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Lime Treatment: Evaluation for Use in Dike Applications in the Netherlands

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Abstract: This study aimed to assess the suitability of lime treatment for use in dikes in the Netherlands. The effect of this technique on the behavior of a Dutch clay was addressed by comparing the detailed response of lime-treated and natural samples at different lime contents (1.25% and 2.25%) and curing periods. A series of laboratory tests consisting of index classification, constant rate of strain, and triaxial and hole erosion tests were performed. The results demonstrated that lime treatment altered the soil response. Differences were observed in the physical, compressibility, strength, and erodibility properties. It was found that lime improved considerably the resistance to compression and erosion, but the effect on hydraulic conductivity was limited. The triaxial test results showed that lime treatment was particularly effective at low stress (<25 kPa) and low strain levels (<10%). During shearing, lime-treated samples exhibited dilative tendencies and enhanced effective strength properties until a stress-strain state was reached that was believed to be related to the breakage of the bonding structure of the sample. The findings of this study demonstrate that the merits of lime treatment can be of particular benefit in dike applications, particularly when the focus is on improving soil erosion resistance. **DOI: 10.1061/(ASCE)MT.1943-5533.0004623.** *© 2022 American Society of Civil Engineers.*

Author keywords: Lime treatment; Organic clay; Dike; Erosion resistance; Compressibility; Shear strength; Stress-strain response.

Introduction

Engineers worldwide are aware of the benefits of lime treatment in soil improvement. This technique has been widely used since the mid-1940s in earth structures (e.g., embankments, roads, railways, highways) for improving the engineering properties of cohesive soils (Little 1995). Thus, the effect of lime on soil properties has been extensively studied by various researchers (Le Runigo et al. 2009; Makki-Szymkiewicz et al. 2015; Elandaloussi et al. 2018; Kumar and Thyagaraj 2021). The addition of lime to cohesive soils generally causes a decrease in plasticity and compressibility and an increase in pH and volume stability against swelling and shrinkage (El-Rawi and Awad 1981; Kennedy et al. 1987; Bell and Coulthard 1990; Rogers and Glendinning 1996; Sakr et al. 2009; Achampong et al. 2013; Kumar and Thyagaraj 2021). Moreover, the addition of lime dramatically modifies the stress-strain response and the erosion parameters of cohesive soils (Chevalier et al. 2012; Mavroulidou et al. 2013b; Bennabi et al. 2016). Lime-treated loamy and clayey soils exhibit a high resistance to internal and surface erosion, whereas their shear strength, friction, and cohesion increase with lime compared to natural soils (Tuncer and Basma 1991; Herrier and Bonelli 2014).

In recent years, several benefits of this technique in hydraulic structures construction or restoration have been reported (Perry 1977; Gutschick 1985; Fleming et al. 1992; Stapledon et al. 2005; Herrier et al. 2018). As a result, the interest of the European hydraulic community in applications of the lime-treatment technique in levees, dams, and dikes has grown (Herrier et al. 2012, 2019; Charles et al. 2014; Bonelli et al. 2018). Recent successful examples include full-scale experiments carried out on dikes built with lime-treated soils with lime-treated soils (Nerincx et al. 2016, 2018; De Baecque et al. 2017; Nerincx et al. 2018) and the application of lime treatment in the reconstruction of river dikes in the Czech Republic that had been destroyed by floods in 2002 (Pavlík 2006).

The Netherlands, with one third of the country lying below sea level, has developed one of the most advanced antiflood systems in the world; it consists of an extensive network of over 22,500 km of dikes and dams. As a result, millions of euros are invested every year in the maintenance and reinforcement of the existing flood defense network. Nowadays, there is a general requirement for environmentally and economically sustainable solutions in the design of flood defenses. From this perspective, lime treatment can be perceived as an innovation in dike upgrades in the Netherlands with the benefits being high with respect to costs, environmental impact, and time. Via application of this technique, the quality of unsuitable construction material can now be improved on site. In addition, owing to the enhanced performance of lime-treated soils in terms of mechanical stability, workability, and erodibility, surface protection measures, such as grass cover, rip-rap, or stone mattresses, may not be required any longer. Moreover, the design of flood defenses can be optimized to allow for lower crest levels and possibly steeper slopes, resulting in space and material savings. Specifically, the design philosophy for dikes in the Netherlands nowadays is not based

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on withstanding a standard design flood level but on the risk of dike failure. This means that a lower probability of failure of the inner slope due to overtopping water can lead to a design that allows for a lower crest level (a higher overtopping rate).

Dutch clays have a relatively high organic content, on the order of 2%–5%. It should be highlighted that, based on findings reported in the literature, the extent to which soil properties are improved after the addition of lime depends on various factors, such as curing time, type of lime, and amount added (Bell and Coulthard 1990; Tuncer and Basma 1991; Bell 1996; Consoli et al. 2011; Mavroulidou et al. 2013b). Among the different factors influencing the effectiveness of lime treatment, the nature of the soils involved is of major importance. According to Bell and Coulthard (1990), the presence of organic matter can delay or inhibit lime hydration, which has detrimental effects on the soil properties of lime-treated clays. A logical first step toward the practical use of lime in flood defense applications in the Netherlands and in other countries where organic soils are present is therefore to evaluate whether lime treatment is successful when applied to soils with organic matter.

This paper presents and discusses a series of tests performed on untreated and lime-treated Dutch clay samples under different lime contents and curing periods. The natural clay used in this study is a poor construction material classified as unsuitable for use in dikes. The results from the tests in this study aim at assessing the impact of lime treatment in improving soil properties that are important in dike construction. This primarily concerns the determination of the physical, compaction, strength, stress-strain, permeability, compressibility, and erosion resistance soil properties.

Materials and Sample Preparation

The soil used in this study was a sandy clay containing 3%–4% organic matter sampled from Warmenhuizen in the Netherlands, approximately 40 km north of Amsterdam. The soil properties and chemical components of this material are summarized in Table 1, and Fig. 1(a) shows its particle size distribution curve. The lime used in this study was the quicklime Proviacal DD sold by Lhoist; the product complies with the EN 459-1:2015 standard (CEN 2015) for building lime and has an available lime ≥ 88% and a reactivity (t_{60}) ≤ 10 min. According to EN 459-1:2015 (CEN 2015), it can be classified as CL 90-Q (R5, P2).

The minimal amount of lime required to improve the soil is known as the lime modification optimum (LMO) (Eades and Grim 1966). The calculated LMO for the tested clay, expressed in terms of percentage of lime by dry mass of soil, was 0.75% and corresponded to a lime percentage for which a pH of 12.4 is reached [ASTM D6276-19 (ASTM 2019)]. To account for the effect of lime

Table 1. Summary of natural and lime-treated Warmenhuizen clay properties

Property	Standard/technique	Natural clay	LMO + 0.5%	LMO + 1.5%
	Geotechnical characterstics			
LL (%)	ISO 17892-12:2018 (ISO 2018b)	31	33	35
PL (%)		18	19	22
PI (%)		13	14	13
SL (%)	DIN 18122-2:2000-09 (DIN 2000)	26	30	34
Clay fraction <0.002 mm (%)	ISO 17892-4:2016 (ISO 2016)	10.8	5.2	5.6
Silt fraction 0.002–0.075 mm (%)		55.6	59.6	61.5
Sand fraction 0.075–4.75 mm (%)		33.6	35.2	32.9
W_i (%)	ISO 17892-1:2015 (ISO 2015)	21.7	—	—
VBS (g/100 g)	EN 933-3:2012 (CEN 2012b)	2.15	1.81	1.61
	Chemical characteristics			
CaO (%)	X-ray fluorescence	6.7	—	—
MgO (%)		1.0	—	—
Al_2O_3 (%)		6.4	—	—
SiO_2 (%)		70.9	—	—
Fe_2O_3 (%)		2.5	—	—
MnO_2 (%)		0.0	—	—
Na_2O (%)		0.8	—	—
P_4O_6 (%)		0.1	—	—
K_2O (%)		1.5	—	—
SO_3 (%)		0.2	—	—
Cr_2O_3 (%)		0.0	—	—
CuO (%)		0.0	—	—
NiO (%)		0.0	—	—
SrO (%)		0.0	—	—
TiO_2 (%)		0.2	—	—
ZnO (%)		0.0	—	—
OC (%)	EN 15935:2012 (CEN 2012a)	3.0–4.2	—	—
	Compaction characteristics			
W_{OMC} (%)	ASTM D698-12 (ASTM 2012)	15.1	18.1	18.9
$\rho_{\mathrm{d,OMC}}$ (g/cm^3)		1.72	1.69	1.68

Note: LMO + 0.5%, LMO + 1.5% = clay treated at 1.25% and 2.25% lime; LL, PL, SL = liquid, plastic, and shrinkage limit, respectively; PI, plasticity index; W_i = water content prior to homogenization and mixing with lime; VBS = methylene blue value; CaO, MgO, Al_2O_3, SiO_2, Fe_2O_3, MnO_2, Na_2O, P_4O_6, K_2O, SO_3, Cr_2O_3, CuO, NiO, SrO, TiO_2, ZnO = calcium, magnesium, aluminum, silicon, iron, manganese, sodium, phosphorus, potassium, sulfur, chronium, copper, nickel, strontium, titanium, and zinc oxide respectively; OC = organic content; W_{OMC} = optimum water content; and $\rho_{d,\mathrm{OMC}}$ = dry density corresponding to optimum water content.

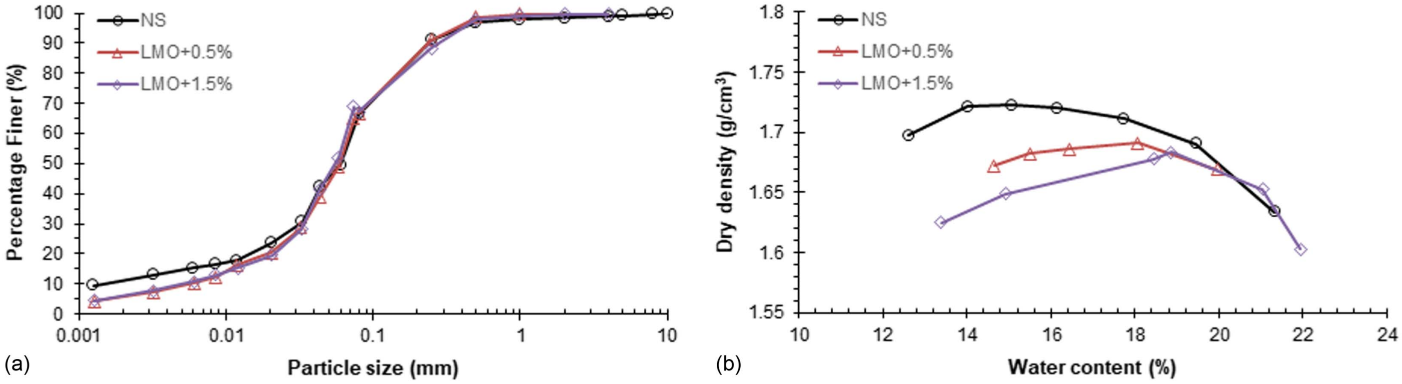


Fig. 1. (a) Particle size distribution; and (b) Proctor compaction curves for untreated and lime-treated Warmenhuizen clay.

content and treatment period, two different lime dosages, 1.25% (LM0 + 0.5%) and 2.25% (LMO + 1.5%), and different curing times (7, 28, 90, and 180 days) were considered in this study.

