Experimental investigation of cement mixing to improve Champlain Sea clay

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ABSTRACT
Soft and sensitive Champlain Sea clay (Leda clay) are commonly found along the St. Lawrence River in Southern Quebec and Southern Ontario. Most infrastructure developments on this kind of soil require ground improvement prior to their constructions. Deep soil mixing (DSM), a ground improvement technique popular in the US, Japan and Scandinavia, has distinct advantages which includes rapid strength increase, large applicable ground area, wide soil type usability, and low environmental impacts. In this study, the application of DSM to Champlain Sea clay was investigated through a laboratory testing program. Champlain Sea clay samples were collected from two sites near the City of Ottawa and tested with different binder types, dosages, and curing times. It was found that cement and slag/cement were both effective binders to efficiently treat Champlain Sea clay. The binder dosage, binder type, and curing duration are important factors which influence unconfined compressive strength (UCS) of the final sample. This paper presents an experimental investigation of the engineering behaviour of cement-treated Champlain Sea clay.

RÉSUMÉ
On trouve l'argile de la mer Champlain (« argile à Leda ») couramment le long du fleuve Saint-Laurent dans le sud du Québec et dans le sud de l'Ontario. La plupart des développements des infrastructures sur ce type de sol nécessitent de l'amélioration de sol avant de leurs constructions. Deep Soil Mixing (DSM), une technique de l'amélioration de sol qui est populaire aux États-Unis, le Japon et la Scandinavie, a des avantages distincts dontl'augmentation rapide de la solidité, la possibilité de traiter une grande surface l'applicabilité sur une large éventail de sols, et les impacts environnementaux faibles. Dans cette étude, l'application de DSM à l'argile de la mer Champlain a été étudiée grâce à un programme d'essais en laboratoire. Des différents types d'échantillons de sol ont été prélevés et testés avec des différents types de liants, les posologies et les temps de durcissement. On a constaté que le ciment de laitier et / ou ciment étaient les deux efficaces pour traiter efficacement l'argile de la mer Champlain. Le dosage du liant, type de liant, et la durée de durcissement sont des facteurs importants qui influent sur la résistance à la compression uniaxiale (UCS) de l'échantillon final. Cet article présente une étude expérimentale du comportement mécanique du ciment-argile de la mer de Champlain traitée.

1 INTRODUCTION

Champlain Sea clay, also known as Leda clay, is a type of sensitive clay commonly found along the St. Lawrence Lowlands region in Ontario and Quebec (Penner 1965). Its high sensitivity proves problematic for the region's infrastructure development (La Rochelle et al. 1970). Champlain Sea clay's liquid limit ranges from 32% to 38% and its plastic limit from 18% to 24% (Kakoli, 2005). Initial undrained shear strength of Champlain Sea clay can vary approximately between 7 to 140 kPa; and sensitivity ranges from 10 to 100 (La Rochelle et al 1970; Quigley et al 1983; Konrad and Seto 1993). Landslides are often triggered in this area due to its low strength, high sensitivity, and quick disturbance. It is crucial to establish a cost-effective ground improvement method to address the challenges associated with this type of clay.

Deep mixing method (DMM) is a ground improvement technique established in Japan as early as the 1970s (Kitazume and Terashi 2012). Its unique advantages over other ground improvement methods include a quick strength increase, high cost efficiency, low environmental disturbance, and wide range of soil applicability (Bruce 2000; Bruce et al. 1998). Due to DMM's ability to treat difficult soils, it soon became a popular technique with many applications in the United States, western Canada, and the rest of the world. However, DMM has never been applied in Ontario due to the lack of test data. Investigations on lime stabilization of sensitive clays are scarce (Locat et al. 1990); however, the results from Locat's study (1990) confirm the viability of using DMM to improve strength of soft sensitive clay.

In this study, the viability of using cement and slag/cement binders to improve sensitive Champlain Sea clay was investigated. Experimental variables include the binder type, binder dosage, curing duration, and soil type.

2 EXPERIMENTAL STUDIES

2.1 Soil Characterization

Champlain Sea clays were obtained from two different locations near Ottawa, Ontario: Arnprior and Kanata. Soil samples received from Arnprior were obtained from a lower depth as compared with the Kanata samples.

