International Journal of GEOMATE, Jan., 2025 Vol.28, Issue 125, pp.64-74
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.125.4672
Geotechnique, Construction Materials and Environment

CONSOLIDATION AND PERMEABILITY CHARACTERISTICS OF LIQUEFIED STABILIZED SOIL PREPARED BY VARIOUS SLURRY DENSITIES

Bingyu Xi[1] and *Yukihiro Kohata[1]

[1]Graduate School of Engineering, Muroran Institute of Technology, Japan

*Corresponding Author, Received: 07 Aug. 2024, Revised: 01 Nov. 2024, Accepted: 02 Nov. 2024

ABSTRACT: Permeability plays a pivotal role in geotechnical engineering, influencing the strength, deformation, and long-term performance of soil structures. Despite the growing interest in liquefied stabilized soil (LSS) as a sustainable backfill material, there is limited research on its use in projects with low permeability requirements. In order to investigate the consolidation and permeability properties of LSS, a series of 1-D consolidation and permeability tests were conducted on LSS with slurry densities of 1.216, 1.280, and 1.344 g/cm^3, a cement content of 100 kg/m^3, and fiber content of 0 and 10 kg/m^3. The consolidation and permeability characteristics of LSS with different slurry densities were compared, and the influence of adding fiber material to LSS was examined. The results indicate that the coefficient of consolidation of LSS decreases with increasing pressure. The coefficient of consolidation increases with the increase in the slurry density of LSS and is minimally affected by the amount of fiber. The coefficient of permeability of LSS is closely related to slurry density, the amount of added fiber material, and the initial void ratio of the specimen. The coefficient of permeability decreases with the increase in slurry density and fiber content. The average coefficient of permeability of LSS is 3×10^{-6} cm/s, which shows high permeability resistance.

Keywords: Liquefied stabilized soil, Fiber material, Slurry density, Coefficient of permeability, Coefficient of consolidation

1. INTRODUCTION

As a common construction material, soft clay presents various engineering challenges, including high natural water content, significant compressibility, low bearing capacity, and low shear strength [1]. These properties result in poor bearing capacity and stability, often leading to uneven settlement and structural deformation in construction projects [2,3]. Therefore, effectively improving the mechanical properties of soft clay has been a long-standing concern in the engineering field [4-7]. In addition to methods such as preloading, deep mixing, and vacuum consolidation [8,9], cement-treated soil stabilization techniques are also effective solutions to address these issues [10]. By reacting with cement and other stabilizing agents, these techniques significantly enhance the compressive strength, shear strength, and stability of the soil [11-13].

In Japan, the widespread utilization of cement-treated soil for foundation reinforcement has yielded substantial benefits, particularly in improving bearing capacity and reducing settlement issues [14]. Since the 1980s, cement-treated soil technology has seen rapid development and has been extensively applied in foundation reinforcement projects for roads, railways, bridges, and underground engineering [15-18]. The promotion of this technology has not only mitigated settlement problems but also significantly increased the bearing capacity and seismic resistance of foundations, providing notable social and economic benefits. Due to its low cost, cement-treated soil has become an economical and efficient choice for large-scale projects, providing long-term stability and durability while achieving significant cost savings [19,20]. Furthermore, with the growing emphasis on environmental protection, the sustainability characteristics of cement-treated soil have become an important factor in its widespread application [21].

Liquefied stabilized soil (LSS) [22] is a type of cement-treated soil created by proportionately blending excavated soil, cement-based solidification materials, water, and additives. Unlike conventional cement-treated soil, LSS is fluid during construction, making it highly workable and easy to place. LSS is used widely as a backfill material in Japan, especially in applications such as underground pipelines, tunnels, foundation pit support, foundation reinforcement, subgrade cushioning, and canal seepage prevention [23-27]. Various engineering properties of LSS exhibit significant enhancements compared to excavated soil, notably excelling in compactness, compressive strength, and shear strength [28-30].

Furthermore, there has been an extensive exploration into the engineering characteristics of LSS, which is fluid before solidification and is prepared as a slurry mixed soft clay with water and cement-based solidification material. According to previous studies, adding organic fiber materials, which are made resembling cotton wadding pulverized waste newspaper, to LSS has notably enhanced mechanical properties on shear and tensile failure, and so on, thereby the amplifying advantages of LSS are found [31,32]. Although previous studies have explored various engineering characteristics of LSS, there remains a significant difference between research and its application in impermeability or seepage resistance. Past research has noted that the evaluation of seepage performance when using Cement-Stabilized Soils as backfill material is still insufficient [33-35].

Permeability is a critical aspect of geotechnical engineering, playing a pivotal role in the stability and performance of various soil structures. As an important parameter, the evaluation of the coefficient of permeability significantly influences the strength, deformation, and overall behavior of soil under different conditions. In particular, the permeability property of soil influences its suitability for applications such as foundation construction, embankment stability, and seepage control. However, there is a scarcity of research findings and engineering instances concerning the application of LSS in projects with anti-seepage or anti-permeability requirements. This lack of knowledge in the literature highlights a significant opportunity for further investigation, as the current understanding of LSS's permeability characteristics remains insufficient. Given the increasing interest in LSS as a sustainable and versatile material, an in-depth investigation into its permeability properties becomes imperative. Specifically, understanding the factors that affect the permeability of LSS will provide valuable insights into its performance in engineering projects. Additionally, the coefficient of consolidation c_v holds great engineering significance as it mirrors the overall consolidation degree and settlement process of the entire soil layer. Accurately assessing this parameter is crucial for predicting soil behavior over time and ensuring long-term stability in construction projects.

Therefore, this study aims to fill this difference by investigating the consolidation and permeability characteristics of Liquefied Stabilized Soil (LSS) prepared under various conditions. Its novelty lies in the addition of fiber materials and the variation in initial slurry density. Based on the results of the consolidation and permeability tests, the effects of changes in slurry density and fiber material content on the consolidation and permeability properties of LSS are discussed. This research offers key insights into how these factors influence the consolidation and permeability characteristics of LSS, providing practical guidance for future urban infrastructure and environmental protection projects and geotechnical engineering applications, promoting the sustainable application of LSS.

