Stabilization of sensitive clays for reuse using a chemical process

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ABSTRACT
Champlain Sea clays are known to have high plasticity and sensitivity, making it difficult for them to be reused as construction materials. This experimental study was conducted to verify the effect of adding chemical products, such as quicklime and a lime co-product; i.e., the LKD (Lime Kiln Dust), on the geotechnical behavior of clays. The results show that the addition of those products to the clay increases the consistency limits considerably. A mass percentage of quicklime of 1.6% (3.4% corresponding percentage for the LKD) is optimal for generating pozzolanic reactions and obtaining sufficient trafficability (consistency index > 0.75) for the material to be reused. A significant gain in shear strength of the amended clays was obtained over a 17-day period. The permeability of the mixtures obtained is of the order of 10^{-7} cm/s.

RÉSUMÉ
Les argiles de la Mer de Champlain sont reconnues pour posséder une plasticité et une sensibilité élevées, rendant difficile leur réutilisation comme matériaux de construction. Une étude expérimentale a été réalisée pour vérifier l'effet de l'ajout de produits chimiques, tels que la chaux vive et un coproduit de la chaux, le LKD (Lime Kiln Dust), sur le comportement géotechnique des argiles. Les résultats démontrent que l'ajout des produits chimiques à l'argile engendre une augmentation des limites de consistance. Un pourcentage massique de chaux vive de 1,6 % (3,4 % pour le LKD) est optimal pour engendrer des réactions pouzzolaniques et obtenir une traficabilité suffisante pour la réutilisation (indice de consistance > 0,75). Un gain significatif de la résistance au cisaillement des argiles amendées a été obtenu sur une période de 17 jours. La perméabilité des mélanges obtenus est de l'ordre de 10^{-7} cm/s.

1 INTRODUCTION

Champlain Sea clays are known to have high plasticity and sensitivity, but are rarely considered as construction materials. A commonly used technique to reuse them is dewatering by spreading, which needs significant time and cost. A complementary technique is to amend the clay with chemicals (e.g., lime). Improving the properties of clayey soils by such treatment is a technique widely used in Europe (e.g., Herrier et al. 2015). In Quebec, this process is mainly employed in road engineering (e.g., MTMDET 2017) and agronomy (e.g., Weiss and Lepage 2010).

The stabilization of a clayey soil with lime is a cold treatment technique that generates two dominant chemical reactions: flocculation and cementation (also called pozzolanic reactions). The phenomenon of flocculation is reflected by the agglomeration of the clay particles in the mixture. Flocculation acts instantaneously on the deformation-loading properties of the soil. As for pozzolanic reactions, they create a process of cementation by creating secondary minerals, such as hydrated calcium silicates (Tironi et al. 2013). These reactions contribute to the increase in the long-term soil resistance (Bell 1988; Thompson 2005). Pozzolanic reactions are triggered at a critical pH level of 12.4 (McCallister and Petry 1992; Locat et al. 1996). Eades and Grim (1966) proposed an experimental method to obtain the critical pH of a mixture as a function of the percentage of lime added. This method is described in ASTM C977.

Adding lime to a clayey soil generates a decrease in the limit of liquidity and an increase in the plasticity limit, thus generating a significant reduction in the plasticity of the soil (Bourkba Mrabent et al. 2017). Moreover, chemical reactions induced by adding lime to clayey soil has little or no influence on the natural water content. The soil, therefore, changes from a plastic state (deformable) to a solid state (rigid), resulting in a significant increase of the material trafficability. The latter is defined as the capacity of a soil to be handled and to be easily densified without loss of significant resistance. The trafficability of a material is related to the consistency index (I_c), which is a function of the water content (w), the liquid limit (w_L), and the plasticity limit (w_P) (Eq. 1).

$$I_c = (w_L - w) / (w_L - w_P) \qquad [1]$$

In the field of agronomy, it has been shown that a clayey soil with a consistency index higher than 0.75 has sufficient trafficability to allow the circulation of agricultural machinery (Gliński, Horabik and Lipiec 2011).

In addition to having an impact on the soil consistency limits, a clayey soil treated with lime promotes the rearrangement of particles (defined as the agglomeration phenomenon), which results in a decrease in maximum dry density and in an increase in the optimal water content of the material. This phenomenon reduces the energy required to achieve a desired degree of compaction (Kavak and Tüylüce 2012; Bourokba Mrabent et al. 2017). Moreover, Louafi et al. (2015) have shown that the gain in shear resistance induced by the addition of lime is as important as the storage time of the material.

