Figure 2). Drilling was again performed with a dry core.

As in 1990, it proved very difficult to pierce through the improved layers of soil. When the drill bit was rotated, the drill core was found to shear off due to the increased strength of the soil, and no consistent sampling could take place. At a depth of 10 m, the upper layers of the underlying ground soil were reached.

Once the sampling operation had been completed, the boxes with the drilling cores were shut and wrapped into plastic bags to prevent the carbonation of the quicklime-improved samples before the analysis was performed.

Preparation of samples

The samples for the tests in 1990 and 2013 were similarly prepared. Following the soil treatment with quicklime and subsequent hardening, the originally fine-grained and loose soil had become much harder over the past 11 and 34 years. This made it impossible to establish soil-mechanic parameters which would have described the soil's shearing behaviour. For this reason, the samples were only tested for their levels of compressive strength.

Cube-shaped specimen with a slenderness ratio of (d/h) between 0.8 and 1.05 were produced from the drill cores and the trenches through a process of dry sawing. These specimens were used to establish the compressive strength. The fragments that were produced during the preparation of the specimen were subsequently used to establish the other test parameters. All samples, specimens and fragments were stored under vacuum conditions until the tests could be performed.

Methods

Table 2 summarises the tests performed to characterise the samples. In 1990, free lime was qualitatively tested with phenolphthalein. For the study in 2013, quantification of the reaction products was needed, so instead of phenolphthalein or diluted acid tests the content of available lime, CaO and CO_2 were – according to EN 459-2 (2010) – chemically analysed. Mineral phase calculation was supported by X-ray diffractometry (XRD) analyses.

Table 2. The test methods used for the samples collected in 1990 and 2013.

Test methods	Year 1990	Year 2013
Compressive strength	DIN 18136	EN 13286-41, with a feed rate of 1 mm/min
Water content	DIN 18121-1	EN 1097-5, specimens for compressive strength
Dry density		EN 459-2, all samples from drill cores
CaO	DIN 1060-2	EN 459-2
Available lime	Phenolphthalein test(qualitative)	EN 459-2
CO_2	–	EN 459-2
Mineral phase analysis	X-ray diffractometry (XRD)	X-ray diffractometry (XRD)

Results

First study in 1990

The results of the drilling core analysis from 1990 for different drilling depths are shown in Figure 3.

After 11 years, drilling samples from the quicklime-improved layers had compressive strength between 1.3 and 3.4 MPa, significantly above the values that are required in aptitude tests for quicklime soil stabilisation schemes (compressive strength after freezing and thawing $\geq$ 0.2 MPa) with quicklime additions of approx. 6% (w/w). This demonstrated that even relatively small additions of quicklime – as long as the quantity requirements for improving soil quality is met – can, given enough time, harden the soil substantially.

The dry density levels of the improved layers were around the compaction ratio of 95% which was required by ZTV E-StB 76 (Forschungsgesellschaft für Straßen- und Verkehrswesen, 1976). The water contents exceeded the value (w_a = 19.5% w/w), which had been established in the contemporary aptitude test for a compaction ratio of 95%. The elevated water content, which did not adversely affect either load-bearing capacity or compaction level, can be explained by the adverse weather conditions that had troubled the building works for their entire duration. Following heavy rainfalls, residual water on the compacted layers had been locked in the embankment when subsequent layers of soil were added.

Still available free lime was proven with a phenolphthalein test.

Mineral phase analysis was performed to establish whether clay minerals had been altered through pozzolanic reactions with the quicklime. Evidence for this alteration through pozzolanic reactions was provided by the phase [($C_3A \times CaCO_3 \times 11\ H_2O$)] (monocarbonate). This phase is identified as a newly generated phase of clay minerals and calcium oxide and is essential for the hardening process (Rygol, 1987).

Second study in 2013

The analysis parameters and results are shown in Table 3.

Compressive strength

The values of compressive strength (R_c) are shown in Table 3. Due to the aforementioned shearing behaviour of the drill, sampling exactly the same depths as in 1990 was impossible. Where samples were taken from similar depths, compressive strengths of samples 3 (R_c = 6.06 MPa) and 4 (R_c = 3.80 MPa) were higher than the values of the 1990 samples (2.8 and 3.4 MPa). All samples on this level (in depths of 2.50–3.30 m) had been treated with quicklime, thus this treatment improved the compressive strength due to long-term reactions between 1990 and 2013.

Water content

These values (Table 3) were consistently lower than those measured in 1990. The data allow the estimation of an average value across the entire drilling depth of w_a = 21% (w/w). The current average value of w_a = 13.8% (w/w) indicates the degree to which the soil in the embankment has been further dehydrated over the past 23 years.

The decrease of the water content is probably related to hydration of reactive lime, whose presence was proven in samples of the 1990 study. Considering the air void content of approx. 12% that was created when the treated layers were compressed inside the embankment, it is also possible that the permeability of the added materials has contributed to this gradual dehydration.

