Prediction of Geotechnical Properties of Lime-Stabilized Soils: Ongoing Research and Preliminary Results

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Abstract. This paper presents statistical models to estimate the geotechnical properties of lime-stabilized fine-grained soils. The geotechnical properties of the un-stabilized and lime-stabilized soils are measured based on the American Society for Testing and Materials (ASTM) standards. These properties include liquid limit, plasticity index, optimum moisture content, maximum dry density, and unconfined compressive strength. Findings indicated that the suggested regression equations exhibit excellent fit of data and can be used reliably and efficiently to predict the geotechnical behavior of lime-stabilized soil, as a rapid inexpensive substitute for cumbersome laboratory techniques. These models can be directly implemented into the design and construction of engineering earthworks including road subgrades, landfill liners, and foundations.

Keywords: Modeling · Lime · Stabilization · Fine-grained soil · Subgrade · Foundation · Geotechnical properties

1 Introduction

Index properties of fine-grained soils are very important since they influence the engineering behavior of such soils and they are linked to soil type and mineralogy. These properties include plastic properties, maximum dry density, optimum moisture content, strength, swelling, and consolidation. Measuring these properties is typically carried out experimentally in the laboratory, which usually takes considerable amount of time and effort.

Knowledge of index properties is necessary as to determine the suitability of soil for an engineering application including earth filling and selection of subgrade for pavement design. Very often, the soil is poor and requires some sort of treatment prior to engineering use. Generally, mixing fine-grained soils with additives improves the engineering behavior and sustainability of soil, and reduces long-term problems including swelling and deformation.

The aim of this paper is to model the geotechnical properties of lime-stabilized fine grained-soils, as reported by Ismeik and Shaqour (2018), with preliminary results derived from an ongoing research project.

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2 Materials and Experimental Work

The clay used in this study is a mixture of kaolinite and montmorillonite with other minerals including muscovite, goethite, gypsum, quartz, feldspar, illite, and hematite. In accordance with AASHTO M145-91 (2012) and ASTM D 2487-11 (2011) standards, the soil is classified as A-7-5 (42) and CH, respectively. A commercial lime is used to stabilize the soil. Physical and index properties of the clay and lime used in this investigation are given in Tables 1 and 2, respectively.

Table 1. Physical and index properties of fine-grained soil

Property	Value
Color	Red
Specific gravity	2.77
Atterberg limits	
Liquid limit (%)	73
Plastic limit (%)	41
Plasticity index (%)	32
Grading	
Coefficient of uniformity, C_u	10.2
Coefficient of curvature, C_c	1.45
Effective diameter, D_{10} (mm)	0.002
Nominal mean size, D_{50} (mm)	0.018
Maximum dry density (kN/m^3)	24.21
Optimum moisture content (%)	14.70
Unconfined compressive strength (kPa)	275
Class classification	
USCS	CH
AASHTO	A-7-5

Table 2. Physical properties of lime

Property	Value
Color	White
Specific gravity	2
Over 90 µm (%)	<9
Over 630 µm (%)	0
Insoluble material (%)	<1
Bulk density (g/l)	600–900
LOI (%)	23.9
pH	12.6
Reactivity (min)	<9

The following procedure is used to prepare the samples. After drying the soil at a temperature of 80 °C, the soil is mixed thoroughly with 2, 4, 6, and 8% lime. Water is added gradually and mixed with the lime-soil mixture until paste becomes homogeneous. Samples are prepared within the proctor mold at optimum moisture content and maximum dry density.

Un-stabilized and stabilized soil samples are experimentally tested to determine index properties of soil. Namely, Atterberg limits, and density-moisture relationships tests are conducted in accordance with ASTM D4318-10 (2010) and ASTM D698-12 (2012) standards, respectively. As for the unconfined compressive strength test, cylindrical samples of 70 mm in length and 35 mm in diameter are tested in accordance with ASTM D2166-13 (2013) standard with a loading rate of 0.1 mm/min.

