World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:16, No:10, 2022

Evaluating the Small-Strain Mechanical Properties of Cement-Treated Clayey Soils Based on the Confining Pressure

M. A. Putera, N. Yasufuku, A. Alowaisy, R. Ishikura, J. G. Hussary, A. Rifa’i

***Abstract*—**Indonesia’s government has planned a project for a high-speed railway connecting the capital cities, Jakarta and Surabaya, about 700 km. Based on that location, it has been planning construction above the lowland soil region. The lowland soil region comprises cohesive soil with high water content and high compressibility index, which in fact, led to a settlement problem. Among the variety of railway track structures, the adoption of the ballastless track was used effectively to reduce the settlement; it provided a lightweight structure and minimized workspace. Contradictorily, deploying this thin layer structure above the lowland area was compensated with several problems, such as lack of bearing capacity and deflection behavior during traffic loading. It is necessary to combine with ground improvement to assure a settlement behavior on the clayey soil. Reflecting on the assurance of strength increment and working period, those were convinced by adopting methods such as cement-treated soil as the substructure of railway track. Particularly, evaluating mechanical properties in the field has been well known by using the plate load test and cone penetration test. However, observing an increment of mechanical properties has uncertainty, especially for evaluating cement-treated soil on the substructure. The current quality control of cement-treated soils was established by laboratory tests. Moreover, using small strain devices measurement in the laboratory can predict more reliable results that are identical to field measurement tests. Aims of this research are to show an intercorrelation of confining pressure with the initial condition of the Young’s modulus (E_0), Poisson ratio (υ_0) and Shear modulus (G_0) within small strain ranges. Furthermore, discrepancies between those parameters were also investigated. Experimental result confirmed the intercorrelation between cement content and confining pressure with a power function. In addition, higher cement ratios have discrepancies, conversely with low mixing ratios.

***Keywords*—**Cement content, confining pressure, high-speed railway, small strain ranges.

I. INTRODUCTION

INDONESIA’S first high-speed railway (HSR) project is designed to connect the country’s major cities of Jakarta and Surabaya, covering a distance of about 700 km and operating at a maximum speed of 300 km/h [1]. It is planned to be constructed at the north of Java Island, close to the Java Sea, and predominantly above lowland areas [2], [3]. The land is mainly comprised of clayey soil characterized by a high compressibility index and high water content. Often, engineers face situations where the ground is unsuitable and is expected to experience an excessive settlement when loaded by the planned loading due to construction and operation. These are limiting obstacles, especially in developing countries where costly techniques are not an option [4]. Cement-treated soil is used for structural elements such as substructures on the railway project. It could improve soft soils’ engineering properties below rail track subgrade and highway base and subbase courses [5].

Generally, railway structures can be divided into ballasted and ballastless structures. The ballasted structures are characterized by high shear strength and low vertical settlement. On the other hand, the ballastless are lightweight structures, yet, they endure better geometric stability, resulting in less differential settlement and lower maintenance costs [6]. The ballastless track structures are generally recommended for an HSR design speed of 300 km/h and relatively weak subgrades, including lowlands [7]. In addition to the track structure, many soil improvement techniques were utilized to improve the mechanical properties of the subsoil and reduce railways settlement. Among those are the railway superstructure (e.g., bridges and embankments) and soil reinforcement techniques, including pile foundation, drained consolidation methods, deep soil mixing (cement columns), and shallow stabilization (shallow cement-treated soils). The latter is a widely adopted technique in developing countries; however, it requires further research to prove its ability and enhance the design and assessment protocols on incremental strength related to mechanical behavior under lightweight structures.

Most studies on cement-treated soils focused on determining the initial mechanical properties at small-strain either by bender element test or resonant column [8]-[10]. Non-destructive testing methods can accurately determine the mechanical properties [9]. However, a few studies focused on the initial stiffness parameters during the shearing process. The literature also mentioned that the degradation mechanical properties are predominant at a lower cement content and assessed by conducting unconfined compressive strength at a constant rate of 1.2 mm/min [10]. Moreover, the modified hyperbola method was developed to estimate cement-treated clayey soil’s

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mechanical properties by evaluating the curvature parameter a, though it strongly depends on the strain rate during the shearing process [11]. For the early curing stage, it is reported that the constant parameter and slope angle on linear function could predict a relation between unconfined compressive strength and initial shear modulus [12]. However, starting from 3 days of the curing period, discrepancies in the initial shear modulus that can be represented using a steep slope curve referred to as b parameter were intorduced. Therefore, it is inevitable that the undrained shear strength of cement-treated clayey soil should be evaluated as a function of confining pressure with cement content [13]. In spite of the existing studies, the degradation of mechanical properties of cement-treated clayey soils subjected to low shearing rates and different confining pressure was not rigorously addressed.

Therefore, this paper elaborates on the stress-strain behavior of cement-treated soil to accurately determine the mechanical properties in small-strain ranges focusing on the cement content under various curing periods and confining pressures. Moreover, the intercorrelation between the confining pressure and the curing period for low and high cement mixing ratios is discussed under a low static shearing rate. This research was performed using a modified triaxial compression test equipped with Local Deformation Transducers (LDT) and Linear Variable Differential Transducer (LVDT) to properly measure the small-strain ranges, where the discrepancies and reliability of the strain measurement are discussed.

