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Investigations on the stabilisation mechanisms of enzyme additives for improvement of soft clays and resulting engineering behaviour

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ABSTRACT

Clayey subsoils have a high affinity for moisture, making their bearing behaviour sensitive to moisture fluctuations, which are expected to increase due to the effects of climate change, distressing to overlying geotechnical structures, such as roadbeds. For subsoil improvement, conventional cementitious stabilisers are effective but carbon-intensive, motivating interest in more sustainable options, including enzyme additives. Research on the mechanical performance and mechanisms of enzyme-based stabilisation remains limited. A series of experiments was thus conducted in this study to investigate the effectiveness of enzyme-based soil stabilisation on the stiffness and strength behaviour. Moreover, the difference in bound water thickness between treated and untreated soil particles was analysed to understand the stabilisation mechanisms in relation to geotechnical response. The results indicate a significant increase in elastic modulus for enzyme-stabilised soils. Treated soils exhibit a reduced affinity for overall gravimetric water and bound water. A smaller water content and greater density in enzyme-treated soils highlight the improvement in soil consistency and thus stiffness and uniaxial compression strength, whereas the effects on shear strength are yet unclear. The reduced bound water thickness indicates a decrease in the overall thickness of the electric double layer around soil particles. Clayey particles are allowed to come closer to each other, thereby improving densification in the enzyme-treated soils. These findings support the premise that the enzyme stabiliser reduces the clayey soil's affinity for water, thereby enhancing its stiffness and strength characteristics.

Keywords: Soil improvement, Enzyme additive, Engineering performance, Stabilisation mechanism

1 INTRODUCTION

With climate change expected to increase extreme weather events such as heavy rainfall and drought (IPCC 2019), frequent wetting and drying cycles can significantly affect clayey soils' mechanical properties due to their strong affinity for water. These moisture fluctuations result in substantial changes in the strength and volume of clay (Sheng et al., 2008). Soils lose strength and swell excessively when wet, then regain strength and shrink upon drying. This moisture-sensitive behaviour is problematic, as it causes damage to overlying geotechnical structures, such as cracking and differential settlement in pavements and construction foundations (Elkady et al. 2015).

Various methods of soil stabilisation are available nowadays. These include mechanical stabilisation, which densifies the soil by expelling air from the voids without significantly altering the water content, and chemical stabilisation, which incorporates additives to improve physico-chemical properties, thereby enhancing ground strength and stiffness (Little et al., 2009). For example, cementitious calcium-based additives are conventionally used to improve clayey subsoils in ground applications; however, they raise environmental concerns due to their intensive energy consumption and carbon emissions. The cement industry releases approximately 0.6 t of CO_2 per ton of cement produced (IEA 2023), accounting for a total of around 4.2% of the global CO_2 emissions (GCP 2023). Such adverse influences of conventional stabilisers necessitate the need for sustainable and effective non-traditional stabilisers, including microbial-induced calcite precipitation, polymer-based stabilisers, and enzyme-based stabilisers. For eco-friendly and developing applications, enzyme stabilisers are emerging to improve engineering performance in geotechnical constructions. Generally, commercial enzyme stabilisers are biochemical solutions formed from fermented organic materials. They consist of three primary elements: (i) electrolytes that interact with clay minerals, (ii) multi-enzyme products that catalyse ion exchange between clay particles and the electrolytes, and (iii) surfactants to reduce the water viscosity, allowing the other two elements to penetrate the soil mass.

Enzyme-based soil stabilisation has been explored as an effective and sustainable alternative to conventional calcium-based stabilisers (e.g., lime and cement) for several decades. Li et al. (2011) reported that an enzyme stabiliser was effective in improving strength and was comparable to cement at 25–30% lower cost. Scholen (1992) documented a durable and dust-free forest road in the field after enzyme treatment. Subsequent studies highlighted improved bearing capacity and reduced swelling in treated soils; for example, Guthrie et al. (2015) reported significant subgrade strength gains. Furthermore, several mechanisms have been proposed to explain enzyme stabilisation. Marasteanu et al. (2005) posited that enzymes facilitate cation exchange in

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clays, neutralising negative charge and allowing denser packing. Tolleson et al. (2003) hypothesised a "catalytic bonding" effect in which enzymes bind soil microbes to form covalent inter-particle bonds with clay. Scholen (1992) argued that enzymes require specific organic molecules to bond with clay, creating cementing agents that limit water uptake. Rauch et al. (2003) described an "organic encapsulation" mechanism in which enzymes neutralise the clay's negative charge and reduce the clay's affinity for moisture, allowing particles to pack more closely together and thereby increase stiffness and strength.

