Experimental Investigation of Cement Mixing to Improve Champlain Sea Clay: A Case Study

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ABSTRACT
This paper presents the results of a laboratory testing program completed on cement-treated soil samples. Soil samples of soft to firm cohesive soils were retrieved at a project site located at County Rd 2/34 and Hwy 401 near the city of Ottawa in MTO's Eastern Region in Ontario, Canada. The objective of the laboratory testing program was to assess the applicability and effectiveness of deep soil mixing (DSM) method with cement in treating sensitive Champlain Sea clay. DSM is an alternative innovative ground improvement technique that has many advantages, including a rapid increase in the soil strength, low adverse environmental impact, cost efficiency, applicability to large improvement area, and wide relevancy to any soil type with an appropriate design. The laboratory test program test parameters included variable cement dosages, mixing methods, and curing durations. Both unconfined compressive strength (UCS) tests and constant rate of strain consolidation tests were carried out on cement-treated samples with different curing times to assess strength gain and compressibility behaviour. Based on the test results, cement can significantly increase the strength of Champlain Sea clay and reduce its compressibility. The goal of this research is to develop alternatives that considers DSM as an option in the ground improvement tool box for application to infrastructure in Ontario.

RÉSUMÉ:
Cet article présente les résultats d'un programme d'essais en laboratoire effectué sur des échantillons de sol traités avec du ciment. Le programme d'essais en laboratoire visait à évaluer l'applicabilité et l'efficacité mélange de sol avec ciment pour le traitement des sols argileux de la mer de Champlain compressibles et de faible résistance. Le mélange de sol avec du ciment est une technique d'amélioration des sols qui a de nombreux avantages, tel qu'une augmentation en résistance au cisaillement, faible risques environnemental, prix compétitif et applicabilité pour diffèrent types de sols. Dans la présente étude, des échantillons d'argile en vrac et relativement peu perturbés ont été recueillis provenant d'un site dans l'est de l'Ontario. Les échantillons prélevés ont été mélangés avec différentes doses de ciment (le matériau liant) et guéri pendant 7, 14, 28 et 56 jours et en effectuant des essais de compression en entre chacune de ces étapes. Le résultat des essais a montré une grande augmentation de la résistance pour les échantillons traités avec du ciment après seulement 7 jours de guérison par rapport aux échantillons non traités. Cependant, la résistance des échantillons traités de ciment n'a pas amélioré considérablement au-delà de 7 jours. De plus, la compressibilité a été réduite de 21 pourcent pour les échantillons traité de ciment. Le but du projet de recherche était de vérifier si les sols argileux de la mer de Champlain traités avec du ciment est une option d'amélioration des sols qui peut être utilisé avec succès pour les projets infrastructure en Ontario.

1 INTRODUCTION

The Ministry of Transportation of Ontario (MTO) sustains its infrastructure by constructing new embankments, widening existing embankments, modifying existing highway profile grades and maintaining existing embankments. Fulfilling this mandate is challenging at sites underlain by highly compressible soils with relatively low shear strengths. Embankment design and construction must consider embankment settlement and stability to ensure the short term and long term performance of the highway embankments.

The MTO is committed to building embankments faster and more cost effectively without compromising quality. Investment in new and innovative technologies is prioritized as part of the Provincial Highway Management strategic direction.

When designing and constructing embankments over low strength compressible soils, intrusive ground improvement technologies are alternatives to conventional methods such as excavation and replacement, lightweight fills, preload and surcharge. Typically, on any given project at the MTO, embankment design alternatives are identified, and the preferred option is selected based on advantages, disadvantages, costs, risks and consequences. This assessment was carried out for the Hwy 401 and County Rd 2/34 Underpass replacement project in Lancaster, Ontario. Ground improvement was selected as the preferred option for the construction of new embankments over a deposit of low strength and compressible Champlain Sea clay situated adjacent to existing embankments at the approaches to a new realigned bridge structure.

Ground improvement technology is a highly specialized discipline and the MTO recognizes that the selection of the preferred ground improvement technology requires expertise and experience provided by specialist Contractors. The MTO equally recognizes that the specialist Contractor requires a high level of understanding of the subsurface model and that conventional laboratory and in-situ testing methods need to be augmented as necessary in order to select an appropriate ground improvement method.