After sampling, the Warmenhuizen clay was homogenized and spread with tap water up to the desired compaction moisture content. The wet soil was thereafter left to hydrate in closed boxes for 24 h to allow moisture equilibrium. Subsequently, the soil was thoroughly mixed with lime and compacted 1 h after mixing (treated soil). A time interval of 1 h is considered to be representative of the time required for the operational activities taking place between lime treatment and compaction at large-scale infrastructure job sites (e.g., loading/unloading and transportation of the treated material). For the homogenized natural soil, compaction was carried out immediately after hydration (untreated soil).

Compaction was performed in cylindrical molds 15 cm in height and 10 cm in diameter according to standard Proctor dynamic compaction [ASTM D698-12 (ASTM 2012)]. Untreated and lime-treated samples were compacted in four layers at 95% of the optimum dry density, $\rho_{d,\mathrm{OMC}}$, and at a water content equivalent to 1.1 times the optimum moisture content, W_{OMC}. According to Herrier et al. (2012), these compaction conditions reduce the permeability of the compacted material. Before compaction, a silicon grease was sprayed on the mold surfaces to minimize friction and facilitate the demolding phase. After the molds were opened, the samples were wrapped in plastic film and left for 12 h with a load of 45 N on the top to avoid the opening of cracks induced by sample demolding. Samples were then trimmed to the dimensions required for testing and, after being wrapped in plastic sheets and sealed in plastic bags to avoid moisture loss, were allowed to cure at a controlled temperature of 20°C ± 1°C and a relative humidity of 40% ± 5%.

Test Methods

The tested soil both in natural and lime-treated states was subjected to various index classification tests that included grain size distribution, Atterberg limits, standard Proctor compaction, and chemical analysis tests. The main identification properties from these tests, along with the relevant standards adopted for their determination, are given in Table 1. The mineralogical composition of the soil was evaluated using X-ray fluorescence tests. The organic content was determined from loss on ignition (LOI) at 550°C [EN 15935:2012 (CEN 2012a)]. Particle size distribution curves were obtained by wet sieving for particles >80 μm and by sedimentometry for the soil fraction with particles <74 μm.

Standard unconfined compression strength (UCS) tests were performed following EN 13286-41:2021 (CEN 2021) for different levels of lime treatment (LMO + 0.5%, LMO + 1.5%) and curing times (7, 28, 90, and 180 days). The tested samples were 50 mm in diameter and 100 mm in height.

The one-dimensional stiffness characteristics of the untreated and lime-treated samples were obtained by performing tests in the Deltares constant rate of strain (CRS) K_0-oedometer (K_0-CRS) apparatus in accordance with ASTM D4186-06 (ASTM 2006). The K_0-CRS apparatus used is described by Den Haan and Kamao (2003) and allows for lateral stress and pore pressure measurements during testing. The K_0-CRS ring used had a diameter of 63 mm, whereas the tested samples had a height of approximately 20 mm. The applied loading scheme consisted of six steps: loading to 100 $\mathrm{kN/m^2}$ (Step 1), followed by unloading to 50 $\mathrm{kN/m^2}$ (Step 2), reloading to 150 $\mathrm{kN/m^2}$ (Step 3), relaxation for 16 h (Step 4), reloading to 600 $\mathrm{kN/m^2}$ (Step 5), and unloading to 10 kPa (Step 6). The applied deformation rate, dh/dt, was 0.3 mm/h, which corresponds to approximately 1.4%/h. With this deformation rate, the pore-water pressure generated at the base of the sample remained within 3%–10% of the applied vertical stress, as recommended by ASTM D4186-06 (ASTM 2006).

Triaxial tests were performed using the triaxial apparatus of the Deltares Geotechnical Laboratory and following ISO 17892-9:2018 (ISO 2018a). The specimens had a diameter and height of approximately 66 and 132 mm, respectively. After saturation with Skempton's B parameter having a value greater than 0.96, the samples were anisotropically consolidated to a range of initial mean effective stresses considered to be representative of the stress level conditions encountered within the dike body ($p_i' = 25$, 50, and 75 kPa). A consolidation stress ratio of $K_c = 0.4$ was applied as determined from the K_0-CRS tests [Fig. 6(f)]. Following consolidation, samples were subjected to monotonic loading under undrained strain-rate control conditions. Details of the samples are included in Table 2. Given the time frame provided in completing this research, only samples after a 90-day curing period were considered for triaxial testing. This curing period was used in the study to evaluate the effect of lime treatment in dike improvement applications, although it was recognized that the chemical reactions between soil and lime could be slow and might even take up to 5 years to be completed (Diamond and Kinter 1965; Bergado et al. 1996).

External and internal erosion are two of the most frequent failure mechanisms of dikes (Danka and Zhang 2015). The former concerns erosion of the dike cover material due to wave overtopping or high water flow velocities. The latter is related to the deterioration of the soil structure caused by seepage water forces. Soil erodibility is therefore one of the key factors in the safety assessment of dikes in whose design the construction materials must comply with

Table 2. Sample characteristics

Test	Test type	Lime content (%)	Curing time (days)	w_c (%)	w_e (%)	ρ_{dry} (kN/m^3)	p_i' (kPa)	K_c	dh/dt (mm/min)
NS	K_0-CRS	Natural soil	—	16.8	—	15.9	—	—	0.0012
LMO + 0.5%_28d	K_0-CRS	LMO + 0.5%	28	19.2	—	15.8	—	—	0.004
LMO + 1.5%_28d	K_0-CRS	LMO + 1.5%	28	19.8	—	15.7	—	—	0.004
LMO + 0.5%_90d	K_0-CRS	LMO + 0.5%	90	19.8	—	16.2	—	—	0.004
NS_25 kPa	TXL	Natural soil	—	16.8	—	17.3	25	0.4	—
NS_50 kPa	TXL	Natural soil	—	16.3	—	17.4	50	0.4	—
NS_75 kPa	TXL	Natural soil	—	16.9	—	17.4	75	0.4	—
LMO + 0.5%_25 kPa	TXL	LMO + 0.5%	90	19.1	—	16.6	25	0.4	—
LMO + 0.5%_50 kPa	TXL	LMO + 0.5%	90	19.2	—	16.6	50	0.4	—
LMO + 0.5%_75 kPa	TXL	LMO + 0.5%	90	19.4	—	16.8	75	0.4	—
LMO + 1.5%_25 kPa	TXL	LMO + 1.5%	90	20.6	—	16.3	25	0.4	—
LMO + 1.5%_50 kPa	TXL	LMO + 1.5%	90	21.4	—	16.2	50	0.4	—
LMO + 1.5%_75 kPa	TXL	LMO + 1.5%	90	20.9	—	16.5	75	0.4	—
NS	UCS	Natural soil	7	16.6	16.1	16.6	—	—	—
NS	UCS	Natural soil	28		16.3	16.6	—	—	—
NS	UCS	Natural soil	90		15.8	16.6	—	—	—
NS	UCS	Natural soil	180		15.6	16.5	—	—	—
LMO + 0.5%_7d	UCS	LMO + 0.5%	7	19.8	19.4	16.4	—	—	—
LMO + 0.5%_28d	UCS	LMO + 0.5%	28		19.8	16.3	—	—	—
LMO + 0.5%_90d	UCS	LMO + 0.5%	90		19.8	16.4	—	—	—
LMO + 0.5%_180d	UCS	LMO + 0.5%	180		18.8	16.5	—	—	—
LMO + 1.5%_7d	UCS	LMO + 1.5%	7	20.4	20.2	16.1	—	—	—
LMO + 1.5%_28d	UCS	LMO + 1.5%	28		20.2	16.1	—	—	—
LMO + 1.5%_90d	UCS	LMO + 1.5%	90		19.5	16.2	—	—	—
LMO + 1.5%_180d	UCS	LMO + 1.5%	180		19.3	16.3	—	—	—
NS_28d	HET	Natural soil	28	17.4	—	17.9	—	—	—
LMO + 0.5%_28d	HET	LMO + 0.5%	28	19.5	—	17.7	—	—	—
LMO + 1.5%_28d	HET	LMO + 1.5%	28	20.2	—	16.0	—	—	—
NS_90d	HET	Natural soil	90	17.4	—	18.0	—	—	—
LMO + 0.5%_90d	HET	LMO + 0.5%	90	19.5	—	17.7	—	—	—
LMO + 1.5%_90d	HET	LMO + 1.5%	90	20.2	—	17.0	—	—	—

Note: NS = natural soil; LMO + 0.5%, LMO + 1.5% = clay treated at 1.25% and 2.25% of lime; TXL, UCS, HET = triaxial, unconfined compressive strength, and hole erosion test, respectively; w_c = water content after compaction; w_e = water content at end of curing period; ρ_{dry} = dry density at start of testing; p_i' = mean effective stress at start of shearing; K_c = ratio of horizontal to vertical effective stress at end of consolidation; and dh/dt = strain rate applied in K_0-CRS testing.

requirements for high erosion resistance. The erosion properties of the natural and lime-treated samples in this study were investigated in the laboratory using the hole erosion test (HET) developed by Wan and Fell (2004) and described in Benahmed and Bonelli (2012). In this test, a drilled soil sample is eroded for a given hydraulic gradient by water flow. During testing the shear stress, τ, applied to the interface between the flowing liquid and the soil and the erosion rate, $\dot{\varepsilon}$, representing the eroded soil volume per unit area and per unit of time are recorded.

Description of Test Results

Particle Size Distribution

Based on Fig. 1(a), it can be concluded that for the lime contents examined in this study, no significant changes in grading were observed for grain sizes higher than 80 μm, whereas for lower sizes lime treatment appeared to enhance the creation of a more granular structure. This resulted in a decrease in the clay fraction present in the lime-treated soil (i.e., 10.3% in natural soil versus 5.3% and 5.2% in LMO + 0.5% and LMO + 1.5% soil, respectively). The development of a more granular structure was possibly due to the cation exchange process by which the clay particles became electrically attracted to one another, causing flocculation/agglomeration (Tuncer and Basma 1991; Little 1995; Sargent 2015), and changes in the plasticity properties of the soil.

