流動化処理土の圧密及び透水特性に関する実験的研究

Experimental Study on Consolidation and Permeability Characteristics of Liquefied Stabilized Soil

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ABSTRACT

Permeability plays a crucial role in geotechnical engineering, directly affecting the strength, deformation, and long-term performance of soil structures. While liquefied stabilized soil (LSS) has garnered significant interest as a sustainable backfill material, research on its application in projects requiring low permeability remains limited. This study explores the consolidation and permeability behavior of LSS through a series of 1-D consolidation and permeability tests to assess its suitability as a low-permeability backfill material. Test conditions included slurry densities of 1.216, 1.280, and 1.344 g/cm^3, cement content of 100 kg/m^3, fiber content of 0 and 10 kg/m^3, and curing periods of 7, 28, 56, and 120 days.

The study compares the consolidation and permeability characteristics of LSS at different slurry densities and examines the impact of fiber addition. Results indicate that the coefficient of consolidation of LSS increases significantly with both slurry density and fiber content, with slurry density being the primary influencing factor. Fiber content showed a relatively smaller effect on the coefficient of consolidation. The overall trend of LSS's coefficient of consolidation was to decrease with increasing pressure, with a notable inflection point corresponding to the consolidation yield stress. Additionally, the study found that the coefficient of permeability of LSS is closely related to slurry density, fiber content, and the initial void ratio of the specimens. As slurry density and fiber content increase, the coefficient of permeability decreases significantly. While fiber content has a relatively minor influence among these factors, adding fiber enhances LSS's impermeability. In this study, the average coefficient of permeability of LSS was approximately 3×10^{-6} cm/s, indicating high impermeability. Although this study did not directly address the impact of fiber length on LSS specimen performance, future research should consider the effect of various fiber lengths on consolidation and permeability to optimize LSS properties further.

Moreover, the study highlights the significant impact of curing time on the consolidation and permeability properties of LSS primarily composed of NSF-Clay. The findings show that the coefficient of consolidation of LSS increases with curing time, while the coefficient of permeability decreases. The overall coefficient of consolidation decreases with increasing pressure; however, this increase is more pronounced with longer curing times, with fiber content having a relatively minor impact. The general trend of LSS's coefficient of permeability is to decrease with increasing consolidation pressure, dropping by one to two orders of magnitude within a pressure range of 9.8 to 1256 kN/m^2. Compared to fiber content, curing time has a more significant impact on LSS's permeability.

This study also compared the consolidation and permeability properties of LSS with those of the base material, NSF-Clay, and found that LSS exhibits higher coefficient of consolidations, lower coefficient of permeability, and a stable void ratio compared to NSF-Clay. Although the void ratio of LSS is slightly higher than that of NSF-Clay under higher consolidation pressures, the coefficient of permeability suggests that the voids in LSS are mainly composed of impermeable micro-pores. The addition of a stabilizer significantly alters the internal particle arrangement within the soft clay matrix, resulting in a denser LSS structure.

In conclusion, this study not only provides experimental support for the application of LSS in low-permeability engineering but also lays a foundation for future research. Future studies should focus on evaluating

the effects of various fiber lengths on the consolidation and permeability properties and the overall mechanical behavior of LSS to further optimize its performance in engineering applications.

CHAPTER 1
INTRODUCTION

1. Introduction

1.1. Problem Statement

In recent years, with rapid economic growth, urbanization in China and Vietnam has progressed rapidly. From 1980 to 2020, China's urbanization rate rose from 19.4% to over 60%, creating immense demand for infrastructure construction, especially in economically developed eastern coastal regions. However, these areas widely feature soft clay layers, which are highly compressible and have low shear strength, severely limiting the speed of building and urban expansion. The challenge of soft soil foundations is a primary issue in numerous infrastructure projects in these cities. Although Vietnam's urbanization started later, it has accelerated in recent years, particularly in major cities like Ho Chi Minh City and Hanoi, where soft ground treatment has become a core issue in infrastructure development. Regions such as the Mekong Delta are widely distributed with soft clay, highlighting an urgent need for foundation improvement. Japan, as a highly developed country, has long completed its urbanization process, yet it still has substantial infrastructure needs for urban renewal, transportation expansion, and seismic-resistant structures. Like China and Vietnam, Japan faces challenges in treating soft soil foundations in many cities, especially in coastal areas. In Tokyo Bay, Nagoya Bay, and other coastal regions, soft clay layers are common, causing settlement and deformation issues in urban projects such as high-rise buildings and underground space developments.

At the same time, urban areas in countries like Vietnam and China are increasingly grappling with severe traffic congestion and air pollution issues. To address these problems, expanding the capacity of existing public transport systems and road networks and establishing new urban high-speed transit systems as soon as possible has become a priority. However, due to limited land in urban areas, metro construction has become a solution in many cities. For instance, large-scale metro projects are underway in Hanoi, Vietnam, with projections indicating substantial excavation over the next decade. However, there is a significant issue with insufficient landfill sites in urban areas, creating challenges for disposing of excavated soil. At the same time, fill materials mainly rely on natural resources like sand and gravel, sourced from rivers and mountains, which negatively impacts the environment. Even in Japan, the soil reuse rate in construction projects is less than 80%, making it essential to improve the effective utilization of excavated soft clay in construction projects.

Soft clay is a common construction foundation material in engineering; however, its unique physical properties present numerous challenges in construction. The high water content, notable compressibility, and low shear strength of soft clay (Terzaghi K,1996) render it incapable of providing adequate bearing capacity, leading to instability issues as a foundational material. These issues are particularly pronounced in infrastructure projects, especially in high-rise buildings, highways, and bridges, where foundation requirements are stringent, often resulting in uneven settlement and foundation deformation, which could ultimately lead to tilting or even structural failure (Indraratna B, 2012; Firoozi A.A, 2017). This is particularly concerning in large public facility projects, such as airports, ports, and railway yards, where the characteristics of soft clay pose a substantial threat to the long-term stability of these foundational structures. Thus, how to effectively improve the mechanical properties of soft clay to enhance its compressive and shear strength has been an important research topic in civil engineering. Solving this issue not only improves the safety of buildings but also extends the lifespan of projects (Eskişar T, 2015; Consoli NC, 2019; Abbil A, 2022; Tamassoki S, 2023).

Engineers have proposed various improvement methods to address the challenges of soft soil foundations, including preloading, vacuum consolidation, and deep mixing techniques. Preloading involves applying an additional load on the soft soil foundation to accelerate consolidation, reducing future settlement and commonly used in foundations for large buildings. This method controls the initial stress conditions of the soil body, gradually expelling pore water from the soil, thereby reducing the compressibility of the soft soil. Vacuum consolidation, on the other hand, utilizes negative pressure to expel pore water from the foundation, accelerating the consolidation process while enhancing the bearing capacity of the foundation. This method's core principle involves creating a negative pressure environment within the soil, forcing pore water to diffuse outward, accelerating soft soil consolidation, and quickly enhancing soil bearing capacity. Deep mixing techniques involve mixing stabilizing materials such as cement or lime directly with the soil underground to improve the strength and stability of the soil. These methods have shown significant effects in improving the mechanical properties of soft clay (Hamdhan I. N, 2024; Dewi R, 2024) However, while effective under certain conditions, these methods are complex and costly, making them unsuitable for all engineering projects, especially large-scale applications where constraints may arise.

With growing construction demands and advances in construction technology, cement soil treatment technology has gradually become another efficient choice for addressing issues related to the mechanical properties of soft clay (Roshan M.J, 2023). This technology involves mixing stabilizing materials like cement with soft clay, prompting chemical reactions that significantly improve its compressive strength, shear strength, and stability (Nusit K, 2017; Kim A-R, 2018; Roshan M.J, 2023). Cement soil treatment technology not only markedly improves the foundation's bearing capacity but also effectively reduces settlement issues (Duan X, 2019), playing a vital role in foundation reinforcement in transportation, construction, and bridge engineering. In Japan, in particular, cement treatment technology has rapidly developed and been widely applied since its introduction in the 1980s, performing exceptionally in large-scale projects such as highways, railways, and tunnels (Zheng G, 2011; Le Kouby A, 2018; Festugato L, 2021; Nazari Z, 2021). Its broad application not only improves the seismic capacity of foundations but also significantly reduces construction costs, making it widely favored for its cost-efficiency and ease of application (Sasanian S, 2014; Ghadir P, 2021).