3 Analysis of Results

3.1 Atterberg Limits

Consistency limits results of the untreated and lime-treated soils are presented in Fig. 1. The liquid limit, plastic limit, and plasticity index for the untreated soil were found to be 66.59, 31.65, and 34.94%, respectively. Treated soil showed relatively marginal change of liquid limit with increasing lime content (1.41%). Addition of lime increased the plastic limit by 56.87% at 2% lime content and thereafter remained almost constant with further increase of lime content. Plasticity index decreased about 64.08% when soil was treated with 2% lime with no further change with incremental addition of lime.

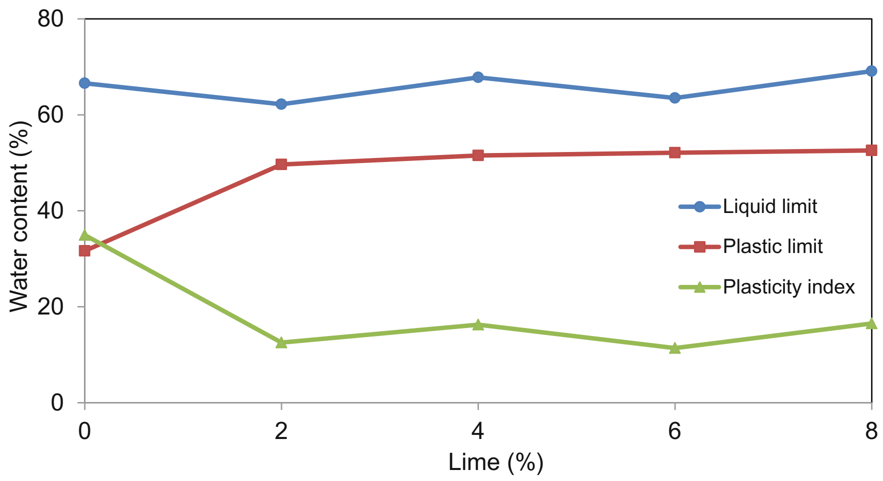

Fig. 1. Influence of lime content on Atterberg limits

Plasticity index reduction is mostly attributed to the increase of plastic limit associated with the addition of lime. Improvement levels are evident due to addition of lime. A concentration of between 2 and 8% is found to reduce the plasticity of soil. Similar results of treated soil are reported by Harichane et al. (2012), Sivapullaiah et al. (2000), and Prusinski and Bhattacharja (1999). The reduction of plasticity of the treated soil indicates that lime can be used to enhance clay workability, which expedites subsequent manipulation and placement of stabilized soil for roads and infrastructures construction.

3.2 Compaction Characteristics

The results of Proctor compaction tests, with various lime contents, are presented in Fig. 2 and summarized in Fig. 3. At 2, 4, 6, and 8% lime contents, compaction curves showed that the maximum dry density of treated soils, 12.81, 12.36, 11.90, and 12.20 kN/m^3, were lower than that of untreated soil 15.01 kN/m^3. Maximum dry density of treated soil was decreased by 14.65% with the addition of 2% lime and slightly reduced with the further addition of lime. The decrease of maximum dry density of soil was 18.72% at 8% lime content. Reduction of maximum dry density is linked to the lower value of specific gravity of lime (2) than that of soil (2.77).

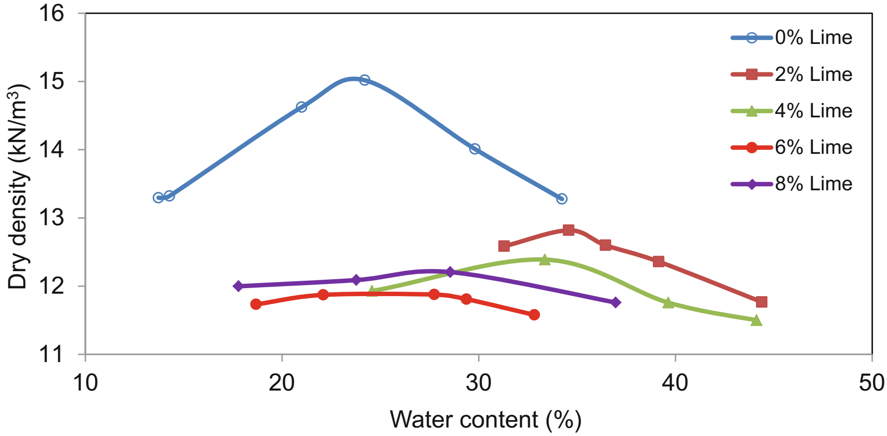

Fig. 2. Density-moisture relationships for the soil before and after lime treatment

