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Lime Remediation of Reactivated Landslides

Traitement à la chaux pour la stabilisation des glissements réactivés

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ABSTRACT: Lime improvement of frictional resistance was examined using samples of Brenna Clay Formation from North Dakota. The montmorillonitic stiff clay samples had a natural water content, plastic limit, liquid limit, clay size fraction, fully softened friction angle, and residual friction angle, respectively, in the range of 42 to 85%, 20 to 40%, 62 to 154%, 60 to 95%, 14 to 24°, and 7 to 9°. Immediately after introduction of hydrated lime, pH increased to a range of 12.2 to 12.7; within hours, however, pH began to decrease. Whereas there was a large increase in plastic limit, the liquid limit response to lime treatment was dependent on the effective confining pressure. Lime treatment increased fully softened friction angle by 5 to 10° at effective normal stress of 100 kPa and by 3 to 5° at 300 kPa. Lime treatment increased the residual friction angle by 3 to 6° at both 100 kPa and 300 kPa.

RÉSUMÉ: L'amélioration par addition de chaux de la résistance en frottement est examinée sur des échantillons de la formation d'argile de Brenna dans le Dakota du Nord. Les échantillons d'argile raide montmorillonitique ont une teneur en eau, une limite plastique, une limite liquide, une fraction de dimension argileuse, un angle de frottement après remaniement et un angle de frottement résiduel respectivement de l'ordre de 42 à 85%, de 20 à 40%, de 62 à 154%, de 60 à 95%, de 14 à 24°, et de 7 à 9°. Immédiatement après l'addition de chaux hydratée, le pH augmente à des valeurs de 12,2 à 12,7 mais commence ensuite à décroître dans les heures qui suivent. L'augmentation de la limite de plasticité suite au traitement à la chaux est importante, l'augmentation de la limite de liquidité dépend cependant de la pression de confinement. Le traitement à la chaux augmente l'angle de frottement après remaniement de 5 à 10° sous une contrainte effective normale de 100 kPa et de 3 à 5° sous 300 kPa. Le traitement à la chaux augmente l'angle de frottement résiduel de 3 à 6° autant sous une pression de 300 kPa plutôt que de 100 kPa.

KEYWORDS: Brenna clay, frictional resistance, lime treatment, landslides.

1 INTRODUCTION

The effectiveness of lime treatment of soils has been commonly evaluated in terms of improved workability and increased undrained unconfined stiffness and compressive strength, in connection to road and airfield construction (Bell 1996). Soil improvement is expected to result from the flocculation of clay minerals and cementing action of lime-soil chemical reactions. On the other hand if the objective of lime treatment is to improve long-term stability of first-time or reactivated landslides in stiff clays and shales, permanent changes in the size and shape of clay particles must be realized to increase drained frictional resistance. Lime-soil interactions that may produce less platy and larger soil particles begin and continue with time under the highly alkaline pH environment. For Brenna clay samples treated with lime, measurements of pH as an indicator of chemical environment, Atterberg plastic limit and liquid limit as indirect measures of changes in particle size and shape, and fully softened friction angle and residual friction angle, were used to examine possible mechanisms of lime-soil interactions. The main variables, in addition to soil mineralogy, are soil water content, lime content, and duration of lime-soil interactions.

2 LIME-SOIL INTERACTION

When dry hydrated lime is thoroughly mixed with a wet soil, lime is consumed, in the absence of carbonation, through two mechanisms: (a) part of the lime particles is adsorbed on soil particles during the mixing process, and (b) part of the remaining lime is dissolved in the soil porewater. The solubility of calcium hydroxide in water is rather small (0.75 g/l). Therefore, the maximum lime content as percent of dry weight

of soil that can dissolve in the porewater during the mixing process is quite small and a function of soil water content (only 1.5% of lime for 5% lime content at soil water content of 100%). Dissociation of hydrated lime to (OH)⁻ and Ca²⁺ leads to a rise in the pH. If enough lime is left, after satisfying the adsorption, soil porewater becomes saturated and pH increases to approximately 12.3 to 12.4. Under the strong alkaline condition, soil mineral particle surfaces become unstable and begin to dissolve in the porewater. Simultaneously, under the elevated pH condition, adsorbed lime particles begin to attack the soil particle surfaces at the points of contact.