Cement soil treatment technology enhances the soil's mechanical properties through chemical reactions, where cement reacts with water and other compounds in the soil to produce hydration products that fill the pores within the soil, reducing its compressibility and increasing its strength. Additionally, by selecting appropriate cement types and mixing ratios, engineers can adjust the effectiveness of cement treatment technology according to different soil properties and engineering requirements. This flexibility enables the widespread application of cement soil treatment technology in various complex engineering environments.

With society's growing emphasis on environmental protection and sustainable development, the environmental aspect of cement-treated soil has also attracted attention. By using excavated soil as material, cement treatment technology effectively reduces soil waste during construction and decreases reliance on natural materials, aligning with the needs of modern green building practices. This technology not only effectively addresses the bearing capacity and settlement issues of soft clay foundations but also offers significant environmental benefits, making it highly suitable and feasible for large-scale engineering projects (Roshan M.J, 2021).

In recent years, Liquefied Stabilized Soil (LSS) (Kuno G, 1997), an improved form of cement soil treatment technology, has received widespread attention. Made from a mixture of excavated soil, cementitious materials, water, and other additives, LSS exhibits fluidity, allowing for more flexible handling during construction and more effective filling and covering of complex terrains or spaces. Unlike traditional cement-treated soil, LSS exists as a fluid during construction, making it extremely efficient and easy to apply in backfilling projects, underground pipelines, and tunnel construction. In Japan, LSS has been widely used for foundation reinforcement and backfilling in underground infrastructure, particularly in pipelines, excavation supports, and bridge foundations, demonstrating excellent stability and durability (Horpibulsuk S, 2005; Consoli N C, 2013). LSS not only addresses limitations in fluidity and construction handling of traditional cement-treated soil but also enhances its mechanical properties, making it a highly competitive material. Compared to untreated excavated soil, LSS shows superior performance in terms of compressive strength, shear strength, and stability, enabling it to meet engineering requirements while reducing material usage and costs (Du Y, 2011; Huang X, 2021). Furthermore, the fluidity of LSS allows it to be easily injected into narrow spaces or complex terrains without the need for heavy machinery, thus improving construction efficiency and reducing environmental disruption. Additionally, the slurry properties of LSS enable it to quickly solidify under various conditions, forming a robust structure that enhances its adaptability and stability in diverse environments.

However, during the soil stabilization phase, the reaction between additives and soil forms a cementitious system, which requires further reinforcement to prevent cracking and excessive settlement under extensive loading. Further research on LSS indicates that adding organic fibers or other reinforcement materials to its mixture can significantly improve its mechanical properties. Studies have shown that organic fiber materials similar to waste newspaper fibers, when mixed with LSS, can enhance its tensile strength and shear resistance. These fibers create a reinforcement effect within the LSS, providing superior performance in actual engineering applications, especially under shear and tensile stresses (Pham Vuong Q, 2021; Hung Khac L, 2022).

To validate the effectiveness of reinforcement and stabilization techniques using waste newspaper fibers and changing slurry density, it is crucial to understand consolidation parameters such as the coefficient of consolidation (cv), coefficient of volume change (mv), and the limiting permeability coefficient (k). The consolidation rate is closely related to cv, while the amount of settlement is directly associated with mv.

Abdi et al. (2008) found that increasing the fiber content and length significantly reduced consolidation settlement, expansion, and crack formation when studying fiber-reinforced soils. In another study, Das and Pal (2012) pointed out that the coefficient of consolidation (cv) increased significantly with the addition of fly ash in stabilized silty clay. Furthermore, Wang et al. (2023) found that the combination of polypropylene fibers and bentonite effectively improved the strength and permeability of loess. Under the optimal dosage, the unconfined compressive strength of loss increased by 149.41%, and permeability decreased by 15.74%.

However, most of the existing literature is limited to the specific types of reinforcement materials, soil types, and stabilizers used, with testing methods primarily focused on unconfined compressive, triaxial, direct shear, and CBR tests. To date, there has been limited research on the one-dimensional consolidation characteristics of liquefied stabilized soil, particularly regarding the combined effects of slurry density, curing time, and organic fiber content, especially in terms of their impact on consolidation settlement, volume change, and permeability.

In this context, the objective of this study is to investigate the correlation between the coefficient of consolidation (c_v) and varying organic fiber content and cement content in soft clay, providing a theoretical basis for improving soil properties and optimizing soil stabilization techniques.

In addition, although previous studies have explored various engineering properties of LSS, significant differences remain between research on permeability performance and practical applications.

Applications of Liquefied Stabilized Soil in permeability mainly span multiple fields. In infrastructure construction, it can serve as a foundation material, improving soil permeability and enhancing foundation stability. In projects such as reservoirs, dams, and tunnels, LSS helps control groundwater levels, reducing seepage effects on structures and increasing safety. In soil pollution remediation, it can seal pollution sources, limit pollutant diffusion through permeability changes, and promote soil restoration. In foundation reinforcement, fluid treatment improves soft soil foundation permeability, promoting groundwater discharge, accelerating consolidation, and enhancing bearing capacity. Additionally, LSS serves as drainage material in urban drainage and sewage treatment systems, facilitating quick water discharge and treatment. In tunnel construction, it helps reduce water seepage and accumulation issues, ensuring construction safety. For seismic design, LSS's permeability can reduce liquefaction risks during earthquakes, enhancing soil stability. Finally, in agricultural soil improvement, LSS improves soil permeability, facilitating water infiltration and retention to enhance crop growth conditions, demonstrating LSS's significant practical importance in improving soil permeability.

However, past studies indicate that evaluations of seepage performance when using cement-stabilized soil as backfill material are still insufficient (Bahar R, 2004; Jamshidi R.J, 2015; Quang N.D, 2015)

Therefore, this study aims to address these gaps by investigating the consolidation and permeability properties of Liquefied Stabilized Soil (LSS) prepared under different conditions. Its novelty lies in the addition of fiber materials and variations in initial slurry density. Based on consolidation and permeability test results, the effects of slurry density and fiber content variations on the consolidation and permeability performance of LSS are discussed. This study provides key insights into how these factors influence the consolidation and permeability properties of LSS, offering practical guidance for future urban infrastructure and environmental projects and promoting the sustainable application of LSS in geotechnical engineering.

1.2. Research Objectives

Liquefied Stabilized Soil (LSS) is a new type of hydraulic composite construction material formed by mixing soil particles, binding materials, water, and other additives in proportion. Its engineering mechanical properties have significantly improved compared to ordinary soil, especially in terms of compactness, compressive strength, shear strength, permeability, and impermeability. Currently, LSS is widely used in foundation pit support, foundation reinforcement, subgrade cushioning, and channel impermeability.

However, soft clay, as a common construction soil, presents engineering issues such as high natural water content, high compressibility, low bearing capacity, and poor shear strength. The use of cement-stabilized soil technology is an effective means to address these problems. In Japan, the widespread application of cement-stabilized soil in foundation reinforcement has achieved good results, and research on liquefied stabilized soil has gradually deepened. The addition of fiber materials significantly improves the shear and tensile failure mechanical properties of LSS, further highlighting the advantages of flowable soil reinforcement technology.

Nevertheless, research on the application of LSS in projects requiring impermeability or anti-permeability is relatively scarce, particularly regarding the permeability characteristics of flowable treatment of soft clay. Therefore, it is necessary to explore the permeability characteristics of flowable-treated soft clay in depth to fill the research gap in this field.

The main goal of this study is to explore the consolidation and permeability characteristics of liquefied stabilized soil (LSS), particularly focusing on the effects of different slurry densities, curing times, and fiber material content on LSS performance. Specifically, the study aims to systematically analyze the consolidation and permeability characteristics of LSS under different mix conditions through a series of one-dimensional consolidation and permeability tests, providing theoretical basis and practical guidance for related engineering applications.