II. MATERIALS AND METHODOLOGY

A. Materials: Soil and Cement Binder

In this study, the Ariake clay was adopted for testing. Disturbed samples were collected from around the Ariake bay, in the western part of Kyushu Island, Japan. The particle size distribution curve of the Ariake clay is shown in Fig. 1. It must be noted that more than 50% of the Ariake clay consists of fine-grained soil. The Ariake clay's liquid limit, plasticity index, and other physical and mechanical properties are indicated in Table I. Based on the Japanese Geotechnical Society Standards (JGS 0051, 2009) [17], the Ariake clay is classified as cohesive soil with a high liquid limit. The odometer test was conducted to determine the compressibility index and the pre-consolidated pressure of the tested sample. Fig. 2 delineates the consolidation curve (e-log p curve), where the results indicate that the sample is over-consolidated.

For the cement binder material, the Portland Cement was used in this study to prepare cement-treated soil samples. Three different binder factors (A_w), 15%, 25%, and 35%, were adopted to prepare the samples. Cement-treated soils were prepared following the standard for making and curing statically compacted stabilized soil specimens based on JGS (0812-2009). For further analysis in the coming sections, the cement content, C, (kg/m^3) was determined using the following equation [14]:

$$C = \{10\rho_t/(1+W_n/100)\} \tag{1}$$

where ρ_t and W_n are the wet soil density and the natural water content, respectively.

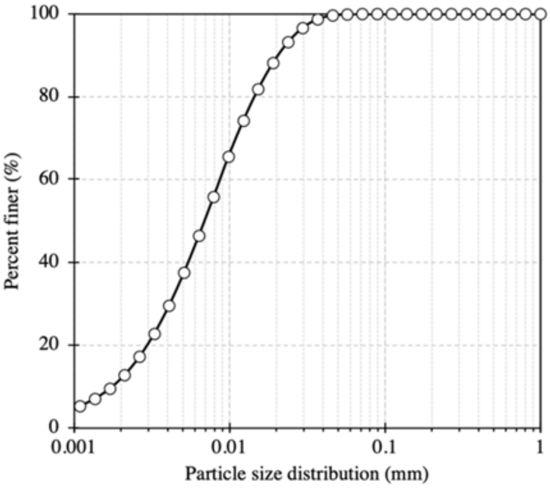

Fig. 1 Grain size distribution of Ariake Clay

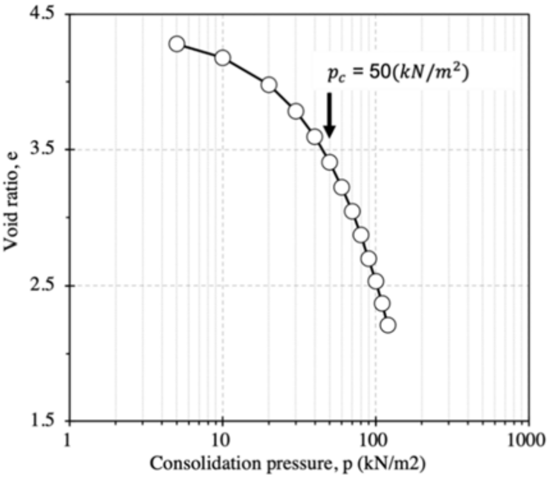

Fig. 2 E-log p curve relationship of Ariake Clay

TABLE I
SOIL PARAMETERS

Soils	Initial Water Content	Soil particle density	Liquid Limit	Plasticity Index	Compressibility Index	Binder Factor	Binder Content
	(%)	ρ_s (g/cm^3)	w_l (%)	I_P (%)	C_C	A_w (%)	C (kg/m^3)
Ariake Clay	232	2.43	100	128.5	2.2	15, 25, 35	55, 92, 128

B. Cement-Treated Soil Preparation

Laboratory soil-cement mixing was performed to represent and evaluate the geotechnical-related properties of the cement-treated soils. The soil-cement samples were prepared using slurry condition of Ariake clay, as delineated in Fig. 3.

The preparation started with sieving the natural soil through a 425 μm sieve opening to ensure the homogeneity of the samples. It must be noted that the water content is two times greater than the liquid limit for the adopted Ariake clay. Under the current conditions, the dry mixing method is recommended for soil-cement sample preparation [15]. Soil-cement mixing was conducted by using electric hand mixing. After mixing, the soil-cement samples were poured into plastic molds with dimensions of 50 mm in diameter and 100 mm in height. The molds were well-sealed to maintain the water content. All the samples were cured at a room temperature of 20 ± 3 °C. The specimens were prepared on 7 days and 28 days of curing. A total of 18 samples were used in this study. Samples differ in the cement content, curing period, and the applied confining pressure during testing.

C. Triaxial Testing Conditions

Triaxial compression tests were conducted for the cement-treated samples cured at 7 days and 28 days to study their mechanical behavior. The testing procedure was done following the JGS 0523-2009 to determine the stress-strain development. At the beginning of testing, the backpressure was raised to 200 kPa to attain the *Skempton's B* coefficient of greater than 0.9. The tests were loaded under undrained conditions and were isotropically consolidated with a 25 kPa confining pressure (σ_3). This specific consolidation pressure was adopted in this study to imitate the in-situ cement-treated soil at shallow depths of around 2.5 m. Due to the sensitivity of capturing the soil behavior under small-strain range conditions, a low shearing rate of 0.05 mm/min was applied for more accurate results.

Capturing the small-strain range and determining the soil stiffness parameters requires utilizing additional measuring devices. In this study, both the LDT and LVDT were used to capture small and large strain ranges, as illustrated in Fig. 4. Moreover, the Axial and Radial LDTs were attached to the tested samples during testing to determine the Poisson's ratio and the shear modulus. The procedure of attaching the LDTs to a cement-treated soil sample was done following [16]. Both LDTs were carefully monitored during shearing and were detached from the sample using a hook line outside the chamber when they reached their maximum displacement capacity.