Accordingly, the MTO invested in a laboratory testing program with the awareness that Deep Soil Mixing (DSM) is one ground improvement option at the Hwy 401/County Rd2/34 site. DSM is a ground improvement technique in which weak and compressible soils are mixed in-situ with a binder (typically cement-based) to improve their strength properties (Kitazume and Terashi 2013). Its advantages over other ground improvement techniques include low vibrations and low spoils. Studies on DSM in Ontario are limited, although Locat et al. (1990) and Li et al. (2016) confirmed the feasibility of using DSM to improve the strength of sensitive marine clay in Ontario.

This paper presents the results of a laboratory testing program that demonstrates improvement in the strength and compressibility characteristics of the cohesive soil present at the Highway 401/County Road 2/34 site when mixed with a suitable binder.

2 ENGINEERING BACKGROUND

The County Road 2/34 Underpass Bridge extends over Highway 401 in Lancaster, Ontario. The existing bridge is about 67 m long and carries the two traffic lanes of County Road 2/34 over the four-lane and median-divided Highway 401. It was constructed in 1963 and consists of a two-span cast-in-place concrete box girder structure with abutments and a central pier founded on piles. The existing embankments are up to 8 metres in height above the natural ground level. Several alignment alternatives were evaluated for the replacement structure during the preliminary design stage and it was decided that the alignment of the underpass would be shifted to the west, immediately adjacent to the existing alignment.

As part of the detail design for the proposed bridge replacement, a foundation investigation was carried out by Golder Associates Ltd. (Golder) to assess the subsurface conditions in the area of the site. In general, the surficial soils at the location of the proposed County Road 2/34 Underpass alignment were found to consist of a surficial layer of fill and/or topsoil (with some localized peat) underlain by a thick compressible clay deposit. The clay extends to depths of about 10 to 11 m and varies from about 9 to 10 m in thickness at the site. The clay is underlain by relatively thin deposits of glacial till and/or sand and gravel which in turn are underlain by limestone bedrock.

The deposit of sensitive and compressible marine clay at the site is known as Champlain Sea clay, which is potentially vulnerable to undergoing significant consolidation settlement when it is subjected to stress increases that exceed the deposit's pre-consolidation pressure. Below the upper weathered portion, the clay has a soft to stiff consistency, but is more generally firm. The average sensitivity ratio of 6, based on remoulded shear strengths in this deposit, indicates a sensitive material. Oedometer consolidation testing was carried out on three samples of clay and the results indicate that the clay is slightly overconsolidated, with pre-consolidation pressures of about 100 to 140 kPa and overconsolidation ratios of 1.4 to 1.8. A summary of the engineering properties that were measured/estimated for the Champlain Sea clay deposit is presented on Figure 1 below.

This subsurface information was used for the foundation design, which included an assessment of the proposed embankments, as discussed below.

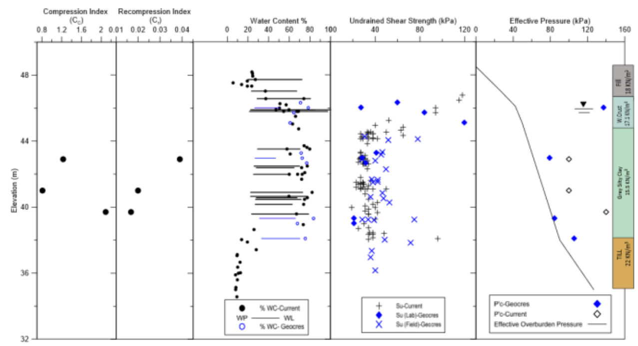


Figure 1. Summary of engineering properties by elevation for the Champlain Sea Clay deposit at the bridge site

3 EMBANKMENT DESIGN

With the alignment of the new bridge structure shifted to the west (immediately adjacent to the existing alignment), new embankments (which will encroach on the existing embankments) are required about 8 m in height and about 15 to 20 m in width at the crest to accommodate this shift. The proposed pavement grades at the new structure will be up to about 0.5 m higher than the existing pavement grades.

A background review of the existing embankments confirmed a history of settlement and settlement related problems during the service life of the existing bridge. The existing bridge was built in 1963 and settlement of over 1.5 m was measured between 1963 and 1984 (see Figure 2). In 1967, the measured horizontal movements between the bridge deck and the abutments ranged from 75 mm to 125 mm. Embankment design consisted of an embankment settlement and stability analyses.

3.1 New Embankment Settlement

The settlement analyses for the new embankments considered the settlement of the native soil beneath the existing embankments, the settlement beneath the new embankments and the differential settlement between the new and the existing embankment fills. Settlements within the fill itself were also considered.

