Comparison of sedimentary environment and geotechnical properties of Lake Agassiz and Ariake clays for application of Deep Mixing Method

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ABSTRACT
Deep mixing method (DMM) is a ground stabilization technique using lime or cement binders. The DMM has gained increasing applications to minimize ground settlements and increase capacity to support structures. It is often used as one of the ground improvement methods in soft ground such as the Ariake Sea coast lowland (Saga) in Japan to support highway embankments. However, there were cases where foundations improved by DMM columns had collapsed. The effectiveness of DMM is highly dependent on the physicochemical properties of natural clays. It is important to understand the sedimentary environment and geotechnical characteristics of the site. So far, there is no case where DMM has been used in Lake Agassiz clay deposits in Manitoba to improve the soft and compressible clay deposits. Data are required to determine the optimal number of admixtures in Lake Agassiz clay. In this paper, the sedimentary environment and geotechnical properties with Lake Agassiz clay and Ariake clay were first compared. There have been a lot of studies on the effectiveness of soil-cement applications in Japan and it is valuable as basic knowledge to compare strength development of Ariake clay and Lake Agassiz clay which has been improved.

RÉSUMÉ
La méthode de mélange en profondeur (DMM) est une technique de stabilisation du sol utilisant des liants à chaux ou au ciment. Le DMM a été plus executé pour minimiser les zones d' affaissement et augmenter la capacité portante des structures. Il est principalement utilisé dans les basses terres côtières de la mer d'Ariake au Japon pour soutenir les remblais routiers. Cependant, dans certains cas, les fondations améliorées grâce aux colonnes DMM se sont effondrées. L'efficacité du DMM dépend fortement des propriétés physico-chimiques des argiles naturelles. Il est important de comprendre l'environnement sédimentaire et les caractéristiques géotechniques du site. Jusqu'à présent, il n'y a pas eu de cas d'utilisation de DMM dans les dépôts d'argile du lac Agassiz au Manitoba pour améliorer les dépôts d'argile molle et compressible. Des données sont nécessaires pour déterminer la quantité optimale d'adjuvants dans l'argile du lac Agassiz. Dans cet article, l'environnement sédimentaire et les propriétés géotechniques de l'argile du lac Agassiz et de l'argile d'Ariake ont d'abord été comparés. De nombreuses études sur l'efficacité des applications sol-ciment au Japon ont été menées et il est important de comparer les résistances au cisaillement non limitées de l'argile Ariake traitée à celles de l'argile lac Agassiz traitée.

1 INTRODUCTION

The performance of rockfill columns in Manitoba has generally been satisfactory. However, significant deformations during and after construction have been reported by Yarechewski et al. (2003). Thiessen et al. (2007) mentioned the factor of the deformations that the riverbank failures in Winnipeg are often triggered by fluctuations in groundwater conditions in fall and spring. As the river level drops following the spring runoff, higher pore water pressures remain in the banks after the stabilizing effect of the floodwater is gone. During summer, the Red River level is controlled by locks at the entrance to Lake Winnipeg. In fall, the river level drops to winter ice level approximately 2 m below the normal summer river level with the same effect.

Soil-cement columns using deep mixing method (DMM) has been considered as an alternative to stabilize riverbanks in Manitoba because the movements require to mobilize their shear strengths are lesser compared to rockfill columns. Soil-cement column (termed DMM column from here onwards) is a deep in-situ admixture stabilization technique using lime, cement or lime-based and cement-based special binders. Compared to other ground improvement techniques, it has little adverse impact on the environment and has high applicability to any kind of soil (if type and amount of binder are properly selected). Improved ground by DMM is a composite system comprising of stiff stabilized soil and the surrounding natural clay.

Geotechnical engineers need to have a better understanding of the interaction of the binder (cement) and natural clay as well as the engineering characteristics of in-situ stabilized soil (Kitazume et al. 2013; Hino et al. 2012). Otherwise, the collapse of structures supported by DMM-improved foundations such as that shown in Figure 1 can happen. This failure happened in the area surrounding the Ariake Sea in Japan wherein the area has extensive clay deposits with thickness varying from 15 m to 40 m. Ariake clay is very soft due to the salt leaching out of the pore water and is characterized by high compressibility and high sensitivity (Hino et al. 2014).