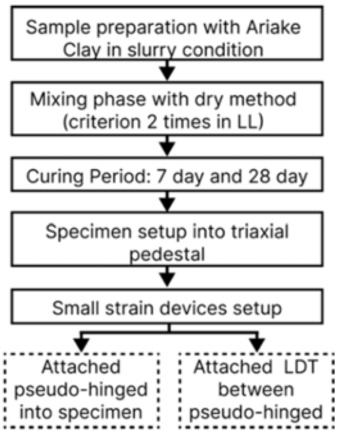

Fig. 3 Schematic diagram of cement mixing procedure

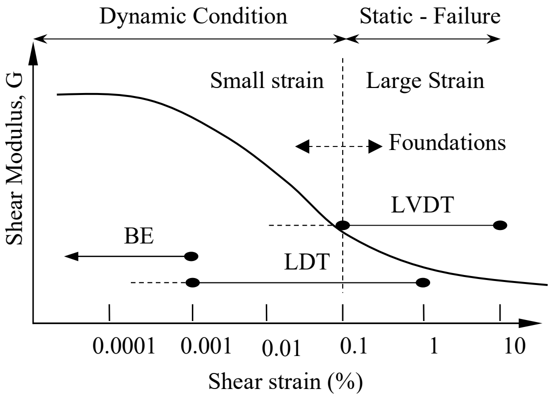

Fig. 4 Typical stiffness variation and variances of strain levels for laboratory tests and structures

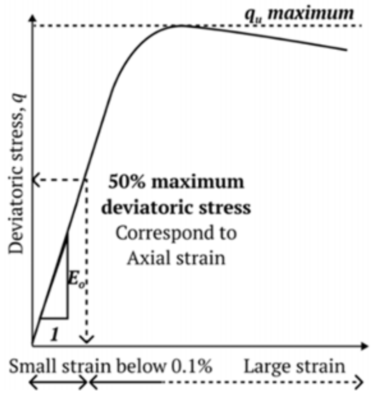

Fig. 5 (a) Young's modulus analysis from Initial condition and 50% of maximum deviatoric stress

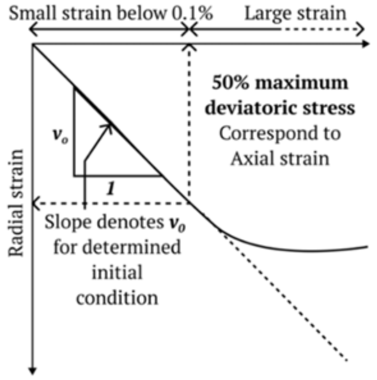

Fig. 5 (b) Poisson's ratio analysis from initial condition and 50% of maximum deviatoric stress

D. Mechanical Properties in Small-Strain Ranges

a) Initial Young's Modulus

The Young's modulus *(E)* was determined from the deviatoric stress and axial strain curves to study the mechanical properties of cement-treated clayey soils as shown in (2):

$$E = \frac{\sigma_1 - \sigma_3}{\varepsilon_a} \tag{2}$$

where $\sigma_1 - \sigma_3$ is the deviatoric stress and ε_a is the axial strain. The secant modulus formula was used to determine the Young's modulus at 50% of the maximum deviatoric stress [16], as explained in Fig. 5 (a). Based on that result, it can be connected with another point with interpolation analysis.

b) Initial Poisson's Ratio

The initial Poisson's ratio in small-strain ranges was determined using the radial and axial strain increments. The equation is delineated as:

$$\nu_{sec}, \nu_o = \left[\frac{\Delta\varepsilon_r}{\Delta\varepsilon_a}\right]_{(\sigma_3 = constant)} \tag{3}$$

where $\Delta\varepsilon_r$ and $\Delta\varepsilon_a$ are the radial and axial strain increment when the deviatoric stress changes by a constant confining pressure. The Poisson's ratio can be observed by using the secant method ν_{sec} and initial strain ν_0 method. Those methods are illustrated in Fig. 5 (b).

c) Initial Shear Modulus

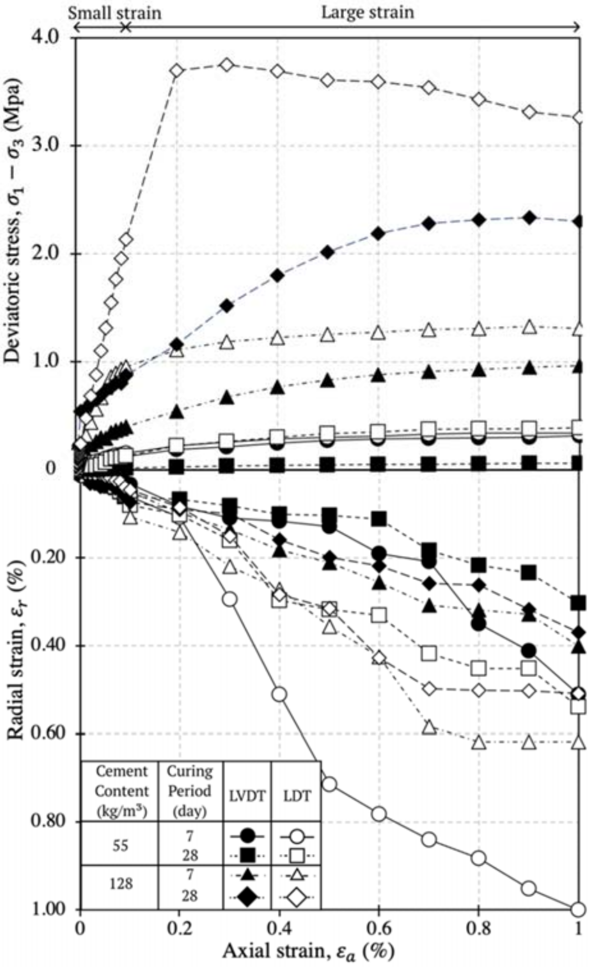

Fig. 6 Influence of cement content 55 kg/m^3 and 128 kg/m^3 at curing period 7 days and 28 days