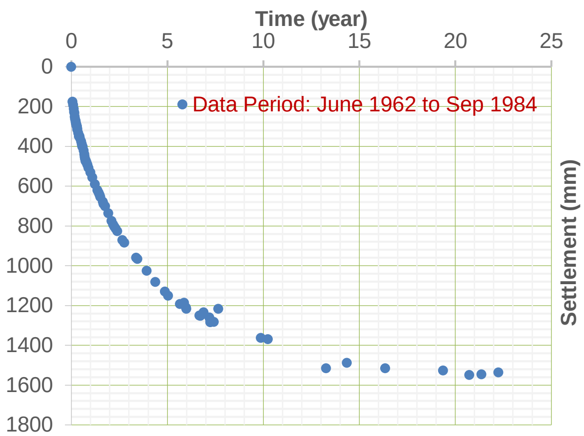


Figure 2. Settlement of existing approach embankment between 1962 and 1984

Analyses were carried out using the commercially-available 'Settle-3D' software. Figure 1 summarizes the pre-consolidation pressure profile and parameters used in the analyses. The analysis was undertaken with an embankment loading induced by a granular fill embankment of 8 m height. The results of the settlement analysis are shown in Figure 3. These settlements would be almost entirely differential in the transverse direction between the existing embankment and the west crest of the new embankment.

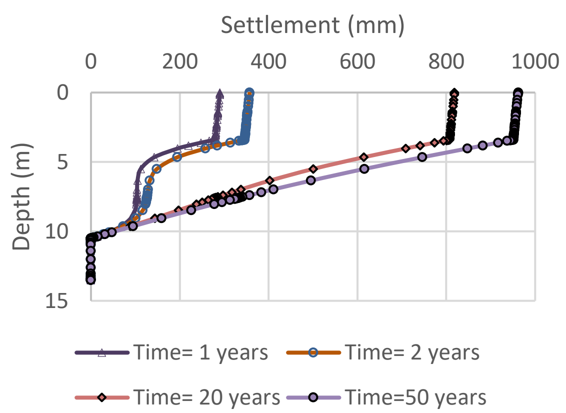


Figure 3. Anticipated settlement for proposed granular fill embankment without any ground improvement

The calculated primary consolidation settlements are estimated to be in the order of 0.8 m (at the location of greatest settlement in the transverse direction). In the longer term, these settlements would increase beyond the estimates given above due to secondary compression (i.e., creep) of the deposit. It is expected that, over a period of 20 years following construction secondary compression could increase these settlements by between 50 and 75 mm. Over a 50-year time frame, the anticipated total settlement (i.e., primary consolidation plus secondary compression) could be in the order of about 1.0 m. The estimated settlements are considered to be excessive and would have a negative impact on the roadway performance. The estimated settlement values also exceed the values typically accepted by MTO for the approaches to bridges for non-freeways, shown in Table 1.

Table 1. Roadway Settlement Tolerances

Distance from Abutment (m)	Tolerable Settlement (mm)
0 to 20	25
20 to 50	50
50 to 75	100
>75	200

The differential settlement rate transversely across the top of the roadway surface also needs to be limited to 100H: 1V for non-freeways.

3.2 Embankment Stability

Static and seismic slope stability analyses of the proposed embankments using conventional earth fills were carried out with the commercially available SLOPE-W software (produced by Geo-Studio 2007). The analyses were carried out for undrained (i.e., short-term) conditions using the soil parameters tabulated in Table 2. Undrained conditions represent the critical condition experienced during and immediately following construction of the embankments. With time, the excess pore water pressures generated in the clay deposit as a result of the loading would dissipate and 'drained' conditions would exist, with a higher factor of safety against instability.

Table 2. Soil Parameters

	Bulk Unit Weight (kN/m^3)	Shear Strength Parameters	
		Angle of Internal Friction	Undrained Shear Strength (kPa)
Embankment Fill	21.5	32	-
Weathered Crust	17.1	-	75
Grey Clay	15.5	-	21-32
Glacial Till	19.0	-	-

The results of the stability analyses indicate that, even with appropriate subgrade preparation and proper placement and compaction of embankment fill materials, the up to 8 m high embankments with side slopes at 2H:1V will not have an acceptable factor of safety (<1.5) against deep-seated rotational instability for the undrained static or for seismic conditions.

3.3 Preferred Embankment Design

Given the significant magnitude and time rate of anticipated settlements and the low factors of safety for global stability, several options were considered to mitigate the anticipated settlements including:

1) Lightweight Fill
2) Preloading
   a. Without Wick Drains
   b. With Wick Drains

c. With Wick Drains and Lightweight Fill

3) Ground Improvement

Ground improvement was selected as the preferred option. The selection of the ground improvement method will be the responsibility of the contractor, who will obtain a proprietary design for this project from a ground improvement specialty contractor. Consequently, the design and construction of the approach embankments will be administered as a Design Build item with Performance and Warranty based specifications.