Figure 1. Collapse at Ashikari-minami Interchange (Saga, Japan) (Miura and Hino, 2018)

2 FACTORS AFFECTING THE STRENGTH OF SOIL-CEMENT ADMIXTURES

The strength of soil-cement columns is usually evaluated using unconfined compression strength (UCS) tests. Cored samples are taken from the columns in the field, 28 days after the installation. Samples are subjected to UCS tests to check if they reached the required strength in the field. It is important to understand the development of strength of treated soil as there are several factors that might affect the strength development of treated clays. Kitazume et al. (2013) mentioned that the strength increases with the increased content in lime and cement. The basic strength increase mechanism is closely related to the chemical reaction between the clay and cement binder. According to Terashi et al. (1983) and Terashi (1997), the factors can be roughly divided into four categories: 1) characteristics of binder, 2) characteristics and conditions of clay, 3) mixing conditions, and 4) curing conditions as shown in Table 1.

3 SAMPLING

Samples of Lake Agassiz Clay were taken from two different sites in Winnipeg (Figure 2) and will be referred to as Site 1 and Site 2, for convenience. Site 1 is located along the Assiniboine River and Site 2 along the Red River. The distance between these two sites is about 27.5 km. The depths of sampling are 3 to 4 m for Site 1, 6 to 9 m and 12 to 15 m for Site 2. As you can seen in Figure 3, the clay sample is brown and inclusions such as gypsum clusters and pebbles were observed. The samples were sealed with plastic wraps at the site before they were transported to the laboratory and placed in an environmental chamber.

Table 1. Factors affecting the strength development of the soil-cement column by DMM

I. Characteristics of binder	a. Type of binder
	b. Quality
	c. Mixing water and additives
II. Characteristics and conditions of soil (especially important for clays)	a. Physical, chemical and mineralogical properties of soil
	b. Organic content
	c. potential Hydrogen (pH) of pore water
	d. Water content
III. Mixing conditions	a. Degree of mixing
	b. Timing of mixing/re-mixing
	c. Quantity of binder
IV. Curing conditions	a. Temperature
	b. Curing period
	c. Humidity
	d Wetting and drying/freezing and thawing. etc.
	e. Overburden pressure

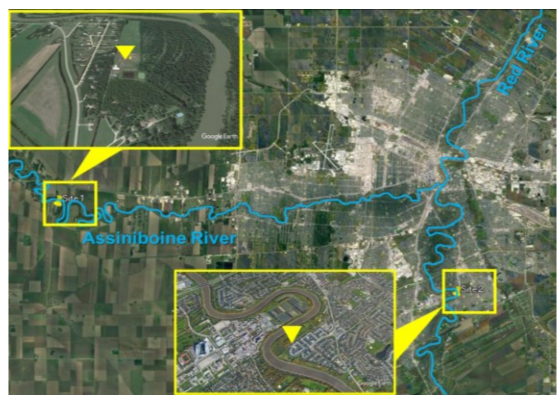

Figure 2. Location of Sampling

Figure 3. Block sampling at site 1

4 SOIL PROPERTIES

4.1 Soil properties with respect to location

Table 2 shows the results of soil property tests performed on Lake Agassiz Clay samples taken from Site 1 and Site 2. In the table, results from Ariake Clay and Champlain Clay are also shown for comparison.

Ariake clay results were from samples collected from the site indicated in Figure 1 prior to the construction of the structure. Champlain Clay, also known as Leda clay, is a type of sensitive and fine grain clay commonly found along the St. Lawrence Lowlands region in Ontario and Quebec (Penner, 1965). Both of Li et al. (2016) and Mohammad Afroz et al. (2018) examined the feasibility of applying DMM.

Lake Agassiz Clay test results indicated that there was no significant difference between samples taken from Sites 1 and 2. These values were comparable to typical properties seen in Table 3 from a study done by Graham et al. (1985). As indicated in Table 2, Lake Agassiz Clay had the lowest natural water content when compared to the others. Its liquid limit was twice as high when compared to Champlain Clay though their plastic limits were similar. This resulted to Lake Agassiz Clay having plasticity indices twice as high as those from Champlain Clay.