Despite growing interest, the efficacy of enzyme stabilisers remains uncertain as studies report inconsistent results: some studies show substantial strength gains, while others (e.g., Parsons et al., 2003) find negligible improvement. This variability is attributed to differences in soil types, enzyme formulations, and curing protocols. Current stabilisation theories emphasised that enzyme-based stabilisers decrease the soil's water affinity, but neglect to discuss the effects of water with various properties in soils, which play distinct roles in contributing to the soil's mechanical properties. Chandler et al. (2017) investigated that enzyme-treated clay soils absorbed less water at a slower rate in capillary rise tests than untreated soils. Capillary water affects apparent soil cohesion and permeability, while bound water influences clay plasticity (and thus strength). Yet the specific impact of enzymes on bound water remains unexamined.

This paper aims to investigate the engineering behaviour of enzyme-stabilised clayey soils, focusing on their stiffness and strength, and to explore the stabilisation mechanism by analysing the thickness of bound water around soil particles. A series of soil mechanical tests was conducted, including the Atterberg limits, Proctor compaction, oedometer test, direct shear test and unconfined compression strength (UCS) tests. Furthermore, the thickness of bound water was experimentally investigated through chemical testing. Based on the above outcomes, this paper discusses the relationship between geotechnical performance and variations in microscale bound water thickness.

2 MATERIALS AND SPECIMEN PREPARATION

The soil material was collected from an experimental site at the University of Siegen. The natural water content after excavation from the site was 21.69 %. Based on Atterberg limit results, the material was classified as a medium-plasticity, close to high-plasticity clay according to DIN EN ISO 14688-2 (Table 1). The grain-size analysis revealed that the soil consisted of 58% clay-sized particles (<0.002 mm) and 42% silt-sized particles. The X-ray diffraction results indicated that the primary clay minerals present are illite and montmorillonite. Standard Proctor compaction tests (DIN EN 13286-2) were employed to determine the optimum water content of the soil and its corresponding density, as shown in Table 1. Approximately 280 kg of clayey soil was utilised in all tests. The commercial enzyme stabiliser product for soil improvement, Road//stabilizr (Earthzyme), was used in this study. The enzyme stabiliser concentration applied in this study is representative of 1 L on 30 m³ of compacted soil in the field.

Before testing, the original soil was pre-processed by air-drying in the laboratory for a week and then ground into a powder that passed through a 2 mm sieve, allowing it to be thoroughly mixed with the enzyme stabiliser. In this study, the samples were planned to experience an optimum moisture content (w_{opt}) of 18.1%. Hence, the enzyme stabiliser was diluted in water to reach a moisture content slightly higher than w_{opt} in treated soils. Soils and stabiliser were then thoroughly mixed using a mixer. After that, all specimens were remoulded and compacted inside a steel mould using standard proctor compaction energy. During the curing stage, the specimens were covered with plastic film and placed in a room with a relatively stable temperature (21 ± 2 °C) and humidity (45 ± 5%), allowing specimens to cure and dry under uniform conditions. The treated and untreated specimens were both prepared and cured in the same conditions.

Table 1 Soil properties.

Parameter	Symbol	Value	Unit
Grain density	ρ_S	2.75	g/cm³
Proctor density	ρ_{proc}	1.72	g/cm³
Optimum water content	w_{opt}	18.1	%
Liquid limit	w_l	48.0	%
Plastic limit	w_p	16.6	%
Plasticity index	I_p	31.4	%

3 SOIL MECHANICAL TESTS

3.1 Testing programme

In this study, oedometer tests (DIN EN ISO 17892-5), direct shear tests (DIN EN ISO 17892-10), uniaxial compression tests (DIN EN ISO 17892-7), and water content analyses (DIN EN ISO 17892-1) were used to evaluate the stiffness, shear strength, compressive strength, and drying performance of enzyme-treated soils. The experimental plan for all tests considered untreated soil samples (control) and soil samples treated with Earthzyme. Soil mechanical tests and water content analyses were conducted after various curing times, including 5, 10, 20, and 50 days.