Plasticity Characteristics

In terms of plasticity, both the liquid and plastic limit increased upon addition of lime while the plasticity index remained constant. The shrinkage limit values indicated that the lime-treated material had a higher volume stability compared to its natural state. It should be noted that for the two lime contents considered in this study, the shrinkage limit was higher than the water content at compaction and the samples were thus not prone to volume changes, which could have led, for example, to the formation of cracks in the dike body.

Compaction Characteristics

The Proctor compaction curves of the natural and lime-treated material are shown in Fig. 1(b). The calculated optimum moisture contents (W_{OMC}) and corresponding dry densities, $\rho_{d,\mathrm{OMC}}$, are given in Table 1. It is evident that for the same compaction effort, lime treatment leads to an offset of the optimum moisture content toward higher values and to a reduction of the maximal dry density. A reduction in the $\rho_{d,\mathrm{OMC}}$ and an increase in the W_{OMC} values of lime-treated soils has been reported in the literature (Osula 1991; Bell 1996) and can also be attributed to cation exchange reactions causing (1) fewer particles occupying larger spaces per unit volume; and (2) an increase in the demand for water during the reaction process (Mavroulidou et al. 2013a). In addition, the changes in W_{OMC} and $\rho_{d,\mathrm{OMC}}$ appear to be proportional to the amount of lime added, a conclusion in line with other studies in the literature (Bell and Coulthard 1990; Herrier et al. 2018).

Unconfined Compression Tests

The variation of unconfined compressive strength (UCS), q_{UCS}, and elastic modulus, E_{UCS}, with lime quantity and curing time is shown in Figs. 2(a and b), respectively, and the developed stress-strain curves are given in Fig. 2(c). To keep the diagram clear only the stress-strain curves for the 90-day cured samples are presented. As shown in Fig. 2(c), the elastic secant modulus, E_{UCS}, is computed from the slope of the straight line joining the point of maximum deviator stress to the origin of the axes.

Both the q_{UCS} and E_{UCS} values of the treated samples increase with curing time. The rate of increase appears to depend on the lime content: the more lime added, the higher the rate. For all testing conditions, however, the lime-treated samples showed a significantly improved behavior with respect to unconfined compression compared to the untreated samples, a behavior acknowledged in the literature (Consoli et al. 2011, 2014).

Many authors have concluded that the gain in the strength of lime-treated samples can be attributed to the chemical reaction mechanisms resulting from the addition of lime to the soil system or to suction stresses that develop due to desiccation (Le Runigo et al. 2011; Mavroulidou et al. 2013a; Elkady 2015). The UCS tests in this study were performed on unsaturated samples, so a suction effect could be expected. The suction developed in the samples was not measured, and it was therefore difficult to identify its contribution to the improved behavior of the lime-treated samples in Fig. 2. Precautions were taken to prohibit samples' desiccation, which increased suction. As explained, after compaction the samples were sealed in plastic bags to avoid moisture loss and left to cured in a humidity- and temperature-controlled environment. The water content of the samples at the beginning, w_c, and at the end of the curing period, w_e, is shown in Table 2. The percentage loss in water content at the end of curing can be considered a simple indicator of the development of suction stresses (Elkady 2015). For samples with the highest lime content (LMO + 1.5%), this percentage ranged between 1% and 5.4% for a curing period of 7–180 days. It is interesting to note that the lime-treated samples showed a considerably improved behavior with respect to UCS testing even after a curing period of 7 days, during which the loss in water content is limited.

Note that natural soil also exhibited a limited (marginal) gain in strength with lime, which could be the result of thixotropic hardening of the tested clay under constant volume and water content conditions (Tuncer and Basma 1991) or of suction stress increase as a consequence of some drying that occurred during sample storage (Table 2).

K_0-CRS Tests

The compression curves of the tested samples are shown for different lime contents and curing periods in Figs. 3 and 4, respectively. Pictures of the lime-treated samples taken prior to CRS testing are

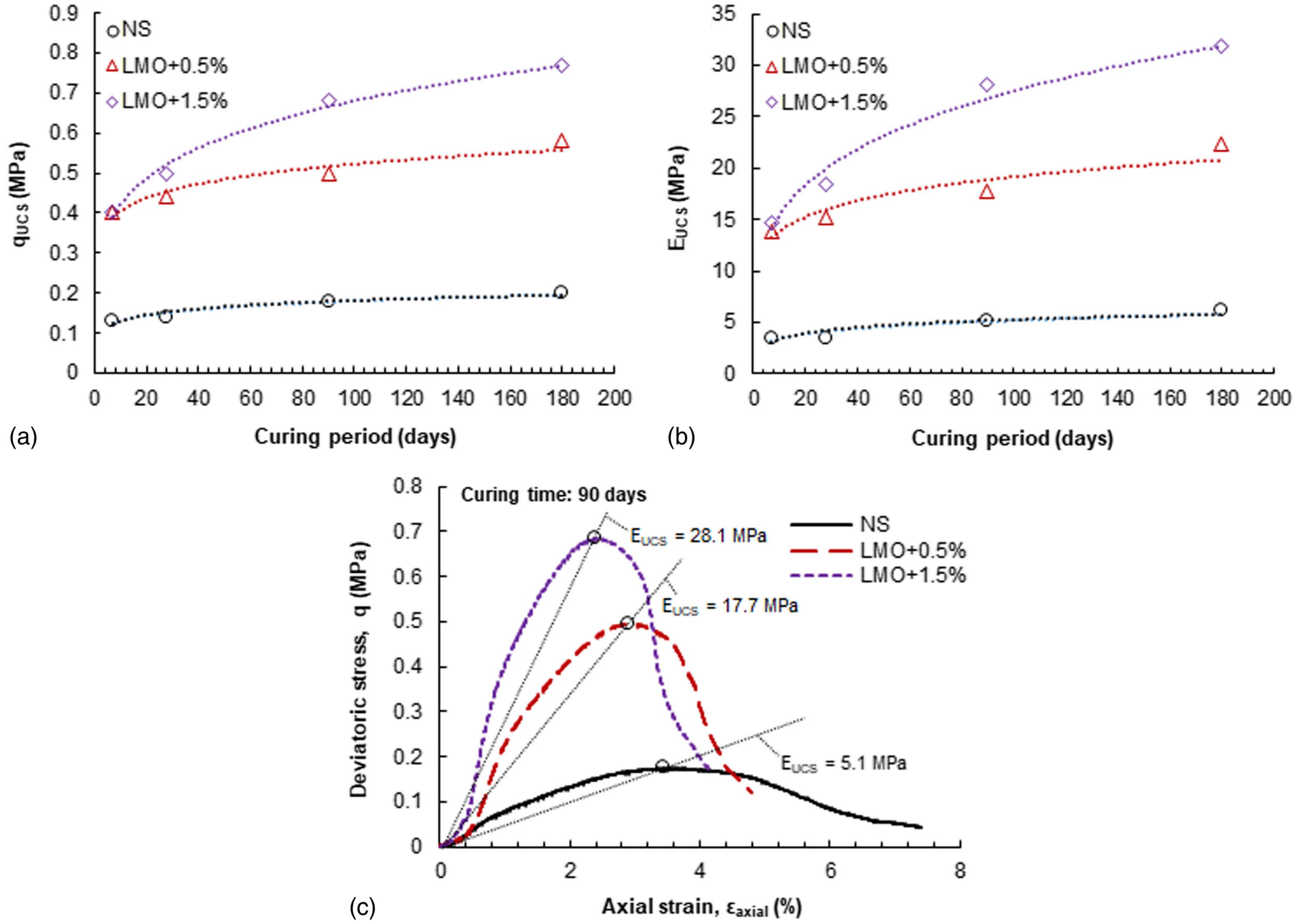
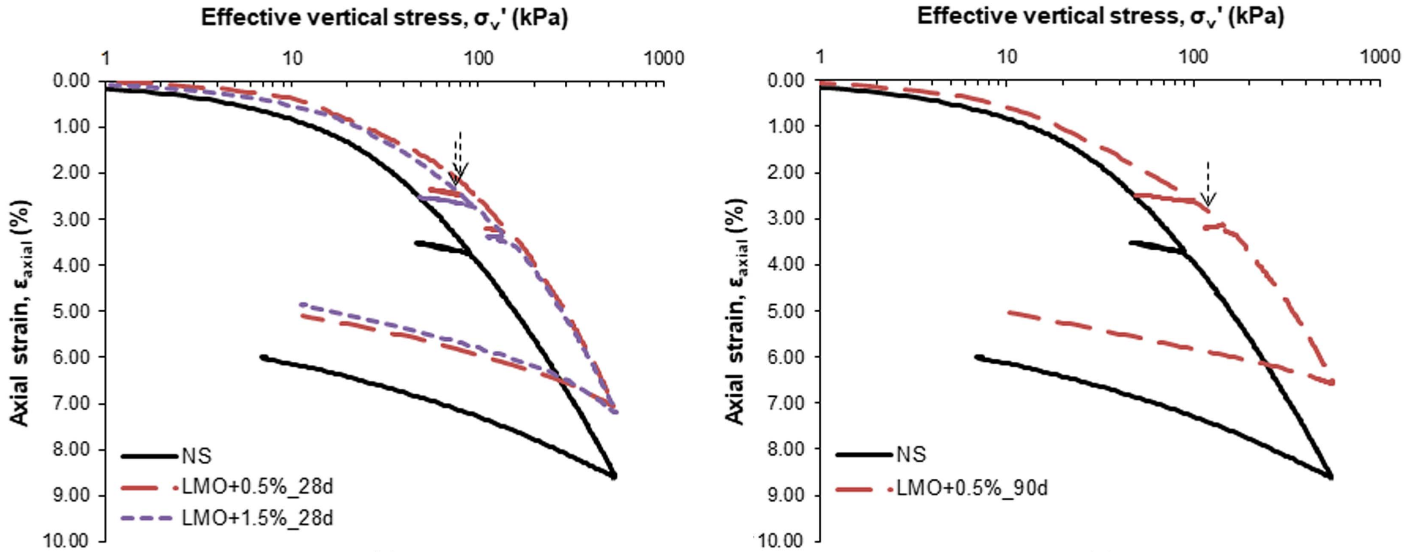


Fig. 2. Development of (a) unconfined compressive strength, q_{UCS}; (b) unconfined compressive elastic modulus, E_{UCS}, with curing period; and (c) cured stress-strain curves for unconfined compression tests on 90-day untreated and lime-treated Warmenhuizen clay samples.



(a)

(b)

Fig. 3. Effect of lime on compression curves of untreated and lime-treated Warmenhuizen clay samples. K_0-CRS tests on samples cured for (a) 28; and (b) 90 days.