Dissolved silica and alumina react with the dissociated calcium hydroxide and form new compounds. As the dissolved hydrated lime is used up in the chemical reactions with silica and alumina, the remaining free lime, if any, dissolves in the porewater and pH is maintained at 12.3-12.4. The dissolution of soil particles and local attack of adsorbed lime on the particle surfaces continue at the initial rate until all free lime is completely consumed. Thereafter, pH begins to decrease as the dissociated calcium hydroxide is used up in the chemical reactions with dissolved silica and alumina. This has been confirmed by pH measurements and chemical analyses conducted by Clare and Cruchley (1957) and Diamond et al. (1964). Dissolution of soil particle surfaces continues at a decreasing rate, becoming insignificant as pH drops to values probably less than around 9 (Eades and Grim 1960, Eades et al. 1962, Hunter 1988). The reaction products begin to harden or crystallize as pH decreases. A calcium hydroxide particle is attached to more than one soil particle, connecting them together and producing silt- and sand-sized flocs and agglomerates (Diamond et al. 1964, Verhasselt 1990). The Atterberg plastic limit increases, often dramatically, because large amount of water is enclosed within the flocs and

agglomerates. In other words, only part of the porewater contributes to plasticity. This is similar to diatoms with poriferous particles in soils such as the Mexico City clay, and andosols containing allophane in which water is trapped within soil aggregates (Mesri et al. 1975, Terzaghi et al. 1996). Both soils display unusually high plastic limits. In summary, total lime content, l_c , is used up through adsorption, l_{ca} , and dissolution, l_{cd} .

The time-dependent manifestation of adsorbed lime is a gradual chemical reaction of calcium hydroxide with soil particle surfaces. As the reaction products continue to form and later harden or crystallize at the reaction sites of adsorbed lime particles, they improve soil particle connections within the flocs and agglomerates that may mature into porous soil aggregates (Baver 1956). The proposed concept of lime particle adsorption on soil particles is somewhat similar to physical adsorption of calcium hydroxide molecules proposed by Diamond and Kinter (1965). However, considering that a clay-sized hydrated lime particle may contain 10^{11} molecules of $Ca(OH)_2$, a more significant time-dependent chemical reaction of adsorbed lime with soil particle surfaces is expected for adsorbed lime particles than for adsorbed lime molecules. Richardson et al. (1994) have mentioned layers of $Ca(OH)_2$ sandwiched between silicate layers.

particle size decreases and therefore, surface area increases, l_{ca} increases. Lime content consumed through adsorption is probably also related to the soil water content as it influences dispersion of soil particles and facilitates thorough mixing to allow full distribution and intimate contact between lime and soil particles, degree of pulverization of hydrated lime, and the intensity of mixing.

Because the solubility of calcium hydroxide in water is very small, for typical soil water contents a very small lime content is required to saturate the porewater. However, experience indicates that pH remains below 12.3-12.4 for lime contents far in excess of that required for the saturation of porewater. This behavior appears to suggest that lime adsorption must be satisfied before lime is dissolved in the porewater to increase the pH. Zolkov (1962) considered it as remarkable that in spite of the very small solubility of lime in water, large amount of lime was required "to bring the pH of the soil slurry to 12.6."

Most of the chemical reaction products have a layer structure, have high surface area, and a particle morphology that has been described as thin plates, foils, and rolled up sheets (Diamond et al. 1964; however sometimes fibers or laths occur which could contribute to particle interlocking, Richardson et al. 1994). On the other hand, adequate but not excessive lime attack may improve morphology of existing soil particles by producing ragged, irregular, frosted or serrated particles and following proper compaction connect them by the new reaction products. These features are expected to improve mechanical behavior of soils.

