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LIME TREATMENT: EFFECTS ON EROSION RESISTANCE AND AGING OF CLAY FOR DIKES

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ABSTRACT

This research focuses on the behavior of lime-treated clay, using low lime contents ranging from 0.5% to 4%, to determine its impact on erosion resistance and aging. A series of laboratory tests, including index classification, Mini Jet Erosion Tests (Mini-JET), Pulse Erosion Tests (PET), and shrinkage tests, were conducted on clay from the Waalbanddijk Neder-Betuwe dike reinforcement project in Gelderland, The Netherlands. The results show that lime treatment reduces the water content, decreases the Plasticity Index (PI), and improves the workability of the clay. Lime treatment also increases the shrinkage limit, reducing volume changes and resulting cracks. Improvements in erosion resistance and aging were already observed with 0.5% lime addition however, significant enhancements were noted increasing the lime addition to 2%. The findings of this study show that lime treatment can help ensure dikes meet safety standards.

Keywords: lime treatment, erosion resistance, mini jet erosion test, pulse erosion test.

INTRODUCTION

Lime treatment is a certified and widely used technique for soil improvement and stabilization within road engineering projects (Konstantinou & Hoffmans, 2018). Soil treatment with lime has a long history of use, dating back to the Romans and the Chinese, who employed it in the construction of works that are still visible today, such as the Great Wall of China (Herrier, et al., 2019).

When lime is added to cohesive soils, it typically results in a decrease in plasticity, an increase in pH, and volume stability against swelling and shrinkage (Konstadinou, et al., 2023). Over the long-term, lime treatment increases the mechanical performance of clayey soils (Herrier, et al., 2018). The process of lime reacting with soils can be described through a series of chemical reactions. One important reaction that leads to the hardening of soil-lime mixtures is the pozzolanic reaction between lime and clay particles. The lime modification optimum (LMO) is the specific amount of lime needed to trigger this pozzolanic reaction (Eades and Grim, 1966; BRRC and EuLA, 2021).

Despite its proven benefits in various applications, the principles of lime treatment for hydraulic earthen structures in the Netherlands remains barely applied. The Netherlands is globally known for its water management and the crucial role that dikes play within the flood defence system. The country has a network of nearly 17,000 kilometres of dikes and dams. Since a quarter of the country lies below sea level and one-third is prone to river flooding, the state has established safety standards for the water barriers. Due to climate change, Dutch rivers are required to manage increased water volumes, and many dikes are currently unprepared for this, failing to meet safety standards, and will require reinforcement. One of these dikes is the Waalbanddijk Neder-Betuwe in the Netherlands. Lime treatment can be seen as an innovative approach to upgrading dikes in the Netherlands, offering significant benefits in terms of cost, environmental impact, and time efficiency (Konstadinou, et al., 2023). Dutch regulations for dikes classify clays in three categories: Erosion Categories (EC) 1 to 3. These categories are based on the Atterberg limits and other soil parameters. EC 1 and EC 2 are erosion-resistant clays and suitable to be used for the entire dike structure, while EC 3 clays are only suitable for the core. However, EC 1 and EC 2 clays are scarcer and more expensive. This research aims to determine if EC 3 clays can be upgraded to be as workable and erosion resistant as EC 1, potentially reducing the costs of dike reinforcement projects.

MATERIALS AND SAMPLE PREPARATION

The soil used in this study was a clay sampled from multiple areas around the Waalbanddijk Neder-Betuwe dike and Maurik, the Netherlands, where both EC 1 and EC 3 clays were collected. Table 1 shows the Atterberg limits of natural clay EC 1 and natural (untreated) and lime treated clay EC 3.

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Table 1 Summary of Atterberg limits natural and lime (CaO) treated clays

Sample	LL [%)]	PL [%]	PI [%]
EC1	85	33	52
EC3 + 0% CaO	39	21	18
EC3 + 0.5% CaO	42	25	17
EC3 + 2% CaO	44	29	15
EC3 + 4% CaO	45	29	16

A representative sample of EC 3 clay was treated with different percentages of lime: 0%, 0.5%, 2%, and 4%. After mixing soil and lime, the samples were produced in Proctor molds and compacted with the Proctor density, representative of compacted clay in a dike. For the erosion tests, untreated EC 1 clay, untreated EC 3 clay, and treated EC 3 clay were used. The curing time of the samples, i.e., how long they were allowed to cure after preparation, was also varied between 7 and 14 days for the Neder-Betuwe samples. All samples were tested in duplicate to eliminate random variations in the results.