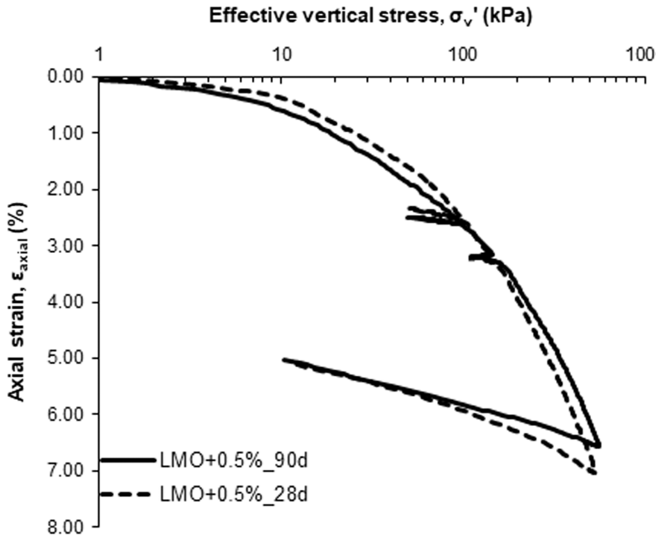


Fig. 4. Effect of curing period on compression curves of lime-treated Warmenhuizen clay samples cured for 28 and 90 days. K_0-CRS tests on LMO + 0.5% samples.

shown in Fig. 5. These figures demonstrate that, overall, the lime-treated samples underwent less compression than the natural soil sample. After a curing period of 28 days the axial strain at maximum loading of the untreated soil was reduced by approximately 20% upon the addition of LMO + 0.5% lime. Further increase in lime content from LMO + 0.5% to LMO + 1.5% and curing time from 28 days to 90 days did not alter the resistance to compression.

The consolidation data were analyzed further in terms of CR, RR, C_α, ν_{ur}, and K_0 parameters. The normal compression, CR, and recompression index, RR, were obtained from the slope of the loading and unloading σ'_v-$\varepsilon_{\text{axial}}$ curve, respectively. The secondary compression index, C_α, was deduced from the relaxation phase during which the vertical stress, σ'_v, reduced with time under constant strain according to the following equation, given by Den Haan and Kamao (2003):

$$\sigma'_v = \sigma'_{vR} \times \left(1 - \frac{CR - RR}{C_\alpha} \times \frac{\dot{\sigma}'_{vR}}{\sigma'_{vR}} \times t\right)^{\frac{-C_\alpha}{CR-RR}} \qquad (1)$$

where σ'_{vR} = vertical stress at the start of relaxation; and $\dot{\sigma}'_{vR}$ and t = relaxation rate and time, respectively. By calculating the CR and RR indices, the only unknown in Eq. (1) is C_α, which is found by best fitting of the stress and time data to the relaxation curves obtained from the CRS tests.

Poisson's ratio, ν_{ur}, which expresses the tendency of a material to expand in directions perpendicular to the direction of loading, is calculated as follows:

$$\frac{\nu_{ur}}{1 - \nu_{ur}} = \frac{\Delta\sigma'_h}{\Delta\sigma'_v} \qquad (2)$$

where $\Delta\sigma'_h$ and $\Delta\sigma'_v$ = change in effective horizontal and vertical stress that occurred during unloading–reloading part of test.

Both the normal compression, CR, and secondary compression index, C_α, reflecting the normally consolidated and time-dependent deformation of the soil samples, respectively, were not affected by the addition of lime or by changes in the curing period [Figs. 6(a and c)]. Regardless of lime content, the increase in curing time, however, acted beneficially in reducing the unloading/reloading stiffness and expansive potential of the samples, as illustrated in Figs. 6(b and d), respectively. These figures show the best-fit relationships between the parameters RR, ν_{ur}, and curing time.

As concluded by Mavroulidou et al. (2013a), Rao and Shivananda (2005), and Balasubramaniam et al. (1989), cation exchange reactions in lime-treated soils cause a chemically induced yield stress that is related to structure and bonding and not to stress history. Based on Casagrande's method, a yield stress (indicated by the arrows in Fig. 3) in the range of 70–120 kPa was determined for the lime-treated samples. In the preyield stress region (σ'_v < 120 kPa), the lime-treated samples showed an improved response to compression compared to the untreated sample. Loading in the postyield stress region might have resulted in a progressive destructuration of the sample and an increase in the compression potential (Rao and Shivananda 2005). This could explain the similar normal compression index values for the untreated and treated samples

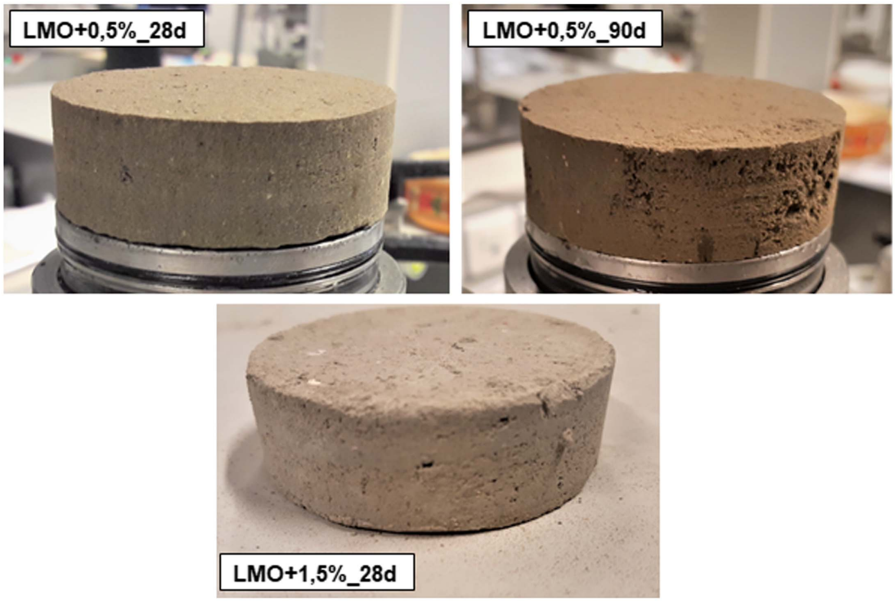


Fig. 5. Untreated and lime-treated Warmenhuizen clay samples prepared for K_0-CRS testing. Photos taken before testing for LMO + 0.5% and LMO + 1.5% samples cured for 28 and 90 days.

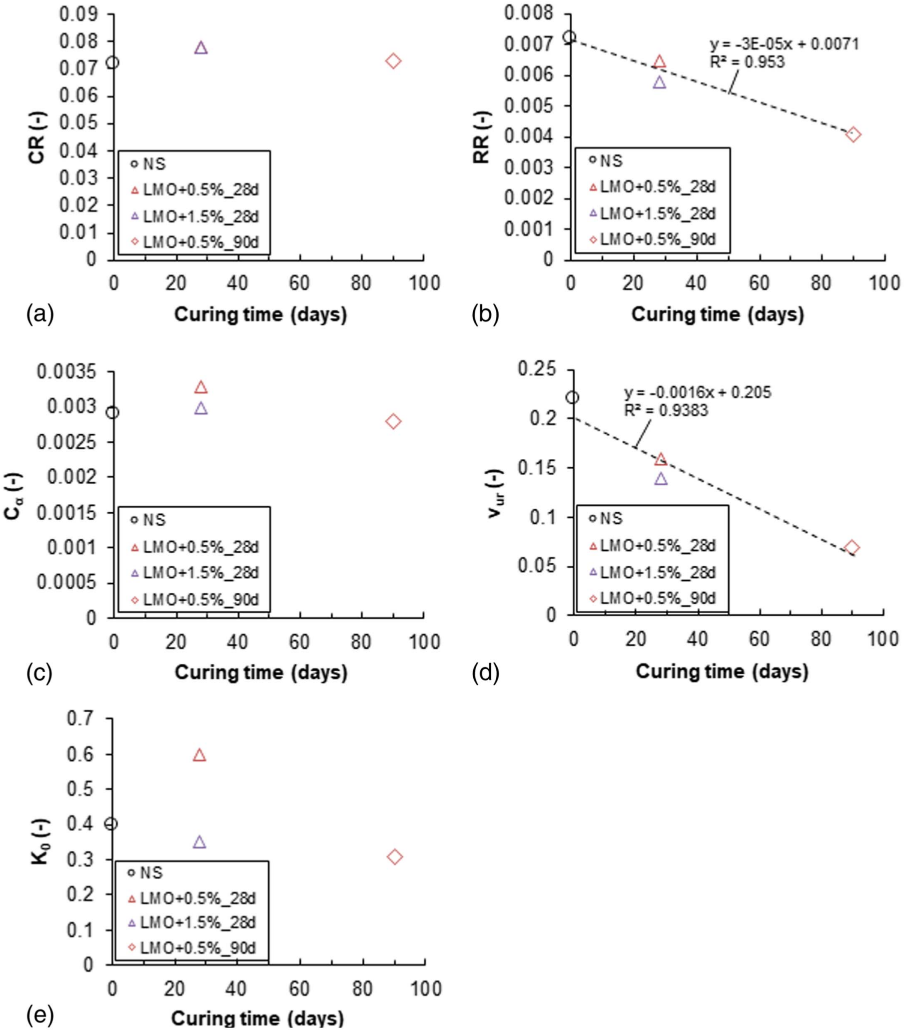


Fig. 6. CRS tests on untreated and lime-treated Warmenhuizen clay samples cured for 28 and 90 days. Variation of (a) normal compression index, CR; (b) recompression index, RR; (c) secondary compression index, C_α; (d) undrained Poisson's ratio, ν_{ur}; and (e) coefficient of earth pressure at rest, K_0; the circle dashed line indicates an outlying point excluded from analysis.