Optimum moisture content was 42.56% higher for the stabilized soil than that of unstabilized soil at 2% lime content. Overall, that the addition of lime increased the optimum moisture content of treated soil at lime contents between 2 and 4%. Thus, as lime contents increases, optimum moisture content increases and maximum dry density decreases, which is in agreement with the studies of Jafari and Esna-ashari (2012), Harichane et al. (2012), and Al-Kiki et al. (2011).

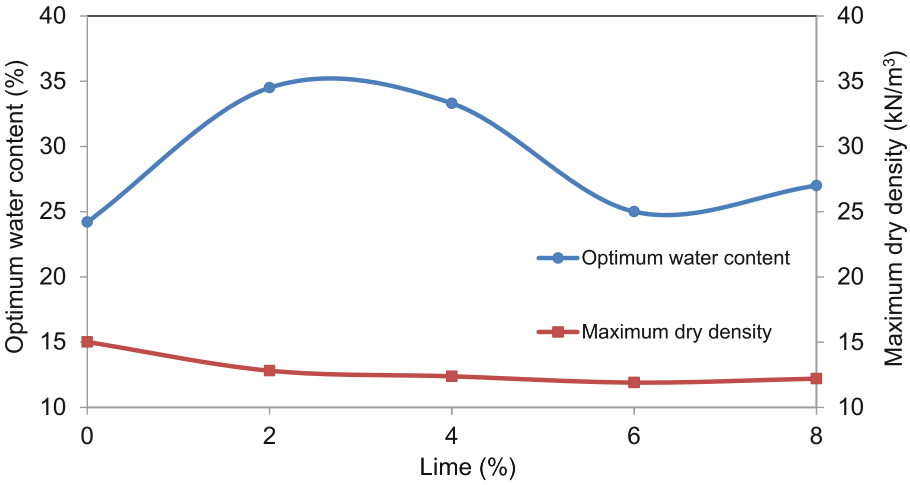

Fig. 3. Influence of lime content on compaction properties

3.3 Unconfined Compressive Strength

Strength results of the untreated and lime-treated soil samples, cured for 28 days, are shown in Fig. 4. The unconfined compressive strength values of untreated soil and 2 and 4% lime contents were 275, 452, and 606 kPa, respectively. The strength of treated samples increased with the increase of lime content until it reaches a peak value of 1632 kPa at 6% lime content. However, further addition of lime to 8% reduced the strength to 1386 kPa.