The quicklime used in this study was a CL 90-Q with more than 88% of free lime, provided by Lhoist SA. This is the highest and purest category of quicklime, and its high purity and reactivity ensure an efficient chemical reaction between the clay and lime particles (NEN-EN-459-1, 2015a).

TEST METHODS

Mini jet erosion test

The Mini-JET was developed by Prof. Al-Madhhachi in 2013 (Al- Madhhachi, 2013). In the Mini-JET, a submerged soil sample is subject to a vertically directed jet stream for a period of 15 to 90 minutes, causing erosion. At various time intervals, the depth of the erosion hole is measured, allowing the erodibility of the sample to be determined. The key parameters determined through the Mini-JET are the cricital shear stress and the erosion coefficient. It is important to note that the shear stresses in this test are not measured directly but are deduced through correlations between measured parameters and their relationships.

The basic equation for the erosion rate (Hanson and Cook, 1997) is as follows:

$$\varepsilon = k_d * (\tau - \tau_c) \tag{1}$$

Figure 1 presents a schematic diagram of the JET erosion setup. In this setup, Hanson and Cook (1997) demonstrated that the critical stress of circular flow can be determined using Equations 2 through 5.

$$\tau = \tau_0 \left(\frac{J_p}{J} \right)^2 \tag{2}$$

$$J_p = C_d d_0 \tag{3}$$

$$\tau_0 = C_f \rho_w U_0^2 \tag{4}$$

$$U_0 = C\sqrt{2gh} \tag{5}$$

Where τ = the applied stress (Pa); τ_0 = the maximum stress within potential core (Pa); J_p= the potential core length (m); J= the equilibrium depth (m); C_d = diffusion constant; d_0= nozzle diameter (m); C_f = friction coefficient; ρ_w = fluid density (kg/m³); U_0^2 = velocity at the jet nozzle (m/s); C = discharge coefficient; g= gravity (m/s²); h= differential head (m) (Wahl, 2016).

To correlate the results of the Mini-JET with those of an original JET, the Mini-JET constant (Cje) is applied. Here, the equilibrium depth or scour is multiplied by this constant. Thus, the formula for the critical shear stress of the Mini-JET is as follows:

$$\tau_c = \tau_0 \left(\frac{J_p}{C_{je} * J} \right)^2 \tag{6}$$

Where τ_c = the cricital shear stress (Pa); C_{je} = the mini-JET coefficient.

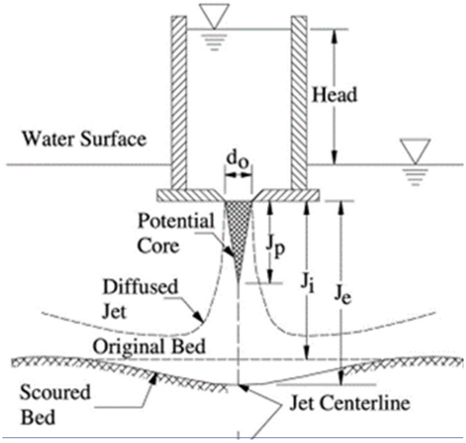

Figure 1 *Schematic diagram of JET erosion setup (Hanson, 1991)*

Pulse erosion test

Prof. J.L. Briaud (Briaud, et al., 2012) developed the Pocket Erodometer Test (PET). This small-scale erosion test involves shooting a standardized water gun at a soil sample and measuring the depth of the scour hole (figure 2). Based on the measured depth, an indication of the erosion category of the soil sample can be given, as shown in Figure 3. The patented Pulse Erosion Test (PET) was developed by Fugro and is procedurally similar to the Pocket Erodometer Test. In the test, an electronically driven device generates pulses automatically, improving repeatability and accuracy, as the method of the Pocket Erodometer can cause variations in the speed of the water jet (Van der Werff, 2023).

Figure 2 *Pocket Erodometer Test procedure (Rahimnejad, 2016)*

The Pulse Erosion Test can be conducted both in the field and in the laboratory. During the test, twenty pulses are generated from a distance of 50 mm at a velocity of 8 m/s. This procedure is repeated three times, and the average value of the three resulting scoured holes is recorded.