The state of the art on treatment of clayey soil with lime has shown that geotechnical properties of a clayey soil vary significantly when adding lime in a ratio between 1 and 6% (Bell 1988). However, clayey soils with a high organic matter content may inhibit the chemical reactions generated by the addition of lime (Tremblay, Leroueil, and Locat 2001).

This article presents the results of an experimental study conducted to test the effects of adding two chemicals; namely, quicklime and a lime co-product, the Lime Kiln Dust (LKD), on geotechnical behavior of Champlain Sea clays.

2 CASE STUDY

2.1 Context

This study was conducted as part of excess clays reutilisation project for the construction of dikes and covering layers for landfill cells in a site located north of Montreal, in the Laurentides region.

Criteria for reusing clays, as required for this project, are summarized as follows:

- $k_{dike} < 1 \times 10^{-7}$ cm/s;
- $k_{covering\ layer} < 6 \times 10^{-7}$ cm/s
- Increase the clay trafficability ($I_c > 0.75$)

2.2 Materials

Remolded clay samples were collected using an excavator during summer 2017. Representative sub-samples were tested in laboratory for geotechnical characterization. Table 1 summarizes the main geotechnical properties of the natural clay.

Table 1. Geotechnical properties of the natural clay

Parameters	Values (%)
Water content (w)	59
Liquid limit (w_L)	50
Plastic limit (w_P)	23
Sand content (particles greater than 80 μm)	5
Silt content (particles included between 2 and 80 μm)	39
Clay content (particles lower than 2 μm)	56

The remolded clay material is composed of clay and silt with traces of sand and is classified as CH according to the Unified Soil Classification System (USCS) based on ASTM D2487. The clay deposit is gray, has a high plasticity, and tends to behave like a liquid when remolded or subjected to vibration. Th clay deposit also has a low consistency index, which indicates that the material contains an inadequate trafficability to allow reuse and efficiently compaction. The natural clay deposit has a pH of 8.35.

Quicklime is mostly composed of calcium oxide (CaO) obtained by controlled calcination of calcareous rocks. The sample used for this study contained 94.8% of total CaO. LKD is a co-product of quicklime and is mainly composed of calcium carbonate ($CaCO_3$) and CaO. The LKD used for this study contained 48.5% of total CaO. This value is subject to variations since the LKD is a bulk product and is not standardized.

2.3 Methodology

Clay samples amended with quicklime and LKD were submitted to the laboratory test program summarized in Table 2.

Consistency limits were determined on clay samples amended to 2, 4, and 6% of quicklime and 5, 10, and 15% of LKD. These chemical contents were based on the results obtained from the procedure described in ASTM C977. Clay samples amended to their optimal quicklime and LKD percentages (I_c of at least 0.75) were subjected to compaction and permeability tests.

Monitoring the gain of undrained shear strength in time was also performed in laboratory for a LKD-amended clay sample and a remolded natural clay sample. The undrained shear strength of samples was measured using a Geonor-type pocket vane calibrated for a measurement range varying between 0 and 260 kPa. Samples were placed in 406 mm x 102 mm x 90 mm molds. Materials were densified by using simple pounding to roughly eliminate voids and agglomerates. Samples were measured daily for a period of over 17 days. They were covered with a plastic film between each measurement to prevent drying during the test.

2.4 Mixture preparation

The following experimental procedure describes the sequence performed in the laboratory to prepare a serie of clay samples amended with quicklime or LKD at a given percentage:

1) Sampling a sufficient amount of natural clay to perform a given series of tests;
2) Evaluating the initial water content of the natural clay, then calculate its dry mass;
3) Calculating the chemical mass to be added to the mixture with Equation 2 to achieve the targeted amendment percentage;
4) Grab-sampling the quantity obtained in step 3;
5) Pouring the chemical on the remoulded clay while homogenizing the mixture with a mechanical mixer over a 5-minute period (rotation frequency of the mixer: 120 rpm);
6) Removing the excess material on the pallets of the mixer and homogenize manually using a trowel;
7) Comparing the total mass of the amended material with the initially mass calculated for validation, then storing the amended sample in an airtight bag or container for 24 to 48 hours to ensure uniformity and hydration (LCPC 2000);

Table 2. Laboratory test program

Test	Standard	Number of tests performed on clay-quicklime mixtures	Number of tests performed on clay-LKD mixtures
Proportion of chemicals for stabilization	ASTM C977	1	1
Consistency limits	BNQ 2501-092	4	4
Water content	BNQ 2501-170	10	10
Modified effort compaction test	BNQ 2501-255	1	1
Standard effort compaction test	BNQ 2501-250	1	1
Reduced effort compaction test[1]	BNQ 2501-250	1	1
Permeability test in a triaxial cell[2]	ASTM D5856	3	4

[1] 15 hammer impacts induced for each layer instead of 25

[2] Samples were tested on the wet side of the compaction curve using the constant flow method

8) Grab-sampling the needed amount of amended clay to perform the desired test; and,
9) Measuring the initial water content of the mixture before performing each test.

