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RESTRAINED SHRINKAGE TEST AND LAB SIMULATION OF MICRO-CRACKING TECHNOLOGY FOR CEMENT-STABILIZED SOILS

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Abstract: Pavement structural layers often present deterioration due to several factors such as mechanical loading, moisture and temperature. Cement-stabilized base and subgrade were documented to have higher stiffness and strength; however, this would come with other issues such as rapid hardening and early shrinkage cracks. Micro-cracking technique has recently been developed as a solution to shrinkage cracking. It consists of creating multiple hairline cracks in the stabilised layer in order to relieve the shrinkage and tension stress concentrations; therefore the development of wide cracks can be controlled. However, researches are still required investigating the ability if this technique to control shrinkage cracking for stabilized soils, as well as the lab simulation of the in-field pre-cracking process. In this research paper, two kinds of soils from southern Ontario (clay and silt) were stabilized with 6%, 9%, 12% cement by weight, respectively. The micro-cracking compaction was conducted at 3 days of curing. After 7 days of moist curing, both the pre-cracked and untreated specimens were retrained at both ends and underwent wetting and drying to initiate shrinkage crack. Meanwhile, flexural strength test for soil beams were conducted on 7 days, 28 days, and 56 days of the curing period. Results indicated that the stabilization effectively improved the durability properties and rupture modulus. With the increase of cement content and curing time, the values can be further improved. Moreover, Blenheim clay with 12% GU treated NM (not micro-cracked) had relatively higher shrinkage potential. The proper amount of cement content for Dresden silt and Blenheim clay accounted for around 6~9%, and at least 9%, respectively. Generally, the study presented a preliminary research for restrained soil shrinkage discussion and also attempted to investigate the pre-cracking process in laboratory circumstances.

1 INTRODUCTION

Fine grained soils for instance clay and silt are sensitive to moisture change. One day they are dry and hard, however another day they are wet and soft (Petry and Little 2002). For centuries, various methods have been adopted by engineers to improve the engineering properties of soils. Among those, cement-stabilization was recognized as an efficient method. The basic chemical mechanisms for cement stabilization include cementitious hydration, cation exchange, particle flocculation/agglomeration, as well as pozzolanic reactions (Prusinski and Bhattacharja 1999). The above reactions could help reduce the plasticity index, to enhance both strength and stiffness, and to improve the workability of clays and silts. The first soil-cement construction was carried out in South Carolina, United States, in 1935. Since then, substantial researches and constructions had been documented for soil-cement design and construction, providing promising results (Das 2015).

The main disadvantages of cement stabilization, on the other hand, include rapid hardening, hydration and drying-induced shrinkage cracking, sulphate attack, high cost, and CO2 emissions etc (George 1973). Silt and clay are more sensitive to wet-dry shrinkage due to the higher plasticity properties, capillary action, and larger specific surface area. Moreover, in order to provide sufficient strength and durability properties, the contents of stabilizers for fine soils are generally 2-5 % higher than those for coarse soils (Adaska and Luhr 2004), resulting in higher moisture requirement in soils. In pavements, shrinkage cracks from an underlying cement-stabilized base and subgrade can also reflect through the surface, allowing water penetration and exacerbating deterioration (Louw and Jones 2015). Micro-cracking technique is one of the pre-cracking technologies discussed recently. The general procedure in the field is to apply a vibratory roller (e.g. 12 ton) over the stabilized layer 24-72 hours after the final compaction. Afterwards, multiple hairline cracks will be created to relieve the shrinkage and tension stress concentrations; therefore the development of wide cracks can be controlled. Several trial micro-cracking sections had been constructed in the UK (Ellis and Dudgeon 2004) and in Texas, US (Sebesta and Scullion 2004). Field tests indicated a significant reduction of transverse cracks in micro-cracked sessions compared to controlled sessions after 20-30 months of service life. Also, a continuous growth of FWD (falling weight deflectometer) modulus was observed which could reach or exceed the values in contemporary controlled sessions. However, researches are still limited regarding the mechanism, effectiveness, and established procedure for such technology (Louw and Jones 2015), and there are very few studies which focus on its laboratory simulations.