Arnprior soils were delivered in undisturbed Laval samples and Shelby tube samples. Kanata soil samples were collected from an excavation site and delivered by Geo-Foundations Contractors Inc. in a disturbed state. Although the samples from Kanata were disturbed, some chunks of clay were still intact; therefore, mini-vane shear test was performed on a chunk of Kanata clay to obtain its undrained shear strength. Their geotechnical properties were thoroughly examined, as shown in Table 1, and used as baseline values for comparison.

Table 1. Soil properties obtained via ASTM standardized tests

Soil Characteristics	Standards	Arnprior Champlain Sea Clay	Kanata Champlain Sea Clay
USCS Symbol		CH	CL
Moisture Content	ASTM D 2216 - 98	49.1	60.5
Liquid Limit	ASTM D 4318 - 00	57.3	29.3
Plastic Limit	ASTM D 4318 - 00	26.9	21.8
Undisturbed Undrained Shear Strength (Mini-vane) (kPa)	ASTM D 4648 - 00	78.7	20.2*
Remolded Undrained Shear Strength (kPa)	ASTM D 4648 - 00	5.7	1.8
Sensitivity	ASTM D 4648 - 00	13.7	11.0
Average Unconfined Compression Strength (kPa)	ASTM D 2166 - 00	151.7	40.4**

* measured in a chunk of soil sample

** 40.4 kPa was based on twice of 20.2 kPa of undrained shear strength, since UCS test could not be completed on Kanata clay due to the limited size of clay chunk.

2.2 Research Variables

Past studies on cement treated soil indicate that many factors contribute to the influence of the final strength of the treated soil. They include the soil type, binder type, binder content, binder proportion, curing period, curing condition and water cement ratio for wet soil mixing slurry (Pathivada 2005; Lorenzo 2004). In this study, the effects of different binder types, binder dosages, and curing conditions on the final strength of the treated soil were examined. Table 2 shows the different type variables used for this study.

Cement material was chosen as a binder candidate due to its successful application in past projects (Pooranampillai et al. 2012); however, cement has never been tested as a binder to strengthen Champlain Sea clay.

Kitazume and Terashi (2012) proposed a minimum binder dosage of 50 kg/m^3 for organic soil. This dosage was used as a starting point in this study, which roughly translates to 5% dosage by soil dry weight. The binder dosage was then increased by doubling the cement content based on experiment progress.

Curing duration of 7, 14, and 28 days were selected based on past research and field trials in cement stabilization of clay (Pathivada 2005; Bergado et al. 1999). The behaviour of 56 day curing duration was also conducted in this study to observe if extra strength increase can occur.

Table 2. Research variables for experimental program

Parameters	Number of variables	Variable descriptions
Sample Locations	2	Arnprior and Kanata clay
Binder types	2	Cement and Slag/cement
Binder dosage (percentage by weight)	9	5, 7, 10, 12.5, 20 & 40 for cement; 28, 40 & 80 for slag/cement
Curing duration (days)	4	7,14,28 & 56
Mixing types	2	dry and wet

2.3 Calculations

The following section explains each parameter's calculation process for sample preparation and data analysis.

$$D_c = M_d \times \alpha \quad [1]$$

Where D_c is the cement dosage by weight, M_d is the dry soil mass of the prepared soil, and α is the predetermined cement dosage according to the testing program.

$$\beta = \frac{Q_u}{q_u} \quad [2]$$

Where β is the ratio of improvement, q_u is the unconfined compressive strength (UCS) of the untreated soil and Q_u is the treated soil's UCS.

$$M = \frac{Q_u}{E} \quad [3]$$

Where M is the modulus factor, and E is the treated sample's elastic modulus.