The shear modulus degradation curve is often evaluated using the Young's modulus and Poisson's ratio. It can also be measured using the initial shear modulus (G_o) as can be applied by using the equation:

$$G = \frac{E}{2(1+\nu)} \tag{4}$$

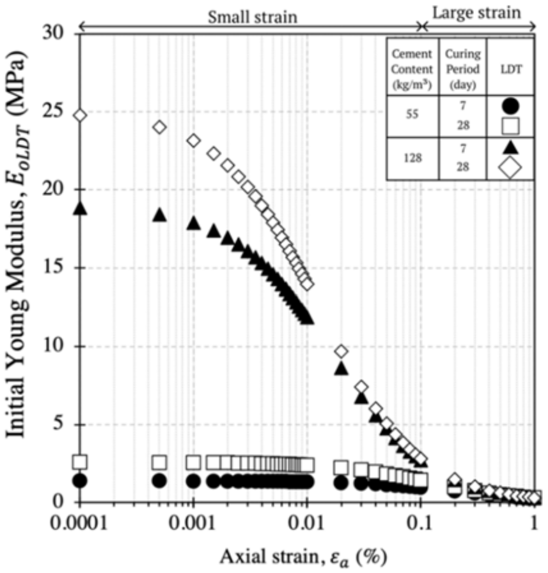

Fig. 7 (a) Degradation of initial Young's modulus (E_{oLDT})

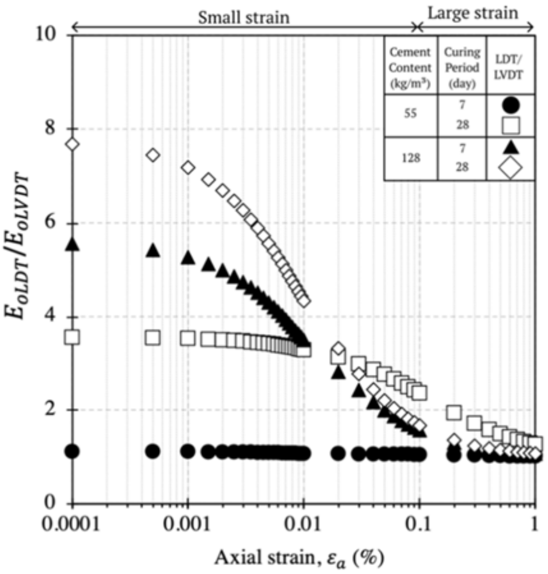

Fig. 7 (b) Ratio between E_{oLDT}/(E_{oLVDT}) with cement content 55 kg/m^3 and 128 kg/m^3 at curing period of 7 days and 28 d

III. CEMENT-TREATED SOIL BEHAVIOR

A. Influence of Curing Period and Cement Content

The relation between the deviatoric stress and axial strain for the 55 kg/m^3 and 128 kg/m^3 cement-treated samples cured at 7 days and 28 days is shown in Fig. 6. All the samples were tested at a constant confining pressure of 100 kPa under a low shearing rate.

Generally, higher cement content samples treated at 28 days showed higher maximum deviatoric stress, where the slope tends to be steeper than the other cement-treated samples. At 7 days of curing, the readings of the LVDT and axial LDT were close for the 55 kg/m^3 cement content samples. However, the LVDT and radial LDT had a higher discrepancy associated with a large-strain range, which might be associated with the bedding error measurement and the accuracy difference between the inside and outside the triaxial chamber. In contrast, the higher cement content with 28 days of curing showed high discrepancies between the deviatoric stress measurement of the axial LDT and LVDT. However, the radial strain with 28 days of curing showed a similar declining curve between 128 kg/m^3 and 55 kg/m^3.

The influence of curing period and cement content can be determined by studying the mechanical properties of the samples. As explained previously, the mechanical properties were obtained using the secant method for small-strain ranges. Based on that, it can be interpolated within small to large strain ranges. Degradation of initial Young's modulus was represented in Fig. 7 (a); high cement content was captured in higher initial Young's modulus compared to low cement content and became non-linear within small strain ranges. Also, the initial Young's modulus has been determined using the LDT and LVDT (E_{oLDT}/E_{oLVDT}), where the ratio in small-strain ranges becomes larger in LVDT measurement.

To confirm the reliability of the LDTs in measuring the initial Young's modulus, the relationship between the axial strain and E_{oLDT}/E_{oLVDT} was plotted for low and high cement content cured at 7 and 28 days, as shown in Fig. 7 (b). For low cement content samples cured at 7 days, the LDT and LVDT showed almost similar results. On the other hand, for high cement content cured at 28 days, higher discrepancies between the axial LDT and LVDT were shown. Similarly, the initial Poisson's ratio determined using the LDTs were plotted for low and high cement content cured at 7 days and 28 days, as illustrated in Fig. 8.