The calculation of the amount of chemicals to be added to the clay sample to obtain a given percentage of amendment is based on the ratio between the mass (M) of the added product and the sum of the dry masses (M_s) of the components of the mixture (Eq. 2). Given that the quicklime percentage that LKD contains is determined by chemical analysis, it is possible to convert the percentage of lime to the equivalent percentage of LKD (Eq. 3).

$$\% \text{ quicklime/LKD} = M_{quicklime/LKD} / (M_{quicklime/LKD} + M_{s\ clay}) \quad [2]$$

$$\% \text{ LKD} = \% \text{ quicklime} / (\% \text{ quicklime}_{LKD} / 100) \quad [3]$$

2.5 Results

At first glance, a significant change in the consistency of the material before and after the addition of the chemicals is observed, as shown in Figure 1. The clay changes from a muddy consistency to a more rigid material that tends to form small agglomerates.

a) b)

Figure 1. Consistency of material before (a) and after (b) the addition of quicklime and LKD

Figure 2 illustrates the variation of the consistency index as a function of the quicklime and LKD percentages added to a clay sample. An optimal percentage of 1.6% for quicklime (3.4% for LKD) was obtained to initiate the pozzolanic reactions within the mixture and to obtain a sufficient trafficability (I_c > 0.75).

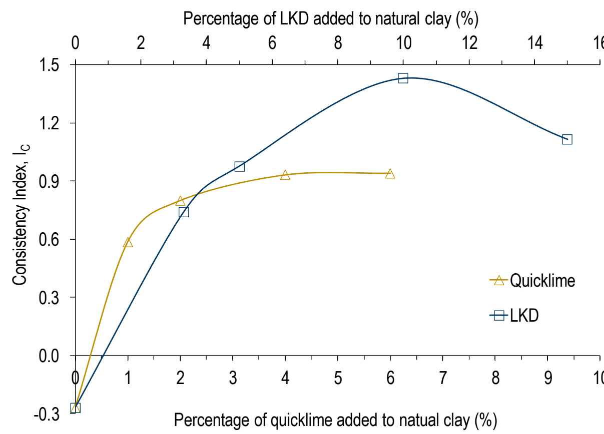

Figure 2. Consistency index as a function of chemical percentages added to the clay

Figure 3 shows the consistency limits of clay samples amended to the optimal quicklime and LKD content established previously. Results show that adding chemicals to clay generates an increase of the consistency limits without affecting the initial water content of the material.

Figure 4 shows the comparison between the undrained shear strength gain in time of a 3.4% LKD-amended clay sample and a remolded clay sample. The shear strength of the amended clays is about 14 times higher than the remolded clay sample after a 17-day ripening period.

Table 3 presents the permeability values obtained on clay samples modified with quicklime and LKD at their optimal percentage. The permeability range of the samples varies between 1.5 and 4.3 x 10^{-7} cm/s for anticipated field conditions (compaction energy and water content).

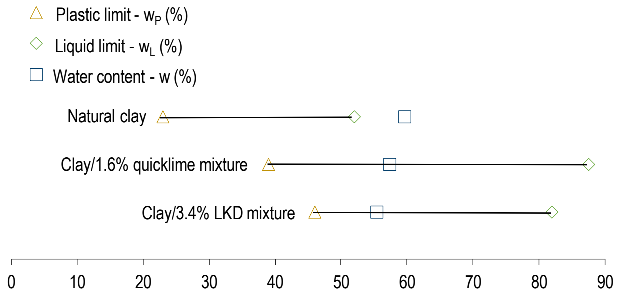

Figure 3. Consistency limits as a function of the optimal chemical content

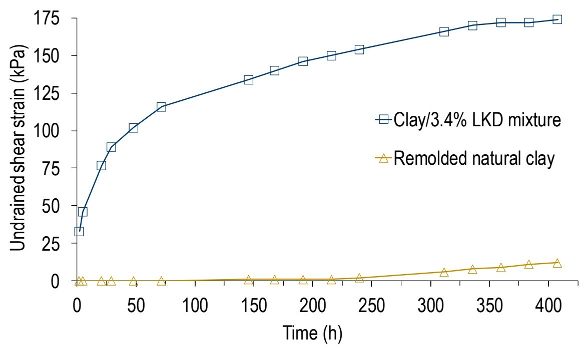

Figure 4. Comparison between undrained shear strength in time for a 3.4% LKD-amended clay sample and a remolded clay sample