The results from the oedometer test in Section 3.2, the direct shear test in Section 3.3, and the water content and density analysis in Section 3.5 are averages of the two single tests conducted for each, for straightforward comparison. The results from the UCS test in Section 3.4 are presented comprehensively, including both single tests of enzyme-treated and untreated specimens.

3.2 Oedometer modulus

Figure 1 shows the oedometer modulus of treated and untreated specimens under varying normal stresses. Both treated and untreated soils experienced a linear to slightly disproportionate improvement with curing time. However, the greater the normal stress, the greater the difference in the oedometer modulus between the enzyme-treated and untreated specimens. This highlights that the improvement effect of the enzyme-treated soil samples is more significant when they experience a greater normal stress.

For the curing time, enzyme-stabilised specimens exhibited a similar elastic modulus range to that of the untreated specimens in the first five days of curing. Then treated soils exhibited a greater oedometer modulus than the untreated specimens after a 10-day curing period, particularly when the normal stress exceeded 200 kPa. Additionally, after 20 days, when the normal stress was 400 kPa, the moduli of the treated and untreated specimens were 20.50 MPa and

12.93 MPa, respectively. This suggests an increase in the oedometer modulus of approximately 58.5%, reaching a peak at this curing time. After that, the improvement percentage of the oedometer modulus remains relatively stable after 50 days of curing, while the absolute values of the oedometer moduli for both untreated samples (37.62 MPa) and treated samples (26.48 MPa) have increased under curing and drying conditions in Section 2. The results further indicate that enzyme-based soil stabilisation requires a slow and sufficiently long improvement process.

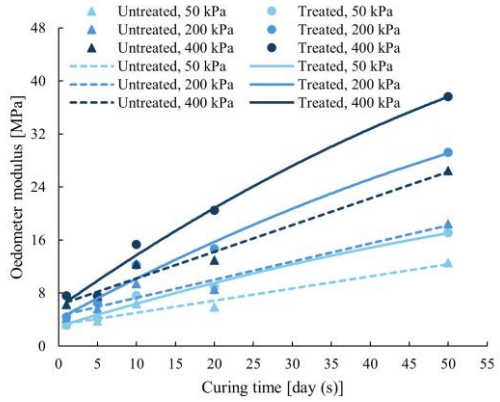

Figure 1 Oedometer modulus of treated and untreated soils (symbols: average test results; lines: regression curves)

3.3 Shear strength

Figure 2 presents the shear strength of enzyme-treated and untreated specimens under different curing times ranging from 1 to 20 days. After one day of curing, the treated specimens exhibited a very similar range of shear strength to that of the untreated specimens under varying normal stresses. After five days of treatment, the regression line started to exhibit a moderately smaller slope compared to untreated soils, but still shared a similar intercept on the vertical axis. This indicates that the enzyme-based stabiliser slightly decreased the friction angle of clayey soils, whereas the cohesion remains unaltered, after five days of curing. By contrast, the regression line for treated samples shows a significantly greater intercept on the vertical axis but a smaller slope after curing and drying for 20 days. This suggests that treated clays perform with higher cohesion but reduced friction.

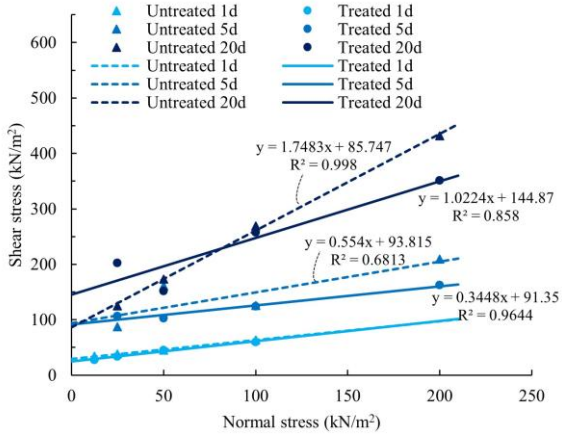

Figure 2 Shear strength of treated and untreated soils (symbols: average test results; lines: regression curves)