3.4 Additional Investigation

As a result of the embankment design analyses discussed above and after further evaluation of the embankment construction alternatives, ground improvement was selected as the preferred construction alternative for the site. However, additional field investigation and laboratory testing was considered necessary to obtain a higher level of understanding of the clay deposit at the site. This better understanding of the clay deposit's characteristics would assist in selecting the most appropriate ground improvement method and would provide specialty contractors with additional information for preparation of their designs.

The additional investigation involved drilling two additional boreholes and two piezocone penetration tests, CPT, (one borehole and CPT at each approach embankment), as well as carrying out advanced laboratory testing on selected soil samples. The advanced laboratory testing consisted of standard and long-term oedometer testing, constant rate of strain oedometer testing, and bench-scale soil mixing experiments. The following sections present the results of the soil mixing that was carried out on samples of the marine clay deposit gathered at the site.

4 DSM INVESTIGATION PROCEDURE

4.1 Soil Sample Collection and Properties

Relatively undisturbed soil samples were retrieved by Golder and delivered for laboratory study at Ryerson University. Three buckets of samples were collected from a borehole advanced at the site (numbered 17-12) as follows:

- Sample 1 was from 3.66 to 5.49 m depth;
- Sample2 from 5.49 to 7.32 m depth; and Sample 3 from 7.32 to 9.14 m depth.

A summary of the physical properties and porewater salinity of the soil samples are provided in Table 3.

Cement was chosen as a binder because of its worldwide acceptability and proven effectiveness as reported in previous research and case studies (Miura et al. 2001; Bell 1996; Bergado et al. 1990; Bergado et al. 1999; Locat et al. 1990). Since dry (delivered pneumatically in dry form) and wet (i.e., pumped slurry form) mixing methods are widely used in North America, both are being considered in this research due to the high water content of the native soil. The binder dosages and curing conditions as described below were chosen based on previous research (Li et al, 2016; Pathivada, 2005; Kitazume & Terashi, 2012; Huang, 2006; Ramirez, 2009) and applicable industry design standards.

Table 3. Physical properties of soil samples

Moisture Content (%)	64 to 74
Liquid Limit (%)	49 and 61
Plastic Limit (%)	30 and 31
Specific Gravity	2.60 to 2.72
Salinity (g/L)	1.615 to 1.956
Sensitivity	4 to 8

4.2 Parametric Study

In this laboratory study, mixing type, binder dosage and curing duration were designated as variables as shown in Table 4.

Table 4. Experimental variables

Variables	Number of variables	Description
Mixing Type	2	Dry, Wet
Dosage (kg/m^3)	4	100, 150, 200 and 250
Curing (days)	4	7, 14, 28, 56

4.3 Sample Preparation Procedures

Two mixing methods were used for the study – the wet mixing method and the dry mixing method. For wet mixing method, a cement slurry with a water to cement ratio of 0.7:1 was prepared. The slurry was mixed with two spatulas by hand for about two minutes to produce a liquid consistency. Clumps and aggregates were crushed to obtain a homogeneous mixture with no visible clumps or sludge. For dry mixing, cement powder was mixed with the soil to achieve the specified dosages.

After mixing, the cement soil mixture (Hobart, 2005) as compacted into 76-cm diameter and 152-mm high plastic cylindrical molds. The prepared samples were then placed into a humid chamber for curing. The chamber has a relative humidity of 95-100 percent and a temperature of 22-25 ^{o}C. This will allow cement to fully react with soil to trigger the Pozzolanic reaction (Kitazume & Terashi, 2012).

Following the specified curing time, samples were carefully removed from the mold by applying an air shock to the end of the mold (Liu et al. 2018).

4.1 Testing Methods

4.1.1 Unconfined Compressive Strength (UCS) Test

Unconfined compressive strength (UCS) tests were conducted to assess the efficiency of cement in improving the strength of the clay collected at the project site. These tests were carried out in accordance with ASTM D2166. There were two types of failure planes observed in the samples: a conical failure plane and a planar one. The conical failure plane was found mainly in the dry mixing samples, while a planar failure plane was noticed mainly in the wet mixing sample. The photographs in Figure 4 show failure modes observed during UCS testing.