It should be noted that the natural water content of Lake Agassiz Clay was close to its plastic limit and that the liquidity indices were 0.2 to 0.4. The wet density could not be measured as the samples were highly fissured but based on the liquidity index values, it was considered that the void ratio of Lake Agassiz Clay was small. In addition, as the liquidity indices were close to zero and the consistency index values were close to unity, the state of the ground was considered to be stable.

The presence of organic matter in the soil is known to affect the strength development of improved soils and is typically determined by performing the loss of ignition (LOI) test. This test is used to measure organic matter content in soils and, though conducted in many countries, there is no available international standard procedure. Some researchers mentioned that the factors influencing the accuracy of the LOI test may include exposure to time, temperature, sample size, furnace type, sample mass, and clay content of samples (Oliver et al. 1999). In this study, all of the ignition loss (L_i) values were obtained using the Japanese Industrial Standard (JIS A 1226 2009). In this method, L_i is the percentage of the reduced mass when the samples were dried at 110 ± 5°C is exposed to a temperature of 750 ± 50°C until a constant weight is obtained. The sample weight is about 2 to 10 g when using a 50 mL crucible and about 2 g when using a 30 mL crucible. The sample is exposed to 750 ± 50°C for 1 hour by an electric muffle furnace capable of heating to 1000 °C or more. The samples were exposed for 4 hours in this study.

4.2 Soil Properties with respect to depth

Figure 4 shows a borehole log by Barracos et al. (1980) with data obtained from samples taken at the University of Manitoba which is located near Site 2. The natural water

Table 2. Soil properties of clay from different locations

	Lake Agassiz Clay			**Champlain Clay 1**		**Champlain Clay 2**	**Ariake Clay**
	Site 1	Site 2		Li et al. (2016)		Mohammad et al. (2018)	Saga (Japan)
Depth / Location	3m-4m	6m-9m	12m-15m	Arnprior	Kanata	Ottawa	Ashikari
Natural water content, w_n (%)	48.4	43.9	55.8	49.1	60.5	64 - 74	81.7 - 143.0
Specific Gravity, G_s (g/cm^3)	2.755	2.723	2.727	-	-	2.6 - 2.72	2.54 - 2.58
Liquid Limit, w_L (%)	99.3	100.4	95.3	57.3	29.3	49 , 61	95.8 - 108.6
Plastic Limit, w_p (%)	35.5	32.1	31.7	26.9	21.8	30 , 61	37.2 - 43.4
Liquidity Index, I_L (%)	0.2	0.2	0.4	0.7	5.2	-	0.73 - 1.59
Plasticity Index, I_P (%)	63.8	68.4	63.6	30.4	7.5	-	52.4 - 68.3
Consistency Index, I_C	0.8	0.8	0.6	0.3	-4.2	-	-0.59 - 0.27
Grain Size Distribution							
medium sand (%)	0.4	1.1	1.4	-	-	-	0 - 2.8
fine sand (%)	0.6	1.2	1.4	-	-	-	1.5 - 8.8
silt (%)	12	4	10.8	-	-	-	28.2 - 53.9
clay (%)	87	94	86.8	-	-	-	40.2 - 62.3
fine fraction content, F_c (%)	99	97.7	97.2	-	-	-	88.6 - 98.5
Activity, A	0.89	0.92	0.86	-	-	-	1.15 - 1.57
Ignition Loss, L_i (%)	14.4	17	16.5	-	-	-	-
Unconfined Compression Strength (kPa)	-	-	-	132	-	-	-
Sensitivity	-	-	-	14	11	4 - 8	-

