

Influence of curing time on the uniaxial compression behavior of raw lime-treated clayey soil

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ABSTRACT

Lime by small percentage is generally used to improve the physical properties and enhance the mechanical strength of unstable weak clayey soil. In this study, tills or clays were treated with two different raw industrial lime and were used for laboratory tests on mechanical properties. A large number of lab tests were performed considering various curing periods of lime-treated soil samples under different loading rates to examine the impacts of time-dependent chemical bonding and available moisture in lime-treated clayey soil. The influence of this raw lime stabilization on weak clayey soil was evaluated through the determination of geotechnical properties (e.g., liquid limit, plastic limit, optimum water content, and mineralogy), and homogenization time of lime-soil mixtures. Our results show that with the increase of curing period, which reflects the higher bonding reaction between lime and clay, the resistance of mixture towards acting load increases but the failure occurs with a lower magnitude of deformation. Additionally, the maximum curing period required to reach peak strength for the optimum moisture content of soil-lime mixture was determined to establish the long-term strength.

RÉSUMÉ

La chaux à faible pourcentage est généralement utilisée pour améliorer les propriétés physiques et renforcer la résistance mécanique des sols argileux faibles instables. Dans cette étude, des tills ou des argiles ont été traités avec deux chaux brutes industrielles différentes et ont été utilisés pour des tests en laboratoire sur les propriétés mécaniques. Un grand nombre d'essais en laboratoire ont été effectués en tenant compte de diverses périodes de durcissement d'échantillons de sol traités à la chaux sous différents taux de charge pour examiner les impacts de la liaison chimique en fonction du temps et de l'humidité disponible dans le sol argileux traité à la chaux. L'influence de cette stabilisation à la chaux brute sur un sol argileux faible a été évaluée par la détermination des propriétés géotechniques (par exemple, la limite de liquidité, la limite plastique, la teneur en eau optimale et la minéralogie) et le temps d'homogénéisation des mélanges chaux-sol. Nos résultats montrent qu'avec l'augmentation de la période de durcissement, qui reflète la réaction de liaison plus élevée entre la chaux et l'argile, la résistance du mélange à la charge agissante augmente mais la rupture se produit avec une amplitude de déformation plus faible. De plus, la période de durcissement maximale requise pour atteindre la résistance maximale pour la teneur en humidité optimale du mélange sol-chaux a été déterminée pour établir la résistance à long terme.

1 INTRODUCTION

Lime, in its different form (the calcium oxide or calcium hydroxide) by very small amount has been using as a construction material in the construction field. It was treated as a soil stabilizer for the road's construction industry since roman time (McDowell 1959). Recently, the lime is still being used as strength enhancement additive material for the stabilization of weak soil encounter in foundations, embankments, slopes for canals (Wilkinson et al. 2010) and even as cementation material in piles for the stability of clayey soil (Abiodun and Nalbantoglu. 2016).

Compared to other stabilizing materials, lime is economical, readily available, and easy to work at minimum skill level during construction. Soil with high plasticity undergoes huge amount of swelling when encountering water (Petry and Little 2002). Cation's exchange due to addition of lime in expansive clay is primary responsible for the reduction in plasticity (Bell and Coulthard 1990; Barker et al. 2006). Lime shows impressive results as a stabilizing agent when mix with high

plastic soil and expansive soil by reducing the swelling pressure (Wilkinson et al. 2010). The lime when added to soil, react with the free available water leading to pozzolanic reaction and chemically behave as cementing material increasing both strength and long-term strength of soil (Khattab et al. 2007).

The mechanical strength of soil is enhanced and improved by the reaction between calcium available in lime and silicates and aluminates from the clay minerals of soil in the presence of available water by producing stable calcium silicates hydrates and calcium aluminate hydrates. This reaction is both available moisture and time dependent, hence can take decades to reach the full-term pozzolanic reactions.

Previously, various researchers (Kumar and Monwar 2012; Rogers et al. 2006; Bell 1996; Al-Swaidani et al 2016; Garzon et al. 2016; Afrin 2017) study the impact of lime on stability of problematic soil and discussed the changes in physio-mechanical behavior of clayey soil. However, it is worth remembering that various researchers (Hilt and Davidson 1960; Kumar et al. 2007) studied the effect of lime

addition quantity in soil for stabilization. The research shows that specific optimum amount of lime only contributes to enhance strength of soil, if added higher quantity than optimum amount, it could lead to adverse effects on both short- and long-term stability. Because unreacted lime has no contribution in shear strength parameters (friction and cohesion) of soil. However, the role of deformation behavior of lime soil mixture with the curing period and cold environment requires comprehensive studies to determine the effectiveness of lime and determine the strain rate dependent rheological behavior.