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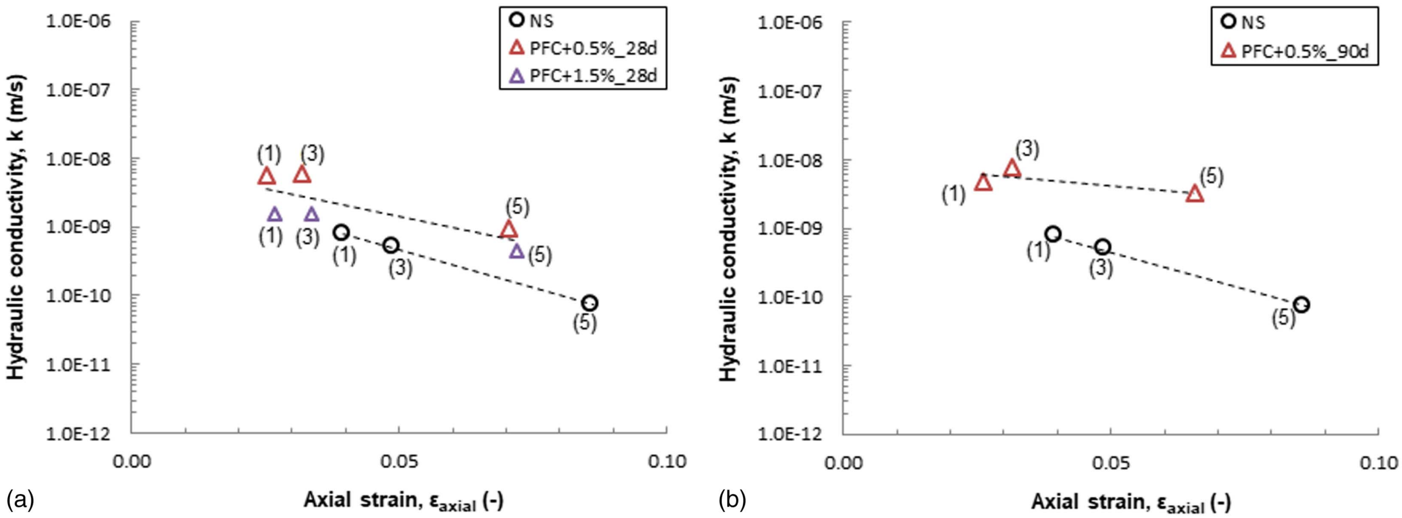


Fig. 7. Variation of hydraulic conductivity, k, with respect to axial strain, $\varepsilon_{\text{axial}}$, for untreated and lime-treated Warmenhuizen clay samples treated for (a) 28 days; and (b) 90 days.

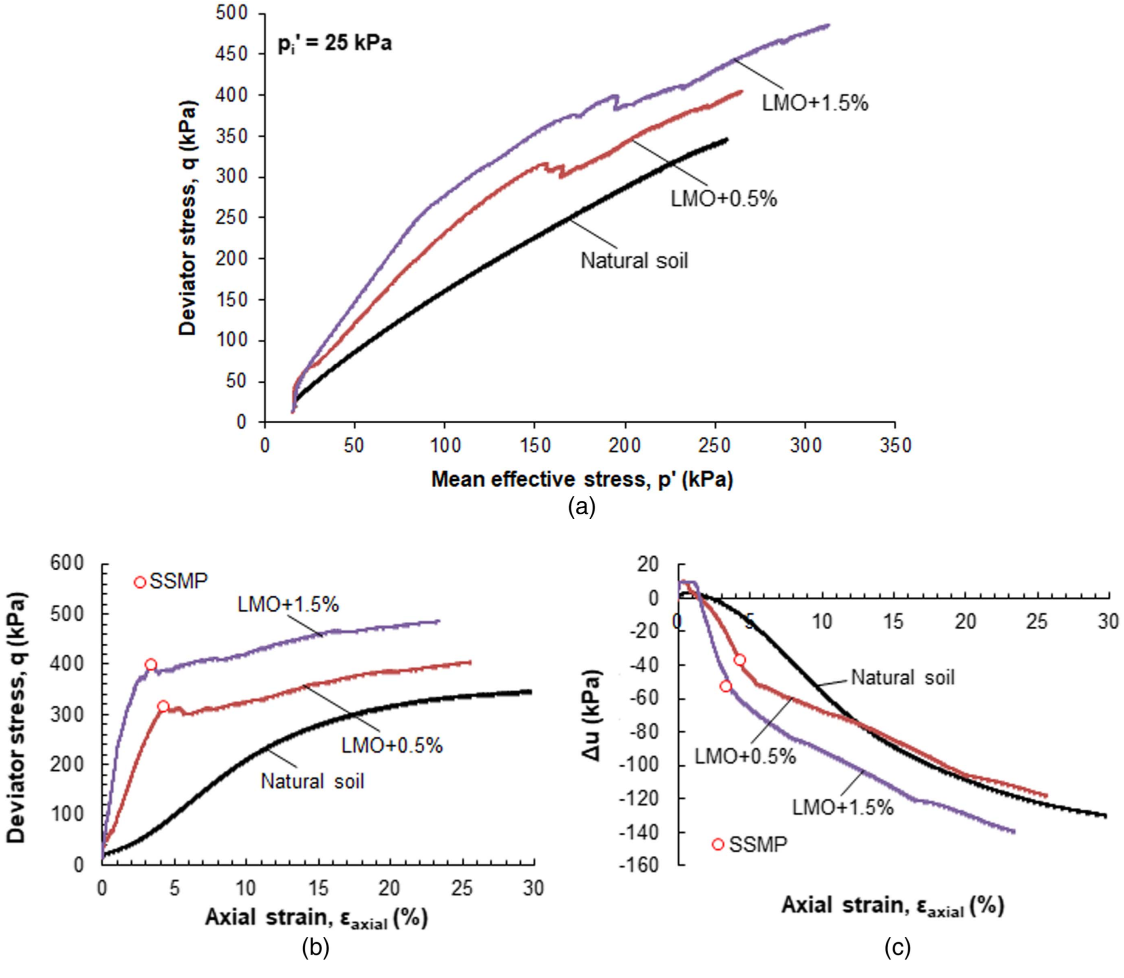


Fig. 8. Undrained triaxial compression tests on untreated and lime-treated Warmenhuizen clay samples at $p_i' = 25$ kPa: (a) effective stress paths; (b) stress-strain curves; and (c) excess pore-water pressure, Δu, against axial strain curves.

in Fig. 6(a) because these indexes were determined for the lime-treated samples at the part of the compression curve in excess of the yield stress ($\sigma_v' > 200$ kPa).

The normally consolidated coefficient of earth pressure at rest, K_0, expressing the ratio between the horizontal effective, σ_h', and vertical effective stress, σ_v', is presented in Fig. 6(e). With the exception of sample LMO + 0.5% cured at 28 days, the K_0 value for all tests had an average value of $K_0 = 0.4$.

The hydraulic conductivity, k, at any time during testing was calculated as follows:

$$k = \frac{\dot{\varepsilon} \cdot H \cdot H_0 \cdot \gamma_w}{2 \cdot \Delta u} \tag{3}$$

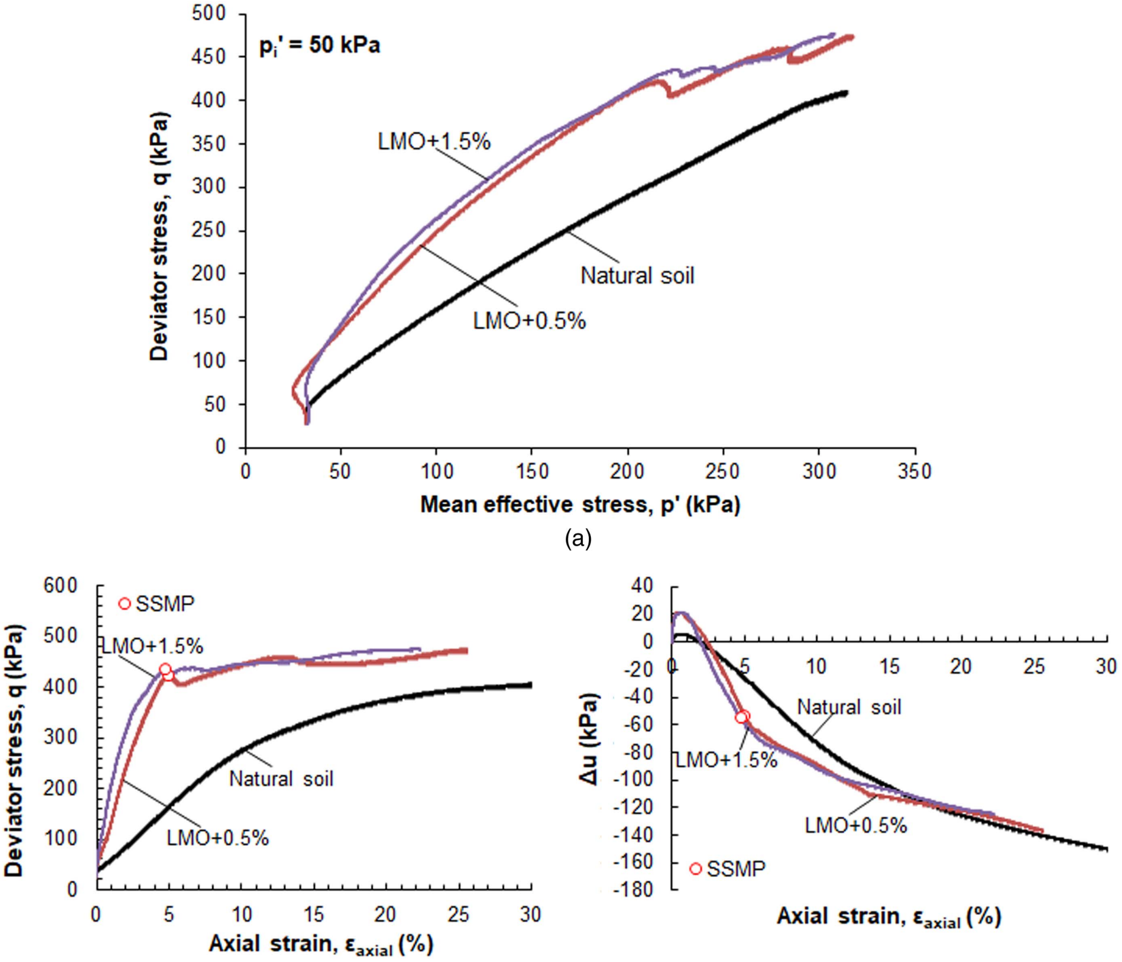
where $\dot{\varepsilon}$ = applied deformation rate; γ_w = unit weight of water at 20°C; H_0 = initial sample height; Δu = excess pressure; and H = sample height at time of assessment.

The hydraulic conductivity as calculated at the end of each loading step (Steps 1, 3, and 5) is plotted against axial strain for the 28- and 90-day treated samples in Figs. 7(a and b), respectively. Note that the hydraulic conductivity of the lime-treated soil was approximately an order of magnitude higher than that of the untreated soil. An increase in the permeability of the lime-treated soils has been reported in various studies (Nalbantoglu and Tuncer 2001; Brandl 1981; McCallister and Petry 1992) and is related to lime treatment–induced changes in soil fabric (Tran et al. 2014). As shown in Fig. 1(a), for grain sizes less than 30 μm, the particle size distribution curves of the lime-treated samples were skewed toward higher gradings, which explained to some extent the observed increase in their hydraulic conductivity measurements. It should be emphasized, however, that the measured permeabilities of the lime-treated samples varied between 10^{-8} and 10^{-9} m/s. According to the unified soil classification system [ASTM D2487-17 (ASTM 2017)], these low permeabilities indicate a rather impervious material.