In this research, two kinds of soils (clay and clayey silt) from a natural subgrade in southern Ontario were stabilized with 6%, 9%, 12% cement by weight, respectively. Restrained shrinkage test was applied to compacted soil beams after 7days of curing. Meanwhile, a micro-cracking process was simulated in lab for specimens with higher shrinkage potentials. On the other hand, flexural strength of both micro-cracked and untreated stabilized soil beams were tested at 7days, 28 days, and 56 days. Therefore, the modulus growth and self-healing properties of micro-cracked soils can be observed. Results of the tests will help to improve the knowledge of shrinkage potentials for cement stabilized soils, and it will introduce a method to simulate micro-cracking process in the lab.

2 MATERIALS AND METHODOLOGY

2.1 Characterisations of soils and cement

Preliminary, target soils were sampled from 2 different natural subgrades located in Chatham-Kent, Southern Ontario. Since the sites were originally used for crop cultivation, there is a considerable amount of organic matters; therefore, the top 10 cm of the soil was removed by a grader. Soils were then excavated and stripped to a depth of 30cm, preparing for mixing and compaction. Soil sampling was conducted when the soil was homogeneous and loose.

Based on the site location, the soils were named as Blenheim clay and Dresden silt. Their natural organic matters content, Atterberg limits, optimum moisture content, soil classification information as well as other geotechnical parameters were summarized below in Table 1.

Table 1: Soil geotechnical characteristics

	Blenheim clay	Dresden silt
Natural organic matter (%)	4.90	4.54
Plasticity index	21	0
Optimum moisture content (%)	17.3	15.9
pH value	4.84	6.51
Clay content (≤5μm) (%)	59	31
USCS* soil group	OH	OL
AASHTO soil group	A-7	A-5
Frost heaving susceptibility	Low	Moderate

* Unified Soil Classification System

Both of the soils had relatively high content of organic matters with approximately 4.5~4.9% by weight. Such matters containing soil humus or humic materials will lead to lower pH values and weaker alkaline environment; and will in turn, interfere with hydration and pozzolanic reactions of cement-treated soils (Harris et al. 2009). The Blenheim clay exhibited moderate plastic properties and had a significant percentage of clay particles; whereas the Dresden silt showed no plasticity. The optimum moisture content of Blenheim clay and Dresden silt under standard compaction effort accounted for 17.3% and 15.9%, respectively.

Cement used in this study is General Use (GU) cement conforming to Canadian Standards Association CAN/CSA-A3001-13. Some technical parameters of the cement were analyzed and presented below in Table 2.

Table 2: Physical and chemical parameters for cement used in research

Parameter	Value	Parameter	Value
w/c ratio by flow test	0.485	Vicat initial setting time (min)	133
Compressive strength 7d (MPa)	22.1	SO_3 (%)	3.9
Compressive strength 28d (MPa)	28.3	MgO (%)	2.5
Blaine fineness (m^2/kg)	383	Loss of ignition (%)	2.3

2.2 Sample preparation and test methodology

The general methodology of the study includes: soil mixing, specimen compaction, curing, micro-cracking compaction, restrained soil beams testing, and flexural strength testing. The schematic flowchart of the procedures is illustrated as follows:

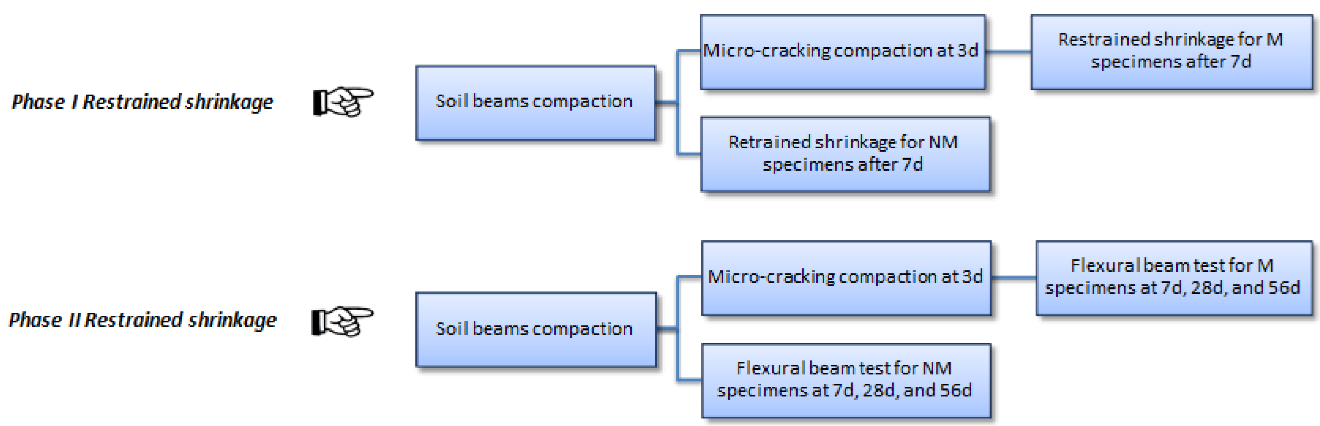

Figure 1: Schematic flowchart for lab tests

During the soil preparation, dry soil and water were initially mixed and mellowed for 24h to allow the moisture to distribute homogeneously. Then, the cement was mixed with wet soil by weight of 6%, 9%, and 12% respectively, and the mixture was compacted in moulds by hammer and tamper according to its optimum moisture content and the corresponding density. The test procedure was generally divided into two major phases: phase I, soil shrinkage potential test, and phase II, flexural beam strength test. The micro-cracking compaction was conducted after 3 days of moist curing, and restrained shrinkage tests started after 7 days of curing. On the other hand, flexural beam tests for micro-cracked (M) and non-micro-cracked (NM) specimens were carried out at 7 days, 28 days, and 56 days of curing respectively.

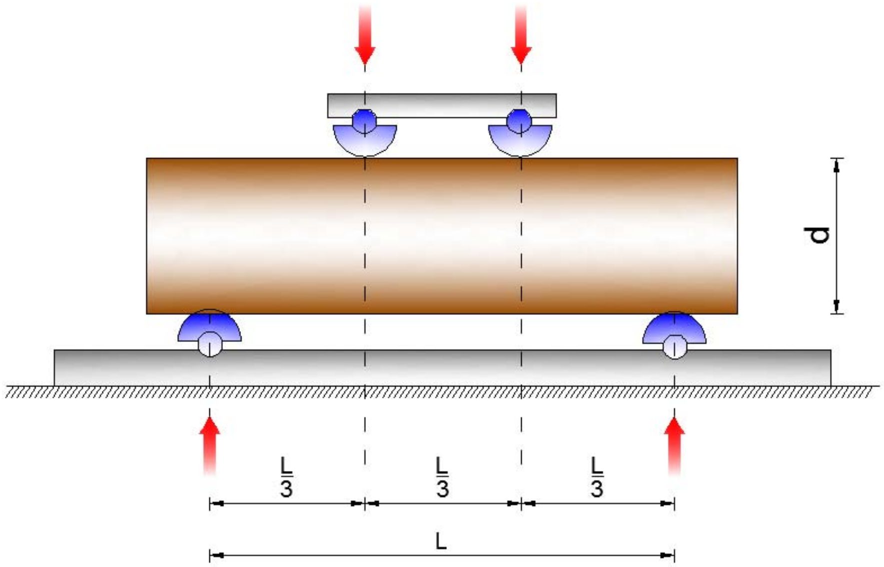

Figure 2: Flexure test of soil-cement by third-point loading method (ASTM D1635)

The flexural strength of the soil beams were then carried out with a third-point loading system (figure 2) as introduced in ASTM D1635, but using a smaller sized specimen (30mm by 30mm by 150mm). Vertical loadings were applied on one-third of the span length at a rate of 1.2mm/min until the specimen failed. The modulus of rupture can then be calculated from the following equation (ASTM D1635):

$$[1]\ \mathrm{R} = \frac{PL}{bd^2}$$

where R = modulus of rupture (MPa), P = maximum vertical load (N), L = span length = 120mm, and b = d equals to average width and depth of specimen = 30mm, respectively.

3 RESULTS AND DISCUSSIONS

3.1 Restrained Shrinkage Test for Stabilized Soil Beams

3.1.1 Durability of Cement Stabilized Soils

As it was illustrated previously, the dry mass of stabilized soil beams were measured at the end of each drying and wetting cycle. Figures 3 and 4 below present the variation of dry mass of the two soils compared to the initial weight, respectively. It should be noted that untreated soil beams were also subjected to wetting, however both of them collapsed during the first submerging period. Most of the stabilized soils, on the other hand, maintained their shape even when undergoing several wetting and drying cycles. In addition, higher cement content normally led to significant improvement of soil durability.