Because some of the reaction products during the stabilization process are amorphous and hydrated, drying of lime-treated soils during stabilization is likely to result in some irreversible dehydration as well as irreversible aggregation.

3 BRENNA FORMATION

The highly plastic lacustrine clays of Lake Agassiz lead to slope instability along the banks of the Red River that separates Grand Forks, North Dakota from East Grand Forks, Minnesota, as it flows north to Lake Winnipeg in Manitoba, Canada (Mesri and Huvaj 2004). The clays of the Red River slopes are the glacio-lacustrine deposits of glacial Lake Agassiz that is believed to have existed from 13,000 to 8,500 years before present, during the Late Wisconsin Glacial Episode of the Pleistocene Epoch (Quigley 1980).

The Brenna Formation, which is characterized as a uniform, soft to firm, dark grey, glacio-lacustrine clay with little or no visible stratification, is full of slickensided surfaces. The major source of sediment for the Brenna Formation was the highly plastic montmorillonitic Pierre Shale bedrock (Quigley 1968, Baracos 1977). The clay size fraction of Brenna Formation ranges from 60 to 95% (Arndt 1977). This unit is divided into Lower Brenna and Upper Brenna members. The natural water content, plastic limit and liquid limit of Lower Brenna are in the range of 42 to 69%, 20 to 40%, and 62 to 103%, respectively, and the corresponding range for Upper Brenna are 60 to 85%, 27 to 38%, and 107 to 154%, respectively. Samples of both Lower Brenna and Upper Brenna were used in the present investigation.

4 TESTS ON LIME-TREATED BRENNIA CLAY

Drained direct shear tests on lime-treated Brenna clay were performed using reconstituted specimens. Drained multiple reversal direct shear tests on precut specimens were used to measure residual shear strength, and drained direct shear tests on uncut specimens were used to measure fully softened shear strength. Air dry Brenna clay was pulverized until all of a representative sample passed the no. 200 US standard sieve.