Table 1 Physical properties of NSF-Clay

Physical parameters	Values
Liquid limit (%)	60.15
Plastic limit (%)	35.69
Plasticity index	24.46
Particle density (g/cm^3)	2.762
Soil classification	CH

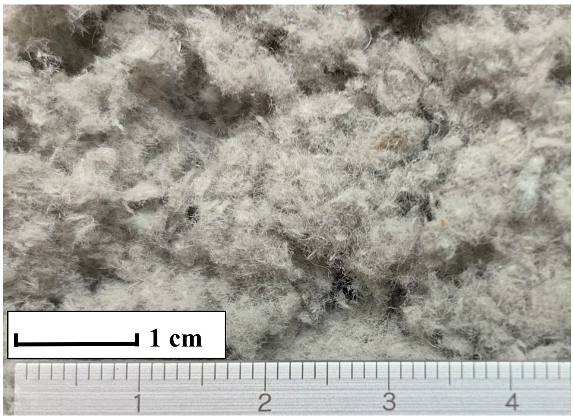

Fig.1 Photograph of Pulverized newspaper (with scale: cm)

2. RESEARCH SIGNIFICANCE

Permeability and consolidation are critical factors in evaluating the application of LSS in geotechnical engineering, making a comprehensive investigation into the consolidation and permeability characteristics of LSS essential. The outcomes of such research are not only a theoretical consideration but also applicable to practice. By bridging a lack of knowledge in this area, this study aims to contribute to both scientific understanding and engineering practice, offering guidance for future applications of LSS in geotechnical projects.

3. MATERIALS AND TESTING METHOD

3.1 Test Materials

In this study, to ensure the homogeneity of soil material, commercially available New Snow Fine Clay (NSF-Clay) [36] was utilized as the base material for testing. The physical parameters of this soil are detailed in Table 1. A specialized cement designed for soft clay was used as the cement-based solidification (Taiheiyo Cement Co. Ltd., Geoset 200). Additionally, waste newspaper, easily accessible in daily life, was chosen as the fiber material. This newspaper was pulverized through a food processor to create a fibered material resembling cotton wadding (Fig. 1). Fiber length is between 0.5 and 3 mm.

3.2 Preparation of Test Specimens

The objective of this study is to investigate the effect of slurry density and fiber content on the consolidation and permeability characteristics of LSS with fiber material. In order to achieve this, three different slurry densities were used. A standard slurry density of 1.280× 10^3 kg/m^3 (Dρ_f = 100 %) was set, and two slurry densities of 1.216 (Dρ_f = 95 %) and 1.344 × 10^3 kg/m^3 (Dρ_f = 105 %) were set by adjusting 5 % increase or decrease from the standard slurry density. Dρ_f is calculated as (current slurry density)/ (standard slurry density) × 100 (%). The amount of fiber material added to each specimen of three slurry densities was set at 0 or 10 kg/m^3, and the specimens were cured for 28 days. The test conditions for each specimen are shown in Table 2.

The prepared LSS mixed fiber material was subjected to a degassing process for 30 minutes under a negative pressure of approximately -90 kN/m². Subsequently, the specimen was poured into 60 × 60 mm commercial plastic molds. The top of each mold was sealed with cling film and cured in humid air at 20 ± 3 °C. For each specimen, three test specimens were produced and left in the molds for 28 days without removing the formwork, residing in the standard curing room.

3.3 Test Method

The experimental procedures followed the steps described in the "Test Method for One-Dimensional Consolidation Properties of Soils Using Incremental Loading" (JIS A 1217: 2009) [37]. The apparatus used for testing is a conventional oedometer, as shown in Fig. 2. After 28 days of curing, the specimen was trimmed and placed in the apparatus. The initial dimensions of the specimen are 20 mm in height and 60 mm in diameter.

Under the conditions of double-sided drainage, the one-dimensional consolidation test using incremental loading with a load incremental ratio of 1 is conducted over a loading range of 9.8 to 1256 kN/m². A vertical load is applied based on the load incremental ratio, and the specimen displacement is measured using a dial gauge under full lateral restraint. The consolidation time for each incremental load step was set to 24 hours. Parameters for the consolidation and permeability characteristics of LSS are derived from the compressive displacement of the specimen at each incremental load step. For each incremental load step, the amount of compressive displacement was recorded at time intervals of 0 s, 6 s, 12 s, 18 s, 30 s, 42 s, 1 min, 1.5 min, 2 min, 3 min, 5 min, 7 min, 10 min, 15 min, 20 min, 30 min, 40 min, 1 h, 1.5 h, 2 h, 3 h, 6 h, 12 h, and 24 h. For a single test condition, three specimens were tested, and if two of the specimens gave valid and similar results, that result was adopted.

Table 2 Test condition for each specimen

Test number	Cement content (kg/m^3)	Fiber content (kg/m^3)	Slurry density × 10^3 (kg/m^3)	Curing days
1			1.216	
2		Pc=0	1.280	
3			1.344	
4	100		1.216	28
5		Pc=10	1.280	
6			1.344	

4. RESULTS AND DISCUSSIONS

4.1 Consolidation Property of LSS

Consolidation is the process by which excess pore water pressure dissipates and effective stress increases under load. The coefficient of consolidation c_v is an important parameter in Terzaghi's one-dimensional consolidation theory [38]. Its magnitude indicates the rate of consolidation progression in soft soil. A higher c_v implies a faster consolidation of the soil layer. In essence, the coefficient of consolidation is a parameter that reflects the consolidation characteristics of the soil layer. This coefficient is not only a vital soil test indicator but also a pivotal parameter in the design of treatments for soft ground foundations. Particularly, the coefficient of consolidation is an essential indicator when the drainage consolidation method is applied to foundations on soft ground. Effective and accurate determination of the coefficient of consolidation is critically important for the accurate prediction of foundation settlement.

There are four primary methods for determining the coefficient of consolidation: indoor consolidation

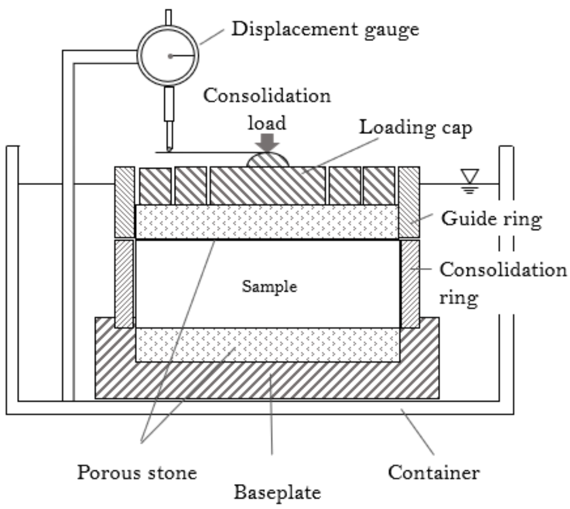

Fig.2 Schematic diagram of test apparatus

testing method, indirect extrapolation method, inversion analysis method, and in-field testing method. Laboratory methods for determining the coefficient of consolidation include the time square root method, time logarithm method, and three-point method. In this experiment, the time square root method was mainly used. At a specific pressure level, record the time it takes for the specimen to reach 90 % consolidation (t_{90}). The coefficient of consolidation at this pressure level is calculated as follows:

$$c_v = \frac{0.848\bar{h}^2}{60t_{90}} \quad (1)$$

In the Eq. (1):

c_v: Coefficient of consolidation, *cm²/s*.