2.4 Equipment List

Two types of binders were used in this study: cement and slag/cement. The cement used in this study is regular Portland Cement (GU) manufactured by St Marys Cement. The cement conforms to Canadian Standards Association (CSA) A3001 standard (CSA, 2013). Slag/cement binder was prepared by CRH Canada Group Inc. using a mix ratio of 75% slag and 25% cement by weight. For compaction, a rod fitted at one end with a plate (60 mm in diameter) welded with nails (20 mm in length) was used. This tool weighs 274 g and measures 470 mm in length, and it was easy to control during compaction. Nails act as puncturing devices to penetrate the soil for homogenization (Figure 1). To prepare the samples, a Hobart A200 Industrial Grade Mixer was used for all mixing and homogenizing operations in this research (Figure 1). The mixer's turning speeds are 61 revolutions per minute (RPM), 113 RPM, and 205 RPM (Hobart 2005). Paper tubes, which are 76 mm in diameter and 300 mm in length, were used as curing containers. Paper tube reduces disturbance to the cured sample, and allows maximum permeation for water curing. Finally, a large plastic tub 108 litres in volume was filled with 150 mm of water and used as a curing environment.

Figure 1. From left to right: compaction rod, Hobart mixing unit homogenizing cement treated clay

2.5 Sample Preparations

Wet mixing was chosen as the primary mixing method because the water content of the natural soil was found below 70%. Thus, the water content of the soil was considered low for dry mixing (Kitazume and Terashi 2012; Sobhan et al. 2012). The cement slurry was prepared by mixing cement with water at a 0.8:1 water to cement ratio. This ratio was based on Pathivada (2005) findings on an optimum water to cement ratio for cement stabilization. Marine clay was then mixed with cement slurry in three equal portions with one minute of mixing at 61 RPM between the additions of each portion of the clay. After each addition, the mixing bowl was scraped by hand to manually homogenize the mixture. Mixing speed was switched to 205 RPM after adding the third batch of cement slurry as needed. The mixing procedure adopted for this investigation was based on Ramirez (2009) procedure for cement stabilization study.

Treated soil samples were then compacted into 381 mm paper tube. Samples were moulded into a ball by hand an approximate diameter of 70 mm. This ball was then dropped into the paper tube and compacted 30 times using specially designed compaction tool. Each drop was controlled at 250 mm by approximation. This continued until the tube was filled with the compacted sample. This procedure was a modified version of Pathivada (2005) compaction method. This method was modified because the initial compaction results were inadequate and led to inconsistent results.

Finally, compacted samples were placed into a plastic tub for water curing. Pathivada (2005) described samples cured in 100% relative humidity with temperature control at 20 ºC and Ramirez (2009) disclosed a curing procedure of placing samples into water filled bath and allowed to cure 7 days. Further studies can be done to examine the effect of curing method.

2.6 Unconfined Compression Strength Test

The unconfined compression strength (UCS) test was used in this research as the main parameter to determine the strength improvement under combinations of different variables. The tests were conducted according to American Society for Testing and Materials (ASTM) Standard D2166. Peak UCS of each sample was used as a benchmark for strength improvement.

In some instances of the sample testing, the height to diameter (H/D) ratio did not adhere to the specified ratio of 2:1 as per ASTM. In some cases, the sample was trimmed to a height of 140 mm and a diameter of 76 mm. Due to the brittleness of the sample, the sample height was kept at the minimum range of allowable H/D ratio in order to prevent any snaps or breakages off the sample. Table 3 summarizes each treated sample's H/D ratio and failure mode. Figure 2 shows typical USC sample failing under the compression load of the test device. The most common type of failure mode was longitudinal failure with a conical failure plane at the breakoff point. Shear failure was also observed on some samples.