Table 3. Permeability test results

Mixture	Initial water content, w (%)	Dry density, ρ_d (kg/m^3)	Final saturation rate, S_r (%)	Permeability, k (cm/s)
Clay-1.6% quicklime	23.7	1586	99.9	2.4E-07
	26.3	1543	99.2	1.5E-07
	29.5	1482	99.8	4.3E-07
Clay-3.4% LKD	23.6	1558	99.9	2.6E-07
	26.4	1497	99.8	2.1E-07
	29.6	1439	99.9	2.9E-07
	51.7	1121	99.8	3.2E-07

3 DISCUSSION

Figure 5 illustrates the compliance interval to fulfill the reuse criteria for clayey soil optimally amended with quicklime and LKD. The boundaries of the interval are defined by the optimum water content evaluated according to the modified compaction energy, the maximum degree of theoretical saturation, the threshold of trafficability, and the threshold of permeability. This figure is intended to be a tool for monitoring the permeability of soils based on their dry density and water content values (using a nuclear/moisture density gauge, for instance). This type of visual tool is widely used in the design of dike and dam cores (e.g., Qian et al. 2002).

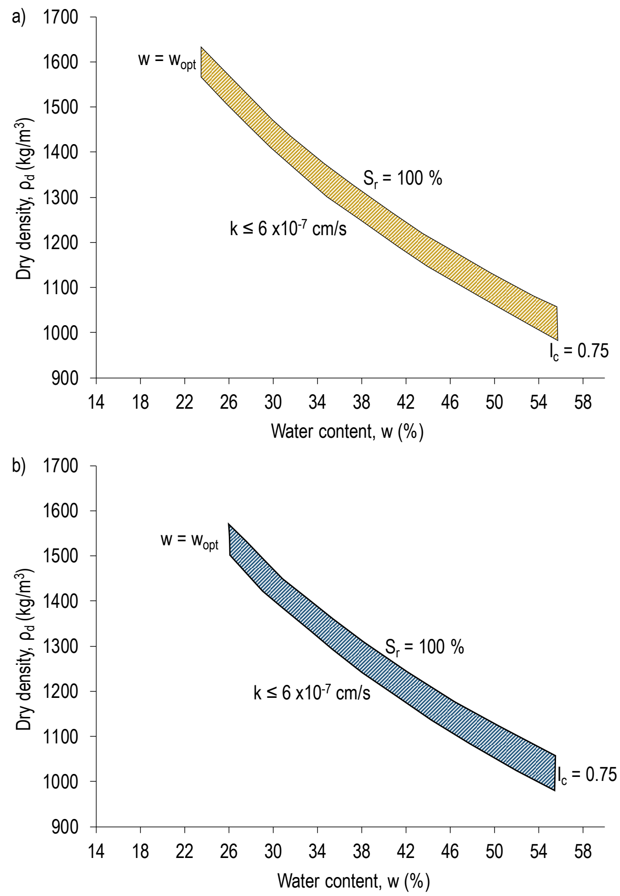

Figure 5. Compliance interval to fulfill the reuse criteria for clayey soil amended with 1.6% of quicklime (a) and 3.4% of LKD (b)

The range of permeability values obtained on clay samples amended to an optimal percentage of lime and LKD demonstrates that such amended materials can be reused for the purposes of the project as covering layers of the landfill cells. However, the permeability requirement is not fulfilled for the anticipated field conditions for the development of dikes. Therefore, it may be possible to increase the percentage of amendment or compaction energy. In that sense, McCallister and Petry (1992) have established that the permeability of amended clayey soils tends to increase until the optimal percentage threshold of amendment (pH of 12.4) is reached; then significantly decreasing once this threshold value is exceeded.