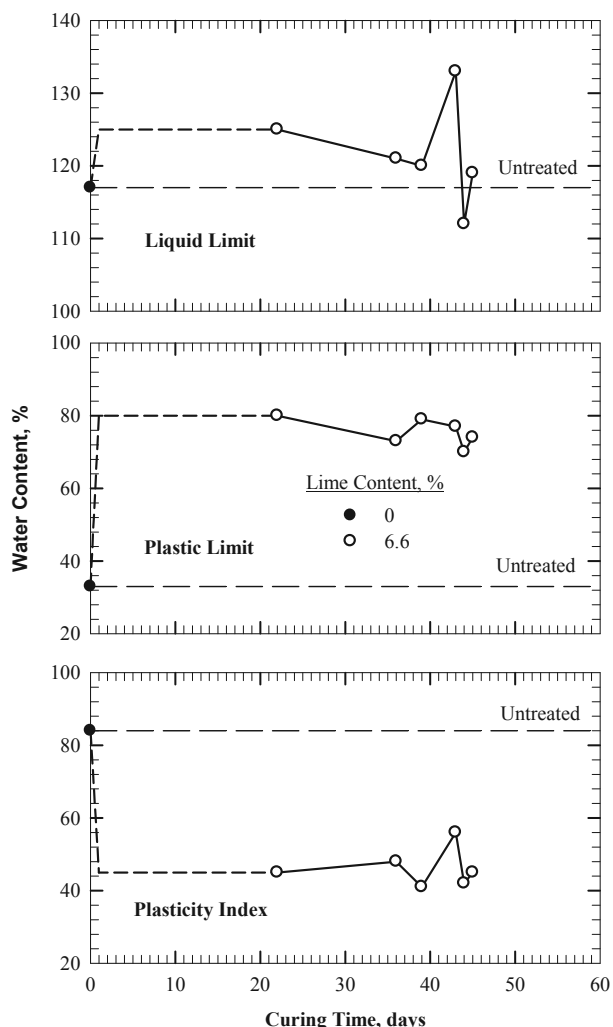


Figure 1. Lime-Brenna clay interaction under effective confining pressure

The lime content required to fully satisfy adsorption is mainly related to soil particle size and shape and therefore, the mineralogy of soil solids (Goldberg and Klein 1952, Eades and Grim 1960) and degree of dispersion or aggregation. As soil

The pulverized clay was mixed with dry hydrated lime, and was thoroughly rehydrated using distilled water. Two halves of the pre-cut specimen were formed by remolding or compaction and separately consolidated inside the top and bottom halves of the shear box using the procedure described by Mesri and Cepeda-Diaz (1986) and Mesri and Huvaj-Sarihan (2012). The consolidation pressure ranged from 100 to 450 kPa, and shear displacement rate was in the range of 3.3×10^{-4} to 5×10^{-4} mm/min.

Lime content as a percent of dry weight of clay ranged from 0 to 10%, and water content was in the range of 30 to 274%. In a few direct shear tests, dry hydrated lime was sprinkled on the exposed shear surface or on the top and bottom, of the direct shear specimen to examine lime diffusion.

For one series of direct shear specimens with lime content of 6.6%, liquid limit and plastic limit were determined at the end of the test. These data are shown in Fig. 1. For another series of lime-treated Brenna clay samples with lime content of 2, 5 and 9% and water content of 80, 100, 150 and 230%, pH and Atterberg limits were measured as a function of time. These samples were sealed; however, they were not subjected to confining pressure. The pH measurements are shown in Fig. 2, and the liquid limit and plastic limit at lime content of 5% and water contents of 80 and 100% are shown in Fig. 3.

The data on residual friction angle and fully softened friction angle from drained direct shear tests are summarized in Table 1. All index tests and direct shear tests reported here were performed at laboratory temperature of $20 \pm 2^\circ\text{C}$.

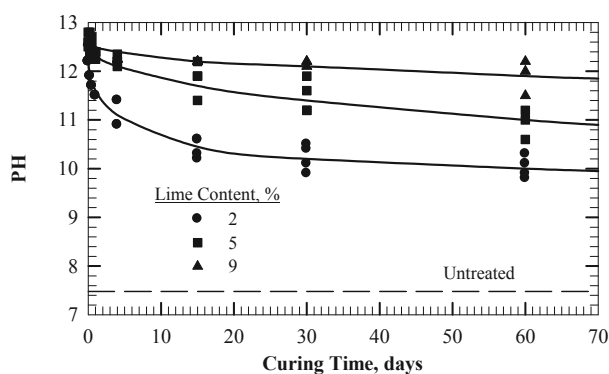


Figure 2. pH measurements of lime-Brenna clay

5 INTERPRETATION OF THE MEASUREMENTS

The pH measurements on lime-treated Brenna clay, such as those in Fig. 2 as well as others, show that immediately after introduction of lime, pH increases to a range of 12.2 to 12.7; shortly thereafter, however, pH begins to decrease. This observed behavior suggests that either within hours no free lime is left to dissociate to maintain pH above 12, or dissociated $(\text{OH})^-$ is simultaneously consumed by the silica and alumina dissolved from Brenna minerals. Nevertheless, during the 60 day observation period, pH remained above 9 suggesting continued lime-clay chemical reactions.

The rather immediate large increase in plastic limit above that of the untreated Brenna clay, such as observed in Figs. 1 and 3 results from flocculation and agglomeration of lime-treated clay, especially as the water content is reduced during the plastic limit measurements. Rapid chemical attack of adsorbed lime on clay particles contributes to the production of porous flocs and agglomerates that entrap water.