Dry mixing sample (LHS) Wet mixing sample (RHS)

Figure 4. Typical failure modes of cement treated samples

4.1.2 Constant Rate of Strain (CRS) Test

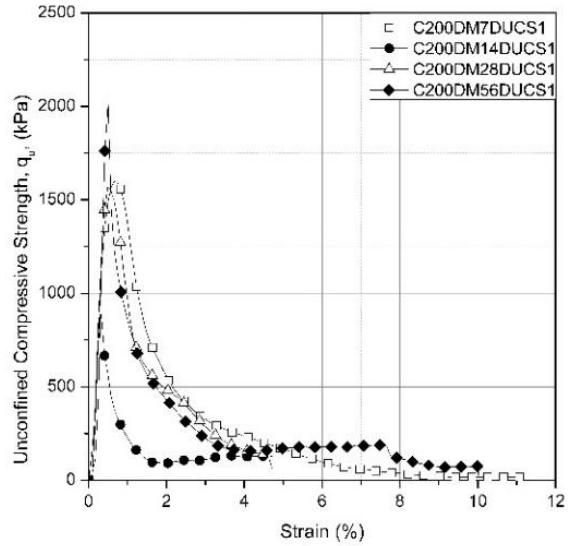
CRS tests were carried out only on treated samples prepared by the wet mixing method. Cement and water were mixed to form a slurry with a water:cement ratio of 0.7:1. The slurry and clay were then manually mixed for 5 minutes using two spatulas. A CRS ring was then filled with the mixture. The sample was wrapped in soft nylons and placed in the curing chamber for the desired curing time. The water content of each mixture sample was measured and the degree of saturation ranged from 90 to 100%, which seemed to indicate the mixing procedure was sufficiently thorough.

After curing, each sample was trimmed and placed onto the machine for testing. The first step was to saturate the sample under a back pressure of about 350 kPa for 24 hours. The second step was to carry out the test at a loading strain rate of 1.0% /hr to a limit pressure of 2.4 MPa and then unload the sample at an unloading strain rate of 0.25% /hr to a limit pressure of 0.1 MPa. The same loading and unloading strain rates were applied for all CRS tests. This loading strain rate was selected to keep the pore water pressure to mean effective stress ratio within the recommended range of 3-15 % as per ASTM standard.

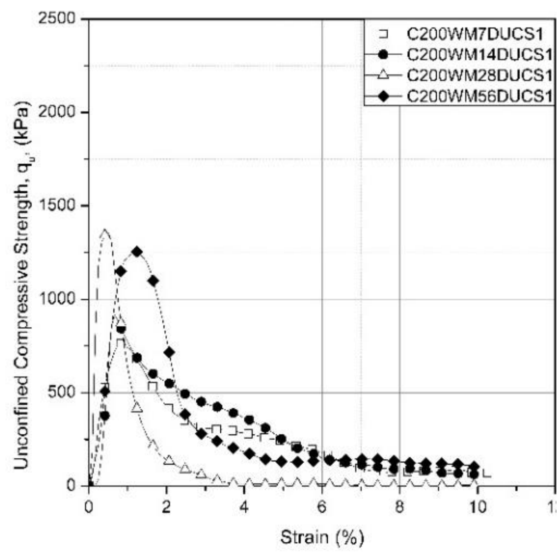
4.2 Experimental Results

4.2.1 Unconfined Compression Tests

Typical stress-strain curves are illustrated in Figure 5 for 200 kg/m^3 dosage samples. It can be seen that most samples reach their peak strengths at a strain value of less than 1%. After that, it gradually loses its strength with increasing strain due mainly to brittle failure of the samples and also lack of lateral confinement. The strain softening behaviour should be considered in the design of mixes for large scale mixing for construction projects.



a) Dry mixing 200 kg/m^3 dosage samples



b) Wet mixing 200 kg/m^3 dosage samples

Figure 5. Typical stress-strain curves of UCS test samples

The impact of different mixing methods on q_u is shown in Figure 6. In general, the dry mixing samples exhibit higher q_u values than those of wet mixing samples. Figure 5 also indicates that the variability in the strength gain may be less with wet mixing than with dry mixing.

The published literature indicates that the total water to binder ratio is a critical factor for the gain in q_u of cement-treated samples. It was found in this study that q_u also decreases exponentially and then perhaps remains relatively constant with increasing total water to cement ratio, as shown in Figure 7.