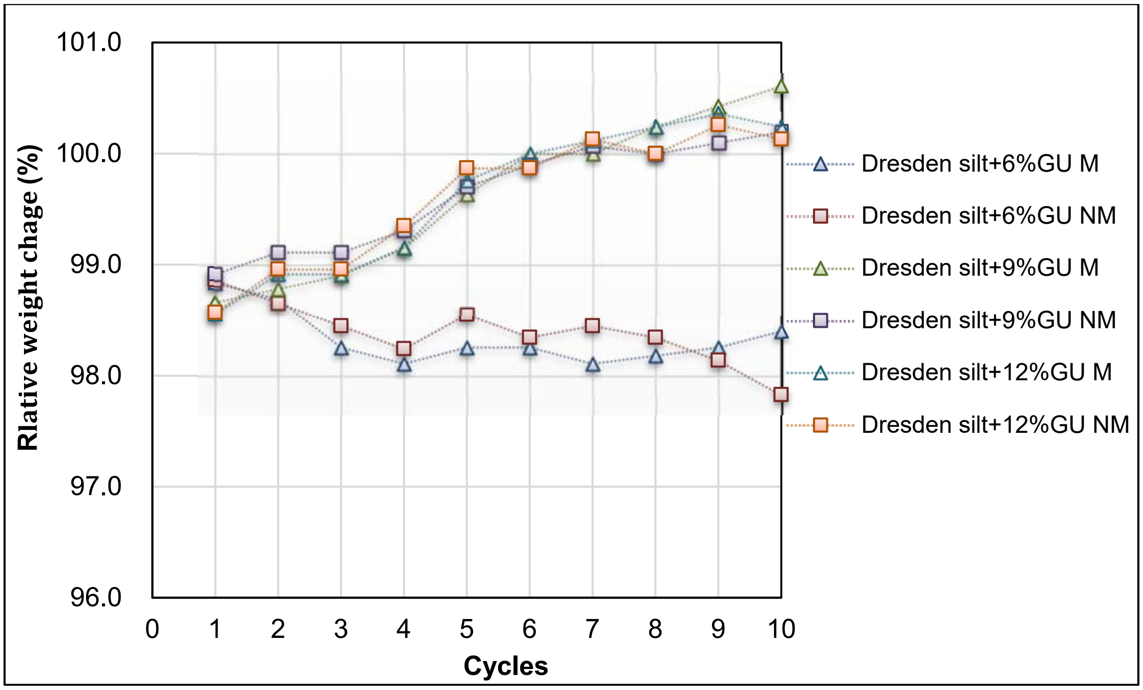

Figure 3: Relative weight change of Dresden silt after each wetting and drying cycle

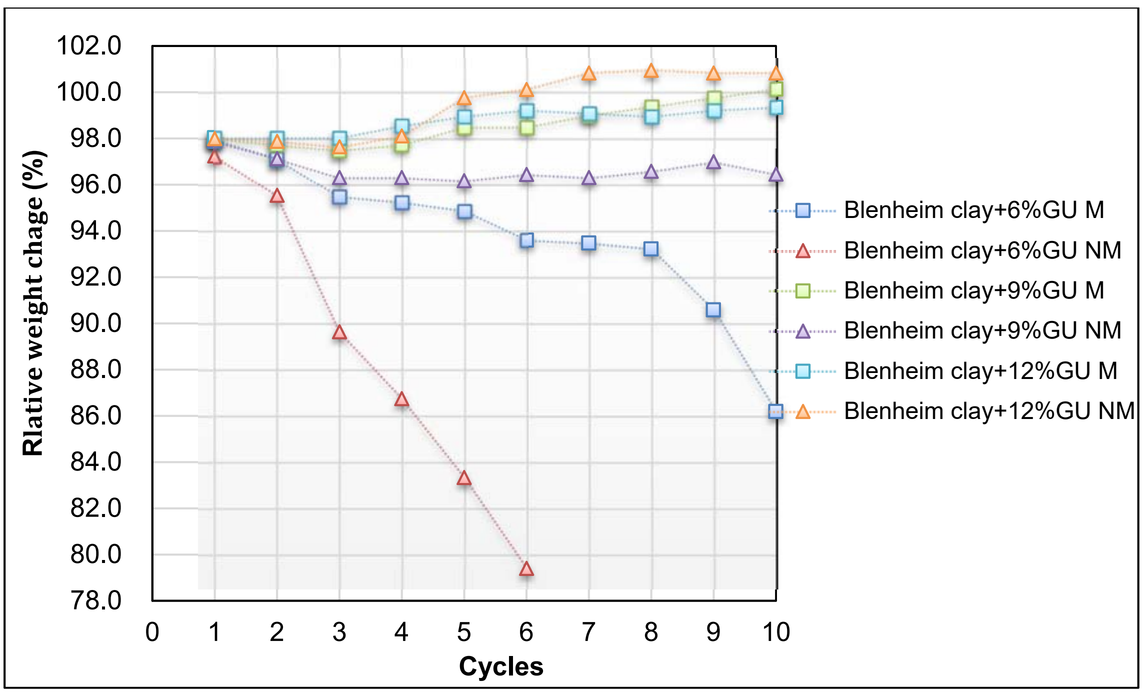

Figure 4: Relative weight change of Blenheim clay after each drying and wetting cycle