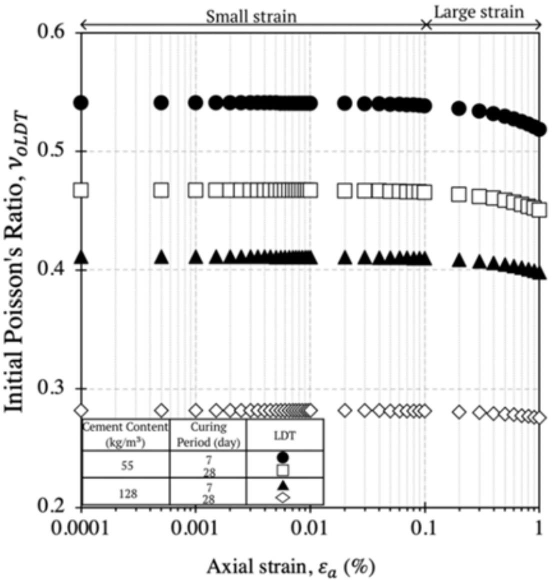

Fig. 8 Degradation of initial Poisson's ratio (v_{oLDT}) with cement content 55 kg/m^3 and 128 kg/m^3 at curing period of 7 days and 28 days

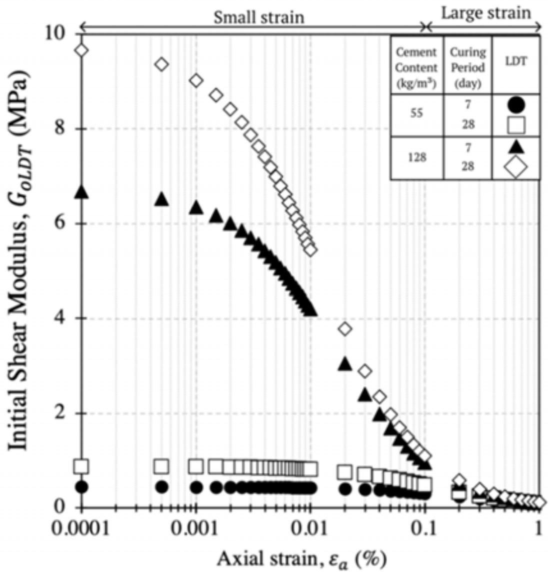

Fig. 9 (a) Degradation of initial shear modulus (G_{oLDT})

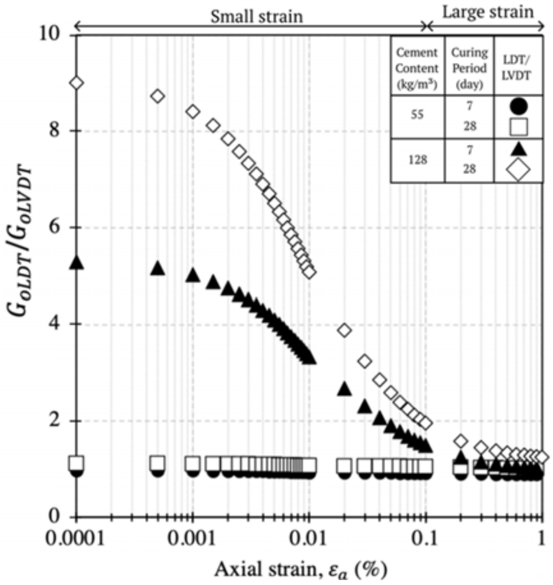

Fig. 9 (b) Ratio between $G_{oLDT}/(G_{oLVDT})$ with cement content 55 kg/m^3 and 128 kg/m^3 at curing period of 7 days and 28 days

Initial Poisson's ratio result obtained higher discrepancies between high and lowest cement content. In high cement content and longer curing period was obtained the lowest Initial Poisson's ratios. The result was generated from secant method in small strain ranges, which is the measurement of axial LDT more reliable rather than LVDT. The shear modulus calculated by (4) showed a similar result to the initial Young's modulus ratios. The degradation modulus was evaluated in Fig 9 (a). It has been shown in Fig. 9 (b), the low cement content with 7 days and 28 days of curing obtained similar ratios between LDTs and LVDT results. That condition was influenced by the initial Poisson's ratio and initial Young's modulus result.

B. *Influence of Confining Pressure and Cement Content*

The axial LDT is suitable for evaluating the bedding error on high cement content to study the curing period's behavior. Deviatoric stress has been plotted against the axial and radial strain measurement in Fig. 10. The present study tests cement-treated soil samples with 25 kPa and 100 kPa of confining pressure. The variation was considered for 28 days of curing under the low shearing rate.

Fig. 10 shows that the discrepancies occur at the beginning of small strain ranges. As can be seen, the higher cement content with higher confining pressure manipulated the effect of strain-softening after reaching a maximum of deviatoric stress at 0.2% of axial strain. Higher cement content showed a typical effect for the brittle-ductile translational failure mode [10].