$\bar{h}$: Maximum drainage distance, equal to half the average of the initial and final heights of the specimen under a certain pressure level, *cm*.

4.1.1 c_v -p relationship

By examining the correlation between the consolidation pressure applied to the specimen and the coefficient of consolidation, we can deduce the variation trend of the coefficient of consolidation for LSS with different slurry densities and fiber contents. Fig. 3 shows the correlation between the coefficients of consolidation and consolidation pressures in consolidation tests. The legend illustrates the different slurry densities ($D\rho_f$ = 95 %, 100 %, and 105 %) and fiber contents (0 and 10 kg/m^3) for the specimens.

As shown in Fig. 3, the experimental results reveal that the coefficient of consolidation of LSS varies between 0.1 and 1.9 × 10⁻¹ cm²/s under the consolidation pressure ranges from 9.8 to 1256 kN/m². It is observed that the coefficient of consolidation of LSS decreases gradually with an increase in consolidation pressure. Within the low-pressure range, the coefficient of consolidation of each specimen is almost constant, and then decreasing. That is, at a consolidation pressure of 100 kN/m², the coefficient of consolidation starts to decrease. After 200 kN/m², the soil becomes progressively denser due to compression, leading to a faster decline in the coefficient of consolidation, and the coefficients of consolidation of LSS specimens with different slurry densities begin to diverge. Around a consolidation pressure of 300 kN/m², the specimen with a slurry density of 95 % already exhibits c_v = 0.4 × 10⁻¹ cm²/s, while the specimens with slurry densities of 100 % and 105 % show c_v = 1.2 × 10⁻¹ cm²/s and 1.7 × 10⁻¹ cm²/s, respectively. After 600 kN/m², the difference between the coefficients of consolidation of LSS with different slurry densities becomes smaller gradually.

4.1.2 The Influence of Slurry Density on Consolidation Characteristics

In order to investigate the effect of slurry density on the consolidation properties of LSS, the relationship between the coefficient of consolidation and consolidation pressure for specimens with slurry densities of 95 %, 100 %, and 105 % is shown in Fig. 4, under the condition of no fiber material addition.

In the absence of fiber material, a comparison of slurry density reveals that at a consolidation pressure of 100 kN/m², the coefficients of consolidation for specimens with slurry densities of 95 % and 100 % exhibit similar values.

When the consolidation pressure increases to 200 kN/m², the coefficients of consolidation for specimens with $D\rho_f$ =95 % and $D\rho_f$ =100 % decrease rapidly, while the decrease in the coefficient of consolidation for specimens with $D\rho_f$ =105 % is less pronounced. It is found that the stress range for rapid changes in the coefficient of consolidation is 200 to 300 kN/m² for $D\rho_f$ =95 % and 200 to 600 kN/m² for

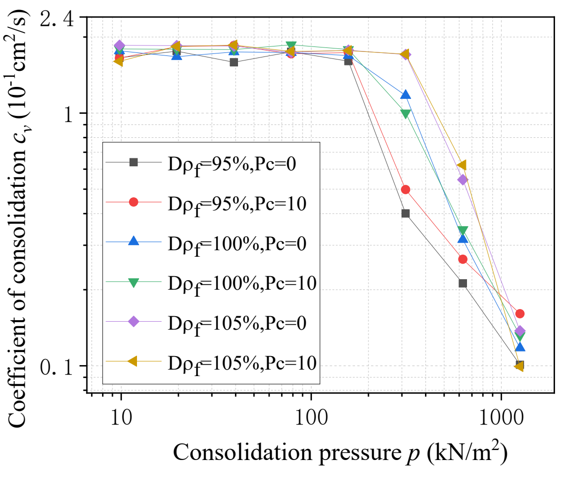

Fig.3 Relationship between the coefficient of consolidation and consolidation pressure

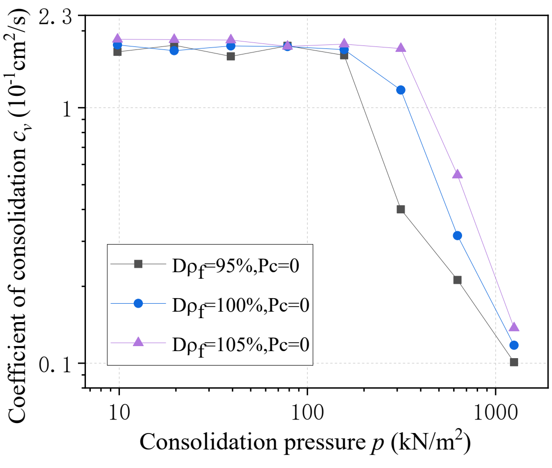

Fig.4 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0)

$D\rho_f$ =100 %. When the consolidation pressure exceeds 400 kN/m², the coefficient of consolidation of the $D\rho_f$ =105 % specimen rapidly decreases, with the stress range for rapid decline being 400 to 600 kN/m². After reaching a consolidation pressure of 600 kN/m², the rate of change in the coefficient of consolidation for all specimens becomes more gradual.

The consolidation yield stress refers to the maximum effective stress that a soil has historically experienced, also known as the pre-consolidation pressure. Once this stress is exceeded, the compressibility of the soil increases significantly. This implies that when the applied pressure is an initial part of consolidation below the yield stress, the soil undergoes minimal deformation, with a slower compression rate, resulting in a relatively high coefficient of consolidation. However, once the pressure surpasses the yield stress, the soil begins to compress more substantially, and the coefficient of consolidation decreases. This is because, above the yield stress, it takes longer for the pore water within the soil to dissipate, thereby slowing the consolidation rate fully.

The consolidation yield stress is typically determined from the e (void ratio) versus log p (stress) curve using methods such as the Casagrande method or the Mikasa method (JIS A 1217: 2009). In this study, the yield stress of LSS was calculated using the Mikasa method, as shown in Table 3.