Generally, results of the current study demonstrate that the LKD used for this study is as effective as quicklime in term of stabilizing clays with high plasticity and sensitivity, thus involving a higher amount of product. In addition, this product can often be obtained at a lower price than standardized quicklime, which can be cost-effective depending on the needs of the project.

As for the shear strength of amended clays, Figure 4 demonstrates that the maximum gain is not necessarily obtained at the chemical concentration threshold required to stabilize the clayey soil, as determined by the method introduced by Eades and Grim (1966). The resistance gain is rather mostly affected by the maturation time (ripening period) of the amended clay (Locat et al. 1996; Louafi et al. 2015). Effort applied during compaction and percentage of amendment could also have an impact on the shear strength of the material.

Results obtained from the laboratory testing have shown that the liquid limit of the clay increases considerably following the addition of chemicals (Figure 3). However, many studies have demonstrated the opposite behavior (Bell 1988; Locat et al. 1996; Bourokba Mrabent et al. 2017). It is important to mention that the substantial increase in the plasticity limit further affects the plasticity index of the soil, and therefore, its trafficability. To establish the potential causes of this disparity, the determination of the consistency limits of the treated soil should be achieved after a longer maturation period.

Overall, some uncertainties persist regarding the different phenomena that may affect the validity and reproducibility of the results. These uncertainties include, but are not limited to:

- *Temperature*. It is known that effectiveness of pozzolanic reactions generated by the addition of quicklime depends on the temperature (Tironi et al. 2013). Mixing and temporarily storing a quantity of treated clay at a high temperature could amplify and accelerate the gain in shear strength.
- *Perpetuity of chemical reactions.* Pozzolanic reactions are responsible for the long-term soil resistance gain and are directly related to the pH of the mixture. If the pH decreases once the clay is treated with chemicals, it could generate an opposite effect and destabilize the soil. There are also uncertainties about the maximum percentage of chemical that can stabilize the clay. Bourkba Mrabent et al. (2017) stated that there is a maximum lime dosage beyond which mechanical performance (consistency limits, shear strength, etc.) will no longer be optimized.
- *Maturation period*. The maturation period of the mixture is an important parameter in the treatment process. For this study, a maturation period varying from 24 to 48 hours was imposed on amended samples before executing a given test, as discussed by LCPC (2000). This could have an impact on the results, knowing the effect between maturation time and certain geotechnical parameters (Louafi et al. 2015). For some projects, immediate results are imperative, while others require a longer maturation period (in the order of several weeks) (Thompson 2005).

Results obtained from this study will be subject verification on field throughout a pilot test. It is important to reiterate that these results were obtained in a laboratory on clay samples of small dimensions. Thereby, the expected behavior may be different depending on the volume of clay tested. The pilot test will be carried out on a large scale to highlight possible disparities induced during the fieldwork and to validate the results obtained in the laboratory. In addition, the construction of a field test board will allow for the development of a control/quality program.

4 CONCLUSION

An experimental study was conducted to verify the effects of adding chemicals, such as quicklime and a lime co-product, the Lime Kiln Dust (LKD), on the geotechnical behavior of Champlain Sea sensitive clays. This study was conducted as part of a project resulting in the reuse of excess clays for the construction of dikes and cover layers for landfill cells in a site located north of Montreal. Criteria for reusing clays, as required for this project, are summarized as follows:

- $k_{dike} < 1 \times 10^{-7}$ cm/s;
- $k_{covering\ layer} < 6 \times 10^{-7}$ cm/s
- Increase the clay trafficability ($I_c > 0{,}75$)

Experimental results have shown that the addition of quicklime and LKD significantly increases the consistency index of the clay, and that the longer the storing time of the amended clay is, the more significantly its shear strength increases.

A sufficient trafficability of mixtures was reached at a minimum percentage of 1.6% for quicklime and 3.4% for LKD. The permeability of the mixtures varies between 1.5 and 4.3 x 10^{-7} cm/s at these optimal percentages for the anticipated field conditions. The increase in the compaction effort and/or in the percentage of amendment must be considered to fulfill the criterion of permeability for the dikes. It is recommended to carry out a pilot test on field to validate the expected behavior of clays amended with quicklime and LKD. On-site permeability monitoring can be performed using measurements of dry density and water content using a nuclear/moisture density gauge.

The aforementioned conclusions are consistent only to clay and chemical samples used in this study. Therefore, prior to the use of this technique on a large-scale project, additional tests will be relevant to establish, for instance, a correlation between different percentages of lime contained in the LKD and the minimum percentage of LKD required to fulfill all conditions and the design criteria required.

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