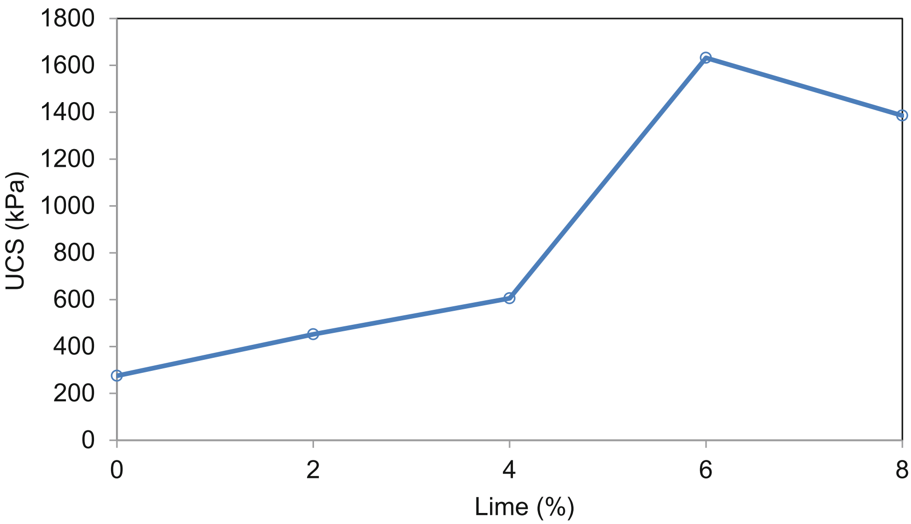

Fig. 4. Influence of lime content on the unconfined compressive strength of soil

The results show that 6% of lime achieves the maximum strength for the clay (5.93 fold). As noticed, the 8% lime strength value was slightly lower than that of 6% lime. This is explained by the negative effect of excess lime, which leads to incomplete hydration reaction between the soil and available water in the mixture. This behavior is similar to other studies reported by Jafari and Esna-ashari (2012), Lin et al. (2007), and Okagbue and Yakubu (2000).

3.4 Statistical Analyses

An attempt is made to determine the relationship between soil index properties and amount of added lime. Statistical regression techniques were employed to predict such relationships. In this context, linear and nonlinear models were developed to establish the association between the independent variable, lime content (L), and depended variables, soil properties, namely, liquid limit (LL), plasticity index (PI), optimum moisture content (OMC), maximum dry density (MDD), and unconfined compressive strength (UCS). As a result, 5 models were developed and grouped into three classes as shown below.

Atterberg limits

$$\mathrm{LL} = 66.473 + 1.904\mathrm{L} - 4.747\mathrm{L}^{0.5} \quad \left(\mathrm{R}^2 = 0.392\right) \tag{1}$$

$$\mathrm{PI} = 34.711 + 5.441\mathrm{L} - 21.938\mathrm{L}^{0.5} \quad \left(\mathrm{R}^2 = 0.937\right) \tag{2}$$

Compaction properties

$$\mathrm{OMC} = 0.227\mathrm{L}^3 - 3.148L^2 + 11.002L + 24.014 \quad \left(\mathrm{R}^2 = 0.973\right) \tag{3}$$

$$\mathrm{MDD} = 15.021 + 0.389L - 2.139L^{0.5} \quad \left(\mathrm{R}^2 = 0.989\right) \tag{4}$$

Unconfined compressive strength

$$\mathrm{UCS} = 297.583 + 666.141L - 516.489L^2 + 127.002L^3 - 8.833L^4 - 18.959N \quad \left(\mathrm{R}^2 = 0.990\right) \tag{5}$$

The reliability of the models is verified with the coefficient of determination (R^2) test. As calculated, the values of R^2 for Eqs. 1 to 5 were 0.392, 0.937, 0.973, 0.989, and 0.990. Since these values are very close to 1, with exception of Eq. 1, we can conclude that these models are valid and useful to estimate reliability and efficiently the physical properties of lime-treated soils used in this study.

4 Conclusions

In this experimental investigation, an effort was carried out to improve the physical properties of fine-grained subgrades used for pavement construction. Benefits of lime treatment of fine-grained soils were quantified. As a result, plastic properties were enhanced, optimum moisture content was increased, and maximum dry density was decreased. An amount of about 6 to 8% lime content was found to greatly improve the unconfined strength of soil, which is an essential parameter for pavement design. Such treatment can significantly reduce permanent deformation (rutting) in flexible pavement due to weak subgrade soil. The suggested models were found useful to determine geotechnical properties of lime-treated clays instead of laboratory testing.

5 Future Additional Research

The work and initial results presented in this publication are preliminary in the context of an ongoing larger research project. It is early to generalize these findings for different clays since the mineralogy of soil has an effect on the treatment process. The experimental laboratory results, modeled in this publication, are obtained from the findings of Ismeik and Shaqour (2018). Additional work is underway to further investigate the durability and long-term performance of lime-treated clays and the outcomes will be published in due course.

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