Considering the consolidation yield stress presented in Table 3, the differences in coefficients of consolidation are substantial before and after consolidation yield stress. Therefore, the selection of the coefficient of consolidation corresponding to different stress levels is crucial in consolidation analysis. Within the scope of this study, for $D\rho_f$ =95 %, where slurry density decreases by 5 %, the soil exhibits low strength, and an increase in load significantly impacts the coefficient of consolidation, showing a tendency for rapid reduction. On the other hand, for $D\rho_f$ =105 %, where slurry density increases by 5 %, the strength of LSS gradually increases, and the consolidation stress range for the rapid coefficient of consolidation decrease progressively shifts. It is considered that the influence of slurry density on the coefficient of consolidation is significant in this study.

4.1.3 Influence of fiber content on consolidation characteristics

The relationship between the coefficient of consolidation and consolidation pressure for specimens is shown in Fig. 5, with slurry densities of 95 %, with fiber content of 0 and 10 kg/m³. From Fig. 5, it is found that under the same slurry density, the coefficients of consolidation of LSS with different fiber content are very close. However, specimens with added fiber material exhibit slightly higher coefficients of consolidation compared to those without fiber material.

Table 3 Consolidation yields stress of LSS

Sample ID	Yield stress (kN/m²)
$D\rho_f$ = 95%, Pc=0	199.5
$D\rho_f$ = 95%, Pc=10	231.6
$D\rho_f$ = 100%, Pc=0	322.5
$D\rho_f$ = 100%, Pc=10	338.6
$D\rho_f$ = 105%, Pc=0	447.5
$D\rho_f$ = 105%, Pc=10	478.6

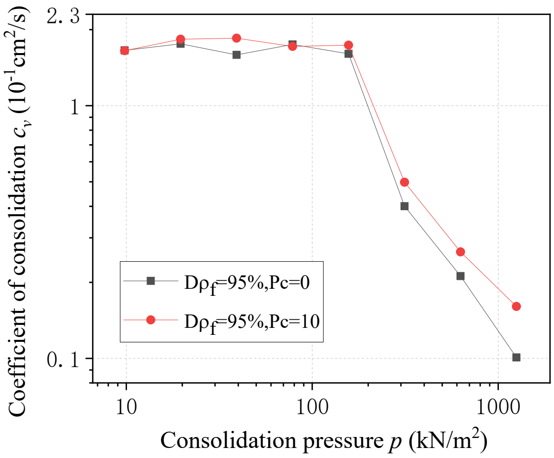

Fig.5 Relationship between the coefficient of consolidation and consolidation pressure ($D\rho_f$ =95%)

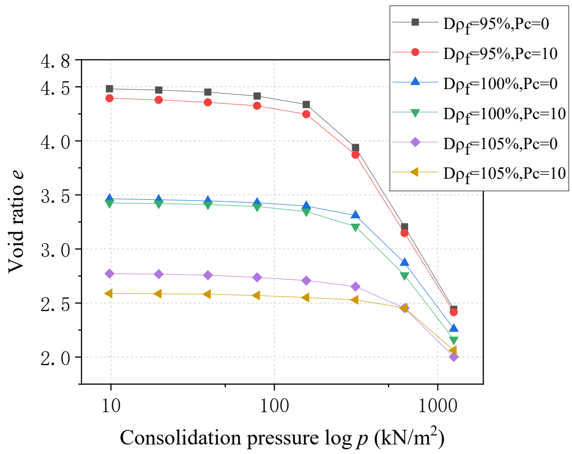

Fig.6 Relationship between void ratio and consolidation pressure

4.1.4 Variation of void ratio with consolidation pressure

The e-log p curves for specimens with slurry densities of 95 %, 100 %, and 105 %, and fiber content of 0 and 10 kg/m³ are shown in Fig. 6. From the trend of e-log p relation, it is found that under consolidation pressures ranging from 9.8 to 1256 kN/m², the void ratio of LSS varies between 2 and 4.5.

The e-log p curve indicates a gradual reduction in void ratio with increasing consolidation pressure for LSS. Moreover, the change in void ratio for LSS is not remarkable at lower consolidation pressures. Fig. 6 also indicates the comparison of the slurry density and fiber content on the void ratio of LSS. The void ratio decreases with an increase in slurry density and fiber material content.

4.1.5 Variation of coefficient of consolidation with void ratio

The c_v -e relations for specimens with slurry densities of 95 %, 100 %, and 105 %, and fiber content of 0 and 10 kg/m³ are shown in Fig. 7. At the low-pressure level, as the consolidation pressure increases, the void ratio decreases rapidly, leading to a sharp decline in c_v. However, when the void ratio reaches a certain value, a decreasing tendency of c_v decreases. For the specimens of $D\rho_f$ = 95 %, the inflection points where c_v transitions from a rapid decline to a more gradual decrease is approximately at 300 kN/m². This indicates that when the consolidation pressure exceeds 300 kN/m², the $D\rho_f$ = 95 % specimen is in a relatively dense state. Similarly, for the specimens of $D\rho_f$ = 100 %, the inflection point is around 600 kN/m², suggesting a relatively dense state when the consolidation pressure exceeds 600 kN/m².

The relationship between compression height and consolidation pressure is presented in Fig. 8. The *CH-p* curve obtained from the consolidation tests shows a clear increasing trend in compression height as the applied pressure increases. In the initial stage, the compression height changes only slightly with increasing pressure, primarily because the pore water within the soil is being expelled at a slower rate. When the pressure exceeds 100 kN/m², the compression height begins to increase, though the rate of consolidation remains relatively slow.

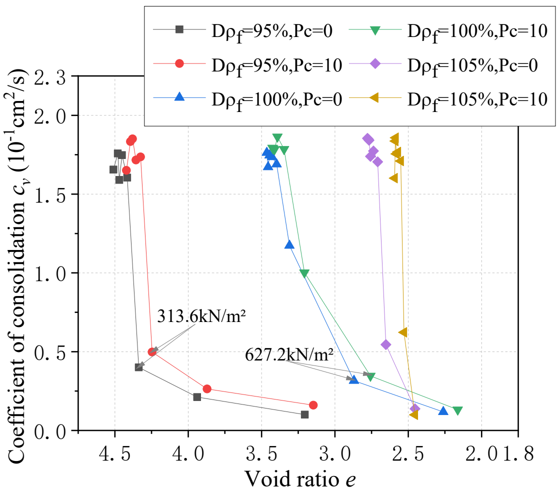

Fig.7 Relationship between the coefficient of consolidation and void ratio

However, at pressures above 300 kN/m², there is a significant increase in compression height, indicating an acceleration of the consolidation process.