When the curing of lime-Brenna clay takes place unconfined, liquid limit dramatically increases above the liquid limit of untreated clay (Fig. 3); whereas when curing takes place under an imposed effective stress condition, such as the σ'_n in

the range of 100 to 450 kPa in the direct shear tests, there is a minor increase in liquid limit (Fig. 1). The interpretation of this significant observed behavior appears to be that when aluminosilicates form in unconfined condition, they hydrate fully, thus holding significant amount of water that contributes to the high liquid limit. On the other hand when lime-clay reaction products form under effective confining pressure, either the resulting aluminosilicates do not hydrate much or they experience irreversible dehydration through consolidation, thus resulting in little change in the liquid limit. The implication of this behavior, which is under more detailed examination, is significant for both laboratory study of lime-soil interaction to improve frictional resistance as well as field application of lime to remediate reactivated landslides.

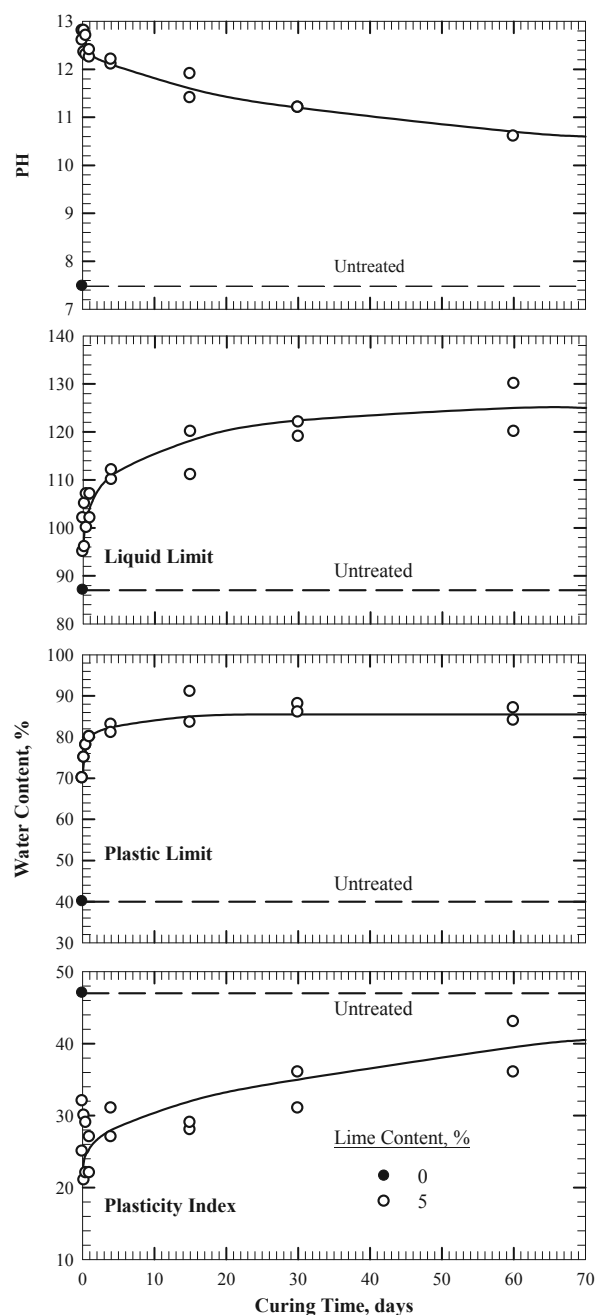


Figure 3. Lime-Brenna clay interaction under unconfined condition

The fully softened friction angle and residual friction angle of stiff clays and shales decrease with the increase in effective normal stress (Mesri and Shahien 2003, Mesri and Huvaj-Sarihan 2012). The secant friction angles of Brenna clay in