First, the research will systematically analyze the variation of the coefficient of consolidation (c_v) of liquefied stabilized soil at different slurry densities (1.216, 1.280, 1.344 g/cm^3). Through standard consolidation tests, the relationship between the coefficient of consolidation and pressure changes will be explored, especially the effect of consolidation yield stress on the coefficient of consolidation, revealing the behavior of the material under different loading conditions.

Second, the influence of different curing times (7, 28, 56, and 120 days) on the consolidation and coefficient of permeability of LSS will be evaluated, focusing on how extending the curing time improves the mechanical properties and impermeability of the soil. The impact of moisture evaporation and cement hydration reactions during the curing process on soil strength will be investigated to find the optimal curing time.

Additionally, the effects of adding different amounts of fiber materials (0 kg/m^3 and 10 kg/m^3) on the consolidation and permeability characteristics of LSS will be examined, analyzing the reinforcement mechanisms exhibited by the fiber materials in the consolidation and permeability tests, and assessing their practical effects on improving soil tensile strength, toughness, and crack resistance.

The study will also systematically investigate the interactions among slurry density, fiber content, and curing time, establishing a mathematical model of the performance influences of LSS. Through data analysis, this research will clarify how these factors collectively affect the mechanical properties and engineering applications of LSS, exploring the optimal mix ratios under different engineering conditions.

By combining theoretical research with practical engineering cases, the potential of LSS in foundation reinforcement, soil impermeability, and other engineering applications will be explored. This study aims to provide scientific evidence for engineering practice, supporting the application of LSS as a new type of construction material in civil engineering and promoting its use in environmental protection and infrastructure construction.

Through systematic experimental research, basic data on the consolidation and permeability characteristics of LSS will be obtained, establishing a complete set of testing methods for the consolidation and permeability of liquefied stabilized soil. This research will enrich the application cases of LSS in engineering, promoting its practical application in foundation reinforcement and environmental protection.

Conclusion

In summary, this study will focus on the consolidation and permeability characteristics of liquefied stabilized soil, integrating experimental and theoretical analyses to explore its application potential in practical engineering, thereby providing effective solutions for improving the engineering performance of soft clay. It is hoped that this research will offer significant references and guidance for the theoretical development and engineering practice of liquefied stabilized soil.

1.3. Organization of Thesis

The structure of this thesis will follow the logic of scientific research, divided into several chapters to systematically present the research process and results regarding the consolidation and permeability characteristics of liquefied stabilized soil (LSS). The specific organizational structure is as follows:

Chapter 1: Introduction

This chapter will introduce the background and significance of the study, elucidating the basic concepts, characteristics, and importance of liquefied stabilized soil in engineering. It will analyze the current state of research in this field both domestically and internationally, identifying existing research gaps and technical challenges, as well as outlining the goals and contributions of this study. Finally, a brief overview of the organization of the thesis will be provided.

Chapter 2: Overview of Liquefied Stabilized Soil

This chapter will present the fundamental concepts, components, historical development, and current applications of liquefied stabilized soil. A literature review will summarize relevant research on the consolidation and permeability characteristics of LSS, the influencing factors, and the effects of fiber material applications. The chapter will focus on significant advancements in liquefied stabilized soil research both domestically and internationally, summarizing the shortcomings of existing studies to provide a theoretical foundation for subsequent research.

Chapter 3: Specimen Materials and Preparation Methods

This chapter will detail the materials and preparation methods used in this research, including the selection of experimental materials, mixing methods, and specific steps for specimen preparation. It will provide a comprehensive description of the experimental preparation process. Additionally, the design rationale will be explained, detailing the selection criteria for different slurry densities, curing times, and fiber content.

Chapter 4: Experimental Equipment and Procedures

This chapter will focus on the experimental equipment and procedures. It will describe the specific experimental methods and protocols, including the steps for consolidation and permeability tests, equipment selection, and data analysis methods. Furthermore, the chapter will detail the methods for processing the results, including the use of the logarithmic time method to calculate consolidation results.

Chapter 5: Results and Discussion of Consolidation Tests Under Different Conditions

This chapter will compare and analyze the coefficient of consolidation, void ratio, and coefficient of permeability of the base material NSF-CLAY and liquefied stabilized soil (LSS) to explore the performance characteristics of NSF-CLAY as a base material.

The experimental results, including testing data on the coefficient of consolidation of LSS under varying slurry densities, curing times, and fiber contents, will be presented. The results will be analyzed in detail using charts and text, discussing the influence of various factors on consolidation characteristics and comparing them with relevant theoretical models. Additionally, this chapter will explore the relationships among void ratio, consolidation pressure, and coefficient of consolidation.

Chapter 6: Results and Discussion of Permeability Tests Under Different Conditions

This chapter will primarily discuss the experimental results related to the permeability of liquefied stabilized soil under different conditions. The analysis will cover the relationships between coefficient of permeability and consolidation pressure, void ratio, as well as the effects of slurry density, curing time, and fiber material content on permeability.

Chapter 7: Conclusion and Recommendations

In the final chapter, the main findings of this research will be summarized, emphasizing the importance of the consolidation and permeability characteristics of liquefied stabilized soil in engineering practice. The limitations of this study will be pointed out, and future research directions will be proposed to provide references for subsequent studies.

References

A list of all the literature cited in this thesis will be provided to ensure the scientific rigor and proper citation of the research.

CHAPTER 2

OVERVIEW OF LIQUEFIED STABILIZED SOIL

2. Overview of Liquefied Stabilized Soil

2.1. Introduction

Liquefied Stabilized Soil (LSS) is a novel engineering material that has attracted significant attention and application in fields such as civil and environmental engineering in recent years. Its primary feature is the creation of a composite material with excellent mechanical properties and impermeability by mixing soil, binding agents (such as cement, lime, or fly ash), water, and other additives in specific proportions. This material is particularly effective in improving soil properties, enhancing structural stability, and reducing soil erosion, making it an effective solution for dealing with soft, muddy, and other problematic soils.

The superior performance of LSS originates from its unique composition and mixing process. With a scientifically optimized mixture, LSS achieves significantly improved compressive strength, shear strength, and impermeability. This has led to its extensive application in foundation engineering, subgrade treatment, dam construction, and environmental management. Particularly in areas with soft soils, the use of LSS has markedly improved the safety and durability of construction projects.

As urbanization and infrastructure development accelerate, traditional soil applications face numerous challenges, such as high compressibility, low bearing capacity, and poor shear strength. Due to its outstanding properties, LSS has become an essential choice to address these issues. It has been successfully applied in numerous domestic and international engineering projects, including ground reinforcement, road repair, and environmental restoration, achieving substantial economic and social benefits.

This chapter provides a comprehensive overview of the composition, historical development, current applications, and related research on LSS. First, it introduces the main components of LSS and their functions, examining the impact of each component on LSS performance. Next, it reviews the historical development of LSS, exploring its evolution in engineering practice and technological advancements. Additionally, it summarizes the current applications of LSS, detailing practical case studies and outcomes across various engineering fields. Finally, the chapter analyzes the current research focus and future development directions for LSS, aiming to provide a solid theoretical foundation and reference for subsequent research.

2.2. Component of Liquefied Stabilized Soil

The composition of Liquefied Stabilized Soil (LSS) primarily consists of a base material, cementitious materials, and fiber materials, with the balanced combination of these components directly impacting its engineering properties. The following section will elaborate on these three components and their influence on the performance of LSS. (Figure 2-1)

Figure 2-1 The components of liquified stabilized soil

2.2.1. Base Materials

The base material is the primary component of Liquefied Stabilized Soil (LSS) and typically consists of natural soil, waste soil, or other suitable soil types. The properties of the base material are crucial to the performance of LSS, including factors such as particle size distribution, plasticity index, moisture content, and density. These characteristics not only affect the consolidation behavior of the soil but also directly influence its permeability and strength.