The compression height in samples with a slurry density of 105 % is noticeably less than in those with a slurry density of 95 %, suggesting that the higher slurry density results in lower compressibility. This is likely because higher slurry density corresponds to a lower initial void ratio. During the consolidation process, changes in the void ratio are influenced by the amount of water expelled from the pores. Since soils with higher slurry density have fewer initial voids, the extent of void ratio change during further compression is smaller. Consequently, as the slurry density increases, the corresponding change in the void ratio is also relatively smaller.

4.2 Permeability Property of LSS

4.2.1 Variation of coefficient of permeability with consolidation pressure

In this subsection, the relationship between the coefficient of permeability (k) of liquefied stabilized soil (LSS) and consolidation pressure is discussed.

The coefficient of permeability is calculated by the following formula:

$$k = \frac{c_v m_v \gamma_w}{100} \tag{2}$$

In the Eq. (2):

k: Coefficient of permeability, *cm/s*.

c_v: Coefficient of consolidation, *cm²/s*.

m_v: Coefficient of volume compression, *m²/kN*.

γ_w : Unit volume weight of water (= 9.81 *kN/m³*)

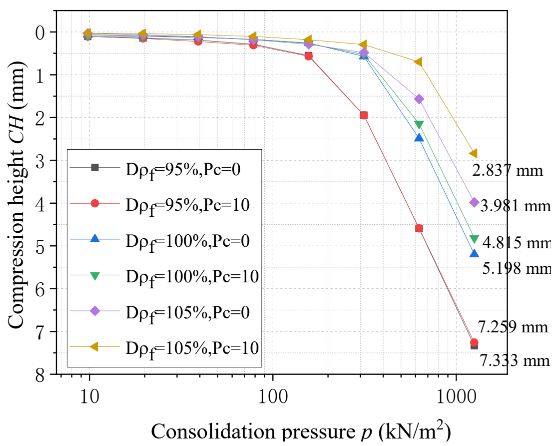

Fig.8 Relationship between the compression height and consolidation pressure

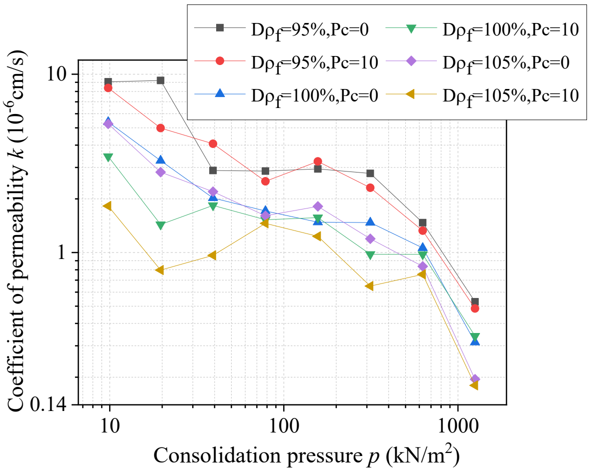

Fig.9 Variation of coefficient of permeability with consolidation pressure

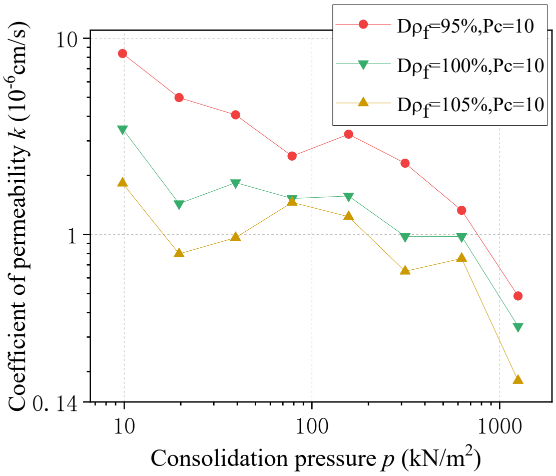

Fig.10 Variation of coefficient of permeability with consolidation pressure (Pc=10)

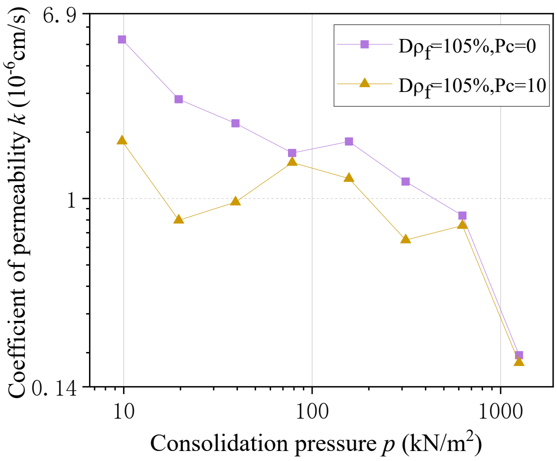

Fig.11 Variation of coefficient of permeability with consolidation pressure ($D\rho_f$ =105 %)

The relationship between the coefficient of permeability and consolidation pressure for specimens with slurry densities of 95 %, 100 %, and 105 %, with a fiber content of 0 and 10 kg/m³ is shown in Fig. 9. As can be seen from the Fig. 9, the coefficient of permeability of LSS gradually decreases with the increase of consolidation pressure. For the LSS specimen with a slurry density of 95 %, the coefficient of permeability decreases from 9.06×10^{-6} cm/s to 5.29×10^{-7} cm/s as consolidation pressure varies from 9.8 to 1256 kN/m². This corresponds to a reduction in hydraulic conductivity by 1 to 2 orders of magnitude.

Similarly, for the LSS with a slurry density of 100 %, the coefficient of permeability decreases from 5.39×10^{-6} cm/s to 3.14×10^{-7} cm/s, with a reduction of more than 10 times, exceeding one order of magnitude. The trend in the change of coefficient of permeability is more sensitive at lower pressures, experiencing a rapid decline in initial loading stages. As the pressure increases, the change becomes less pronounced, and after consolidation pressure reaches 100 kN/m², the decreasing trend slows down. Among these, the coefficient of permeability of LSS with a slurry density of 95 % is most affected by consolidation pressure, followed by 100 %, and 105 % is least influenced by consolidation pressure.