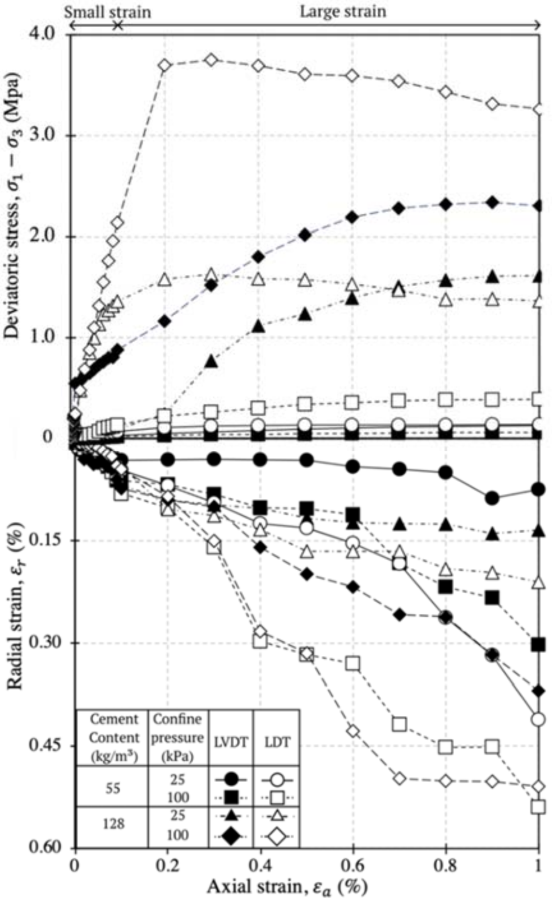

Fig. 10 Influence of cement content 55 kg/m^3 and 128 kg/m^3 in 25 kPa and 100 kPa of confining pressure

A similar method was applied to determine the influence of confining pressure and cement content within the mechanical properties of cement-treated clayey soils. It was described as a close-range ratio between Axial LDT and LVDT. Related to the degradation of initial Young's modulus as illustrated in Fig. 11 (a), it comprises the influence of confining pressure on 28 day of curing period were shown significant discrepancies between 25 kPa and 100 kPa within small strain ranges. High cement content obtained higher discrepancies between axial LDT and LVDT, as shown in Fig. 11 (b). Moreover, the Poisson's ratio measurement had a similar trend compared to the influence of cement content, as shown in Fig. 12. Also, a declined curve has been observed in degradation of initial Shear modulus at 25 kPa of confining pressure as can be seen in Fig. 13 (a), which was correlated to the degradation of initial Young's modulus.

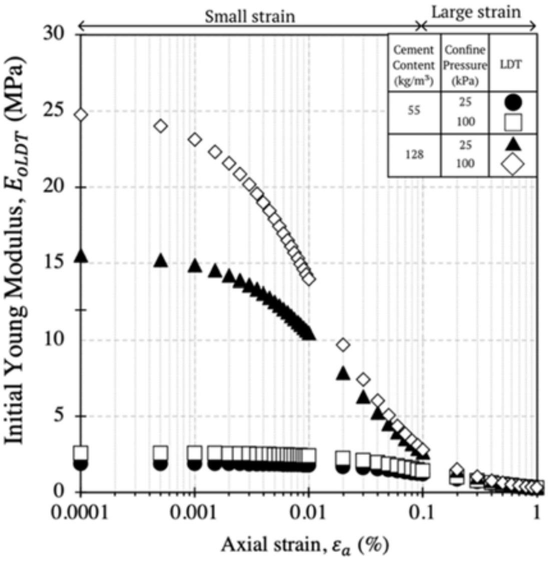

Fig. 11 (a) Degradation of Initial Young's modulus (E_{oLDT})

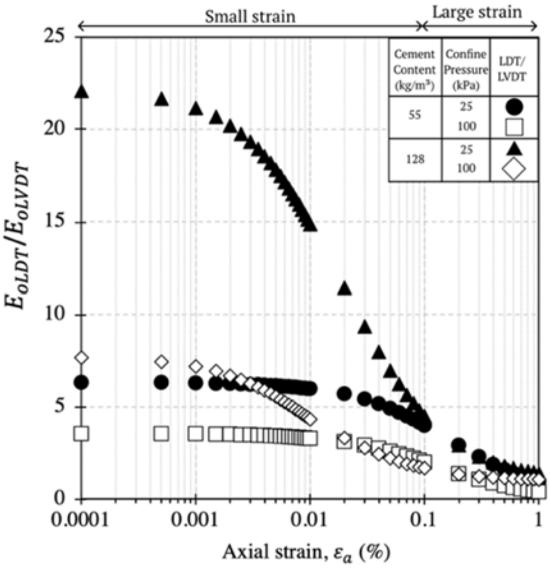

Fig. 11 (b) Ratio between $E_{oLDT}/(E_{oLVDT})$ with cement content 55 kg/m^3 and 128 kg/m^3 in 25 kPa and 100 kPa of confining pressure

The degradation modulus shows a similar trend between low cement content and confining pressure, it can compare with 7 days and 28 days of the curing period, based on Figs. 9 (a) and 13 (b), respectively. Thus, the higher cement content with the influence of confining pressure (25 kPa and 100 kPa) was described as discrepancies between the measurement of Axial LDT and LVDT in small strain ranges. It was explained from the results that it was possible to get the high accuracy of stiffness modulus within small strain ranges. The test needs to be conducted with LDTs. It can be evaluated that the initial

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degradation modulus is more stable, starting from small-high strain ranges using the secant method analyses. Furthermore, these results can discuss the gradient of coefficient parameter and increment slope of initial mechanical properties with different curing periods and confining pressure.

IV. EFFECT OF CONFINING PRESSURE IN SMALL-STRAIN MEASUREMENT RELATED TO THE CEMENT CONTENT

Intercorrelated power function of confining pressure has been observed in this section, it was subjected to the initial mechanical properties' coefficient and cement content. The assumptions of constant value are based on the previous research conducted to predict the increment strength with the curing period [12]. The relationship between confining pressure and mechanical properties can be suggested as:

$$\ln|E_o, \nu_o, G_o| = \ln\alpha + \beta\ \ln(\sigma_3/P_a) \tag{5}$$

$$|E_o, \nu_o, G_o| = \alpha(\sigma_3/P_a)^{\beta} \tag{6}$$

where σ_3/P_a is the confining pressure which has normalized with atmospheric pressure in the same units, α is the coefficient parameter regarding the intercorrelation between differences of cement content and confining pressure. For β are the slope rate of coefficient parameters between differences of cement content and confining pressure. To describe the good correlation between those coefficient parameters (α and β) in simple power function, it was required the evaluation of initial mechanical properties subjected to the different of σ_3/P_a, cement content (kg/m^3) and curing period (day).