In summary, various experimental approaches have been used to study the long-term role of lime on soil strength and soil stabilization. Although, the increase in strength of soil with the addition of lime is studied by various researchers considering the stress path, physical properties or decrease in porosity leading to increase in density. A thorough understanding of change in lime soil mixture deformation behavior with curing period and loading rate is required to acquire the liability in the long-term usage.

In this study, we conducted large number of uniaxial compressions tests and double punch test using three different loading rates at room temperature. The deformation behavior of lime-soil mixture and the role of curing period on deformation path are studied to fill the gap present in the most previous studies. Uniaxial compression test is effective when the soil under consideration is used for shallow foundation (Girgis et al. 2020) which is the mostly the case for stabilizing the highway foundations and canal linings. While the double punch approach to study the tensile strength is most effective and conservative approach to capture the brittle tensile behavior (Akhtar et al. 2021).

2 EXPERIMENTAL RESULTS AND PHYSICAL PROPERTIES OF SOIL

A series of experimental uniaxial compression tests and double punch tests were conducted on natural Marbelton clay till, which was extracted from a depth of 1 to 3 meter in a site in Quebec, Canada. The particle size distribution of the soil using the dry sieve technique was performed to extract soil passed through sieve size of 2.5 mm. The air-dried soil was mixed with required amount of demineralized water followed by hand mixing of raw lime kiln dust of 3.4 % by dry weight with wet soil. The lime-soil mixture was left for two hours in hermetic conditions required for the homogenization of mixture. After two hours of homogenization, the soil lime mixture was then compacted and then put into plastic bags and pail along with molds for the intended period of curing. The soil is kept for curing in mold to avoid a damage to the sample. The Atterberg limits and other physical properties of this soil mixture are given in **Table 1** while the composition and chemical properties of the applied lime is given in **Table 2**.

Table 1 Atterberg limits data and other physical properties of the soil.

Characteristics (%)	Marbelton clay
Natural soil Bulk density (kg/m ³)	2030
Lime-soil bulk density ¹ (kg/m ³)	2146
Water content ² (%)	14.25
Specific gravity	2.66
Liquid limit (%)	22.8
Plastic limit (%)	20.54
Plastic Index (%)	2.34
Clay (mass percentage)	45

¹Density of soil sample after two hours of mixing with lime

²water content of specimens at time of preparation

Table 2 Composition and chemical properties of lime kiln dust.

Characteristics (%)	Lime dust
Bulk density (kg/m ³)	865
Specific gravity	2.7
pH (%)	12.45
Total Calcium oxide (%)	62.7
Total calcium Ca (%)	44.8

2.1 Experimental procedure

The setup for the uniaxial compression test along with special design sub-loading frame and location of strain measuring LVDT is given in **Figure 1**. The sample size for compression test is 2-inch x 4-inch. The LVDT was attached at the top to measure axial strain and the displacement-controlled loadings technique was used in lab tests with three different deformation rates (1 mm/minute, 3 mm/minute, and 9mm/minute). While the setup for the double punch test is given in **Figure 2**. The sample size for double punch test is 2-inch x 2-inch.



Figure 1. Setup for the compression tests.



Figure 2. Setup for the Double punch tests.

2.2 Experimental results

The deformed samples under uniaxial compression tests and double punch tests by the end of loading at various loading rates are given in **Figures 3** and **Figure 4**, respectively. The figure shows that at a lower deformation rate (i.e., 1mm/minute), the deformation path is penetrated through out the soil sample while a local deformation pattern can be seen at the top of soil sample without any visible longitudinal failure distribution at higher deformation rate (i.e., 9mm/minute). However, a combination of both type of deformation behavior were noticed at a loading rate of 3mm/minute. By contrast, no such a behavior is visible in double punch tests. It is because, during double punch test, the contact area is very small, and it does not affect the deformation behavior. The degradation behavior of the physio-mechanical strength parameters of this lime-soil mixture during compressive loading depends on the deformation rate and curing period. The schematic views, as presented in **Figure 5** and **Figure 6**, are given to clearly states the modes and effect of curing period on the physio-mechanical strength of lime-soil mixture. The outcomes are summarized in the following:

1. At lower loading rate (1mm/minute), the stress is distributed with higher mobilization of particles on microscale level through soil sample leading to higher strength and the soil goes through three unique and distinctive modes of deformation (i.e., linear elastic, plastic hardening, and shear softening). The crack contributing to failure of sample appears through out the section.
2. At higher deformation rate (9mm/minute), the stress concentrates on local area, causing a widening of micro cracks, produced due to the lime and water reaction. However, the soil encounters through three unique and distinctive modes of deformation but failure occurs at lower value of axial strain. The micro-cracks join other nearby micro-cracks and reach to nearby surface due to quick loading and fracture the area close to loading.
3. The curing period increases the strength of lime-soil mixture due to continuous reaction between available water and lime content leading to interparticle shrinkage casing soil particles agglomeration but the strain at deformation decreases with the increase of curing period

and the mechanical strength behaviour of soil changes to be brittle.