4.2.2 The Influence of Slurry Density on Permeability Characteristics

In order to investigate the effect of slurry density on the permeability properties of LSS, the relationships between the coefficient of permeability and consolidation pressure of LSS with slurry densities of 95 %, 100 %, and 105 % are shown in Fig. 10. Comparing different slurry densities, it is found that, under similar conditions, higher slurry density corresponds to a smaller coefficient of permeability for LSS. Particularly, the coefficient of permeability of LSS decreases rapidly with the increase of cement content in the initial loading stages. The coefficient of permeability for $D\rho_f$ = 95% is 8.4×10^{-6} cm/s, which is greater than the coefficient of permeability for $D\rho_f$ =100 % (3.5×10^{-6} cm/s) and $D\rho_f$ =105 % (1.9×10^{-6} cm/s). The coefficient of permeability of LSS of $D\rho_f$ =95 % is approximately twice that of $D\rho_f$ =100 % and four times that of $D\rho_f$ =105 %.

As shown in Fig. 10, the coefficient of permeability maintains a steady trend around a consolidation pressure of 100 kN/m, then gradually decreases, ultimately reaching the order of 10^{-7}. This is considered that all specimens become denser with consolidation. In other words, LSS is considered to be improved into an impermeable material under high pressure. The LSS used in this study, with a curing period of 28 days, achieves a coefficient of permeability on the order of 1×10^{-6} cm/s, which is generally suitable for common engineering applications.

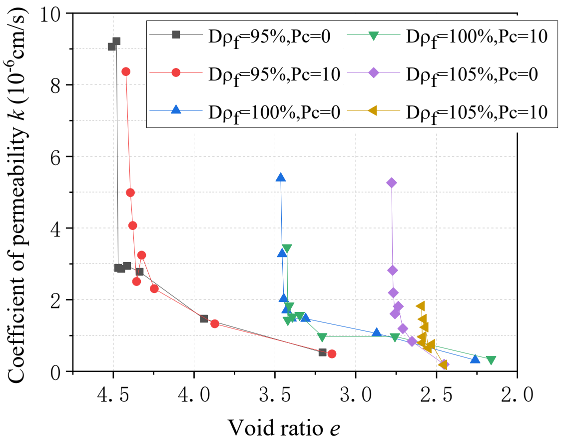

Fig. 12 Variation of coefficient of permeability with void ratio

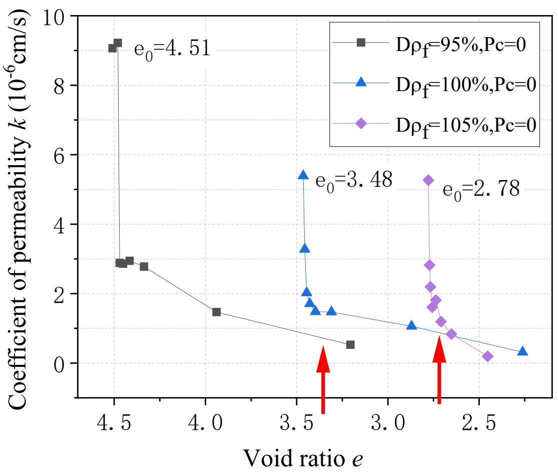

Fig.13 Variation of coefficient of permeability with void ratio with consolidation pressure (Pc=0)

4.2.3 The influence of fiber content on permeability characteristics

As shown in Fig. 11, under the same slurry density conditions, comparing different fiber content, Fig. 11 demonstrates that in the absence of fiber material (Pc=0), the coefficient of permeability of LSS is approximately 5.3 × 10^{-6} cm/s. In contrast, for LSS with a fiber content of 10 kg/m^3, the coefficient of permeability ranges between 1.8×10^{-6} cm/s. This indicates a significant decrease in permeability when fiber material is added, suggesting that the addition of fiber material can reduce the permeability of LSS. The coefficient of permeability of LSS is influenced by the size of the void in the soil and the flowability of the slurry. Therefore, as the slurry density of the LSS is increased, the pores become denser and the coefficient of permeability decreases.

4.2.4 Variation of coefficient of permeability with void ratio

Fig. 12 presents the relationship between the coefficient of permeability and void ratio and the comparison of specimens with slurry densities of 95 %, 100 %, and 105 %, with fiber content of 0 and10 kg/m³. For cohesive soils, changes in water channels in the soil can lead to significant variations in the coefficient of permeability. From Fig. 12, it is found that the void ratio *e* and the coefficient of permeability *k* in consolidation tests are in direct proportion. As the void ratio decreases, there is an overall decreasing trend in the coefficient of permeability. It is considered that as the consolidation pressure increases, the liquid water in the pores of LSS is gradually replaced by air, resulting in a smaller network of connected capillaries and fewer effective pores, which reduces the path of water through the pore skeleton, leading to a decrease in the coefficient of permeability.

As depicted in Figure 13, the results indicate that after consolidation, under the same void ratio conditions, the coefficient of permeability decreases with the increase in initial void ratio e_0. This phenomenon may be considered for the following reasons:

1. Soils with higher cement addition content (slurry density in this study) have coarser particles, greater bulk weight, smaller porosity, and greater coefficient of permeability.

2. With a smaller initial void ratio e_0, the structural strength of the soil skeleton is lower, and the arrangement of soil particles is looser. Under the influence of consolidation pressure, flattened clay particles are more prone to reorient and rearrange, leading to the filling of pore channels by finer particles and a significant reduction in the coefficient of permeability.

In this study, the consolidation and permeability tests of LSS specimens with various slurry densities showed an average coefficient of permeability as low as 3×10^{-6} cm/s. According to the reference values in the literature, the coefficient of permeability of Cement-Stabilized Clay is usually in the range of 3×10^{-5} cm/s to 3×10^{-3} cm/s. Our experimental results are significantly lower than this range, indicating that LSS has an extremely high permeability resistance [39-41].

In this study, the length of the fiber materials used ranged from 0.5 mm to 3 mm. While the effect of fiber length on the properties of the LSS specimens was not directly addressed, it is important to recognize that fiber length can significantly influence the mechanical behavior of soil mixtures. Previous studies have shown that variations in fiber length can alter the reinforcement efficiency and overall performance of composite materials [42,43].

Given the complexity of this relationship, further investigation into the scale effect of fiber length on the properties of LSS is recommended. Future research should focus on systematically evaluating how different fiber lengths affect consolidation and permeability characteristics, as well as the overall behavior of the soil.