Table 3 Summary of laboratory test results

Soil Location	Binder*	Dosage (percent by weight)	Curing Length (days)	H/D ratio	Failure Mode	UCS (kPa)
Arnprior	C	5	7	2.0	Shear	190
Arnprior	C	5	14	1.7	Longitude	81
Arnprior	C	5	28	2.0	Longitude	134
Arnprior	C	12.5	7	1.8	Shear	312
Arnprior	C	12.5	14	2.0	Conical	1050
Arnprior	C	12.5	28	2.4	Shear	278
Kanata	C	7	7	2.0	Conical	361
Kanata	C	7	14	1.8	Longitude	284
Kanata	C	7	28	1.9	Longitude	330
Kanata	C	10	7	2.0	Shear	718
Kanata	C	10	14	2.0	Crush	546
Kanata	C	10	28	2.1	Conical	391
Kanata	C	10	56	2.1	-	282
Kanata	C	20	7	2.0	Conical	822
Kanata	C	20	14	2.1	Conical	704
Kanata	C	20	28	2.0	Conical	1323
Kanata	C	20	56	2.0	-	848
Kanata	C	40	7	2.1	Longitude	939
Kanata	C	40	14	2.0	Longitude	1173
Kanata	C	40	28	2.0	Did not fail	2071
Kanata	C	40	56	2.0	Conical	1543
Kanata	SC	28	7	2.1	Conical	1052
Kanata	SC	28	14	2.0	Conical	909
Kanata	SC	28	28	2.0	Longitude	1354
Kanata	SC	28	56	2.0	-	1593

Kanata	SC	40	7	2.0	Longitude	939
Kanata	SC	40	14	2.0	Conical	1173
Kanata	SC	40	28	2.1	Crush	2071
Kanata	SC	40	56	2.0	Crush	1543
Kanata	SC	80	7	2.0	Longitude	1626
Kanata	SC	80	14	2.1	Longitude	1644
Kanata	SC	80	28	2.0	Did not fail	2089**
Kanata	SC	80	56	2.1	Did not fail	2068**

* C stands for cement binder and SC stands for slag/cement binder

** The tests were stopped before sample failure due to the limit of load frame was reached.

Figure 2. From left to right: conical failure, shear failure, and crushing failure

3 RESULTS ANALYSIS AND DISCUSSION

3.1 Unconfined Compression Strength

Strength improvements were observed after treating Arnprior clay with cement binder. However, initial strength improvements were inconsistent due to the poor compaction quality at the beginning. Table 3 shows the UCS of poorly compacted Arnprior samples, which were lower compared to Kanata samples.

Initial trials at a low cement dosage of 5% by weight, or 57 kg/m^3, yielded marginal improvement for Arnprior clay. The UCS vs. strain profile in Figure 3 demonstrates 5% cement treated sample mimicked the untreated Arnprior clay's profile closely without much strength improvement. The poor compaction method caused deep cracks and discontinuities on the samples, which weakened the structural integrity and lowered the UCS. When the sample dosage was increased to 12.5% (144 kg/m^3), one UCS increased to 1050 kPa for 14 day cured Arnprior clay with a strength increase ratio of 8. However, the strength from other samples was only marginally improved due to inconsistent compaction. Figure 3 shows the inconsistency in strength improvement for 12.5% cement treated samples.

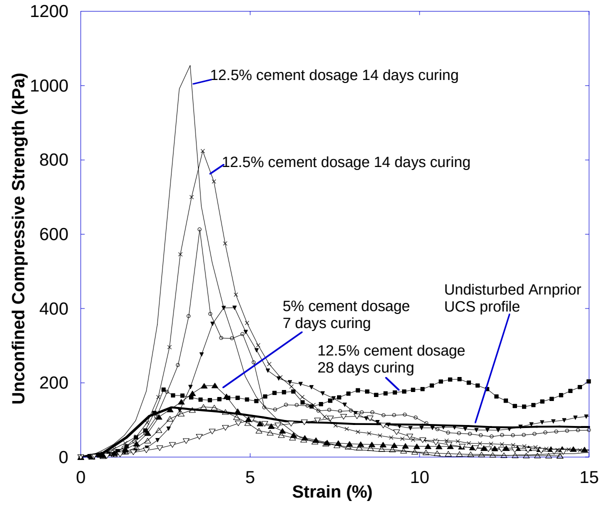

Figure 3. Stress vs. strain curve of cement treated Champlain Sea clay from Arnprior, Ontario

When testing with Kanata clay, cement and slag/cement were applied to compare the improvement in UCS. An improved compaction method led to more consistent UCS results. Cement dosages of 10% and 20% by weight (103 kg/m^3 and 207 kg/m^3) were first applied to Kanata clay (Figure 4). Desirable results were immediately observed with an UCS of 718 kPa for one sample treated with 10% cement and 1323 kPa for one sample treated with 20% cement. Binder dosage was further increased to 40% cement by weight to verify its effectiveness and an UCS of 2071 kPa was recorded for one sample. An attempt was made to lower cement dosage (Table 3); and an UCS of only 330 kPa was recorded for samples treated with 7% cement dosage (72 kg/m^3). Further studies can be conducted to find the optimum dosage to efficiently and economically treat Champlain Sea clay.