The lime reacts with the available moisture in the soil leading to increase in strength. The peak strengths measured under axial compression test at various loading rate and curing period is given in **Figure 7a**. It can be seen that the peak strength increases with increase of curing period attributed to the more reaction between the lime and water. However, **Figure 7c** shows that at higher loading rate the strength decreases by a considerable amount. This behaviour is in consistent with the schematic view (Figure 4). Because at a low deformation rate (1mm/minute), the sample has enough time to transfer the acting load through out section but at a higher loading rate (9mm/minute), the accumulated grains develop due to lime and water reaction takes the initial load but can not transfer through out the section.

Figure 7b also shows that with the increase in curing period, the strength of the sample reach to the peak value at lower strain under both high and low deformation rates leading to aggressive brittle failure. It is because, with the increasing curing period, more lime reacts with available free water in soil sample creating more solid granular particles and micro-cracks. When the load is applied, the stress can no longer transfer inside the soil sample leading to sudden failure. Additionally, this phenomenon is more prominent at higher loading rates.

The double punch yields similar pattern of strength increase with curing period as uniaxial compression tests, but it should be worth mentioning that the natural soil strength is more at higher loading rate than lower loading rate but after mixing with lime the lower loading rate yields more strength than higher loading rate (**Figure 8**).

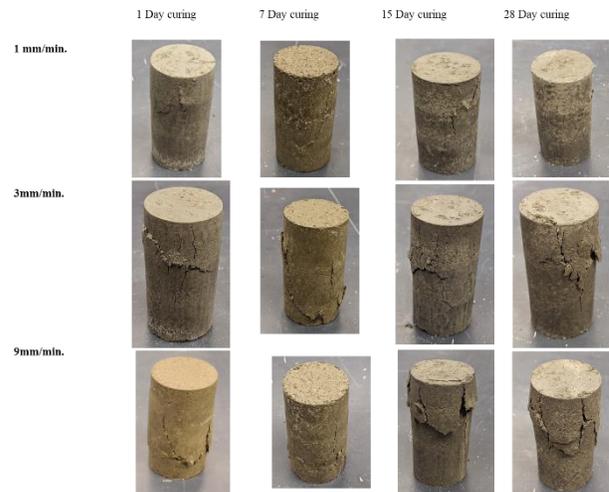


Figure 3. Post-failure photos of UCS test samples at different applied deformation rates and curing period.

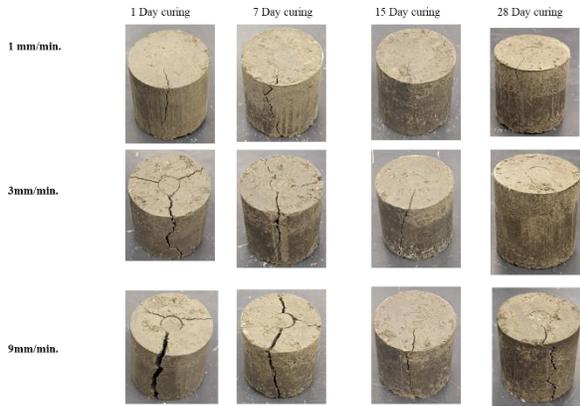


Figure 4. Post-failure photos of Double punch test samples at different applied deformation rates and curing period.

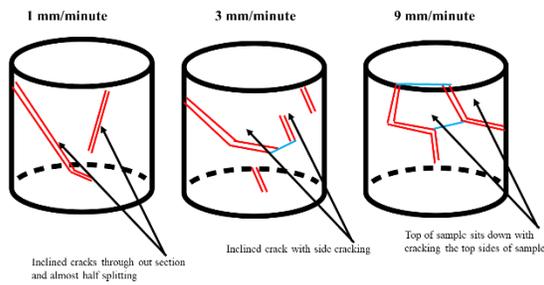


Figure 5. Schematic view of failure modes in the lime-soil mixture samples under the uniaxial compression tests.

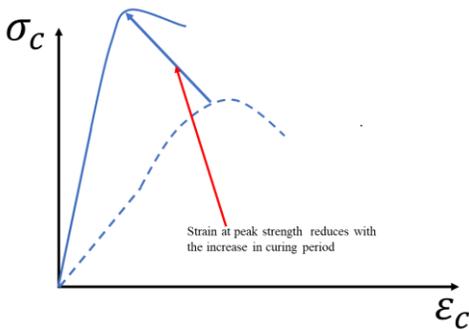


Figure 6. Schematic view of deformation depending on curing period.