Table 3. Values of the analyses from the second study.

Drilling depth	Parameter	Compressive strength	Free water	Loss on ignition	Available lime	CO_2	CaO	$CaCO_3$	
		(Mpa)	(% w/w)	(% w/w)	(% w/w)	(% w/w)	(% w/w)	(% w/w)	
	method	EN 13286-41[a]	EN 459-2	EN 459-2	EN 459-2	EN 459-2	EN 459-2	Calculated[b]	
m	Conditions	Delivery condition	Delivery condition	Dried	Dried	Dried	Dried	Dried	Layer rating (–)
0.70	Sample 1	–	16.6	4.95	0.14	0.42	1.23	1.0	Untreated
1.05	Sample 2	1.6	12.9	5.47	0.45	0.93	2.81	2.1	Treated
2.50	Sample 3	6.1	17.1	6.85	0.84	1.12	6.17	2.5	Treated
3.30	Sample 4	3.8	12.8	6.51	0.91	1.35	5.95	3.1	Treated
3.90	Sample 5	–	15.4	5.32	0.19	0.94	3.17	2.1	Treated
4.80	Sample 6	1.8	8.6	5.28	0.00	0.59	2.40	1.3	Treated
5.80	Sample 7	1.2	11.5	5.15	0.16	0.47	1.22	1.1	Untreated
5.70	Sample 8	–	11.1	7.20	0.63	2.32	5.71	5.3	Treated
6.10	Sample 9	–	19.2	10.50	2.59	2.64	13.90	6.0	Treated
7.10	Sample 10	–	13.3	6.38	0.40	1.62	4.70	3.7	Treated
7.80	Sample 11	–	15.9	5.71	0.33	1.63	3.87	3.7	Treated
8.50	Sample 12	–	14.0	5.81	0.26	1.61	3.47	3.7	Treated
9.10	Sample 13	1.3	13.5	6.37	0.28	2.25	4.06	5.1	Treated
9.90	Sample 14	0.7	11.6	4.27	0.00	1.85	0.61	4.2	Untreated
Average for treated layers		2.9	14.0	6.5	0.6	1.5	5.1	3.5	

[a]Loading rate = 1 mm/min, slenderness = 1.
[b]From CO_2.

Content of available lime and CaO

The establishment of the available lime content allowed the unique identification of the quicklime-improved layers of soil in the embankment. Any level of available lime detected can only have been produced by the treatment with quicklime, because the original soil cannot contain any available lime. Results demonstrate that reactive lime is still present in the soil 34 years after it had been added (Table 3). The levels of available lime correspond with the total content of CaO in the layers under review, which means that layers with higher levels of CaO are also characterised by higher levels of available lime (Table 3). The soil investigation that was performed in 1977 before the construction project could begin had revealed that the original soil contained approx. 1.3% (w/w) of CaO.

In this light, the CaO contents (< 1.3% w/w) of samples 1, 7 and 14 are no longer considered for the purposes of the analysis. On the basis of the analysis that was performed on the other samples, an average CaO content of 5.1% (w/w) was calculated. Considering the original CaO value of 1.3% w/w for the untreated soil, the quicklime-treated layers of the analysis received on average a CaO enrichment of 3.8% (w/w).

Excluding the aforementioned three samples, an average available lime level of 0.63% (w/w) is established. Therefore, 3.2% (w/w) of the added CaO has reacted, i.e. 84% of the average amount of added CaO of 3.8% (w/w). This reaction contains carbonation and pozzolanic reaction between clay minerals and quicklime (Figure 4).

The identified CaO contents are marginally higher as the mean value of 2.45% CaO from the calculated average value for the consumption of quicklime after construction was completed. Due to the construction conditions, local higher CaO values are possible. These are based on higher water contents of the original soil, influences from weathering and construction processes.

Carbonate content

The carbonate content (Table 3) was established by determining the CO_2 content of the samples. Using the analytic configuration that was outlined in the above – i.e. exclusion of the values from the samples 1, 7 and 14 (< 1.3% w/w) – an average calcium carbonate content of 3.5% (w/w) was established in the quicklime-treated layers of soil.

X-ray phase analysis

The samples for the mineralogical analysis (XRD) were selected on the basis of the previously conducted investigations. A comparative analysis of samples from untreated as well as quicklime-treated layers of soil was designed to establish whether or not the pozzolanic reactions had generated new mineral phases.