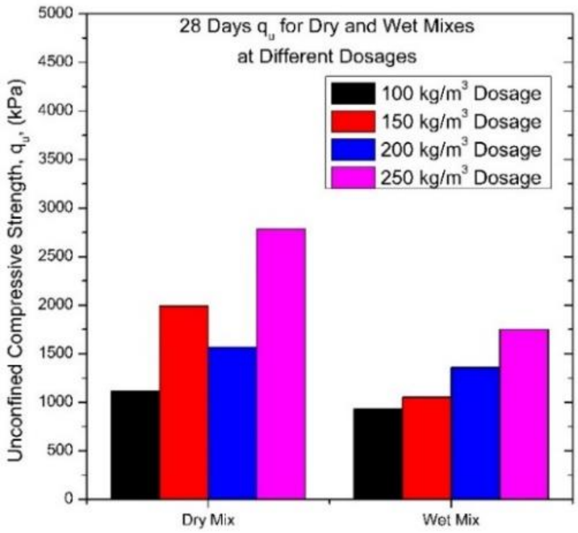


Figure 6. Impact of mixing method on q_u of cement-treated samples

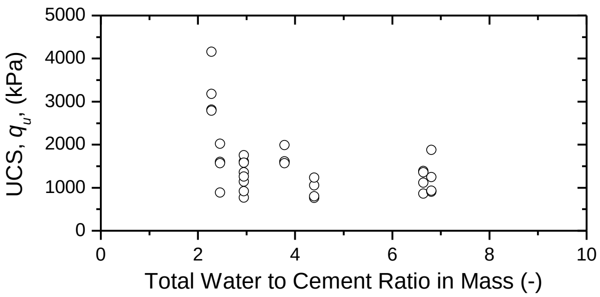


Figure 7. Impact of total water to cement ratio on q_u of all samples

The impact of the dry density of the cement-soil sample on q_u is shown in Figure 8 for all 32 samples regardless of their dosage, curing, and mixing conditions. It can be seen that q_u increases with increasing dry density of the treated samples except one of the samples.

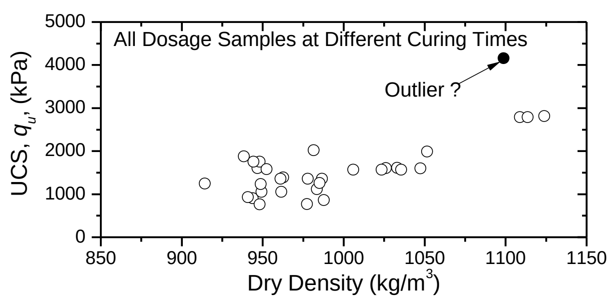
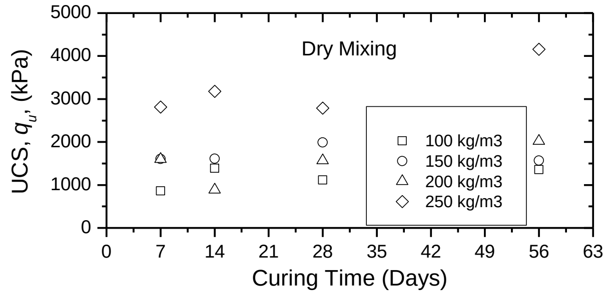
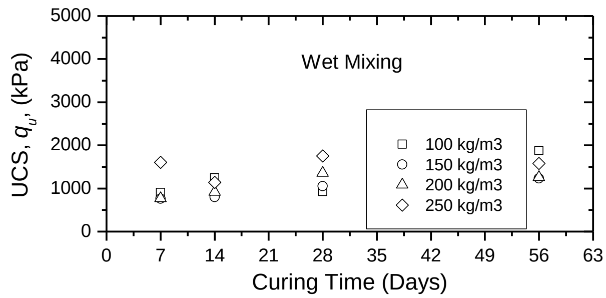


Figure 8. Impact of dry density on q_u of all samples

The impact of curing time on q_u of cement-treated samples is shown in Figure 9. There is no observable trend in the strength change with time, particularly for dry mixing samples. The high salinity in the clay sample may contribute to less prominent change with time.



a) Dry mixing samples at different curing times



b) Wet mixing samples at different curing times

Figure 9. Impact of curing time on q_u of samples

A preliminary statistical analysis was carried out based on all 32 UCS test results regardless of dosage, curing, and mixing conditions. The average value of q_u is 1553 kPa with a standard deviation of 763 kPa for all samples.