Table 1 correspond to effective normal stresses of 100 kPa and 300 kPa. Lime treatment of Brenna clay increased fully softened friction angle by 5 to 10° at effective normal stress of 100 kPa, and by 3 to 5° at 300 kPa. Lime treatment increased the residual friction angle by 3 to 6° at both 100 kPa and 300 kPa. These results suggest formation of stable clay aggregates through the lime-clay chemical reactions. These increases in frictional resistance were realized with lime contents in the range of 3 to 8% and treatment periods of 2 to 8 weeks. The detailed correlation between improvement in frictional resistance of Brenna clay as well as other stiff clays and shales, with lime content and with duration of treatment, is under further investigation with additional index and direct shear tests, including scanning electron observations of reaction products.

Table 1. Frictional resistance of lime-treated Brenna clay

Sample	I _c (%)	Curing (days)	w ₀ (%)	[φ [°] _{fs}] _s ¹⁰⁰	[φ [°] _{fs}] _s ³⁰⁰	[φ [°] _{rs}] _s ¹⁰⁰	[φ [°] _{rs}] _s ³⁰⁰
1	0.0	0	67	15	14	9	7
2 ^a	0.0	0	111	24	-	9	6
3 ^b	3.0	7	74	-	-	-	7
4	3.0	11	98	17	-	11	9
5 ^a	3.0	28	30	-	-	11	8
6 ^b	3.0	54	74	-	-	-	9
7 ^c	4.0	1	74	-	-	11	-
8	5.0	11	109	20	-	11	11
9 ^a	5.0	7	111	29	-	15	10
10 ^{a,d}	5.0	120	111	34	-	13	-
11	5.0	40	274	-	17	-	12
12	5.0	56	274	-	-	12	12
13	6.6	3	75	20	18	13	13
14	6.6	8	97	18	-	15	-
15	6.6	14	75	-	-	13	13
16	6.6	26	64	20	-	11	-
17	6.6	26	77	-	21	-	11
18	6.6	-	105	-	18	-	16
19 ^c	8.0	0.4	74	-	-	16	-
20 ^a	10.0	180	111	36	-	-	-

Notes:

- a- Lower Brenna was used for these specimens.
- b- Lime was sprinkled on top and bottom of the sample to investigate the treatment caused by lime diffusion.
- c- Lime was sprinkled on the shear surface.
- d- Lime-treated sample was stored for 120 days before being placed in the shear box.

For the 27th Avenue slide in Grand Forks, North Dakota (Mesri and Huvaj 2004), with entire slip surface in Brenna clay at residual condition, 5% lime content treatment of fifty percent of the slip surface increases computed factor of safety from 1.00 to the range of 1.26 to 1.37 (φ_r[°] = 7 to 8° increases to φ_r[°] = 12°). This level of lime remediation effort is expected to have a significant effect on rate of movement of the slide.

A combination of horizontal directional drilling (HDD), mechanical deep mixing (MDM) with augers and paddles, and dry jet mixing (DJM), together with signal receivers at the ground surface, is being investigated for introducing lime into clay along a pre-existing slip surface. The longest crossing of HDD to date has been 2000 m and borehole diameter of up to 160 mm.

6 CONCLUSIONS

Remediation of the montmorillonitic Brenna clay from North Dakota using lime contents of 3 to 8% and treatment periods of 2 to 8 weeks increased drained fully softened friction angle by 3 to 10° and drained residual friction angle by 3 to 6°, in the

effective normal stress range of 100 to 300 kPa. The increase in drained frictional resistance suggests formation of stable clay aggregates through lime-clay chemical reactions under the highly alkaline pH 12.5 to 9.8 environment measured over a period of 8 weeks. The measurements of liquid limit as an indicator of changes in particle size and shape resulting from lime treatment must be carried out on samples cured under an effective stress condition rather than sealed but unconfined. Unconfined lime treatment results in a significant increase in liquid limit, thus underestimating the decrease in plasticity index and associated increase in frictional resistance resulting from lime remediation.

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