Triaxial Tests

The responses of the untreated and lime-treated samples tested at the effective stress level of $p_i' = 25$ kPa are compared in Fig. 8. The stress paths are shown in Fig. 8(a), and the stress-strain and excess pore-water pressure against the strain curves are shown in Figs. 8(b and c), respectively. Similar figures are produced for the samples tested at $p_i' = 50$ kPa (Fig. 9) and at $p_i' = 75$ kPa (Fig. 10).

It can be observed from Figs. 8–10 that lime treatment modified the shearing behavior of the tested samples. For axial strains less than 10% the lime-treated samples showed a distinctively stiffer response to loading. At the beginning of shearing, the lime-treated samples showed a more contractive behavior compared to the natural soil samples, resulting in a higher development of excess pore-water pressure [Figs. 8(c), 9(c), and 10(c)]. After the change from contractant to dilatant response, the behavior reversed, with the treated samples showing for axial strains within a range 10% higher dilative tendencies than their untreated counterparts. At higher strains, the rate of increase in deviator stress with axial strain declined for the case of treated samples. The points marking the change in the rate of development of deviator stress are indicated by the open circles in Figs. 8(b), 9(b), and 10(b); the corresponding points on the excess pore-water pressure-strain curves are shown in Figs. 8(c), 9(c), and 10(c). These points will be referred to in this



(a)

(b)

(c)

Fig. 9. Undrained triaxial compression tests on untreated and lime-treated Warmenhuizen clay samples at $p_i' = 50$ kPa: (a) effective stress paths; (b) stress-strain curves; and (c) excess pore-water pressure, Δu, against axial strain curves.

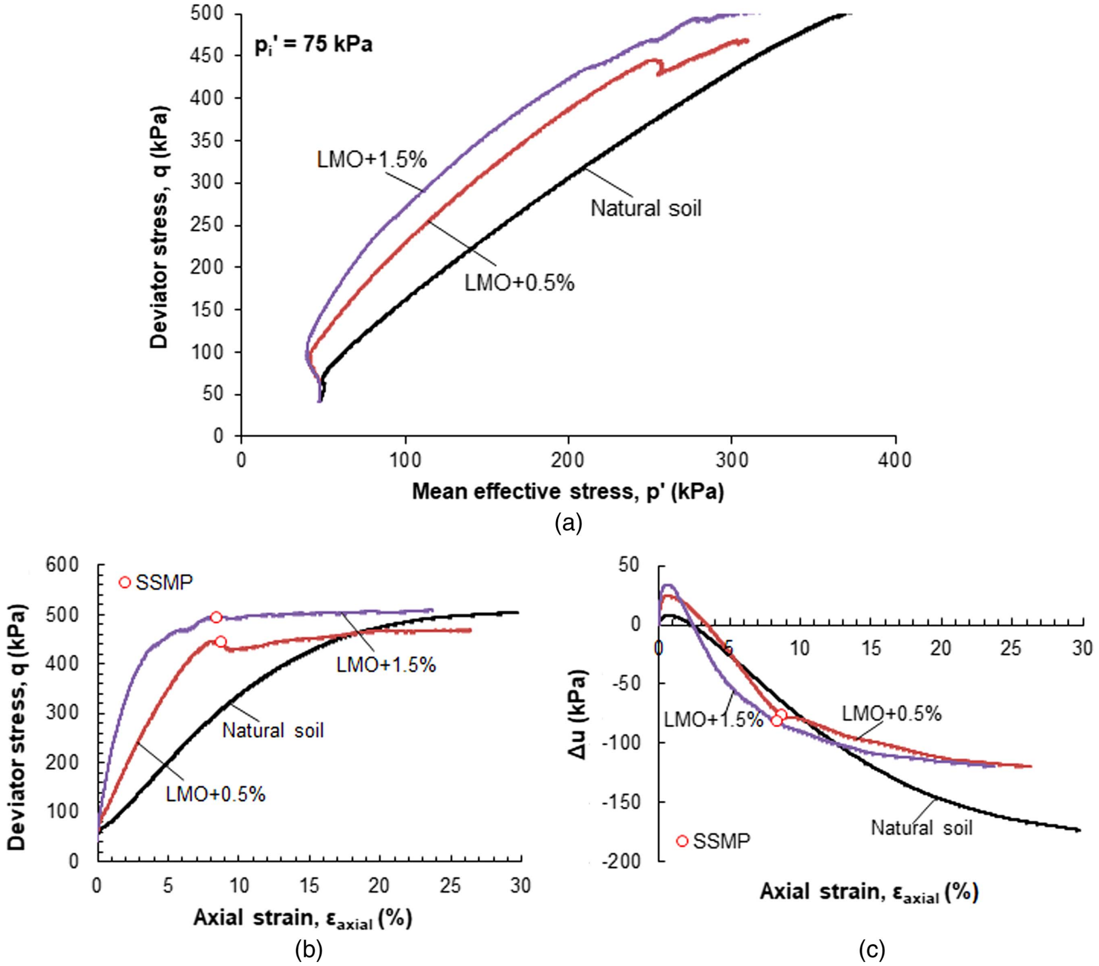


Fig. 10. Undrained triaxial compression tests on untreated and lime-treated Warmenhuizen clay samples at $p_i' = 75$ kPa: (a) effective stress paths; (b) stress-strain curves; and (c) excess pore-water pressure, Δu, against axial strain curves.

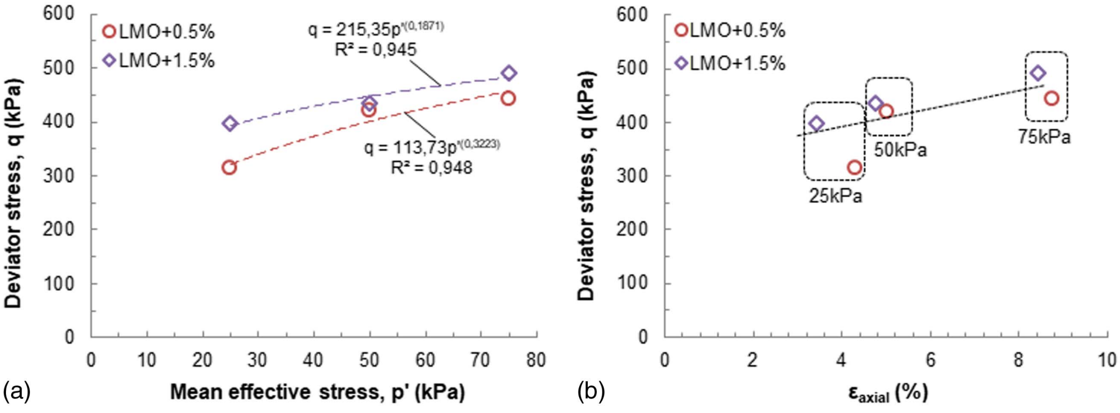


Fig. 11. Variation of deviator stress at stress-strain modification points, q_{SSMP}, with respect to (a) initial mean effective stress, p_i'; and (b) axial strain, $\varepsilon_{\mathrm{axial}}$, for LMO + 0.5% and LMO + 1.5% Warmenhuizen clay samples.

study as stress-strain modification points (SSMPs). It is interesting to note that after reaching these points, the deviator stress dropped slightly, indicating a brittle behavior of the tested samples. It is known in the literature that the chemical reactions in lime-treated soils are expected to produce a brittle material (Tuncer and Basma 1991; Mavroulidou et al. 2013b).

The deviator stress at the SSMPs, q, is plotted with respect to consolidation stress level, p_i', and axial strain, $\varepsilon_{\mathrm{axial}}$, in Figs. 11(a and b), respectively. It appears that q_{SSMP} increases with stress level and lime content. It is interesting to note, however, that the axial strain level required to reach the SSMPs receives for each consolidation stress approximately the same value irrespective of the

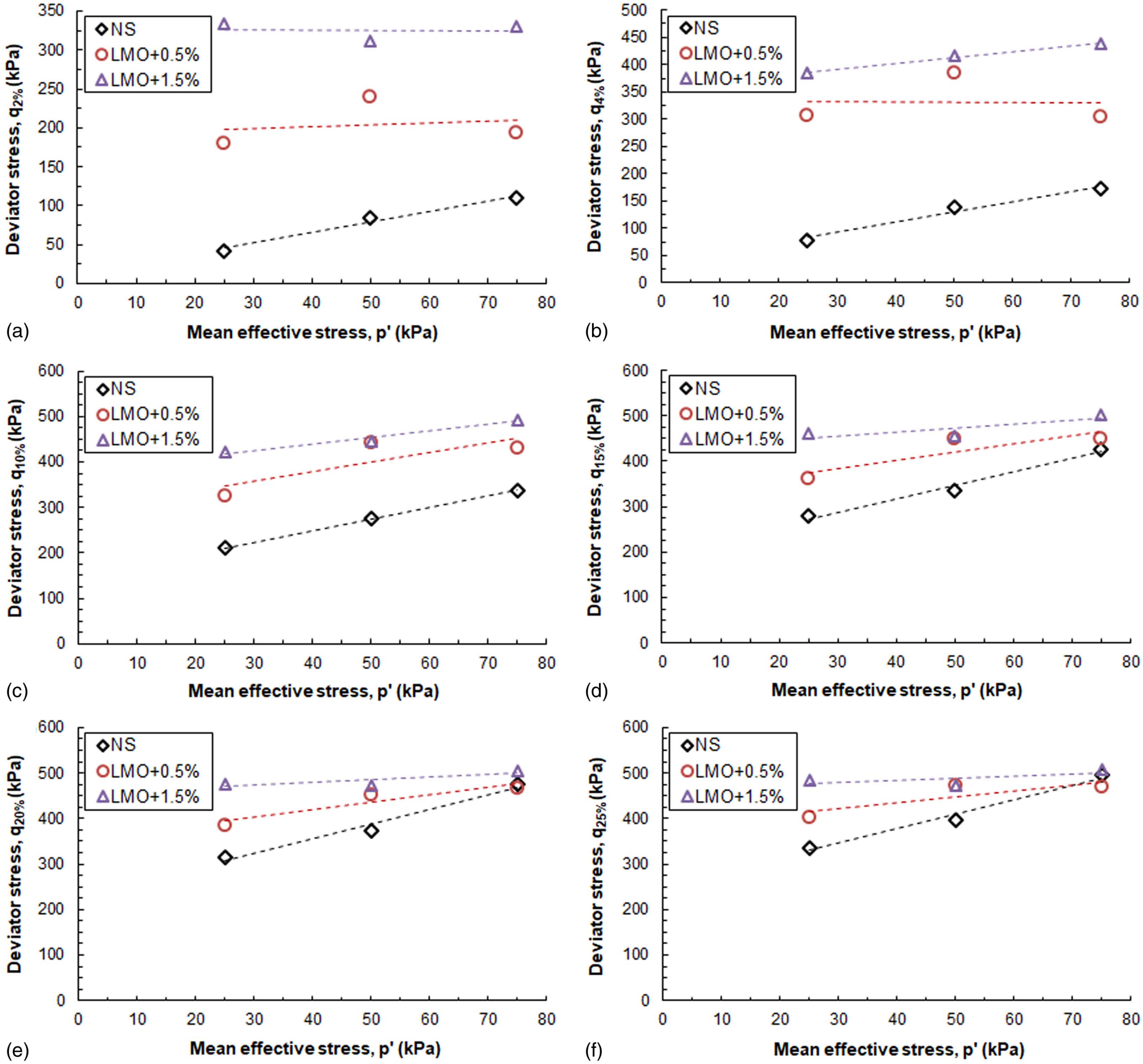


Fig. 12. Variation of deviator stress, q, at: (a) 2%; (b) 4%; (c) 10%; (d) 15%; (e) 20%; and (f) 25% axial strain with respect to initial mean effective stress, p_i'.

lime content. For the applied testing conditions, stress levels, and lime contents, the SSMPs are encountered within an axial strain range of $4\% < \varepsilon_{\text{axial}} < 10\%$.