Particle Size Distribution: The particle size distribution of the base material significantly impacts the performance of LSS. Generally, finer-grained soils provide a larger specific surface area, enhancing the bonding strength of cementitious materials and increasing soil strength. However, an excessively fine particle size may increase soil plasticity, potentially affecting stability. Therefore, selecting a base material with an appropriate particle size distribution is essential to meet specific engineering requirements.

Plasticity Index: The plasticity index is a key measure of soil plasticity, reflecting its flow and deformation characteristics at varying moisture levels. A higher plasticity index may increase soil fluidity when wet, negatively affecting the consolidation properties of LSS. Therefore, choosing a base material with a moderate plasticity index can improve both construction and long-term stability of LSS.

Moisture Content: Moisture content significantly influences the workability and consolidation properties of the base material. An optimal moisture level promotes the reaction between cement and the base material, enhancing strength. However, excessively high or low moisture levels can adversely affect LSS performance. Controlling the moisture content of the base material can improve the compressive strength and permeability resistance of LSS.

Improvement Treatments: Through improvement treatments, such as bio-soil modification or chemical treatments, the compressive strength and permeability resistance of LSS can be significantly enhanced. For example, adding a suitable amount of chemical modifiers to the base material can alter the soil's physical and chemical properties, strengthening its bond with cementitious materials and thereby improving the overall performance of LSS.

Most soils in liquefied stabilized soil method are soft soils. The stabilization has been performed to achieve desirable engineering properties. The main purpose of liquefied stabilized method is to recycle excavated soil for backfilling processes for construction projects. Therefore, almost types of excavated soils can be used for this method. However, fine-grained granular materials are the easiest to stabilize due to a large surface area in their contact diameter. The excavated soils can be modified to perform mainly with the purpose of improving their usability in construction. At present, excavated soils are stabilized by binders which are selected in relation to the type of soil. The stabilization has improved the strength of the soils and their resistance to softening.

In this study, NSF-CLAY was used as a homogenous base material, which was a commercially available cohesive soil with very clearly defined physical properties shown in Table 2-1.

Table 2-1 Physical parameters of NSF-Clay

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

2.2.2. Cementitious Materials

In stabilizing a soil, these are hydraulic (primary binders) or non-hydraulic (secondary binders) materials that when in contact with water or in the presence of pozzolanic minerals reacts with water to form cementitious composite materials. The commonly used binders are cement, lime or fly ash. In order to decide which binder should be used, the analysis have been performed based on test results and in fact condition of projects.

Cement

Cement had been known as the binding agent since the invention of soil stabilization technology in the 1960's. It may be considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil. This can be the reason why cement is used to stabilize a wide range of soils. Numerous types of cement are available in the market; these are ordinary Portland cement, blast furnace cement, sulfate resistant cement and high alumina cement. Usually the choice of cement depends on type of soil to be treated and desired final strength. Hydration process is a process under which cement reaction takes place. The process starts when cement is mixed with water and other components for a desired application resulting into hardening phenomena. The hardening (setting) of cement will enclose soil as glue, but it will not change the structure of soil. The hydration reaction is slow proceeding from the surface of the cement grains and the Centre of the grains may remain unhydrated. Cement hydration is a complex process with a complex series of unknown chemical reactions. However, this process can be affected by presence of foreign matters or impurities, water- cement ratio, curing temperature, the presence of additives, and specific surface of the mixture.

Cement-based materials serve as essential binding agents in Liquefied Stabilized Soil (LSS), typically involving ordinary Portland cement, slag cement, or other specialized cements. The type of cement, its dosage, and the cement-to-water ratio significantly affect the strength, toughness, and durability of LSS.

1. Type of Cement: Different types of cement have varying effects on the performance of LSS. Ordinary Portland cement provides good strength and permeability resistance, while slag cement excels in durability and corrosion resistance. In practical applications, choosing the appropriate type of cement based on engineering requirements and environmental conditions can optimize LSS performance.
2. Cement Dosage: The amount of cement directly influences the strength and consolidation properties of LSS. Increasing cement dosage can enhance compressive strength and toughness, but excessive cement may raise costs and reduce elasticity and crack resistance. Therefore, designing the cement dosage scientifically and reasonably, considering the base material and engineering demands, is essential.
3. Cement-to-Water Ratio: The cement-to-water ratio plays a critical role in determining LSS performance. Excessive water content can increase soil fluidity, compromising consolidation, while insufficient water may prevent complete hydration of the cement, reducing strength. Controlling the cement-to-water ratio during LSS preparation is thus key to achieving optimal soil properties.
4. Interaction Between Cement and Base Material: The interaction between cement and the base material promotes consolidation, forming a stable soil structure. Cement particles undergo hydration in the presence of water, producing binding agents like calcium hydroxide that fill the gaps between base material particles, enhancing overall soil stability. Adjusting the cement-to-base material ratio can further improve the mechanical properties of LSS.

In this study, Geoset 200 provided by Taiheiyo Cement Co. was used as cement stabilizer, which was a cement-based solidifying agent for soft clay and problematic soil.

Lime

Lime is the oldest traditional stabilizer used for soil stabilization. Lime-treated soil was studied extensively in the literature. Numerous field and laboratory studies were conducted to evaluate the improvement of geotechnical properties by lime. Several types of soils, lime contents and curing conditions and methodologies were used for this purpose. The mechanism of treatment comprised hydration, cation exchange, flocculation-sag glomeration of soil particles and pozzolanic reaction to form Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) as cementitious materials. The factors affecting lime treated soil are lime content, curing time, curing temperature and soil mineralogy. Soil-lime mixtures have advantages and disadvantages. Its advantages comprise significantly increase soil strength, reduce plasticity (increase workability) and increases soil durability. In addition, a considerable reduction in consolidation settlement and improve compressibility characteristics were observed. Unclear behavior was noted for the permeability of soil lime mixture when compared with the original soil. Carbonation, sulfate attack and environment impact are a number of the disadvantages of lime-treated soil. Some studies were conducted to provide some guidelines to reduce the deleterious effects of these cons. Magnesium oxide and hydroxide can be proposed as alternative for lime since they possess chemical characteristics make them eligible to overcome the mentioned cons. Moreover, the result of few conducted studies used magnesium-based additives to stabilize the soil was significant improvement achieved in soil strength, workability and durability. Therefore, it is needed to conduct extensive studies to determine the efficiency of this material in soil stabilization.

Fly ash

Fly ash has been used successfully in many projects to improve the strength characteristics of soils. Fly ash can be used to stabilize bases or subgrades, to stabilize backfill to reduce lateral earth pressures and to stabilize embankments to improve slope stability. Typical stabilized soil depths are 15 to 46 centimeters. The primary reason fly ash is used in soil stabilization applications is to improve the compressive and shearing strength of soils. The compressive strength of fly ash treated soils is dependent on:

- To enhance strength properties
- Stabilize embankments
- To control shrink swell properties of expansive soils
- Drying agent to reduce soil moisture contents to permit compaction

Class C fly ash can be used as a stand-alone material because of its self-cementitious properties. Class F fly ash can be used in soil stabilization applications with the addition of a cementitious agent (lime, lime kiln dust, CKD, and cement). The self-cementitious behavior of fly ashes is determined by ASTM D 5239. This test provides a standard method for determining the compressive strength of cubes made with fly ash and water (water/fly ash weight ratio is 0.35), tested at seven days with standard moist curing.

The self-cementitious characteristics are ranked as shown below:

- Very self-cementing > 500 psi (3,400 kPa)
- Moderately self-cementing 100 - 500 psi (700 - 3,400 kPa)
- No self-cementing < 100 psi (700 kPa)

It should be noted that the results obtained from ASTM D 5239 only characterizes the cementitious characteristics of the fly ash-water blends and does not alone provide a basis to evaluate the potential interactions between the fly ash and soil or aggregate.

The use of fly ash in soil stabilization and soil modification may be subject to local environmental requirements pertaining to leaching and potential interaction with ground water and adjacent water courses.