5. CONCLUSIONS

This study conducted experimental research on the consolidation and permeability characteristics of Liquefied Stabilized soil composed mainly of NSF-Clay, with variations in slurry density and fiber content. The conclusions derived from this study are as follows:

1) The coefficient of consolidation of LSS increases with higher slurry density and fiber content. Among these factors, slurry density plays a primary role, while the influence of fiber content on the coefficient of consolidation of LSS is relatively small.

2) The overall trend for the coefficient of consolidation of LSS is a decrease with increasing pressure, and the inflection point of the rate of decrease is related to the consolidation yield stress.

3) The coefficient of permeability of LSS is closely correlated with slurry density, fiber material content, and the initial void ratio of the specimens. Slurry density is a significant factor influencing the permeability of LSS, with the coefficient of permeability decreasing notably as slurry density increases.

4) Fiber content has a relatively small impact on the consolidation and coefficient of permeability of LSS. However, the addition of fiber material contributes to reducing the permeability of LSS. In this study, while the effect of fiber length on the properties of the LSS specimens was not directly addressed, it is important to recognize that fiber length can significantly influence the mechanical behavior of soil mixtures. Future research should focus on systematically evaluating how different fiber lengths affect consolidation and permeability characteristics, as well as the overall behavior of the soil.

5) The average coefficient of permeability of LSS is around 3×10^{-6} cm/s, which shows high permeability resistance.

Based on the experimental results, empirical relationships between the consolidation and coefficient of permeability of LSS and parameters such as initial slurry density, fiber content, void ratio, and consolidation yield stress are summarized. These findings provide a basis for the design of LSS mixtures and the estimation of related parameters.

6. ACKNOWLEDGMENTS

We would like to express sincere gratitude to Ms. Watanabe (graduate student of Muroran Institute of Technology), Mr. Akiyama, and Mr. Sato (undergraduate student of Muroran Institute of Technology) for specimen preparation.

7. REFERENCES

[1] Terzaghi K., Peck R. B., Mesri G., Soil Mechanics in Engineering Practice (3rd ed.). Wiley, 1996, pp. 122-206.

[2] Indraratna B., Rujikiatkamjorn C., Balasubramaniam A.S., McIntosh G., Soft Ground Improvement Via Vertical Drains and Vacuum Assisted Preloading, Geomembranes, Vol. 30, 2012, pp. 16-23.

[3] Firoozi A.A., Guney Olgun C., Firoozi A.A., Barghini M.S., Fundamentals of soil stabilization. Geo-Engineering, Vol. 8, No.26, 2017. https://doi.org/10.1186/s40703-017-0064-9.

[4] Eskişar T., Altun S., Kalıpcılar İ., Assessment of Strength Development and Freeze–Thaw Performance of Cement Treated Clays at Different Water Contents. Cold Regions Science and Technology, Vol. 111, 2015, pp. 50-59.

[5] Consoli NC., Filho HCS., Segadães L., Cristelo N., Effect of Wet-Dry Cycles on The Durability, Strength and Stiffness of Granite Residual Soil Stabilised with Portland Cement. Proceedings of the XVII ECSMGE-2019, 2019, pp. 1–7.

[6] Abbil A., Kassim A., Ullah A., Rashid A.S.A., Roshan M.J., Numerical Analysis of Embankment Resting on Floating Bottom Ash Columns Improved Soft Soil. IOP Conference Series: Earth and Environmental Science, 2022, 1022, 012023. https://doi.org/10.1088/1755-1315/1022/1/012023.

[7] Tamassoki S., Daud N.N.N., Wang S., Roshan M.J., CBR of Stabilized and Reinforced Residual Soils Using Experimental, Numerical, And Machine-Learning Approaches. Transportation Geotechnics, Vol. 42, 2023, 101080. https://doi.org/10.1016/j.trgeo.2023.101080

[8] Hamdhan I. N., Anugrah R. F. V., Nurhaliza S., The Effect of Soil Improvement Patterns Using Deep Cement Mixing (DCM) On Soft Soil Settlement. International Journal of GEOMATE, Vol. 27, Issue 119, 2024, pp. 120-126.

[9] Dewi R., Saggaff A., Hanafiah., Rahayu W., The Hydrolysis Characteristics and Compressibility of Soft Clay Soil Improved Using VCM. International Journal of GEOMATE, Vol. 26, Issue 113, 2024, pp. 26-33.

[10] Roshan M.J., Rashid A.S., Wahab A.N., Hezmi M.A., Jusoh S.N., Norsyahariati N.D.N., Tamasoki S, Yunus N.Z.M., Razali R., Effects of Ordinary Portland Cement on The Soil-Water Characteristics Curve of Lateritic Soil. Suranaree Journal of Science Technology, Vol. 30, 2023, 010183, pp. 1-10.

[11] Nusit K., Jitsangiam P., Kodikara J., Bui H.H., Leung J.L.M., Advanced Characteristics of Cement-Treated Materials with respect to Strength Performance and Damage Evolution. Journal of Materials in Civil Engineering, Vol. 29,

2017, Issue 4. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001772.

[12] Kim A-R., Chang I., Cho G-C., Shim S-H., Strength and Dynamic Properties of Cement-Mixed Korean Marine Clays. KSCE Journal of Civil Engineering, Vol. 22, 2018, pp. 1150-1161.

[13] Roshan M.J., Abedi M., Correia A.G., Fangueiro R., Application of Self-Sensing Cement-Stabilized Sand for Damage Detection. Construction and Building Materials, Vol. 403, 2023, 133080. https://doi.org/10.1016/j.conbuildmat.2023.133080

[14] Duan X., Zhang J., Mechanical Properties, Failure Mode, and Microstructure of Soil-Cement Modified with Fly Ash and Polypropylene Fiber. Advances in Materials Science and Engineering, Vol. 2019, pp. 1-13. https://doi.org/10.1155/2019/9561794

[15] Zheng G., Jiang Y., Han J., Liu Y-F., Performance of Cement-Fly Ash-Gravel Pile-Supported High-Speed Railway Embankments over Soft Marine Clay. Marine Georesources & Geotechnology, Vol. 29, Issue 2, 2011, pp.145-161.

[16] Le Kouby A., Guimond-BarrettA., Reiffsteck P., Pantet A., Mosser J. F., & Calon N., Improvement of Existing Railway Subgrade by Deep Mixing. European Journal of Environmental and Civil Engineering, Vol. 24, Issue 8, 2018, pp.1229-1244.