The effect of lime treatment on the stress-strain response to shearing is clearly shown in Fig. 12, where the deviator stress developed at various strain levels ($\varepsilon_{\text{axial}} = 2\%$, 4%, 10%, 15%, and 25%) is plotted with respect to the mean effective stress, p_i', for all sets of tests. The lime-treated samples showed overall a higher deviator stress compared to the untreated samples, at least for the lime contents, consolidation stress, and strain levels examined in this study. It should be emphasized, however, that the gain in strength due to lime treatment became less prominent as the strain level increases. It is remarkable that the deviator stress of the treated and untreated samples coincided at a strain level of $\varepsilon_{\text{axial}} = 25\%$ and $p_i' = 75$ kPa. It should also be noted that an increase in deviator stress with stress level was evidenced in all test series, it was, however, more pronounced for the case of untreated samples.

The increase in the deviator stress of the lime-treated samples relative to the untreated ones, Δq, is expressed for a given strain level as follows:

$$\Delta q(\%) = \left(\frac{q_{\text{lime-treated}} - q_{\text{untreated}}}{q_{\text{untreated}}}\right) \times 100 \qquad (4)$$

Using Eq. (4), the Δq values were calculated at strain levels of 2%, 4%, 10%, 15%, and 25% and are plotted for the LMO + 0.5% and LMO + 1.5% samples in Figs. 13(a and b), respectively. Fig. 13 illustrates that lime treatment was predominantly beneficial at lower strains and lower effective stress levels. The notable

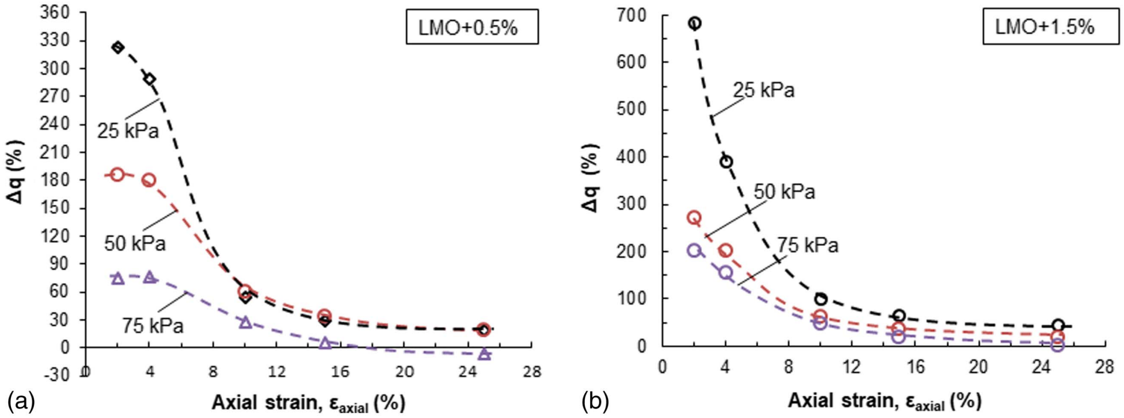


Fig. 13. Percentage increase in deviator stress due to lime treatment for different effective stress and axial strain levels. Triaxial compression tests on (a) LMO + 0.5%; and (b) LMO + 1.5% Warmenhuizen clay samples.

reduction in Δq for axial strains, $\varepsilon_{\text{axial}} < 10\%$, was associated with the presence of the SSMPs, possibly indicating a change in the state of the cohesive bonds of the lime-treated samples.

For each test series (natural soil, LMO + 0.5%, LMO + 1.5%) the best-fit lines were drawn through the effective stress state points in the q–p' plane for which $\varepsilon_{\text{axial}} = 2\%, 4\%, 10\%, 15\%$, and 25%. The mobilized friction, φ', and mobilized cohesion, c', were determined at different axial strain levels from the slope and intercept of these lines, given as follows by Eqs. (5) and (6), and are plotted for comparison in Fig. 14:

$$\phi' = \sin^{-1}\left(\frac{3m}{6+m}\right) \tag{5}$$

$$c' = \frac{(\alpha \tan \phi')}{m} \tag{6}$$

where m = gradient of slope (q/p') at designated axial strain level; and $\alpha = y$-intercept.

Fig. 14 shows a strain-level dependency of the mobilized friction angle and cohesion, which can be directly linked to the presence of SSMPs. For axial strains lower than the axial strain corresponding to the SSMPs, lime treatment resulted in higher cohesion and internal friction angles. In contrast, upon exceeding the SSMP axial strain level, the cohesion and friction angle sharply decreased to a constant value irrespective of strain-level considerations. It should be nevertheless highlighted that, despite the significant loss in cohesion of the lime-treated samples, their residual cohesion value remained higher than that of the untreated samples.

The deformation shape of the samples at the end of shearing is shown in Fig. 15. As can be seen in this figure, the natural soil samples failed in a bulging mode, whereas shear planes developed for the treated samples whose presence was more dominant as lime content increased; for the LMO + 0.5% samples, two shear planes cut through the sample crossing each other, whereas for the LMO + 1.5% samples, several failure planes formed.

The authors speculate that the SSMPs were associated with the breakage of the cementitious bonds within the sample. Cementitious bonding products form as a result of pozzolanic reactions. Various authors have argued that these reactions occur over long time scales (months to years) and can therefore be considered as long–term reactions (Boardman et al. 2001; Nicholson 2015; Sargent 2015). Mineralogical, microstructural, and compositional analyses, which could verify the formation of cementitious compounds, were not performed in this study. It is thus fair to acknowledge that the response of lime-treated samples to shearing might also be associated with the geomechanical changes in the material caused by short-term reaction mechanisms, such as hydration, cation exchange, and flocculation/agglomeration of clay minerals.

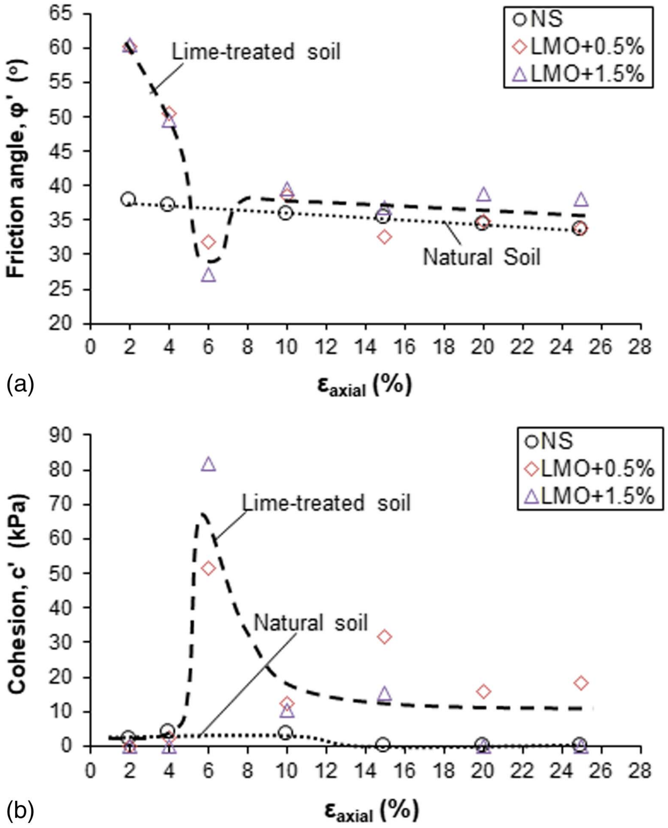


Fig. 14. Variation of mobilized: (a) friction angle, φ'; and (b) cohesion, c', against axial strain, $\varepsilon_{\text{axial}}$.

HET Tests

Fig. 16 shows the relationship between the erosion rate and the shear stress for the tested samples at different lime contents and curing periods. Fig. 16 is divided into erosion categories, as proposed