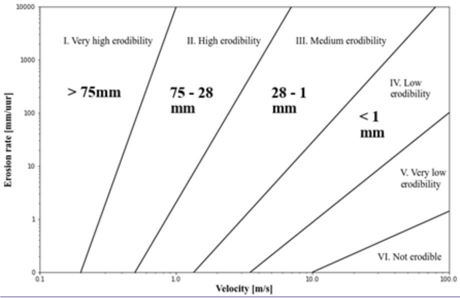

Figure 3 *PET erosion depth ranges and the corresponding erosion categories (Briaud, 2012 and Rahimnejad, 2016)*

Shrinkage test

Two parameters that are important for assessing the aging of clays are the shrinkage limit and the shrinkage ratio. These two parameters can be determined according to ASTM-D4943-18 test: Standard Method for Shrinkage Factors of Cohesive Soils by the Water Submersion Method. The water content of the sample is adjusted so that the created groove closes after approximately 10 blows in the Casagrande apparatus. The shrinkage limit refers to the water content at which the transition of the soil state from a semi-solid to solid occurs. Beyond this water content, there is no further volume reduction. The shrinkage limit is calculated as follows:

$$SL = w - \left[\frac{(V - V_d)\rho_w}{m_s}\right] \times 100 \qquad (7)$$

Where SL = the shrinkage limit (%); w = the water content (%); V = the volume of the wet sample (cm^3); V_d= the volume of the dry sample (cm^3); ρ_w = the density of water (g/cm^3); m_s = the mass of the dry sample (g). The shrinkage ratio is defined as the percentage shrinkage with a 1% reduction in water content in the shrinkage zone (Raedschelders, 1987). Thus, the shrinkage ratio describes the volume change due to the variation in water content and is calculated as follows:

$$R = \frac{m_s}{(V_d \times \rho_w)} \qquad (8)$$

Where R = is the shrinkage ratio (%). A lower value of R is desirable to prevent forming cracks in the clay by desiccation.

RESULTS

Soil parameters

When lime is added to the soil, the water content reduces (known as drying effect). This reduction is almost as large as the percentage of lime that is added to the soil, as shown in Table 2.

Table 2 *Lime treatment and water content*

Sample	Water content [%)]
EC3 + 0% CaO	31.4
EC3 + 0.5% CaO	30.7
EC3 + 2% CaO	29.2
EC3 + 4% CaO	28.4
EC3 + 4% CaO	45

Lime treatment further increases the plastic limit and, to a lesser extent, the liquid limit. This results in a decrease in the plasticity index, as shown earlier in Table 1. All these changes have an influence on the consistency index (CI), calculated by dividing the difference between the natural moisture content and the liquid limit and by the plasticity index (PI). It can be considered as an indication of the relative shear strength: when CI increases, so does the soil's compactness. For Dutch dikes the outer layer needs to have a CI of 0.75 or higher and for the core a value of CI = 0.60 or higher (TAW, 1996). Table 3 shows the results of lime treatment on the CI of the tested clay.

Table 3 *Lime treatment and consistency index*

Sample	Consistency index CI (%)
EC3 + 0% CaO	0.41
EC3 + 0.5% CaO	0.66
EC3 + 2% CaO	0.96
EC3 + 4% CaO	1.06

Mini jet erosion test

Almost all of the erosion parameters of lime-treated soil samples follow the trend: an increase in critical shear stress and a decreasing erosion coefficient. The erosion coefficient decreases by a factor of two and in some cases by a factor of six, indicating a lower erodibility. This is shown in Figure 4.

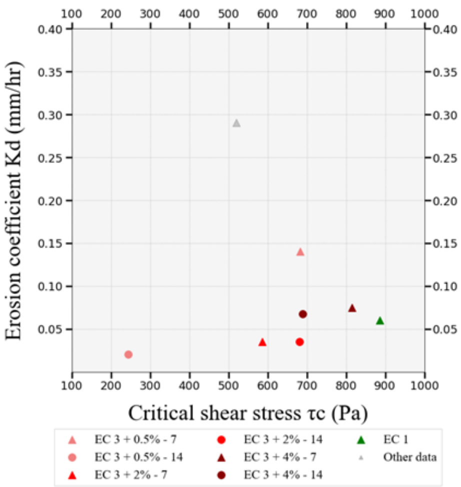

Figure 4 *Erosion results Mini-JET (R.W. Pinke, 2024)*

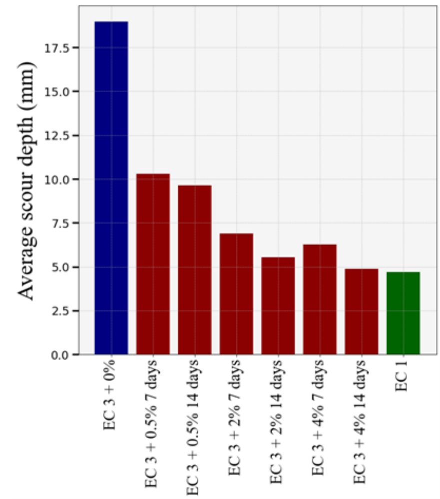

Figure 5 *Erosion results PET (R.W. Pinke, 2024)*

Table 4 Erosion results Mini-JET

Sample (+ CaO)	Kd [mm/hr]	τ_c [Pa]
EC3 + 0%	0.29	519.6
EC3 + 0.5% -7	0.14	683.0
EC3 + 0.5% -14	0.02	244.5
EC3 + 2% -7	0.035	585.8
EC3 + 2% -14	0.035	681.7
EC3 + 4% -7	0.075	815.6
EC3 + 4% -14	0.0675	689.3
EC1	0.06	886.4

Lime treatment shifts the data towards that of the firmer EC 1 clay from Maurik. Notably, 2% and 4% lime additions produce results closest to the Maurik clay. Even a 0.5% lime addition shows improvement in erosion parameters, albeit to a lesser extent.