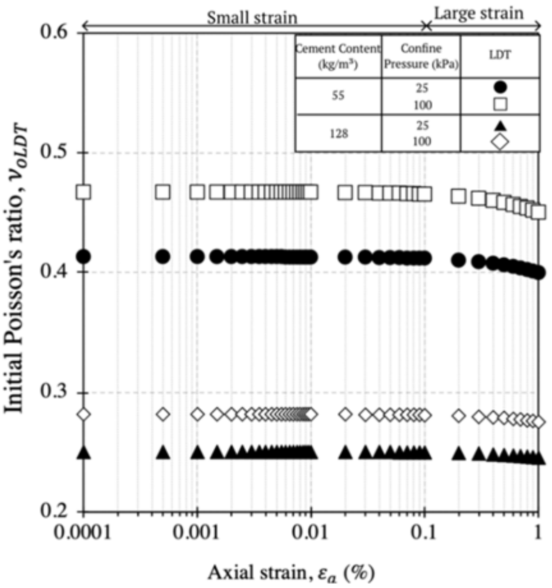

Fig. 12 Degradation of Initial Poisson's ratio (ν_{oLDT}) with cement content 55 kg/m^3 and 128 kg/m^3 in 25 kPa and 100 kPa of confining pressure

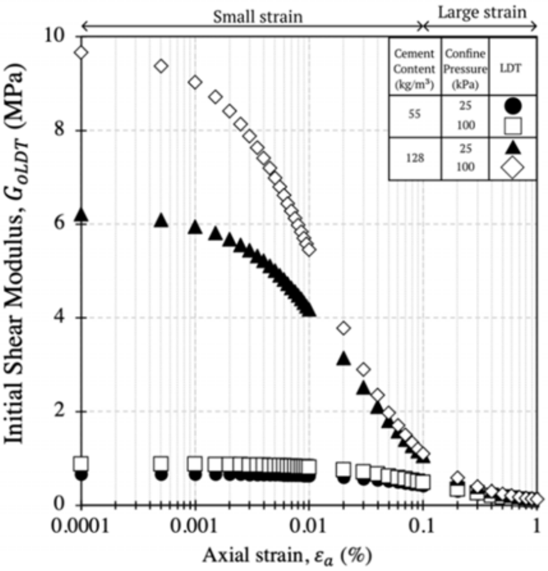

Fig. 13 (a) Degradation of Initial Shear Modulus (G_{oLDT})

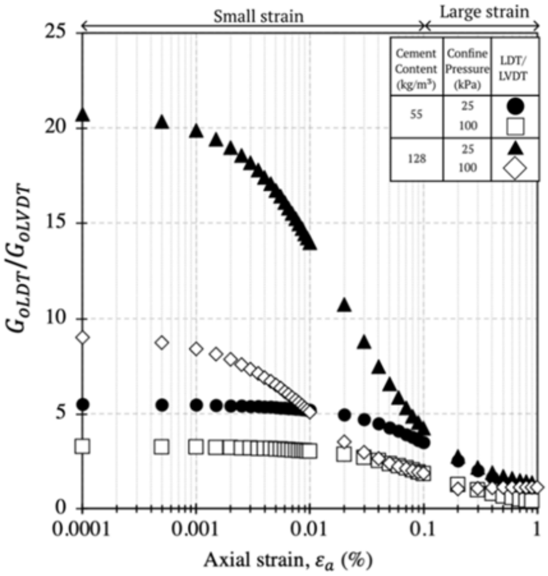

Fig. 13 (b) Ratio between G_{oLDT}/(G_{oLVDT}) with cement content 55 kg/m^3 and 128 kg/m^3 in 25 kPa and 100 kPa of confining pressure

The variation of logarithm of initial Young's modulus (E_o/P_a) and (σ_3/P_a) were plotted in Fig. 14. It was described an increment curve for all the cement-treated samples at 7 days and 28 days of curing. The correlation between low cement content and different of (σ_3/P_a) has been shown, the large discrepancies are compared in different curing periods. It is found that increasing confining pressure subjected to the different cement content has shown a good correlation using the power function to obtain the increment modulus within small strain ranges. Significantly, higher cement content has discrepancies that compared to low cement content. It was observed that there were differences between the increment of deviatoric stress within the small strain and the initial condition of the Young's modulus. However, the increment modulus of LDT with higher cement content represented low discrepancies subjected to the curing period.

The variation of logarithm of initial Poisson's ratio (υ_o/P_a) and (σ_3/P_a) were plotted in Fig. 15. It was shown linear curvature increment for all the cement-treated samples at 7 days and 28 days of curing. The axial-radial LDT has significantly expressed the differences, especially in high cement content, with high discrepancies of initial Poisson ratios associated with curing periods. It was influenced by the shearing process in small strain ranges that have attained the maximum deviatoric stresses.