Dresden silt showed minimum weight loss after the wetting and drying deterioration; hardly any soil particles were seen peeled off from beam mass (figure 5). Silt with 6% GU cement showed a slight downward trend regarding the dry weight; nevertheless, the overall structure remained hard and stable during the wetting and drying. Meanwhile, silt with higher cement ratio (9% and 12%) had a continuous growth in the dry weight. The reason for this growth was due to the cement hydration: water which had reacted with cement was retained after drying, and the amount of retained water increased as the hydration continued. Empirically, the amount of retained water was estimated by 1/4 of cement percentage (PCA 1992).

On the other hand, the cement stabilized Blenheim clay showed much weaker durability properties than silt. Starting from the second cycle, non-micro-cracked Blenheim clay with 6% GU exhibited significant loss of weight; and it collapsed after 6 cycles, losing approximately 20% of soil particles compared to the initial state. Clay specimens mixed with 9% or more cement were more stable during the test; the weight of specimens remained consistent or slightly increased. According to PCA (1992) manual for soil-cement laboratory test, the permit loss of soil-cement sample after wetting and drying cycles shall not exceed 10% by dry weight of Dresten silt (A-5) and 7% of Bleinheim clay (A-7). From the perspective of wetting and drying, 6% GU stabilizing can be acceptable for Dresden silt. However for Blenheim clay, cement ratio around 9% or above can meet the criteria. Future mix design researches will investigate the Dresden silt with cement ratio between 6% and 9%. For Blenheim clay, the researchers intend to investigate the use of other hydraulic road binders including supplementary cementitious materials for this type of difficult soil.

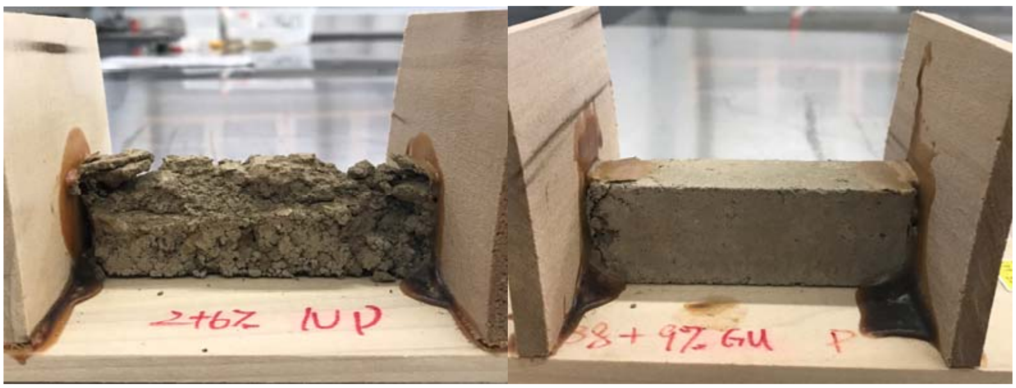

Figure 5: State of soil beams after 6 cycles: Blenheim clay with 6% GU NM (left), Dresden silt with 9% GU M (right)

Specimens which had experienced micro-cracking showed improved performance of water resistance and durability properties. But the improvement was not considerable due to a short curing period (7d). Moreover, there were some difficulties on how to quantify the cracks produced by micro-cracking. The soil beams were visually seen to have a denser and stiffer structure. Consequently, whether the durability improvement was contributed by micro-cracking or "second compaction" is unclear.

3.1.2 Shrinkage potential of cement stabilized soils

After each drying period, restrained soil beams were visually inspected for the appearance of cracks and deformation. Since the soil beams were restrained at both ends, drying shrinkage of the soils will yield transverse cracks in the beams.