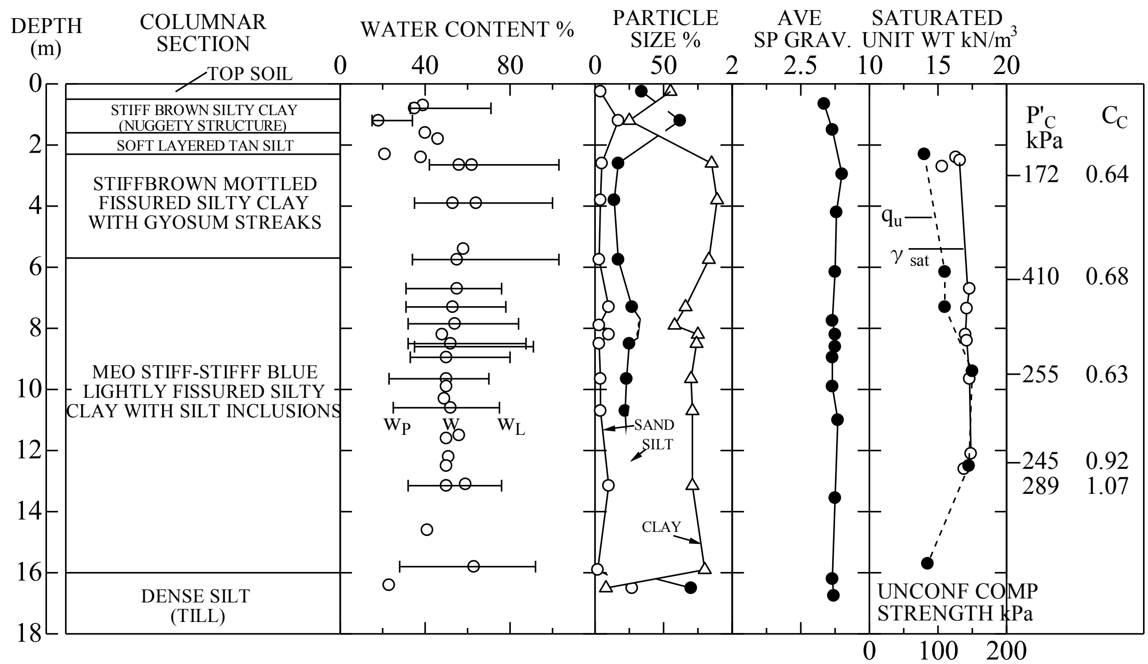

Figure 4. Borehole log data from Barracos et al. (1980)

content is almost constant at about 50 to 60% regardless of the depth, with the least value near the surface. The plastic limit shows the same tendency as the natural water content, but the liquid limit decreases as the depth increases. Due to this, the liquidity index and sensitivity increases. The fact that the compression index increases with depth also suggests that ground instability increased. On the other hand, it can be seen that the unconfined compression strength increases with depth.

Table 3. Geotechnical properties of Lake Agassiz Clay at Winnipeg by Graham et al. (1985)

Moisture Content (%)	54 - 63
Liquid Limit (%)	65 - 85
Plasticity Index, I_P (%)	35 - 60
Undrained Shear Strength, S_u (kPa)	50 - 75
Sensitivity	3 - 4
Compression Index, C_c	0.6 - 1.1
Clay Fraction (%)	70 - 80
Dominant Mineralogy	Smectite

Figure 5 shows a borehole log from the Ariake Sea coastal lowlands. The data shown in Figure 5 are the site investigation results before the construction of the interchange shown in Figure 1. The natural water content of the marine Ariake Clay layer Formation ranged from 100 to 150%, and all values are above the liquid limit. The unconfined compression strength is less than 30 kN/m^2 and the compression index is more than unity, indicating that the material has high compressibility. The sand content increases from a depth of 11.4 m where the Mitagawa layer Formation appears, and the natural water content becomes about 50% or less.

5 APPLICABILITY OF DEEP MIXING METHOD (DMM)

The sensitivity (S_t) can be estimated from the relationship between liquid index (I_L) and the undrained shear strength (S_u) as suggested by Mikasa (1979). Using the I_L from Table 2 and S_u in Table 3, the S_t of the sample in this study was estimated in Figure 6. The range enclosed by a red square shows the sensitivity of Lake Agassiz Clay. The data of Ariake clay shown in Figure 6 uses the results of previous ground investigation sampled from multiple points in the Ariake Sea coastal lowland. Although it varies depending on the location and depth, it has high sensitivity in overall. On the other hand, as shown in Table 3, the sensitivity of Lake Agassiz Clay is estimated about 2 to 5 confirming that it has low sensitivity. If DMM is implemented in Lake Agassiz Clay, it is suggested to increase the sensitivity of the soil at the predetermined depth or location. The cement could be mixed in with the soil while pulling out the mixing blade in order to increase soil sensitivity and ensure a homogeneous mix of soil and cement.