4.2.2 Constant Rate of Strain Consolidation

The change in the compressibility due to cement mixing is shown in Figure 10. Compared to a Cc value of approximately 0.5 for the untreated remolded sample, Cc reduces to less than 0.1 for a pressure range from 100 to 1000 kPa. There is no apparent yielding for all cement treated samples until after 1 MPa. This yield strength is significantly higher than the pre-consolidation pressure of about 100 to 140 kPa estimated for the clay from oedometer tests.

The change in the coefficient of volume change, $Mv=\Delta\varepsilon v/\Delta\sigma v$, due to cement mixing is shown in Figure 11. *Mv* is reduced by at least one order of magnitude due to cement mixing. No appreciable impact on *Mv* with different cement dosages was found with the tested samples.

The change in the coefficient of permeability, *k*, due to cement mixing is shown in Figure 12. The range of *k* values for cement treated sample is much larger than that of the remolded clay sample.

The change in the coefficient of consolidation, c_v, due to cement mixing is shown in Figure 13. The coefficients of consolidation for cement-treated samples are larger than that of the remolded untreated clay sample but vary in a wide range.

Due to a limited number of CRS tests, it is difficult to make any quantitative conclusions.

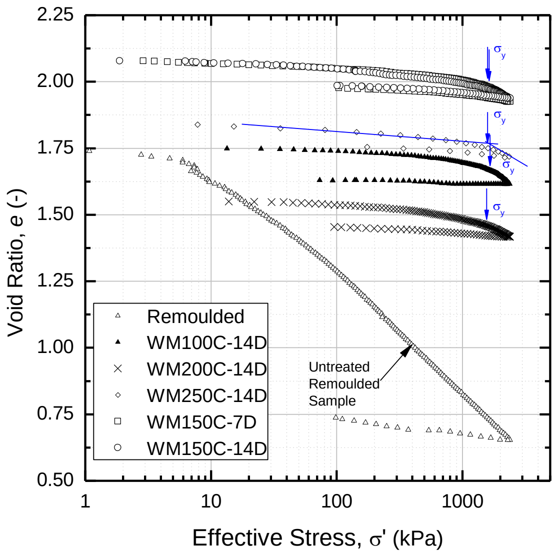


Figure 10. Change in compressibility due to cement mixing

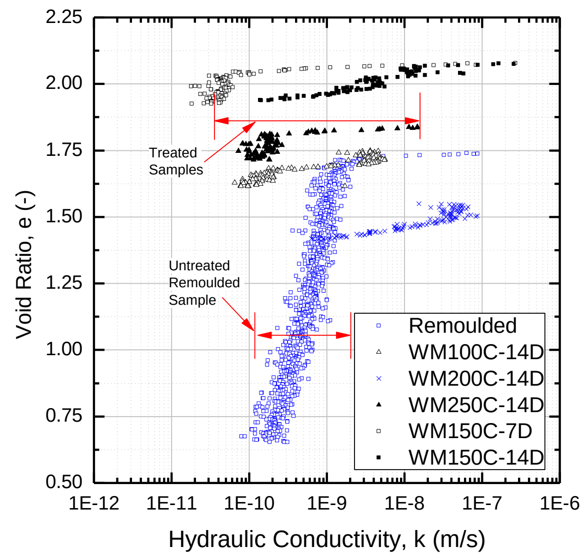


Figure 12. Change in permeability due to cement mixing

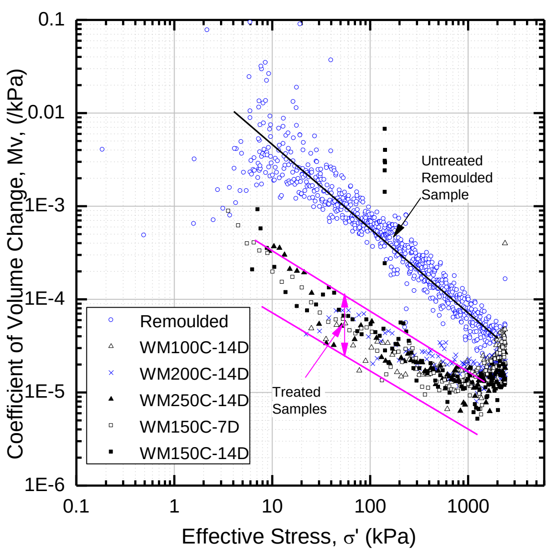


Figure 11. Change in the coefficient of volume change due to cement mixing

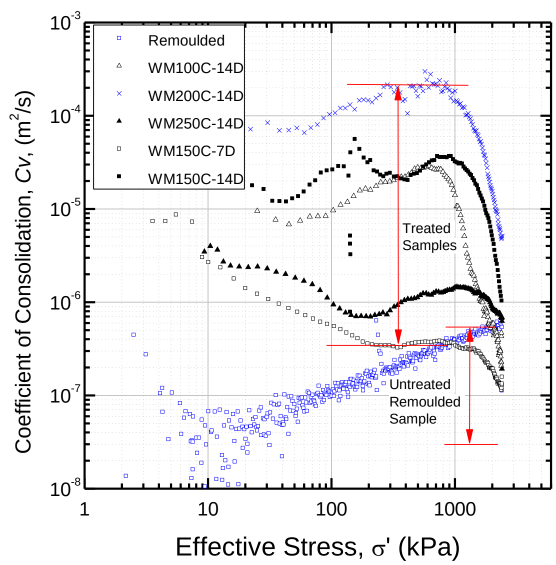


Figure 13. Change in coefficient of consolidation due to cement mixing

5 SUMMARY AND CONCLUSIONS

The feasibility and efficiency of improving the strength and compressibility characteristics of sensitive Champlain Sea clay with ordinary Portland cement was investigated in this study. Relatively undisturbed clay samples collected from a project site near the intersection of Highway 401 and Country Road 2/34 in Lancaster, Ontario, and were mixed with cement using both dry and wet mixing methods at different dosages and curing durations. UCS tests and CRS consolidation tests were carried out to evaluate the strength and compressibility characteristics of cement-clay mix samples.

The test results reveal that cement mixing can significantly improve the strength and compressibility characteristics of the Champlain Sea clay at the project site. Samples prepared by the dry mixing method tend to exhibit higher UCS values than samples prepared using the wet mixing method.