Among all the soil beams, the Blenheim clay specimen with 12% GU NM was the only specimen that had some extent of shrinkage potential. It exhibited shrinkage crack at the end of the third cycle; and the cracks became wider with the cycles ongoing. Subsequently, soil particles were peeled off from the beam surface during the submerging period. On the other hand, the same specimen that underwent micro-cracking showed no visible shrinkage cracking during the test. Therefore, the micro-cracking process enhanced the soil beam durability and/or relieved the tension potential. The other clay and silt specimens maintained their general integrity during the wetting and drying cycles.

Figure 6: State of soil beams Blenheim clay with 12% GU NM after 3 cycles (left), Dresden silt with 12% GU NM after 10 cycles (right)

Literature review indicates that the organic matter and soil mineral have crucial influences on the swelling and shrinkage properties. Expansive clay minerals, e.g. montmorillonite, had a large specific surface (SSA) and held a large cation exchange capacity (Luo 2007). High content of montmorillonite clay in the soil mass will result in a high water-hold capacity, high swelling and shrinkage potential, and high plastic property. However, according to the soil investigation, both candidate soils did not have high plastic property. The organic matters and clay particles in Blenheim clay brought relatively higher potential of shrinkage during cement stabilization, but generally the shrinkage and swelling potential for the two kinds of soils were not distinct. In the future, it is also necessary to introduce other soils which have different mineral components and higher plasticity properties for comparison. From the aspect of shrinkage potential investigation, 9% of cement dosage is optimum to both improve the durability as well as to prevent drastic hydration.

3.2 Flexural beam test

Results of rupture modulus were calculated based on equation [1] introduced previously. Samples were tested at the curing age of 7days, 28 days, and 56 days, respectively.