Soil Stabilization to Improve Soil Strength

Fly ash has been used successfully in many projects to improve the strength characteristics of soils. Fly ash can be used to stabilize bases or subgrades, to stabilize backfill to reduce lateral earth pressures and to stabilize embankments to improve slope stability. Typical stabilized soil depths are 15 to 46 centimeters (6 to 18 inches). The primary reason fly ash is used in soil stabilization applications is to improve the compressive and shearing strength of soils. The compressive strength of fly ash treated soils is dependent on:

- In-place soil properties
- Delay time
- Moisture content at time of compaction
- Fly ash addition ratio

2.2.3. Fiber Material

The addition of fiber materials significantly enhances the mechanical properties and durability of Liquefied Stabilized Soil (LSS). Commonly used fibers include polypropylene fibers, glass fibers, and natural fibers. These fibers primarily improve LSS's crack resistance and toughness, reducing the likelihood of fractures. Additionally, they help improve the soil structure and increase its impermeability.

Polypropylene Fibers: Polypropylene fibers are widely used synthetic fibers in LSS, known for their excellent crack resistance and toughness. By dispersing within the LSS, polypropylene fibers effectively increase the soil's tensile strength and resistance to cracking, thereby reducing the formation of fractures. Studies show that adding an appropriate amount of polypropylene fibers can significantly improve the long-term performance of LSS.

Glass Fibers: Glass fibers, due to their high strength and modulus, are commonly employed to reinforce LSS. Their inclusion enhances both tensile and bending properties and improves durability by reducing moisture erosion of the soil. Thus, glass fibers show promising potential in enhancing LSS applications.

Organic Fibers: Organic fibers such as straw and wood fibers are also used to modify LSS. These fibers possess good biocompatibility and ecological characteristics, improving soil performance while minimizing environmental impact. Natural fibers contribute to enhanced crack resistance and soil toughness in LSS.

Fiber Dosage and Distribution: The amount and distribution of fiber materials are crucial to LSS performance. An optimal fiber dosage can effectively enhance soil toughness and crack resistance, but excessive fibers may clog the soil structure, reducing its strength. Therefore, a well-designed fiber dosage and even distribution are key factors for the successful modification of LSS.

As shown in Figure 2-2, waste newspapers were chosen as the fiber material. This newspaper was pulverized through a food processor to create a fibered material resembling cotton wadding. Fiber length is between 0.5 and 3 mm.

Figure 2-2 Fiber material made by pulverized newspaper

2.3. Historical Development

2.3.1. Historical Background

Engineering Challenges of Soft Soil

Soft soil is widespread in coastal, river valley, and lake regions worldwide, particularly in some Asian countries like Vietnam, China, and Japan. Soft soil foundations are common in construction, posing notable engineering issues such as high water content, compressibility, low bearing capacity, and low shear strength. These characteristics present potential risks in building foundations, especially in urban infrastructure, road construction, and high-rise building projects.

1. High Compressibility and Settlement Issues

   One of the most significant engineering drawbacks of soft soil is its high compressibility. When a structure is built, the soil compresses under the building's load, causing foundation settlement. Due to its high water content and large void ratio, soft soil is prone to significant compression and volume changes under external forces. This compressive behavior can lead to uneven settlement, causing structural deformation, cracking, and even local instability, posing serious safety risks in large-scale projects.

2. Foundation Instability Due to Low Bearing Capacity

   The low bearing capacity of soft soil limits its viability as a foundation material. Buildings on soft soil foundations may exert weight beyond the soil's capacity, leading to shear failure or excessive settlement. Without appropriate treatment, soft soil foundations struggle to meet the safety and stability demands of modern construction, a challenge especially critical for high-rise buildings and infrastructure like subways, airports, and roads.

3. Sliding and Collapse Risk Due to Low Shear Strength

   The low shear strength of soft soil increases the risk of lateral deformation and sliding failure under external loads, especially on sloped terrains. This weakness not only affects foundation stability but also threatens the long-term safety of structures like embankments, retaining walls, underground pipelines, and tunnels.

4. Swelling and Softening Effects with Increased Moisture

   Soft soil tends to soften with increased moisture, further reducing its strength. In coastal areas or regions with frequent seasonal rainfall, soft soil absorbs water, causing a rapid decline in soil strength. Over time, groundwater rise or rainwater infiltration may exacerbate this issue, ultimately compromising foundation bearing capacity and stability.

Demand for Soft Soil Improvement

To effectively address the engineering challenges of soft soil, soil improvement techniques are essential. The primary goals are to increase the bearing capacity, shear strength, and compressive resistance of soft soil, reduce foundation settlement and deformation, and ensure long-term stability and safety under building loads. Common soft soil improvement methods include:

1. Cement Stabilization

   Cement stabilization involves mixing cement with soft soil to create a consolidated body through hydration reactions, thereby enhancing soil strength and stability. This method, by adding an appropriate amount of cement to the soil, forms bonding between soil particles, significantly improving shear strength and bearing capacity and reducing settlement issues. Cement stabilization is widely applied in foundation treatment, foundation reinforcement, and road engineering.

2. Vacuum and Load Precompression Methods

   Vacuum precompression applies negative pressure on the foundation to expel pore water, reducing soil water content and increasing density and strength. Load precompression involves adding heavy loads on top of soft soil to simulate future building loads, causing anticipated settlement before construction. Both methods effectively lower the compressibility and settlement rate of soft soil, particularly useful for large-area soft soil foundation treatment.

3. Dynamic Compaction and Deep Compaction Techniques

   Dynamic compaction and deep compaction apply intense external impacts to compress soil voids, enhancing soil density and shear strength. These methods are suitable for shallow soft soil treatment or projects requiring rapid soil strength improvement, especially in infrastructure like roads and airport runways.

4. Addition of Fiber Materials

   Research on adding fiber materials to improve soft soil performance has gained widespread attention in recent years. Fiber materials (e.g., waste paper fibers, plastic fibers) improve soil tensile and shear strength and reduce brittle failure risks. Fibers form a network structure by intertwining, increasing soil cohesion and deformation capability. This method is especially suited for treating backfill materials and soft soil foundations with high stability requirements.

Future Prospects of Improvement Technologies

In soft soil foundation engineering, environmentally friendly and low-carbon soil improvement technologies are emerging as a trend, reflecting growing awareness of environmental protection. For instance, the use of excavated construction soil combined with cement-based solidification materials and fiber materials can effectively enhance soft soil mechanical properties while reducing reliance on natural resources.

In Japan, LSS technology has been widely applied in soft soil foundation reinforcement and seismic resistance. Combined with fiber materials, this technology shows promising applications in improving foundation bearing capacity, reducing settlement, and enhancing seismic performance. Despite significant progress in soil improvement, further research is needed on the consolidation and permeability characteristics of soft soil to optimize the material mix design for different engineering requirements. Continued research and technological innovation will play a critical role in urban infrastructure development, providing more reliable foundation treatment solutions for sustainable development.

2.3.2. Historical Development

Before the 1980s, traditional soil improvement methods like drainage, compaction, and reinforcement were primarily used to address the engineering issues of soft and muddy soils. While these methods increased soil bearing capacity to some extent, they were limited in mitigating liquefaction risks and soil deformation.

In the 1990s, the concept of Liquefied Stabilized Soil (LSS) began to take shape and gain recognition. Scientists discovered through experiments and theoretical studies that mixing cement and other binding materials with soil could significantly improve soil's physical and mechanical properties. Particularly in liquefied soil improvement, the application of LSS offered new insights for addressing this challenge.

During the 1990s, researchers at home and abroad began foundational studies on LSS, exploring the relationship between its composition, mixture ratios, and performance. Many studies demonstrated that an optimal amount of cement and careful selection of base materials could effectively increase the compressive strength, impermeability, and stability of LSS.

The original concept comes from the United States, soil mixing was first developed by Intrusion-Prepakt, Inc. of Cleveland Ohio (Liver et al. 1954) as “Intrusion Grout Mixed-in-Place Piles”.