A trial test was performed to utilize dry mixing and check for any advantage over wet mixing. With the same dosage of 10% cement (103 kg/m^3), an UCS was recorded at 954 kPa for sample cured for 14 days. This encouraging result suggests dry mixing method may yield a higher UCS value than wet mixing method; however, the sample's 28 day UCS was only 731 kPa, which is similar to strength obtained from wet mixing. Further investigation is needed to evaluate the effectiveness of different mixing methods on Champlain Sea clay strength improvement.

Slag, a by-product of iron production, has the potential to produce a pozzolanic reaction under alkaline conditions (Kitazume and Terashi 2012). In this application, slag was mixed with cement in a 3:1 ratio by weight as a strength improvement binder for Champlain Sea clay.

Samples treated with 28% slag/cement (290 kg/m^3) recorded a UCS of 1052 kPa for only 7 days of curing; after 28 days of curing, the peak UCS reached 1354 kPa (Figure 5). For a dosage of 28% slag/cement, there was 7% cement by weight was added to soil, which is an efficient approach to improve soil strength. Samples treated with 40% slag/cement (414 kg/m^3) recorded peak

UCS of 994 kPa for 14 days of curing. The dosage was increased to 80% slag/cement (828 kg/m^3), and a peak UCS of 1626 kPa was recorded after 7 days of curing. A sample treated with 80% slag/cement (828 kg/m^3) and cured for 28 days reached 2000 kPa, which was the upper limit of the testing device.

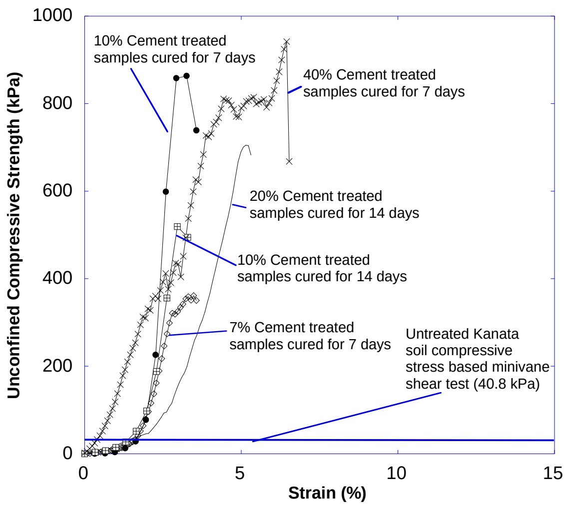

Figure 4. Stress vs. strain curve for cement treated Kanata clay

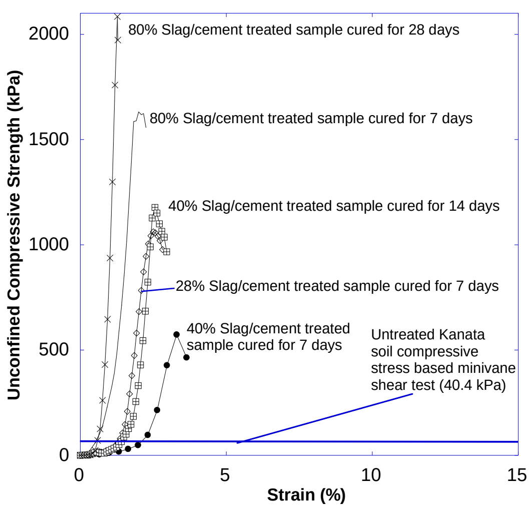

Figure 5. Stress vs. strain profile for samples treated with slag/cement binder

3.2 Sample Density

Sample density can influence a treated soil's peak UCS. A sample with poor compaction will tend to have a low density, which is likely to produce a lower than average UCS. However, a high density sample does not guarantee high UCS. For example, a 12.5% cement treated sample cured for 7 days had a density of 1.817 g/cm^3, but its peak UCS was only 318 kPa. Increasing density results in increasing UCS for cement treated Arnprior clay.