Pulse erosion test

The measured scour depth of the erosion holes is shown in Figure 5, where the same trend is seen as with the mini-JET: the erosion resistance increases with a higher lime content.

In these results the difference between the different curing times is better visible than with the Mini-JET results. Here it shows that even after 7 additional days of curing more, there is a less deep scour hole in the sample.

The PET results indicate that untreated EC3 clay has an average scour depth of 19 mm, while EC1 clay has an average scour depth of 5 mm. All treated EC3 clay samples show scour depths ranging between 10 mm and 5 mm. Based on these results, there is a noticeable difference in erodibility between untreated EC3 and lime treated EC3 clay. However, according to the Briaud classification, both fall within erosion category III 'Moderate erodibility', as this category ranges from 28 mm to 1 mm scour depth.

Shrinkage test

The results of the shrinkage tests, collected in table 5 show that the shrinkage limit increases with the addition of more lime to the soil. At the same time, the shrinkage ratio decreases. This means that the soil becomes less sensitive to swelling and shrinkage after lime treatment. All shrinkage tests were performed in duplicate, and the reported results are the average values. For the mixtures with +0.5% and +4% lime, only one measurement is available due to issues during the waxing process. Air pockets between the wax and clay can distort volume readings, leading to unreliable shrinkage data. Since the procedure relies heavily on manual handling, some variability is inevitable. Due to limited time and material availability, these tests were not repeated.

Table 5 Shrinkage limit (SL) and ratio (SR)

	0 %	0.5 %	2 %	4%
SL	19.6	19.9	23.9	23.4
SR	1.66	1.62	1.57	1.55

DISCUSSION

In this study, the erosion categories defined by the PET were found to be too broad to effectively classify Dutch dike clays such as Neder-Betuwe and EC1 clay. Although all tested samples fall into PET category III, labeled as "Moderate erodibility", this classification fails to capture the differences in erosion resistance between clay types that are critical in Dutch dike engineering. The PET classification was developed with a broader range of soil types in mind (e.g., sand, silt, clay, rock), and does not distinguish between these important internal variations within clay, which can make this categorization misleading for dike engineering. A more detailed breakdown of PET category III into subcategories like III[a], III[b], and III[c] would allow for a more accurate classification of dike clays based on their erosion resistance.

Moreover, for the shrinkage tests of the clay from Neder-Betuwe, all samples were performed in duplicate. However, for two samples, only one result is available, which may affect the aging results.

Additionally, this study used small-scale erosion tests, providing a small-scale representation of the erosion mechanism. However, erosion behavior in real-world conditions may differ due to larger-scale processes and interactions. Therefore, it could be valuable to complement these small-scale tests with large-scale experiments such as wave overtopping tests to investigate whether similar erosion patterns occur under more realistic conditions.

CONCLUSIONS

The addition of low lime contents to a Dutch clay significantly improves erosion resistance and helps meeting dike safety standards. Lime treatment increases the cohesion and strength, reducing erodibility as shown by Mini-JET and PET tests. It also lowers the plasticity index, improving the workability of wet clay, but reducing the workability of normal clay. This allows processing wetter clay during construction, without pre-drying, saving time and space during the reinforcement projects. The shrinkage limit increases, and the shrinkage ratio decreases, making the clay less prone to swelling and cracking, therefore, enhancing durability. Even small lime additions show noticeable improvements, with higher contents yielding even better results. These findings suggest that upgrading local EC 3 clay with lime is a viable solution for dike reinforcement projects in the Netherlands.

However, it is important to note that these tests were conducted on a single clay type. To generalize these findings, further research is recommended on other Dutch dike clays to assess the broader applicability of lime treatment.

Additionally, a new method for the characterization of erosion resistance of Dutch clays is currently being developed. Although this method is currently limited to clays in the Wadden Sea region and focuses on large wave conditions, it is expected to be extended to all Dutch dikes in the future. The effect of lime addition should therefore also be evaluated within this new framework to ensure its relevance and effectiveness under the updated classification system.

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