In 1961, the mixed in place already used under license for more than 300 000 lineal meters of piles in Japan for excavated support and groundwater control. Continued until early 1970’s by Seiko Kogyo Company, to be suggested by diaphragm walls and deep mixing method (Soil-Mix Wall). In addition, Herrin and Mitchen (1961) suggested that there is no one of optimum lime content with which maximum strength of lime stabilized soils can be expected under all conditions. That is, for a specific condition of curing tine and soil type an optimum lime content which caused a maximum strength exists.

The development and research on deep mixing started from laboratory model tests in 1967 by the Port and Harbour Research Institute of Japanese Ministry of Transportation. Research was continued by Okumura, Terashi et al. through 1970’s including 1- investigation of lime-marine reaction, and 2- developing appropriate mixing equipment. Unconfined compressive strength (UCS) of 0.1 to 1 MPa achieved. Early equipment (Mark I-IV) used the first marine trial near Hamada Airport (10 m below water surface). In addition, Swedish Lime column method for treating soft clays under embankment using unslaked lime was researched (Kjeld Paus, Linden- Alimak AB, in cooperation with Swedish Geotechnical Institute, Euroc AB, and BPA Byggproduction AB). And then, this follows observations by Paus on fluid lime column installation in the United State.

In the late 1960’s, China reported to be considering implementing Depp lime mixing concept form Japan.

Development of Soil Mixed wall method for retaining walls, using overlap multiple augers was started in Japan by Seiko Kogyo Co. of Osaka in 1972 to improve lateral treatment continuity and homogeneity/quality of treated soil.

The first Japanese full-scale Deep Mixing project was conducted in 1974. First applications in reclaimed soft clay at Chiba (June) with and Applications elsewhere in Southeast Asia follow the same year. In addition, intensive trials conducted with Lime Columns at Ska Edeby Airport, Sweden: basic tests and assessment of drainage action (columns 15 m long and 0.5 m in diameter). In 1974, first detailed description of Lime Column method by Arrason et al. (Linden Alimaik AB). And the first similar trial embankment using Swedish Lime Column method in soft clay in Finland (6 m high, 8 m long; using 500-mm-diameter lime cement columns, in soft clay) in 1974.

In 1975, deep mixing’s first appearance in an international forum in Bangalore, India, a Swedish paper on Lime Colum by Broms and Boman. In addition, a Japanese paper on Deep Lime Mixing (DLM) by Okumura and Terashi were presented to the Swedish paper on lime columns (Broms and Boman), and Japanese paper on DLM (Okumura and Terashi) presented at same conference in Bangalore, India. Both countries had proceeded independently to this point. Limited technical exchanges occur thereafter. Following their research from 1973 to 1974, PHRI develops the forerunner of the Cement Deep Mixing (CDM) method using fluid cement grout and employing it for the first time in large-scale projects in soft marine soils offshore. (Originally similar methods include DCM, CMC (still in use from 1974), closely followed by DCCM, DECOM, DEMIC, etc., over the next five years). In addition, First commercial use of Lime Column method in Sweden for support of excavation, embankment stabilization, and shallow foundations near Stockholm (by Linden Alimak AB, as contractor and SGI as consultant/researcher) in 1975.

Public Works Institute Ministry of Construction, Japan, in conjunction with Japanese Construction Machine Research Institute began research on the Dry Jet Mixing (DJM) method using dry powdered cement (or less commonly, quick-lime) in 1976. It was also the same year that Soil Mixed Wall (SMW) method used commercially for first time in Japan by Seiko Kogyo Co.

In 1977, Cement Deep Mixing (CDM) method had been marked development. CMD method Association established in Japan to coordinate technological development via a collaboration of industrial and research institutes and the first practical use of CMD (marine and land uses). First design handbook on lime columns (Broms and Boman) published by Swedish Geotechnical Institute. China commences research into CDM, with first field application in Shanghai using its own land-based equipment in 1978.

The first commercial using in Japan of Dry Jet Mixing was marked in 1980, and then it quickly superseded Deep Lime Mixing (DLM) with land-use only. In addition, DJM Association established in Japan. After that, in 1983, Eggestad publishes state-of the-art report in Helsinki dealing with new stabilizing agents for the Lime Column method.

In 1984, SWING method developed in Japan, followed by various related jet assisted (W-R-J) methods in 1986, 1988, and 1991. The Tenox Company reported more than 1000 projects completed with SCC method in Japan (1989), prior to major growth thereafter (9000 projects to end of 1997, with a $100 to 200 million/year revenue in Japan and elsewhere in Southeast Asia). And then, in 1990, Dr. Terashi, involved in development of DLM, CDM, and DJM since 1970 at Port and Harbor Research Institute, Japan, gives November lectures in Finland. Introduces more than 30 binders commercially available in Japan, some of which contain slag and gypsum as well as cement. Possibly leads to development of “secret reagents” in Nordic Countries thereafter.

Low Displacement Jet Column Method (LDis) developed in Japan in 1991. In the same year, Bulgarian Academy of Sciences reports results of local soil-cement research and Geotechnical Department of City of Helsinki, Finland, and contractor YIT introduce block stabilization of very soft clays to depths of 5 m using a variety of different binders.

In early 1990s, first marine application of CDM at Tiajin Port, China: designed by Japanese consultants (OCDI) and constructed by Japanese contractor with his own equipment (Takenaka Doboku).

In 1991, Chinese Government (First Navigational Engineering Bureau of Ministry of Communications) builds first offshore CDM equipment “fleet”, using Japanese technology used for first time (1993) at Yantai Port. (Reportedly the first wholly Chinese Design-Build DMM project.). And Jet and Churning System Management (JACSMAN) developed by Fudo Company and Chemical Grout Company in Japan.

DJM Association Research Institute publishes updated Design and Construction Manuals (in Japanese) in 1993. In the same year, CDM Association claims 23.6 million m3 of soil treated since 1977. And SMW claims 4000 projects completed worldwide since 1976, comprising 12.5 million m2 (7 million m3). According to report in Japan, from 1977 to 1995, more than 26 million m3 of CDM treatment reported and about 15 million m3 of DJM treatment.In 1997, SMW method used for massive ground treatment project at Fort Point Channel, Boston, MA (largest DMM project to date in North America), and other adjacent projects. Input at design stage to U.S. consultants by Dr. Terashi (Japan).

From 1998 to around the year 2000, a variety of numerical modeling work has been performed on the interaction of soil cement columns in soft clays, for example Kerin and Karstunen (2009), Chai et al. (2010) and Abushara et al.

(2009. There studies have focused on settlement reduction from “T” shaped columns, “cross” shaped columns and “multi columns” supported embankment loading.