For Kanata clay, most samples' density congregates at 1.6 g/cm^3, which is an indication of improved compaction. For cement treated and slag/cement treated Kanata clays, increasing density correlates with higher UCS.

3.3 Water Content

Throughout this experiment, treated and cured sample's water content was not used as a testing variable. Dosage was calculated based on the virgin soil sample's water content before treatment. However, a small variation in the water content between each sample still exists. The water content of cured samples was taken directly before the sample undergoes its UCS test. Cement treated Arnprior clay with lower water content will have higher UCS. Samples with higher water content will have lower UCS. This trend agrees with the basic mechanism of cement stabilization (Kitazume and Terashi 2012) where reduction of water content serves as a short term strength increase for target soil.

Kanata clay cement treated sample displayed similar trend to the Arnprior samples with similar water content. For slag/cement treated samples, an increase in the water content of the treated sample increases the sample's final UCS (Figure 6). This trend may be caused by an increase in sample's workability during sample compaction, which resulted in homogenous and uniform cured column free of surface defects and cracks. Samples prepared this way have high UCS.

3.4 Elastic Modulus

A comparison between Arnprior clay's UCS and its elastic modulus revealed a directly proportional relationship (Figure 7). The higher the sample's UCS the higher its elastic modulus.

For Kanata clay treated with cement, elastic modulus increases with increasing UCS (Figure 8). The degree of increase varies with different cement dosage. For Kanata clay treated with slag/cement, a directly proportional trend between UCS and elastic modulus is present. However, UCS tapered off for 80% slag/cement treated samples while modulus continues to increase (Figure 9). This phenomenon can be attributed to testing frame's strength limits, which failed to completely shear the 80% slag/cement treated sample. Therefore, a high elastic modulus (6 MPa) was observed for the 80% slag/cement sample while its UCS stayed at 2000 kPa.

According to equation 3, a modulus factor is computed based on UCS divided as elastic modulus. Table 4 shows a higher modulus factor correlates to a lower UCS. A high modulus factor could represent a highly brittle sample.

3.5 Ratio of Improvement

Ratio of strength improvement, given by equation 2, measures the degree of improvement after clay undergoes binder treatment. Ratio of improvement was calculated using undrained shear strength obtained from mini-vane shear strength test for Kanata clay, and UCS obtained from UCS test for Arnprior clay. Figure 10 illustrates minimum improvement from 5% cement dosage, whereas a dosage of 12.5% can improve Arnprior's UCS up to a factor of 8. This result confirms the viability of using cement to improve Champlain Sea clay; however, the improvement is highly dependent on the dosage of binder.

For cement treated Kanata clay, the ratio of improvement reached 25 times for 10% cement dosage, which is very encouraging (Figure 11). With an increasing cement dosage, the ratio of strength improvement also increases in a directly proportional relationship. For slag/cement treated Kanata clay, a directly proportional relationship can be found between ratio of improvement and slag/cement dosage with high improvement ratio of up to 50 (Figure 12).

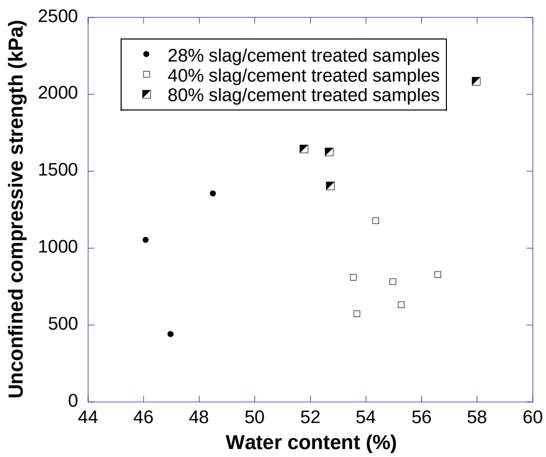

Figure 6. UCS vs. water content for slag/cement treated Kanata clay

Table 4. Correlation between average modulus factor and average UCS

Soil	Binder*	Dosage (%)	Average Modulus Factor (M)	Average UCS (kPa)
Arnprior	C	5.0	2191	129
Arnprior	C	12.5	1825	490
Kanata	C	7.0	1844	358
Kanata	C	10.0	1248	653
Kanata	C	20.0	1349	974
Kanata	C	40.0	2259	1394
Kanata	SC	28.0	1266	1110
Kanata	SC	40.0	1021	801
Kanata	SC	80.0	625	1848