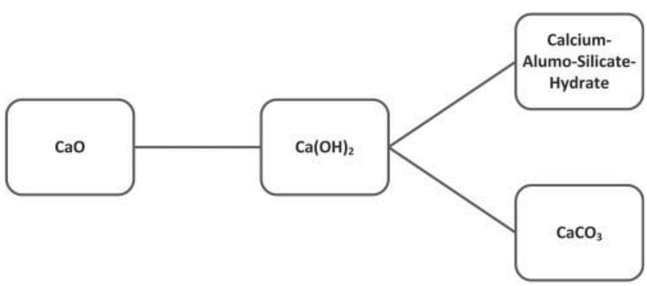

Figure 4. Reaction parts of soil treatment.

An exact selection of mineral phases proved to be fraught with uncertainties, due to the presence of numerous mineral phases and subsequent peak interactions which made it difficult to ensure an unambiguous identification. Nonetheless, the phases ‘calcium-silicate-hydrate’ and ‘calcium-aluminium-oxide-carbonate-hydrate’ could be identified and provided conclusive evidence for the conversion of clay minerals in the wake of pozzolanic reactions with quicklime. This corroborates and confirms the generation of a new phase of clay minerals and calcium oxide which had been proven for the first time in 1990.

Calculations

Target of the study was the calculation of the percentages of pozzolanic reactions, carbonation and resulting available lime after 34 years, named as carbonation quotient, pozzolanic quotient and available lime quotient.

Calculations are based on the average values of the lime-treated layers and a CaO content of approx. 1.3% (w/w) in the original soil based on investigations in 1977.

The pozzolanic quotient has to be calculated from the average CaO addition and the amount of consumed CaO in the carbonation reaction, as follows:

$$CaO_{(PR)}[\%\ w/w] = CaO_{(s)} - CaO_{(os)} - CaCO_{3(s)} \cdot F_{CaO}, \tag{1}$$

where

$CaO_{(PR)}$, CaO used in pozzolanic reaction

$CaO_{(s)}$, average CaO content samples (5.1% w/w)

$CaO_{(os)}$, CaO content original soil before treatment (1.3% w/w)

$CaCO_{3(S)}$, average $CaCO_3$ content samples (3.5% w/w)

F_{CaO}, factor calculation CaO from $CaCO_3$ (0.56).

$$\text{Degree of pozzolanic reaction} = \frac{CaO_{PR}}{CaO_{(s)} - CaO_{(os)}} \cdot 100. \tag{2}$$

The soil original carbonate content is unknown, making a direct calculation of the carbonation quotient impossible. Thus, the carbonation quotient was determined by:

$$\text{Degree of carbonation} = \frac{CaO_{(S)} - CaO_{(OS)} - AL_{(S)} - CaCO_{(PR)}}{CaO_{(S)} - CaO_{(OS)}} \cdot 100, \tag{3}$$

where $AL_{(s)}$, average available lime content samples (0.6% w/w).

The available lime quotient is calculated by the following equation:

$$\text{Available lime quotient} = \frac{AL_{(s)}}{CaO_{(s)} - CaO_{(os)}} \cdot 100. \tag{4}$$

From the calculation of the Equations (1)–(4), the following quotients are received:

Degree of pozzolanic reaction: 47%;

Degree of carbonation reaction: 37%;

Degree of available lime reaction: 16%.

Conclusions

This study had been initiated to provide evidence for the long-term stability of lime-improved earthworks on a structure with high and long-term stability and by relying on data that reflected actual practice. With these criteria in mind, it was decided to conduct the study on soil samples from a motorway embankment, completed in 1979, which had been built by excavated soil (200,000 m^3/354,000 t from a hollow) which had then been treated with approximately 8850 t quicklime (CL 90-Q).

In 1990, drilling was performed at km 543.7 of the motorway A3 in southeast Germany. Contemporary analysis showed the soil samples to possess uniaxial compressive strengths of between 1 and 3 MPa. The existence of available lime was qualitatively verified by the application of phenolphthalein without quantifying the amount of available lime.

In 2013, the same area of the motorway was drilled. Samples were collected to investigate the development of compressive strength levels and the degree of pozzolanic reaction and carbonation of the quicklime over 34 years.

Compressive strength had indeed further increased since 1990 due to the ongoing pozzolanic reaction. Moreover, the soil still contained available lime, indicating that the hardening of the soil was still ongoing, 34 years after the completion of the project.

The X-ray phase analysis demonstrated that the new generation of phases is stable and consistent, due to pozzolanic reaction of the clay minerals with quicklime.

In this study, it is the first time that a degree of carbonation has been determined in a real embankment using soil treatment with quicklime. The amount of available lime and the current (total) CaO content suggest that the quicklime which had been used 34 years ago for the treatment of the soil had achieved a degree of pozzolanic reaction of 47% and a degree of carbonation of 37%, leaving 16% of available lime in the treated soil. Further increase in compressive strength is likely if enough water and clay fraction are available for pozzolanic reaction, which is to be expected at the studied building site. This increase can be affected through an integration of available lime in the pozzolanic reaction and by further carbonation.

Funding

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