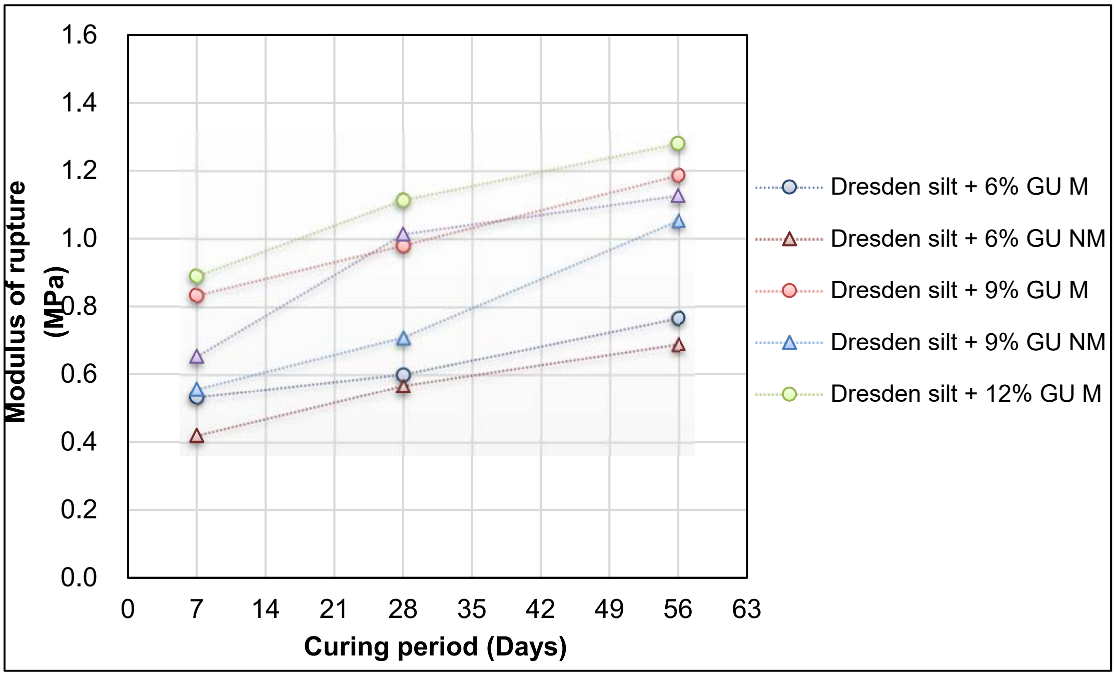

Figure 7: Modulus of rupture of Dresden silt

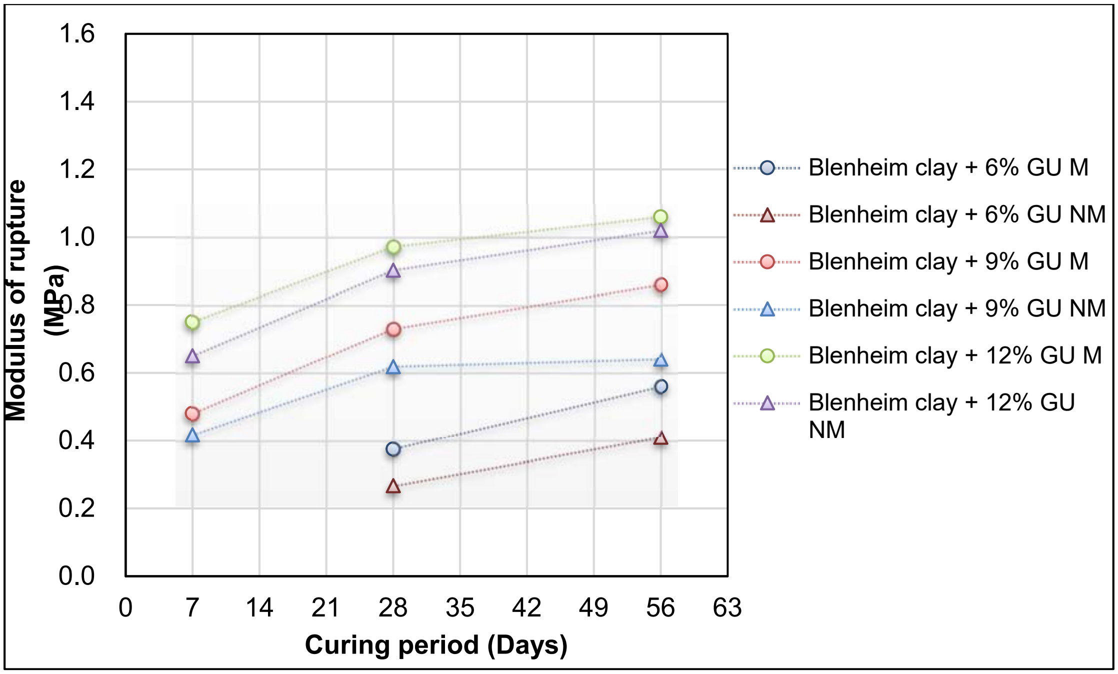

Figure 8: Modulus of rupture of Blenheim clay

As was presented in Figures 7 and 8, with the cement content increasing, both M and NM samples had significant growth of rupture modulus. Furthermore, a longer period of curing will lead to larger modulus values. Between them, stabilized Dresden silt generally had a higher modulus of rupture in all cement ratios and curing ages.

As it was discussed previously, the organic matters reduced the soil pH, and affected the hydration and pozzolanic reactions. Thus the stabilized Blenheim clay exhibited relatively lower strength and stiffness than stabilized Dresden silt. Particularly, Blenheim clay samples with 6% GU at the age of 7d were too weak; and the test results were not able to be acquired. On the contrary, the rupture modulus of 12% GU stabilized Dresden silt with micro-cracking compaction accounted for a high of 1.28 MPa at the curing age of 56d.

The principle for the micro-cracking process is to create intensive, tiny cracks to reduce the stiffness temporally at the early age of curing (Luo 2007). As a consequence, the stiffness and compressive strength will be reduced in the field (Louw and Jones 2015). However, from Figures 7 and 8, there was no obvious decrease of modulus of micro-cracked soils specimens compared to untreated ones. On the contrary, specimens which experienced micro-cracking compaction had higher rupture modulus than their counterparts with the same cement content, even at early ages. From the authors' point of view, the stabilized soils were "secondly compacted" rather than micro-cracked. Several reasons caused this phenomenon: first, 3 days of moist curing did not lead to a stiff soil mass before micro-cracking. In other words, the micro-cracking compaction didn't damage the bonding between soil particles, but creating a more compact and dense soil structure. Second, the soil type and mineral components resulted in a low shrinkage potential and crack propagation property. So the multiple micro-cracks didn't appear after the micro-cracking process. Third, the compaction was conducted on a wet state soil which allows plastic deformation, whereas in the field, inadequate curing will lead to severe drying shrinkage and crack propagation. Overall, soils after stabilization and micro-cracking processes will have an improved rupture modulus, and the values of modulus grew continuously with the curing ongoing. Nevertheless, more research work is needed in order to study the effects of soil types and curing condition on micro-cracking technology.