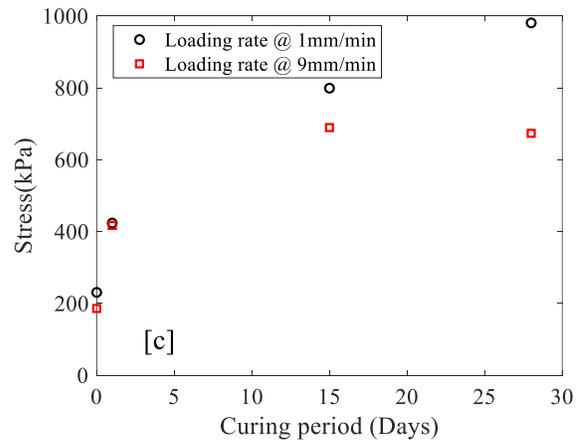
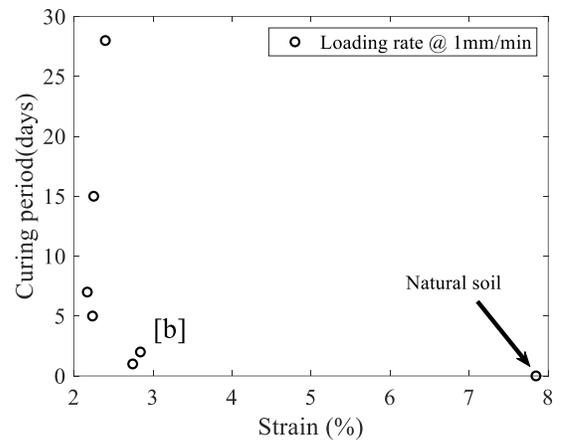
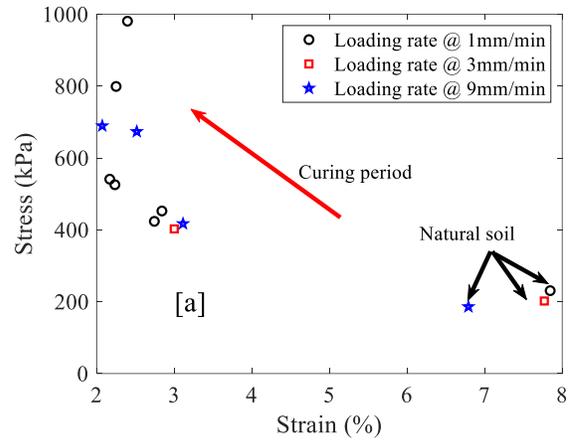


Figure 7. Relation for peak stress, strain and curing period at various loading rates.

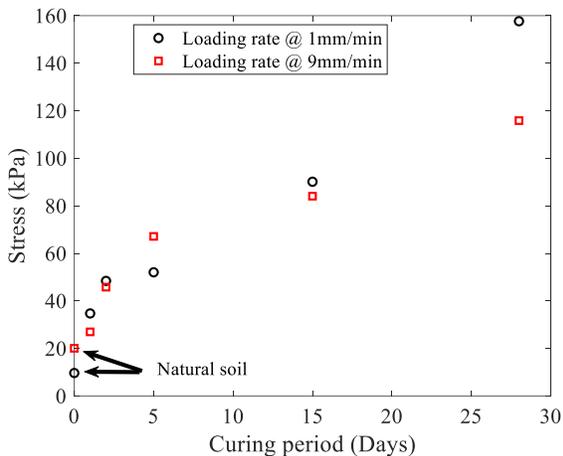


Figure 8. Relation for peak stress and curing period at various loading rate under double punch test.

3 SUMMARY AND CONCLUSIONS

The use of raw industrial lime to enhance the strength of clayey silty soil yields promising results. Our experimental results show that the strength of lime soil mixture is dependent on loading rate and curing time. The lime soil mixture yields more strength with the increase in curing period at both higher and a lower deformation rate under both uniaxial compression test and double punch test. The peak strength of lime soil occurs at lower strain with the increase of curing period and higher loading rate but the strain at failure seizes reducing after 7 days of curing. However, the increase in strength ratio of lime soil mixture to natural soil slows down with the increase of curing period. In this study, our experimental results assume the stability of strength increase at 28 days of curing. Presently, we do not include the effect of available water content, Poisson ratio, creep behavior and freeze and thaw effects in the soil, and it is recommended to be included in the future study.

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