* C stands for cement and SC stands for slag/cement

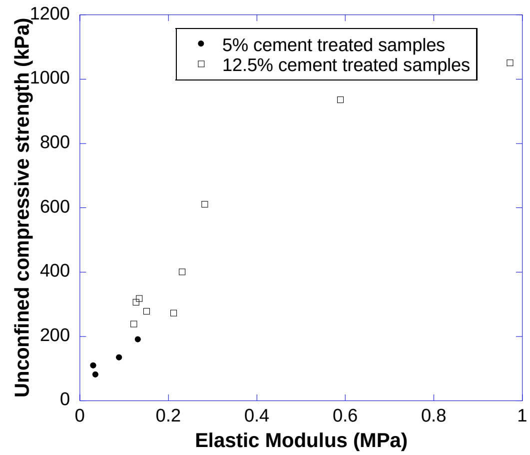

Figure 7. UCS vs. elastic modulus for cement treated Arnprior clay

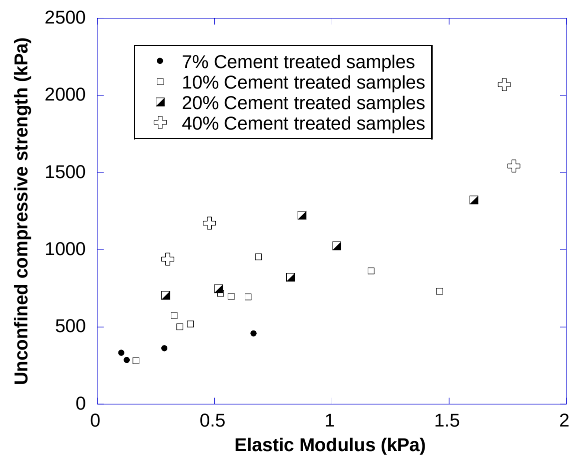

Figure 8 UCS vs. elastic modulus for cement treated Kanata clay

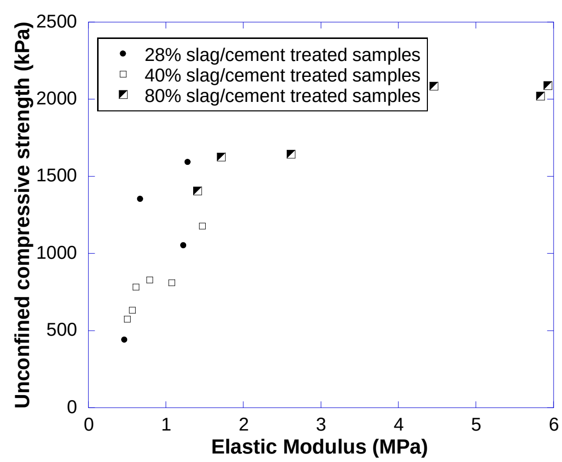

Figure 9. UCS vs. elastic modulus for slag/cement treated Kanata clay

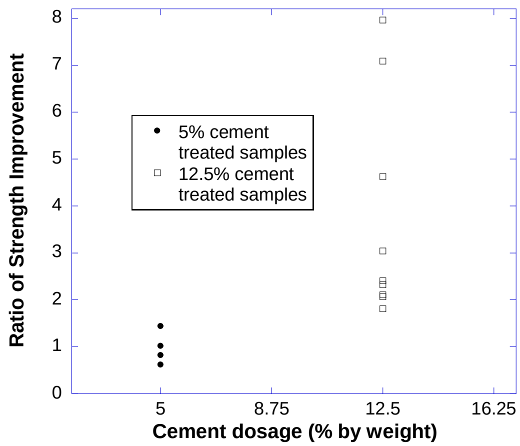

Figure 10. Ratio of improvement vs. binder dosage for cement treated Arnprior clay