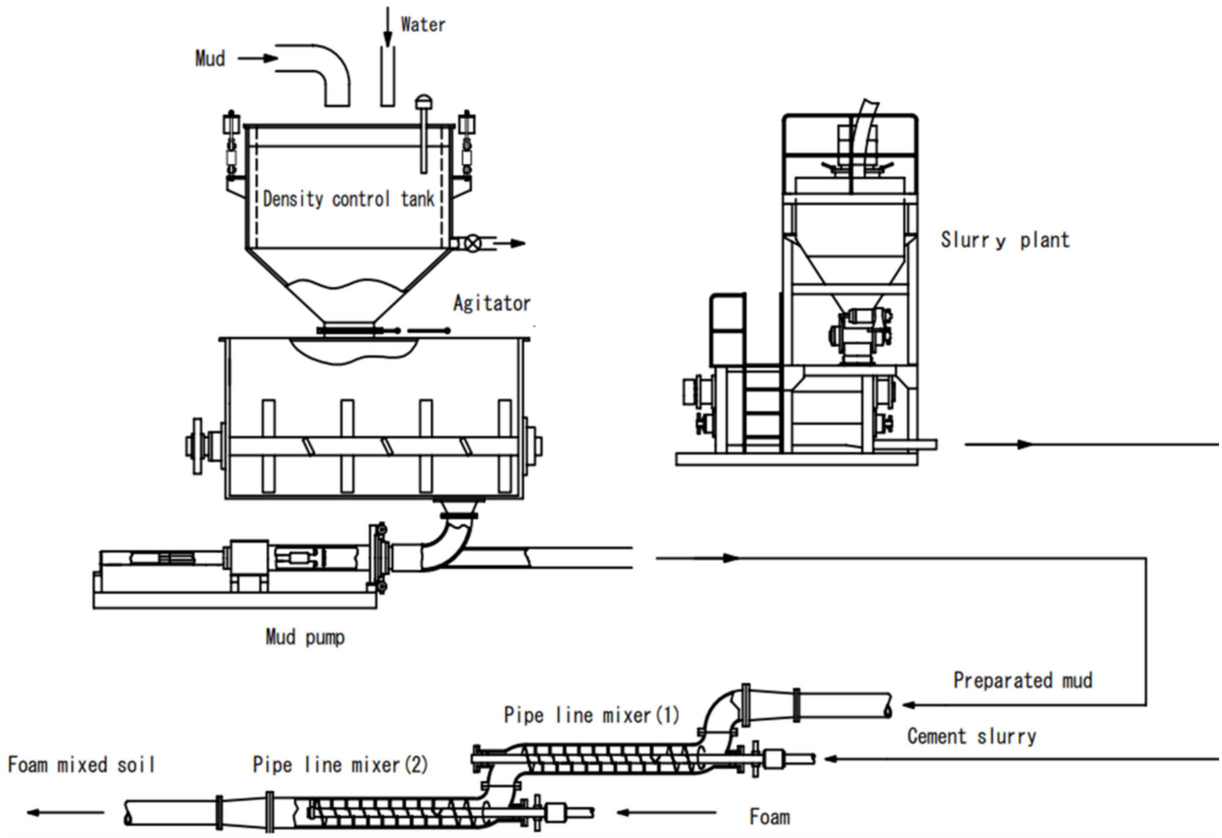

Figure 2-3 Production system for foam mixed lightweight soil

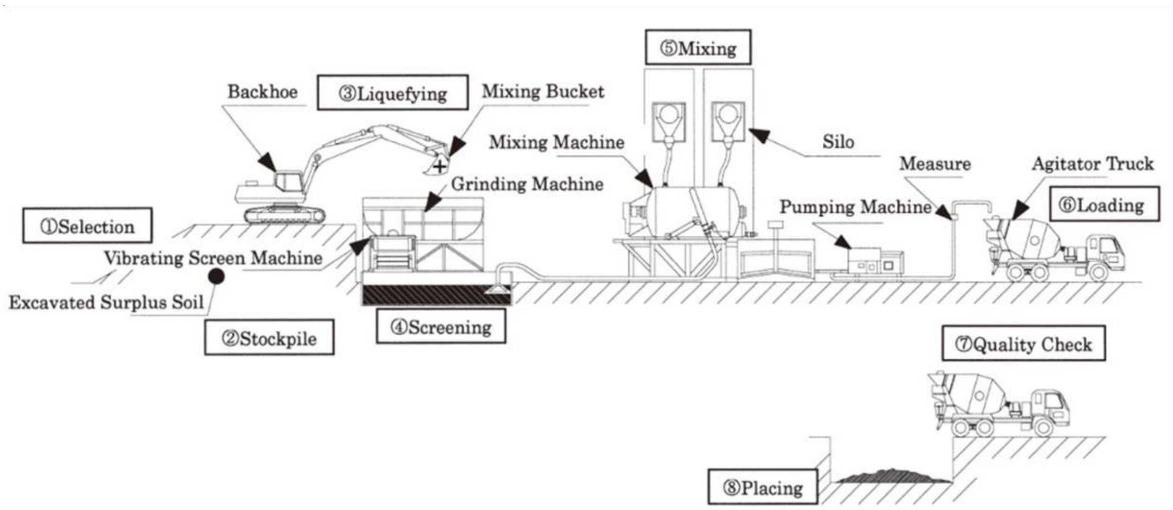

Figure 2-4 Flow of Liquefied soil stabilized method (Tomoharu et al., 2005)

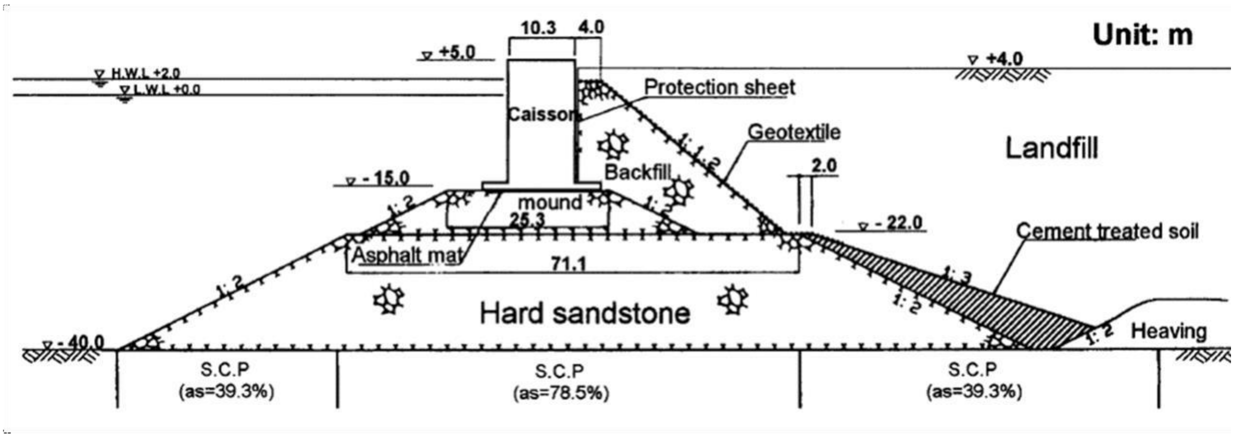

Figure 2-5 Cement treated soil using as slope protection (Tang et al., 2001)

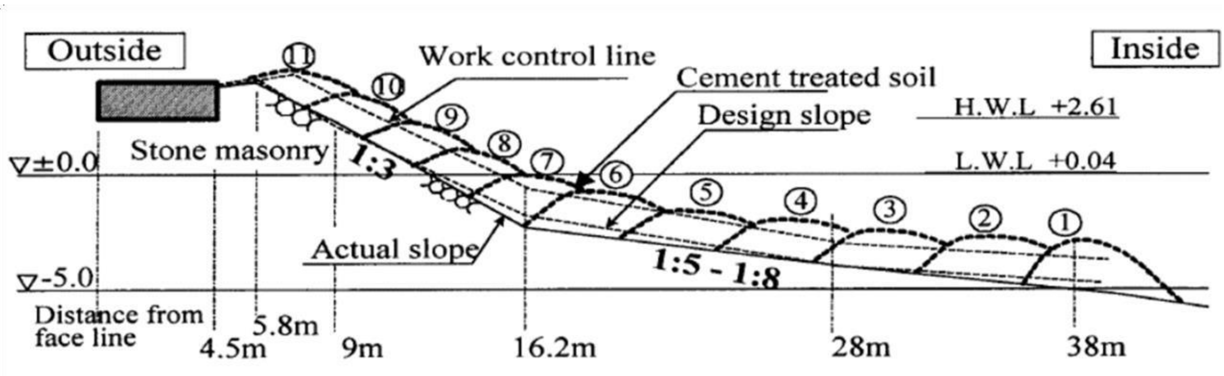

Figure 2-6 Placement of cement treated soil along slope (Tang et al., 2001)

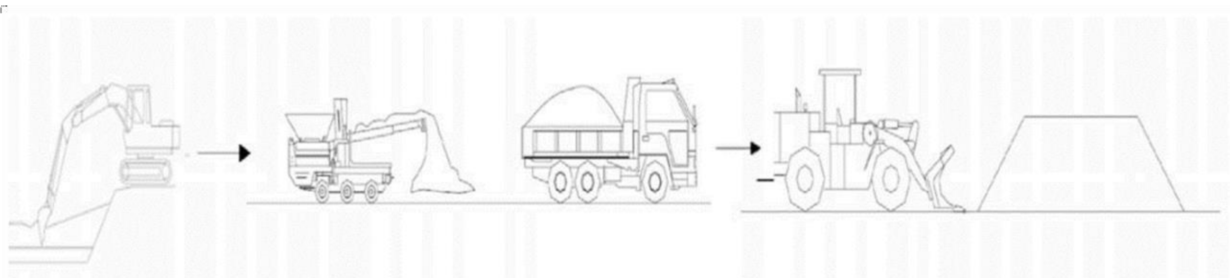

Figure 2-7 Placement of cement treated soil along slope (Tang et al., 2001)

2.4. Application of LSS

As a novel engineering material, liquefied stabilized soil (LSS) is widely used in civil engineering, environmental engineering, and related fields due to its excellent mechanical properties and adaptability.