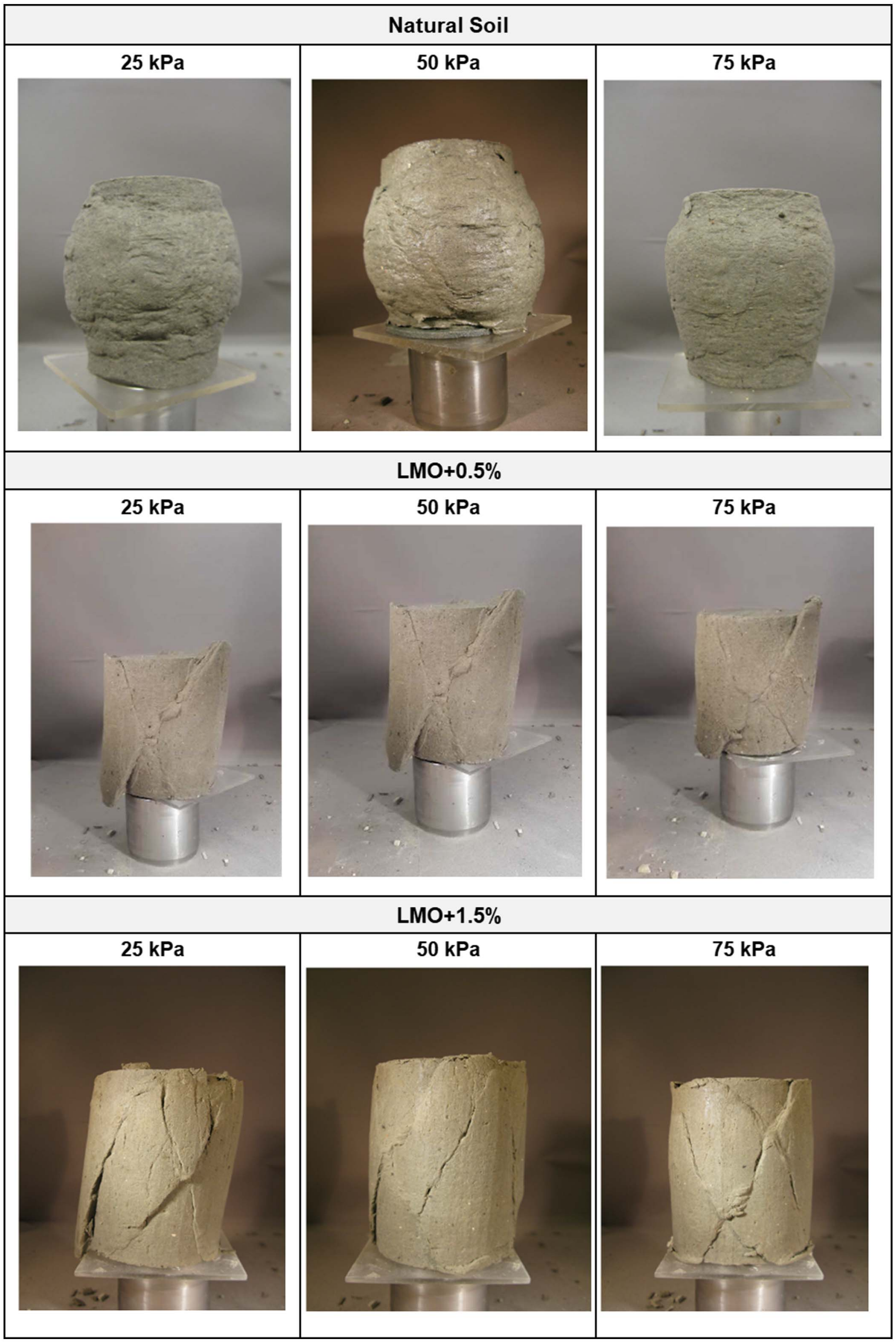


Fig. 15. Deformation pattern of untreated and lime-treated Warmenhuizen clay samples after undrained triaxial compression testing at different initial mean effective stress levels.

by Briaud et al. (2017). These categories were developed on the basis of erosion test data and the experience of the authors and provide practicing engineers with a first-order estimate of the erodibility of the soils.

The erosion curves of the natural and lime-treated soils clearly differentiated. With lime addition the soil moved from the medium erodibility to the low erodibility class. The impact of curing time and lime content on the evolution of the erosion curves was limited. Nevertheless, irrespective of curing time and lime content, the resistance to erosion of the treated soil was significantly improved; for a given erosion rate, shear stress on the order of five times higher than that of the natural soil was recorded. These results are promising for applications of lime-treated soils in dike construction. It should be highlighted that HET tests are mainly designed for assessing the internal erosion resistance of soils. To a certain extent, however, the HET tests also provide useful insights into behavior with respect to external (surface) erosion. In any case, site-specific erosion testing that accounts for differences in the nature of a hydraulic attack on an eroding surface remains the best practice.

Discussion

Clay is traditionally used in the Netherlands as construction material for dikes, provided that the material meets the prevailing

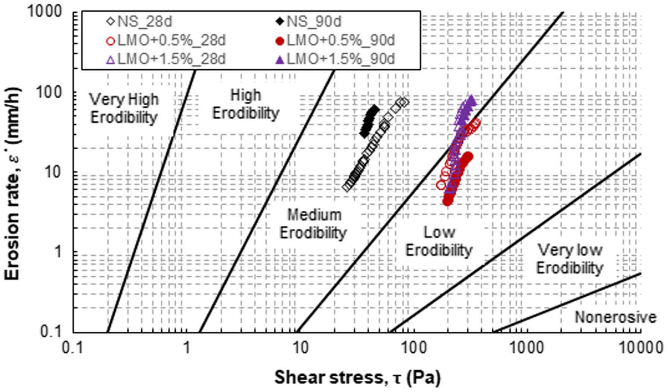


Fig. 16. Erosion rate, $\dot{\varepsilon}$, against shear stress, τ, for untreated and lime-treated Warmenhuizen clay samples after 28 and 90 curing days.

quality requirements reported in RAW (2015). The soil parameters of the natural and lime-treated soil from this study are presented in Table 3 in the context of the RAW (2015) requirements. According to this table the natural soil is classified as unsuitable for use in dikes. The addition of lime led to improvements in the shear strength, compressibility, and erosion resistance properties of the tested poor-quality clay. Considering these results, lime treatment can be justly considered a technique whose application in the dike industry is well worth investigating.

It is important to stress that the quality requirements reported in RAW (2015) are applicable only to cases involving natural materials. Lime-treated soils undergo substantial textural and property changes as a result of the chemical reactions that occur between the lime and the soil. Consequently, evaluation of the suitability of a treated clay for use in dike applications based on criteria intended for natural soils is inappropriate and could steer one toward

Table 3. Soil parameter requirements for material use in dikes in the Netherlands: a comparison with soil properties of tested natural and lime-treated clay

Soil parameter	Requirements for material use in dikes	Tested natural clay	Tested lime-treated clay
1. Sand content (>63 μm)	≤40% (WBI 2017)[a]	~10%	~10%
2. Plasticity index (PI)	≥18% and >0.73 × ($W_L - 20$) (WBI 2017)[a]	PI = 13	15 (0.75% of Proviacal DD) 14 (1.25% of Proviacal DD) 13 (2.25% of Proviacal DD)
3. Liquid limit (W_L)	≥40% (WBI 2017)[a]	31	34 (0.75% of Proviacal DD) 33 (1.25% of Proviacal DD) 35 (2.25% of Proviacal DD)
4. Consistency index (I_c)	≥0.75; revetment material (TAW 1996)[a] ≥0.60; core material (TAW 1996)[a]	1.02[b]	1.08 (0.75% of Proviacal DD)[b] 1.09 (1.25% of Proviacal DD)[b] 1.32 (2.25% of Proviacal DD)[b]
5. Organic content	<5% by weight	3.0%–4.2%	No data available
6. Salinity (NaCl g/L water)	<4%	No data available	No data available
7. Shear strength	After compaction the dry density must be at least 97% of the Proctor density at the present water content of the soil[c]	See remarks for the tested lime-treated clay	The unconfined compressive strength (UCS) of the lime-treated samples is higher by approximately a factor of two compared to the natural soil. The difference increases as the percentage of lime and curing time increases. Triaxial compression tests have shown that the use of lime is predominantly beneficial at low axial strains (<10%) and at low effective stress levels (25–50 kPa).
8. Permeability	As above	As above	The permeability of the lime-treated material, although higher than that of the natural material, remains very low, on the order of 10^{-8} m/s (cf. 10^{-9} m/s) (natural material).
9. Stiffness	As above	As above	The elastic modulus of the lime-treated samples as defined from UCS tests is higher by approximately a factor of four compared to the natural soil. The difference increases as the percentage of lime and curing time increases.
10. Compressibility	As above	As above	The lime treatment has a favorable effect on the compressibility of the material, which is reduced compared to that of the untreated material.
11. Erosion resistance	If requirements (1) + (2) + (3) + (4) + (5) + (6) are fulfilled, the material is classified as erosion resistant (WBI 2017)		Via the performance of hole erosion tests the resistance to erosion was found to significantly increase with lime addition.

[a] The requirement is applicable only for the case of natural material. In the case of lime-treated material, it is to be expected that this requirement might not be applicable.

[b] After the material is reconstituted and recompacted under a water content on the so-called wet side of the Proctor curve.

[c] It is considered that fulfillment of this requirement will ensure that the shear strength, permeability, stiffness, and compressibility properties of the soil will be adequate for the material to be used in dikes, provided that the material also fulfills Requirements (1)–(6).

misleading conclusions. This necessitates the need to establish regulations that comply with the use of lime in the treatment of natural soils.

Although not limitative, one of the promising applications of lime treatment is in enhancing the external erosion resistance of the inner slope of dikes. Crest height in the Netherlands is raised such that overtopping rates exceeding 0.1 L/s/m would have a probability of occurrence not greater than 1/10,000 per year. Raising the crest height brings additional spatial and cost demands. Furthermore, in the light of climate change, higher water levels and wave heights are expected in the future, and greater crest heights will be required to reduce the probability of overtopping to acceptable limits. The HET tests in this study showed that the erosion resistance of lime-treated clay was significantly improved. Hence, the use of a lime-treated cover layer will likely reduce the erodibility of soil, allowing a higher volume of overtopping water and, thus, lower crest heights.

Despite promising results, lime treatment is currently rarely used in dike applications in Europe. One of the main drawbacks of lime treatment might be the absence in practice of guidelines as to what may be regarded as new material. Existing guidelines are suitable only for natural soil deposits, not for clay with additives.

A first step in formulating procedures and design guidelines (methods) for the practical application of lime treatment on dikes is to upgrade from small-scale laboratory testing to large-scale, prototype testing in the field. In this connection, a full-scale dike experiment is planned for 2021 on a section of the primary dike directly beneath the Dutch–Belgian border. This field test, sponsored by the Dutch Flood Protection program (HWBP), aims at (1) quantifying the erosion resistance of a lime-treated cover layer present in the inner slope of the dike using an overtopping simulator; and (2) setting up a design method for further applications of lime treatment in dikes as an erosion resistance–enhancing measure.

Conclusions

In this study, the effect of lime treatment on the geotechnical properties of a Dutch clay was thoroughly investigated via the performance of various types of tests. As far as the authors know, limited studies are available that incorporate a diverse testing program and analysis of results for the assessment of lime treatment technique on natural clays. In addition, the suitability of this technique in dike applications in the Netherlands has not been addressed in the literature to date. The results obtained show that the addition of lime has a favorable effect on the compressibility, UCS, and volume stability of a material. Lime treatment changed the stress paths of samples during triaxial testing. Overall, the shear strength, effective friction angle, and cohesion increased with lime percentage. The rate of increase for the lime-treated samples compared to their natural counterparts was found to be stress-strain dependent. In addition, lime treatment does not seem to have a significant impact on permeability, which remained low for all tested samples. In contrast, lime treatment is particularly effective at improving the erosion resistance of a material.

From an experimental viewpoint, the findings of this study confirm the efficacy of lime treatment for clays with organic content on the order of 3%–4% and support the use of lime treatment in dike upgrades, primarily as a countermeasure against erosion.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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