Since the soil activity (A) indirectly indicates its physicochemical properties, it is used as a reference for the applicability of ground environment methods. The activity is determined by dividing the plasticity index by the clay content below 2 μm. It is classified as a high activity if A has a value of 1.25 or more, normal activity if 0.75 to 1.25, and low activity if A is less than 0.75. Figure 7 shows the

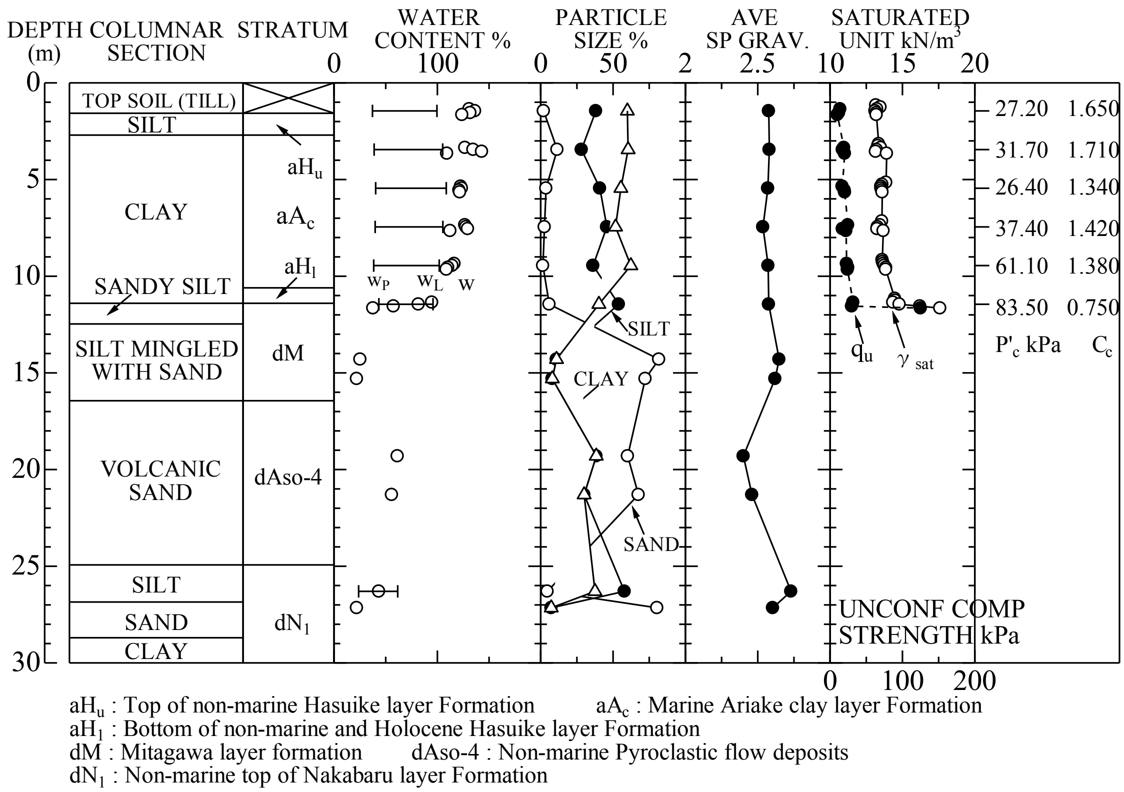

Figure 5. Borehole log data Ariake Sea coastal lowland

activity of Lake Agassiz Clay and Ariake Clay. The activity of Lake Agassiz Clay ranged between 0.86 and 0.92 and is classified as normal activity. Ariake Clay showed high activity with many values above 1.25. Looking at the relationship of activity and clay minerals, as can be seen in Figure 7 that smectite (montmorillonite) has high activity and is sensitive to chemical reactions due to its high specific surface area and cation exchange capacity. It also has the high liquid limit regardless of the particle size distribution. On the other hand, clay containing mostly kaolinite would be insensitive to chemical reactions due to its low specific surface area and cation exchange capacity, in addition to its low liquid limit regardless of the particle size distribution.