4 CONCLUSION

From the laboratory tests and analyses of the data, the following conclusions and discussions can be drawn:

1. Cement stabilization effectively improved the durability properties and rupture modulus of the studied soils. Along with the increase of cement content and curing time, the values can be further improved. The lab test results of restrained shrinkage and flexural beam tests, showed that the proper cement content for Dresden silt with the 6~9% range, and the adequate cement content for Blenheim clay should at least be around 9% by dry weight. It was also found that Blenheim clay with 6% GU cement by weight did not have enough durability against wetting and drying cycles. The research provided a preliminary study of cement-soil behaviours, future mix designs will address the physical properties of Dresden silt with cement ratio between 6% to 9%. For Blenheim clay, the researchers intend to investigate the use of other hydraulic road binders including supplementary cementitious materials as this soil type is particularly difficult to stabilize and requires more research.

2. The stabilized Dresden silt had weight fluctuation controlled within ± 5% compared to the initial weight. For the Belenheim clay 6% GU could not maintain the initial shape after the recommended wetting and drying cycles, whereas the 9% and 12% GU stabilized clays were much more stable regarding the wetting and drying durability. Apparent shrinkage cracks only appeared on 12% GU treated Blenheim clay NM at the end of the third wetting and drying cycle. So the micro-cracking process in this test improved the soil's durability and reduced the shrinkage potential.

3. Flexural beam test indicated that all the soil specimens had significant growth of rupture modulus. Furthermore, longer periods of curing will lead to larger values of modulus. The stabilized Dresden silt generally had higher modulus of rupture in all cement ratios and curing ages.

Before micro-cracking process, the stabilized soils were cured for 3 days in an ideal condition, thus the soil was in a moist condition. Furthermore, modulus tests were conducted on specimens within 2 months of curing period, so the recovery of stiffness in a longer period of time was not investigated. Therefore, in the future studies, research is still required to investigate the following aspects of the micro-cracking process: soil types, the time of applying micro-cracking, the moisture control before micro-cracking, and stiffness gaining in longer curing period. Generally, the study presented a preliminary evaluation of restrained soil shrinkage and also attempted to investigate the micro-cracking in laboratory scenarios.

References

Adaska, W. S., and Luhr, D. R. May, 2004. Control of reflective cracking in cement stabilized pavements. In *Proceedings of 5th International RILEM Conference on Cracking in Pavements* (pp. 309-316).

ASTM D1635/D1635M-12 Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading, ASTM International, West Conshohocken, PA, 2012, https://doi.org/10.1520/D1635_D1635M-12

Das, B. M. 2015. Fundamentals of Geotechnical Engineering. 5th Ed. Cengage Learning, USA.

Ellis, S., and Dudgeon, R. 2004. Pre-cracking as a technique to minimise reflection cracking in semi-rigid pavement structures-long term performance monitoring. In *5th International RILEM Conference on Cracking in Pavements-Mitigation, Risk Assessment and Prevention. Edited by Petit C., Al-Qadi IL et Millien A* (pp. 325-332).

George, K. P. 1973. Mechanism of shrinkage cracking of soil-cement bases. *Highway Research Record*, 442.

Harris, P., Harvey, O., Puppala, A., Sebesta, S., and Rao, S. 2009. Mitigating the Effects of Organics in Stabilized Soils: Technical Report (No. FHWA/TX-09/0-5540-1). Research Report No. FHWA/TX-09/0-5540-1 Texas Transportation Institute, Texas A&M University, College Station, Texas.

Louw, S., and Jones, D. 2015. *Pavement Recycling: Literature Review on Shrinkage Crack Mitigation in Cement-Stabilized Pavement Layers* (No. UCPRC-TM-2015-02).

Luo, R. (2007). *Minimizing longitudinal pavement cracking due to subgrade shrinkage*. The University of Texas at Austin.

Petry, T. M., and Little, D. N. 2002. Review of stabilization of clays and expansive soils in pavements and lightly loaded structures—history, practice, and future. *Journal of Materials in Civil Engineering*, ***14***(6), 447-460.

Portland Cement Association. 1992. *Soil-cement laboratory handbook*. Portland Cement Association.

Prusinski, J., and Bhattacharja, S. 1999. Effectiveness of Portland cement and lime in stabilizing clay soils. *Transportation Research Record: Journal of the Transportation Research Board*, (1652), 215-227.

Sebesta, S., and Scullion, T. 2004. *Effectiveness of minimizing reflective cracking in cement-treated bases by microcracking* (No. FHWA/TX-05/0-4502-1,).