3.4 Unconfined compression strength

The specimens in this study were initially remoulded and trimmed to fit the size of the UCS test cylinder, which has a diameter of 35-36 mm and a height of 72-73 mm. These specimens for UCS tests were then cured and dried to a moisture content (~5%) similar to that of the oedometer samples after complete drying (50 d), before testing. Figure 3 illustrates the results of the unconfined compression test. The results clearly show that the treated soil showed a higher strength than the untreated soil under the same vertical strain, with an average peak compressive strength at failure approximately 30.37% higher. This observation is in line with the findings of Chandler et al. (2017). Additionally, the enzyme-treated specimens also exhibited a lower failure strain compared to the untreated specimens. This highlights the higher resilient modulus of treated soils, which is consistent with the results of the oedometer modulus presented in Section 3.2.

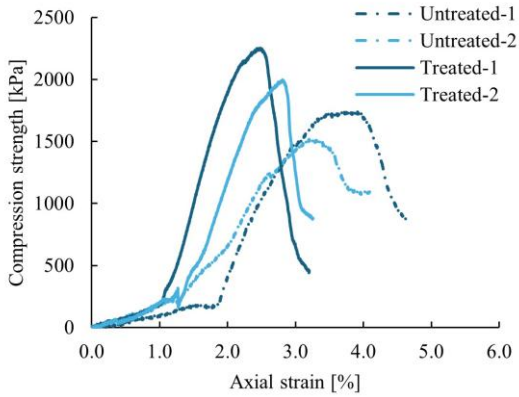

Figure 3 Unconfined compression strength test results

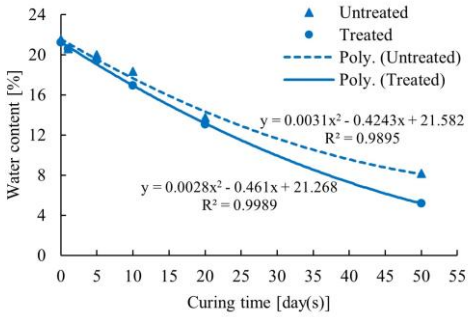

Figure 4 Water content under different curing times

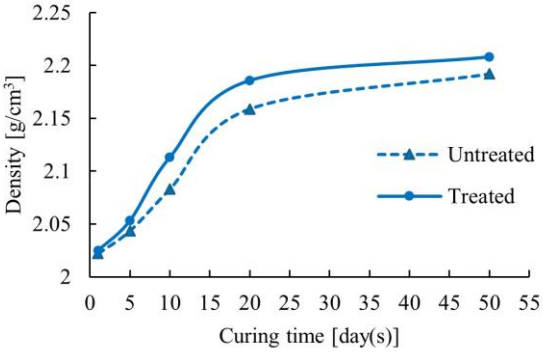

Figure 5 Density under different curing times

3.5 Water content and density

Results presented in Figure 4 indicate that the overall water content of the enzyme-treated samples was lower than that of the untreated samples over the curing process. The deviation between them increased after 10 days of curing and then became significant (2-3%) after around 30 days. The results indicate that enzyme-stabilised samples generally exhibit a lower water content, particularly after 50 days of curing. This means an enzyme-based stabiliser allows soil specimens to release more water compared to untreated specimens under the same curing and drying conditions. The greater reduction in water content in enzyme-treated specimens suggests that the consistency of the treated specimen may have improved, thereby leading to increased stiffness and strength, as confirmed by the larger oedometer modulus and the higher failure compression stress. Figure 5 further illustrates the increase in soil density over various curing times. The density was calculated based on the mass and volume of the oedometer samples. The presumption is that decreased moisture leads to shrinkage and an increase in density, with a consequent increase in strength.