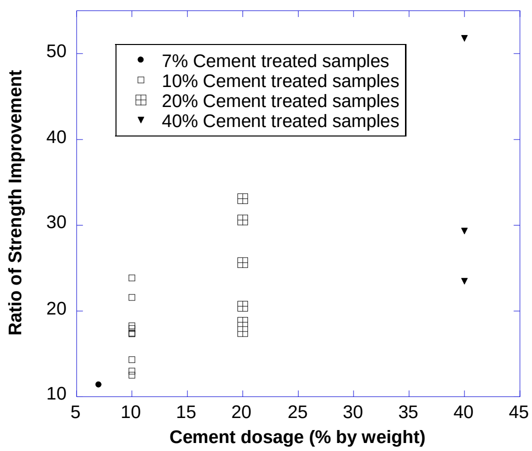

Figure 11. Ratio of strength improvement vs. binder dosage for cement treated Kanata clay

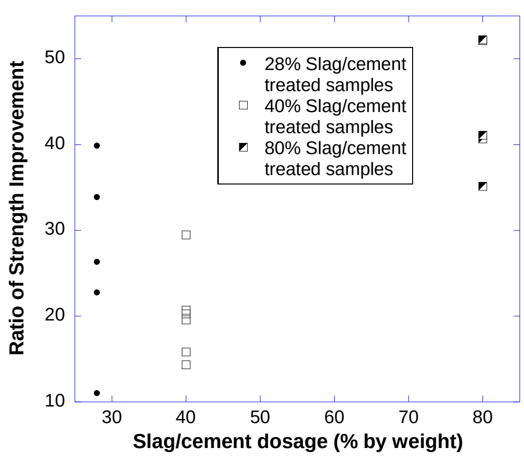

Figure 12. Ratio of strength improvement vs. binder dosage for slag/cement treated Kanata clay

4 CONCLUSIONS

In conclusion, cement and slag/cement treatment of Champlain Sea clay were very effective. Based on tests, a cement dosage of 12.5% by weight (144 kg/m^3) can effectively improve Arnprior clay. A tenfold increase in compressive strength was recorded for 12.5% cement treated Arnprior soil. UCS test results from cement treated and slag/cement treated Kanata clay recorded a even more significant increase of 50 times. A cement dosage of 20% (207 kg/m^3) was effective in treating Kanata clay, and a slag/cement dosage of 28% (290 kg/m^3) was effective in treating Kanata clay. Initially, UCS test results from cement treated Arnprior clay were not consistent due to a poorer compaction method. Long curing tube, heavy tools, thick compaction layer, and inappropriate sample removal were all factors contributing to a poorly cured sample. While a general trend of strength improvement was recorded, the ratio of strength improvements was highly dependent on sample preparations, curing condition, and testing procedures. Interoperations of result should be approached with caution.

For binder treated Kanata clay, increasing curing duration resulted in an increasing UCS, which agrees with past studies where prolonged reaction time for cement produced better UCS. Future studies can examine different curing methods such that the samples remain exposed to moisture on all faces.

An increase in water content often results in a lower UCS for cement treated Arnprior clay. This trend is prevalent for treated Arnprior clay with a 12.5% cement dosage, which agrees with Locat's (1990) finding on lime stabilization of Leda clay. For slag/cement treated Kanata, an increase in water content results in an increased UCS. A possible explanation could be that increased sample water content increases sample workability during preparation, which produced homogenous sample free of surface defects and cracks.

Elastic modulus for binder treated Arnprior clay increases with increasing UCS. The same relationship between elastic modulus and UCS is found for binder treated Kanata clay. Increasing modulus factor for both types of samples reduces UCS, which could be a reflection of low sample ductility.

For further studies, improvements to testing methods can be made to improve understanding between experimental relationships. In addition, lime can be used as a binder candidate and compared with cement and slag/cement. Next, short and long term consolidation can be performed on treated samples to obtain long term soil behaviour under loading. Finally, additional binder dosages and curing conditions can be studied and refined to obtain an efficient cement dosage.

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