Cement can improve the compressibility of site clay within a short period of time. At 7-day curing time, the cement-treated soil has already become significantly less compressible than the remolded clay and the treated soil samples did not yield before the axial stress reached 1 MPa. After 7 days, there was not much appreciable strength improvement with time observed in the samples.

The current findings suggest that soil mixing is feasible provided that a methodology can effectively mix the cement in situ. Future studies will be required to gain a further knowledge on the efficacy of ground improvement for the Champlain Sea clays. The future studies shall include but not be limited to, assessing long-term influence from pore fluid chemistry, standardizing sample preparation and laboratory testing procedure, field performance compared to laboratory tests, and quality control of DSM in Champlain Sea clay in the field.

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REFERENCES

Bell, F. (1996). Lime stabilization of clay minerals and soils. *Engineering Geology, 42*, 223-237.

Bergado, D., Ahmed, S., Sampaco, C., & Balasubramaniam, A. (1990). Settlements of Bangna-Bangpakong Highway on Soft Bangkok Clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 136-155.

Bergado, D., Ruenkrairergsa, T., Taesiri, Y., & Balasubramaniam, A. (1999). Deep Soil Mixing Used to Reduce Embankment Settlement. *Ground Improvement*, 145-162.

Hobart. (2005, April). *A200 Mixer Technical Manual.* Retrieved March 3rd, 2016, from Hobart Corp: https://my.hobartcorp.com/kroger/TechnicalServiceManuals/A200%20Technical%20Manual.pdf

Huang, P., Patel, M., Santagata, M., & Bobet, A. (2009). *CLASSIFICATION OF ORGANIC SOILS.* West Lafayette: Purdue University.

Kitazume, M., & Terashi, M. (2013). *The Deep Mixing Method.* Tokyo: CRC Press.

Li, S., Kirstein, A., Gurpersaud, N., & Liu, J. (2016). Experimental investigation of cement mixing to improve Champlain Sea clay. *GeoVancouver 2016.* Vancouver: Canadian Geotechnical Society.

Liu et al. (2018). *Cement Mixing to Treat Sensitive Champlain Sea Clay.* Final Report, Ryerson University

Locat, J., Berube, M., & Choquette, M. (1990). Laboratory Investigation on the Lime Stabilization of Sensitive Clays: Shear Strength Development. *Canadian Geotechnical Journal*, 294 - 305.

Miura, N., Horpibulsuk, S., & Nagaraj, T. (2001). Engineering behavior of cement stabilized clay at high water content. *Soils and foundations*, 33-45.

Pathivada, S. (2005). *Effects of Water-cement Ratio on Deep Mixing Treated Expansive Clay Characteristics.* Arlington: The University of Texas at Arlington.

Ramirez, J. (2009). *Cement Stabilization of Organic Soils for Controlling Secondary Compression Behavior.* MASc Thesis, Florida Atlantic University.