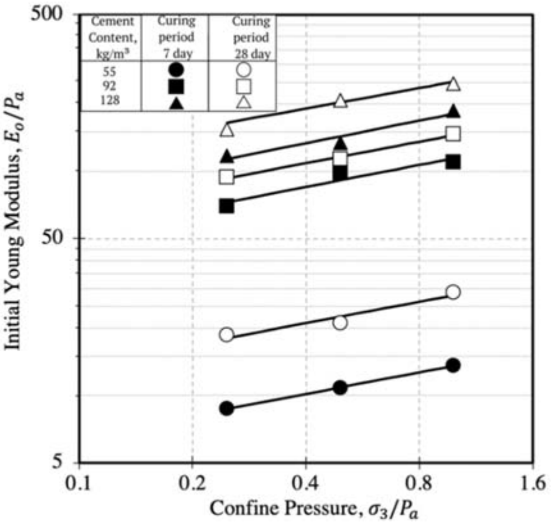

Fig. 14 Initial Young's modulus and confine pressure in small strain ranges

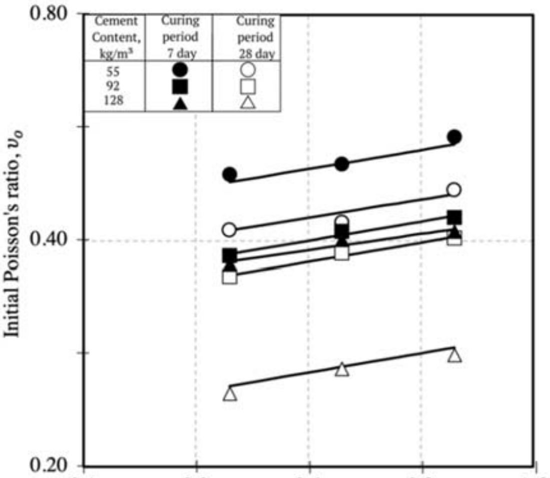

Fig. 15 Initial Poisson's ratio and confining pressure in small-strain ranges

The initial shear modulus was observed in the small strain ranges using the Poisson ratio and Young's modulus result. Through these parameters, the increment curve has been illustrated in Fig. 16. The condition was started on a similar increment condition related to the initial Young's modulus subjected to the different curing periods. Furthermore, another parameter needs to be mentioned to describe the increment stiffness modulus influences, such as confining pressure subjected to small strain ranges. Increment mechanical properties with confining pressure show a similar trend curve. As Figs. 14 and 15 determined, response in slight strain ranges positively relates to increment and to confining pressure. Moreover, the applicability of increment mechanical properties was proposed to estimate the elastic condition of initial modulus and small strain effect on cement-treated clayey soils. However, the increment mechanical properties were fitted with a power curve according to increasing confining pressure. It was correlated with cement content. Also, the coefficient parameters were obtained from the gradient slope of the relationship between the logarithm of initial mechanical properties and (σ_3/P_a). In addition, the effect of confining pressure may be influenced by the initial mechanical properties. Furthermore, cement-treated clayey soil's determination effect at a small strain range was recommended using the axial LDT and radial LDT at a slow shearing rate. In addition, the confining pressure application in triaxial measurement especially in small-strain ranges can be the significant relationship between an increment of coefficient parameter (α) and (β) with increased mechanical properties.

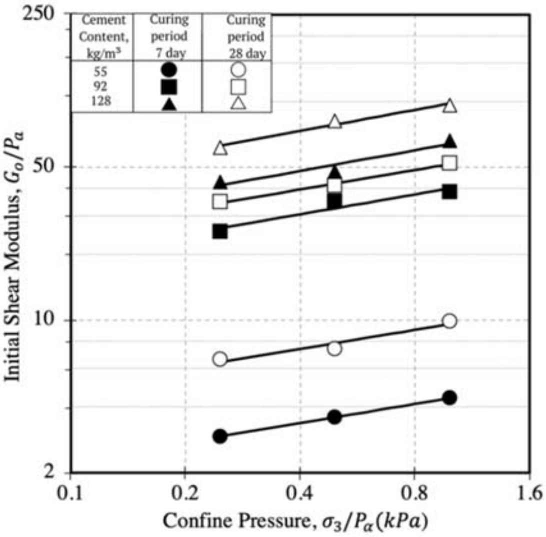

Fig. 16 Initial shear modulus and confining pressure in small strain ranges

V. CONCLUSION

In this study, the mechanical properties including the initial Young's modulus (E_0), shear modulus (G_0), and the Poisson's ratio for cement-treated clayey soils were investigated using triaxial consolidated undrained $(\overline{CU})$ equipped with small strain measurement devices (LDTs). Samples were sheared after 7 days and 28 curing days. The shearing rate was set at 0.05 mm/min. A confining pressure of 25 kPa, 50 kPa and 100 kPa was adopted for testing. Based on those experimental results, the main conclusions can be delineated as follows:

1. For low cement content mixtures (55 kg/m^3) under 7 days and 28 curing days, the Young's modulus (E_0) and the

shear modulus (G_0) degraded following a linear pattern within the small strain range before converging to constant values. In contrast, the high cement content samples showed minor degradation in the Young's modulus (E_0) and the shear modulus (G_0).

2. Significant discrepancies of measured axial-radial strain with LDTs and LVDTs were initially started from small-strain ranges, especially in high cement content (128 kg/m^3). Therefore, it was found that using LDTs to determine the mechanical properties of cement treated soils is necessary to ensure accurate and reliable determination of the mechanical behavior properties of cement treated soils.
3. A power function model was proposed to evaluate the development of the initial Young's modulus (E_0) and shear modulus (G_0) development with the applied confining pressure for cement treated soils under various curing periods.

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