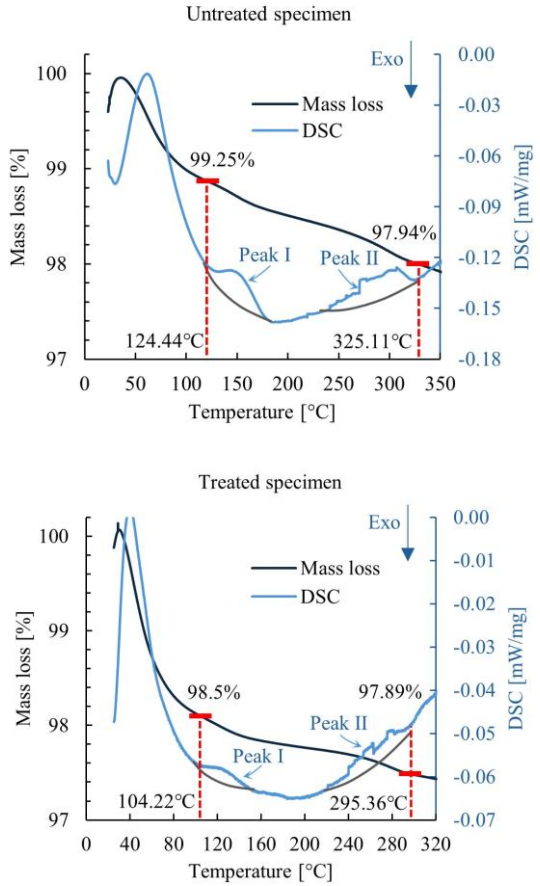

Figure 6 Mass loss and DSC results of treated and untreated soil specimens

4 ANALYSIS OF BOUND WATER THICKNESS

4.1 Testing programme and calculation

For the analysis of the bound water thickness around soil particles, simultaneous thermal analysis (STA) tests, Brunauer-Emmett-Teller (BET) analysis, and density analysis using the gas pycnometer method were conducted in the lab of the Chemistry and Structure of novel Materials at the University of Siegen. STA analysis combines thermogravimetric and differential scanning calorimetry (DSC) in a single instrument to analyse the sample's mass change and heat flow simultaneously. The variation of mass loss and energy absorption/release of soil samples during a heating and dehydration process can thereby be monitored and measured together. BET analysis can be utilised to determine the specific surface area of soil particles. The Micromeritics AccuPyc gas pycnometer was used to determine the density of the grain particles.

The soil particle's surface surrounded by bound water is referred to as the "hydrated sample". The volumes of the hydrated (V_{hs}) and dehydrated (V_s) samples can be obtained from their densities and masses, respectively. The calculation formula is as follows:

$$V_{hs} = m_{hs}/\rho_{hs} \quad (1)$$

$$V_s = m_s/\rho_s \quad (2)$$

where, V_{hs}, m_{hs}, and ρ_{hs} are the volume, mass, and density of the hydrated sample, respectively. V_s, m_s, and ρ_s are the volume, mass, and density of the dehydrated soil, respectively. The physical properties of bound water were investigated, including the volume of bound water (V_{bw}) and the assumed thickness of the bound water film (h_{bw}). The parameters can be described by Eqs. (3-4) neglecting the volume change of dried clay particles with water content. The method of calculating V_{bw} is expressed as Eq. (3):

$$V_{bw} = V_{hs} - V_s \quad (3)$$

where, V_{bw} is the volume of bound water. The thickness of the bound water layer can be described as given in Eq. (4):

$$h_{bw} = V_{bw}/S_0 \quad (4)$$

where, h_{bw} is the thickness of the bound water layer, and S_o is the specific surface area of all the dehydrated sample particles. For the above Equations (1-4), five parameters need to be measured in this study to calculate the thickness of bound water (m_{hs}, ρ_{hs}, m_s, ρ_s, S_0). m_{hs} and m_s can be determined using STA. ρ_{hs} and ρ_s were determined by density analysis, and S_0 was measured using the BET method (N_2 adsorption) (Wang et al. 2020). Given the significant change in elastic modulus that took place after 20 days of curing, all specimens for the analysis of the bound water thickness were thus cured for 20 days.