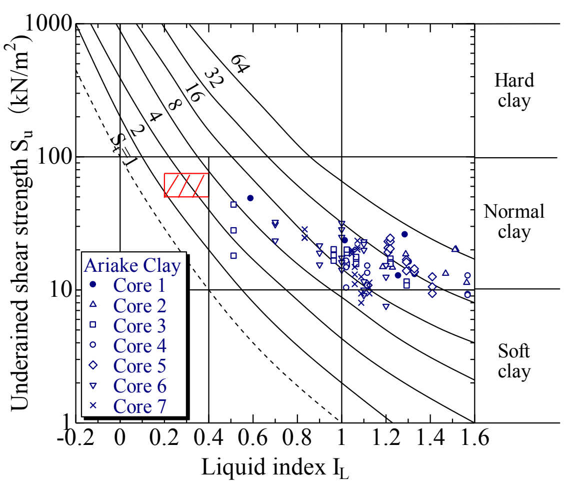

Figure 6. The relationship between I_L-S_u

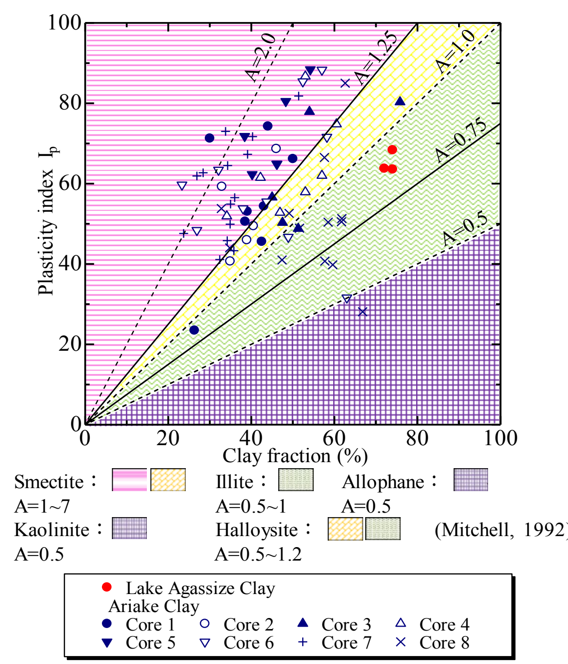

Figure 7. The distribution of activity

While it is challenging to determine the activity of the soil after DMM has been applied, it is possible that the improved ground might have an activity of 0.5 to 1.25 since Lake Agassiz Clay is considered to be mostly interlayered smectite and illite. It is still necessary to be careful because the physicochemical properties of the soil containing other minerals would differ from the results in this study.

6 SUMMARY

In this paper, the sedimentary environment and geotechnical properties of Lake Agassiz Clay were compared with those of Ariake Clay from the viewpoint of application of DMM. Based on the investigation results, the following conclusions can be drawn:

- The soil quality test results of the soil samples used in this study were characterized as having a natural water content close to the plastic limit and high plasticity and can be regarded as a typical Lake Agassiz Clay.
- The clay at shallow depths is stiff and the sensitivity ratio is low. However, there is the tendency of the liquidity index and consolidation index to increase as depth increases.
- The soil activity of Lake Agassiz Clay, which is a measure of chemical reaction, is normal, and the main clay minerals in this study are considered to be interlayered illite and smectite.
- The soil test results of Ariake clay shown indicated its characteristics with respect to the location (or area) and depth. As far as the authors know, the data on geotechnical properties with the above-mentioned perspective since the ground investigation by Baracos in the 1980s. It is desirable that a more detailed ground investigation be conducted when applying DMM, in order to eliminate the concern that the changes in the ground environment would have on geotechnical properties of the improved soil

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