[17] Festugato L., Venson GI., Consoli NC., Parameters Controlling Cyclic Behaviour of Cement-Treated Sand, Transportation Geotechnics, Vol.27, 2021, 100488. https://doi.org/10.1016/j.trgeo.2020.100488

[18] Nazari Z., Tabarsa A., Latifi N., Effect of Compaction Delay on The Strength and Consolidation Properties of Cement-Stabilized Subgrade Soil. Transportation Geotechnics, Vol. 27, 2021, 100495. https://doi.org/10.1016/j.trgeo.2020.100495

[19] Sasanian S., Newson T.A., Basic Parameters Governing the Behaviour of Cement-Treated Clays, Soils and Foundations, Vol. 54, 2014, pp.209-224.

[20] Ghadir P., Zamanian M., Mahbubi-Motlagh N., Saberian M., Li J., Ranjbar N., Shear Strength and Life Cycle Assessment of Volcanic Ash-Based Geopolymer and Cement Stabilized Soil: A Comparative Study. Transportation Geotechnics, Vol. 31, 2021, 100639. https://doi.org/10.1016/j.trgeo.2021.100639

[21] Roshan M.J., Rashid A.S.B.A. Geotechnical Characteristics of Cement Stabilized Soils from Various Aspects: A Comprehensive Review. Arab J Geosci, Vol. 17, No.1, 2024. https://doi.org/10.1007/s12517-023-11796-1

[22] Kuno G., eds, Liquefied stabilized soil method Recycling technology of construction-generated soil and mud, Gihodo publication, 1997, pp.1-102 (in Japanese).

[23] Horpibulsuk S., Miura N., and Nagaraj T S., Clay–Water⁄ Cement Ratio Identity for Cement Admixed Soft Clays, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131, Issue 2, 2005, pp. 187-192.

[24] Consoli N C., De Moraes R R., Festugato L., Parameters Controlling Tensile and Compressive Strength of Fiber-Reinforced Cemented Soil, Journal of Materials in Civil Engineering, Vol. 25, Issue 10, 2013. pp. 1568-1573.

[25] Zhang Z., Omine K., Flemmy S.O., Evaluation of the improvement effect of cement-stabilized clays with different solidifying agent addition and water content, Journal of Material Cycles and Waste Management, Vol. 24, 2022, pp. 2291-2302.

[26] Chen L., Shi J., Cui H., and Cui L., Analysis of construction generated soil as filling material for consolidation pile, Journal of Harbin University of Commerce, Vol. 28, No.3, 2012, pp. 345-347. (in Chinese)

[27] Chen S., Shi J., Yu T., Huang J., Effects of Freezing-Thawing Cycle of Compressibility of Cement Soil, Applied Mechanics and Materials, Vol. 419, 2013, pp. 837-841.

[28] Du Y., Fan R.D., Compressibility and permeability behavior of two types of amended soil-bentonite vertical cutoff wall backfills, Rock and Soil Mechanics, Vol. 32, Issue 1, 2011, pp. 49-54.

[29] Huang X., Li J., Xue Q., Use of self-hardening slurry for trench cutoff wall: A review, Construction and Building Materials, Vol. 286, 2021, 122968. https://doi.org/10.1016/j.conbuildmat.2021.122959.

[30] Horpibulsuk S., Miura N., and Bergado D.T., Undrained Shear Behavior of Cement Admixed Clay at High Water Content. Journal of Geotechnical and Geoenvironmental Engineering, vol. 130, Issue 10, 2004, pp. 1096-1105.

[31] Pham Vuong Q., Kohata Y., Effect of Liquefied Stabilized Soil as Backfilling Material on the Building under Seismic Condition, International Journal of GEOMATE, Vol. 20, Issue 77, 2021, pp. 155-162.

[32] Hung Khac L., Kohata Y., Strength and deformation properties of liquefied stabilized soil prepared by various conditions, International Journal of GEOMATE, Vol. 23, Issue 98, 2022, pp. 179-188.

[33] Bahar R., Benazzoug M., Kenai S., Performance of Compacted Cement-Stabilised Soil, Cement and Concrete Composites, Vol.26, Issue 7, 2004, pp.811-820.

[34] Jamshidi R.J., and Lake C.B., Hydraulic and Strength Properties of Unexposed and Freeze–Thaw Exposed Cement-Stabilized Soils, Canadian Geotechnical Journal. Vol. 52, Issue 3, 2015, pp. 283-294.

[35] Quang N.D., Chai J.C., Permeability of Lime-And Cement-Treated Clayey Soils, Canadian Geotechnical Journal. Vol. 52, Issue 9, 2015, pp. 1221-1227.

[36] Cui Y., and Kohata Y., Influence of cement solidification agent and slurry density on mechanical property of liquefied stabilized soil, International Journal of GEOMATE, Vol. 19, Issue 73, 2020, pp. 177-184.

[37] JIS A 1217: 2009, Test Method for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, 2009 (in Japanese).

[38] K. Terzaghi., Principles of Soil Mechanics: IV - settlement and consolidation of clay, Engineering News-Record, Vol. 95, No. 3, 1925, pp. 874-878.

[39] Diana W., Hartono E., Muntohar A S., The Permeability of Portland Cement-Stabilized Clay Shale, IOP Conference Series: Materials Science and Engineering, 2019, No. 1, 012027. https://doi.org/10.1088/1757-899X/650/1/012027

[40] Satomi T., Kuribara H., Takahashi H., Evaluation of Failure Strength Property and Permeability of Fiber-Cement-Stabilized Soil Made of Tsunami Sludge, Journal of JSEM, Vol. 14, 2014, pp. 303-308.

[41] Zhang L., Dang F., Gao J., Ding J, Measurement and Investigation on 1-D Consolidation Permeability of Saturated Clay considering Consolidation Stress Ratio and Stress History, Geofluids, Vol. 2021, 2021, pp. 1-21.

[42] Tabakouei A. R., Narani S. S., Abbaspour M., Aflaki E., Siddiqua S., Coupled Specimen and Fiber Dimensions Influence Measurement on The Properties of Fiber-Reinforced Soil, Measurement, Vol. 188, 2022, 110556. https://doi.org/10.1016/j.measurement.2021.110556

[43] Yan Y., Huang M., Qin M., Xie Z., Ou S., A Study on The Mechanical Behaviour of Mixed Fiber-Reinforced Soil, Case Studies in Construction Materials, Vol. 20, July 2024, e02879. https://doi.org/10.1016/j.cscm.2024.e02879