4.2 Analysis of bound water

Bound water is defined as water electrochemically absorbed by the clay surface within the electrical double layer (Zhang et al. 2021; Yuan et al. 2018). As bound water is located in the innermost layer of the clay particle surface and affected by electrostatic forces, hydrogen bonds, and ionic bonds, it is more difficult to discharge from the soil mass than gravimetric water. Mitchell et al. (2005) highlighted that the emission of water on the soil mineral surface is endothermic, and the temperature required for releasing bound water ranges from 100 to 300 °C. Gardner et al. (2001) stated that crystal water within the clay lattice is released when heated to temperatures between 400 °C and 800 °C. The temperature ranges at which thermal reactions occur vary slightly for different clay materials.

The STA results in this study, as shown in Figure 6, indicate that the DSC curves of both the treated and untreated specimens exhibit two endothermic peaks during the

dehydration process, with overall temperatures ranging from approximately 104 °C to 325 °C. When the direction of the fluctuation peak shown in the DSC curve is opposite to the direction of the exothermic arrow in the figure, the range between the peak and the baseline (grey line) represents an endothermic process. The dehydration temperature range in this study is relatively consistent with previous outcomes (Mitchell et al. 2005). Therefore, this suggests that loosely bound water begins to be released at the first peak, and tightly bound water is completely released at the end of the second peak. Based on this principle, it can be determined that the bound water in untreated specimens was released starting at 124.44 °C and ending at 325.11 °C. The bound water in treated specimens was released starting at 104.22 °C and ending at 295.36 °C. The mass of bound water released in this temperature range was thereby determined using the corresponding mass loss curve (for m_{hs} and m_s) for solving Equations (1) and (2). Additionally, the specific surface area (S_0) and densities (ρ_{hs} and ρ_s) can also be measured under specified hydration temperature conditions. The calculated results indicate that the bound water thickness of enzyme-treated soil is around 5.271 Å, which is less than 6.608 Å in the untreated soil, representing a decrease of around 20.23%.

Overall, both the overall water content and the thickness of bound water at the microscopic level were reduced in enzyme-treated soils, emphasising the effectiveness of the enzyme stabiliser in reducing the clay's affinity for moisture. Particularly, treated soils exhibited higher dry density and greater apparent cohesion, suggesting that although the bound water is a small fraction, its modification has non-negligible effects on clay micromechanics and, in turn, on macroscopic engineering behaviour (higher oedometer modulus and compressive strength). On the other hand, bound water forms part of the electric double layer; consequently, a reduction in the thickness of the bound water will lead to a decrease in the thickness of the double layer between clay particles. Clayey particles are thus allowed to be closer to each other, thereby improving the potential for higher cohesion and densification in enzyme-treated soils. Furthermore, the reduction in bound water implies fewer strongly hydrated cations surrounding soil particles, which neutralise negatively charged clays, and decreases during the curing time. This emphasises the role of enzyme stabilisers in promoting the ion exchange process of hydrophilic cations. Moreover, hydrated cations are distributed throughout the double layer, including bound water and free water. Hence, the observed reduction in total water content indicates that the free-water/pore-water domain is also affected.

5 CONCLUSION

This study investigated the potential improvement in stiffness and strength to assess the attributes of an enzyme additive applied to clayey soils. Additionally, chemical tests were conducted to explore the enzyme stabilisation mechanism by analysing the thickness of bound water around soil particles. The oedometer test results revealed that enzyme-treated soils exhibited a higher oedometer modulus than the untreated soils after 10 days of curing. The improvement effect of the enzyme-treated soil samples is more significant when they experience a greater normal stress load, and this improvement requires a slow process. Furthermore, the enzyme-treated specimens exhibited higher unconfined compression strengths and a lower water content. On the other hand, the results from direct shear tests do not yet allow for a reliable conclusion; they need to be studied further for a sound mechanical behaviour.

The chemical tests indicated a lower thickness of bound water in the enzyme-treated soils compared to the untreated. This consequently leads to a decrease in the thickness of the electric double layer between clay particles, allowing the particles to approach each other more closely, thereby improving their cohesion and densification. Additionally, the reduction in bound water emphasises the role of enzyme stabilisers in catalysing the ion exchange of hydrophilic cations, thus influencing the environment of gravimetric water in the electrical double layer between soil particles.

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