In 1997, Kuno et al. presented one of several applications of LSS method: filling a cavity under pavement of urban road (Figure 2.8). The cavity is inferred mainly in the way that the submerged backfilled sand in the ground is washed out little by little to a nearby open space, for example sewage pipes, and thus, a cavity is created and grown.

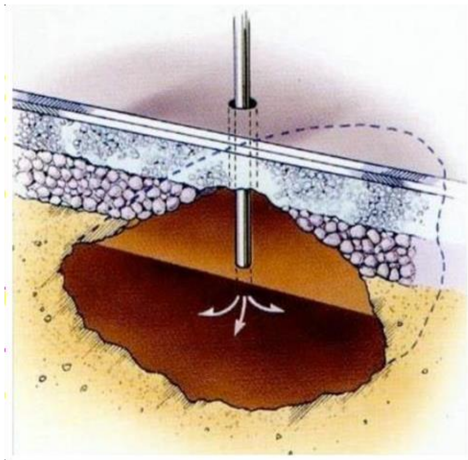

Figure 2-8 Use of LSS for filling cavity under road surface

This application is thought to be possible of decreasing time and cost comparing to a conventional method. Thus, two kinds of filed performance tests were conducted in order to verify capability and applicability of the method and acquire necessary field data for future maintenance works. The first field performance test used an on-site plant and a stabilized soil of low strength and relatively high flow condition while the second test use remote plant and stabilized soils of high strength and low flow condition. The tests were evaluated in term of adequate mix proportion, working system, working time, filling outcome, occupation of road, result of quality control test, and so on. Through two sequential field performance tests, it is confirmed that the method possesses good capability of filling cavities under the pavement and make it possible to decrease time and cost.

Murata (2011) reported that LSS consists of slurry made of on-site soil, water, cement and sand of clay as appropriate LSS is used for backfill at upper part of a cut and cover tunnel and as an invert material of a shield tunnel (Figure 2.9). Pit sand is usually used for backfilling, but LSS is much better than the sand, because it is easy to use with on-site soil and LSS can be buried without compaction into a narrow space.

The lower part of shield tunnel is usually buried by low-strength concrete (unconfined compressive strength: about 10 MN/m2). From the environmental point of view, however, LSS, which can reuse on-site soil, is now often use. Mixture of LSS was designed from the results of unconfined compressive tests and repeated loading tests. Then, it was designed the unconfined compressive strength of liquefied soil should be 6 MN/m^2 for safety purpose. To hold this strength level for some on-site soil, a very large amount of cement is needed (300 ~ 400 kg/m3 of LSS). So, a method to mix wasted fiber materials into LSS has been studied in order to increase the strength and ductility and decrease the total material cost. Studied have been promoted on what types of wasted fiber material are available and what rigidity level of wasted fiber material is needed.

The design of strength and quality control method of LSS used as building foundation is proposed by Onishi et al. (2005). The results of the research pointed out that it is feasible for LSS to apply for the building foundation in future perspective. Another application of LSS is for constructing fences or retaining walls. Yoshihiro et al. (2006) reported that concrete block construction, which is common for these structures, tens to collapse under strong earthquakes, thus causing a threat to traffic, whereas liquefied stabilized soil block construction is capable of avoiding such damage due to the greater toughness of the material. Also, soil blocks are advantageous over concrete blocks in term of appearance. In their research, they have examined the effects of adding PVA fiber to LSS blocks under atmospheric condition. Tests were carried out on the drying shrinkage properties, resistance to atmospheric exposure, and uniaxial compressive strength. It found that PVA fiber reduces the drying shrinkage, crack propagation, and compressive strength of LSS block.

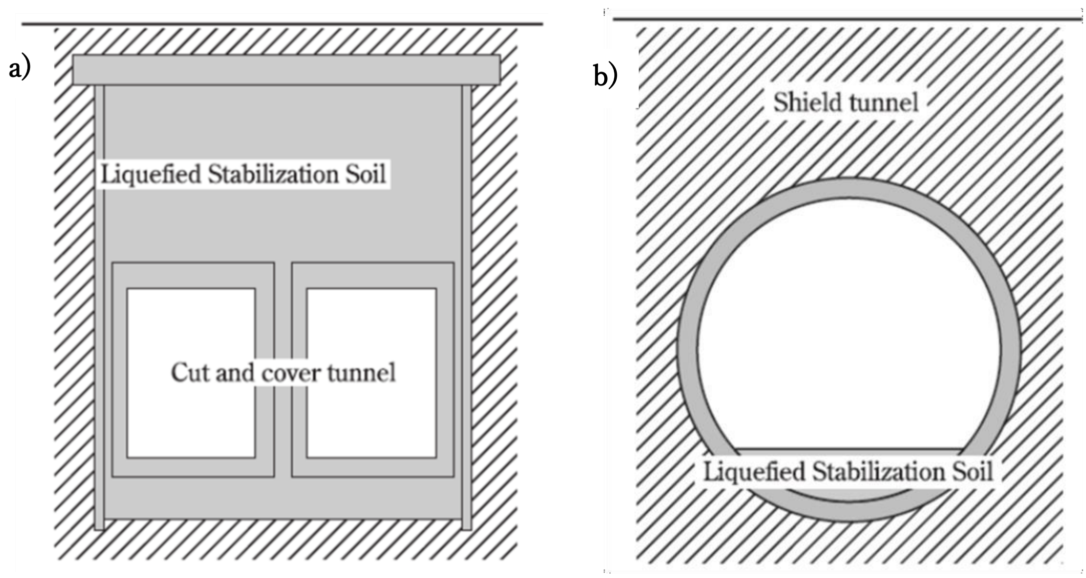

Figure 2-9 a) LSS used for backfill at upper part of cut and cover tunnel; b) LSS used for invert material of shield tunnel

Recently, most underground pipelines have been backfilled by LSS. Figure 2-9 shows a construction site of the pipelines using LSS. Kawabata et al. (2008) conducted full scale field test for buried pipe using steel pipe of 3500 mm-diameter and 26 mm-thickness. Five cases of backfilling methods were applied. From the test results, it was found that the behavior of buried pipe was strongly influenced by the stiffness of backfilling method. In particular, the pipe which is backfilled with LSS showed stable behavior. Moreover, Kashiwaghi et al. (2009) and Kawabata et al. (2010) have proposed a method for thrust restraint using LSS. Mode l pit experiments using a model pipe having a diameter of 260 mm were carried out in order to examine the effectiveness of the LSS for the thrust restraint of buried bend. LSS was applied to the passive area of the model pipe and dry silica sand was used as backfill material. The model pipe was laterally loaded at a speed of 1 mm/min after backfilling to simulate the thrust force.

The lateral resistance and horizontal displacement of the model pipe were both measured. The earth pressure distributions of the passive ground were observed. The results showed that the lateral resistance of the bend in using LSS was increased. It is verified that LSS is an effective backfill material for thrust restraint. Also, other experimental research results showed that the bending stiffness in case using LSS with geosynthetics was increased Kawabata et al. (2009). In addition, the passive resistance was considerably increased in case using LSS with geogrid Kawabata et al. (2008). The following Figure 2-10 is more examples of using LSS for various backfilling works in Japan.

In 2006, Kohata has proposed a reinforcement method for LSS by mixing crushed newspaper as a fibered material into LSS and carried out a series of unconfined compression tests and triaxial tests. The results indicated that by reinforcement effect, brittle property of LSS mixed with fibered material after the peak was improved.

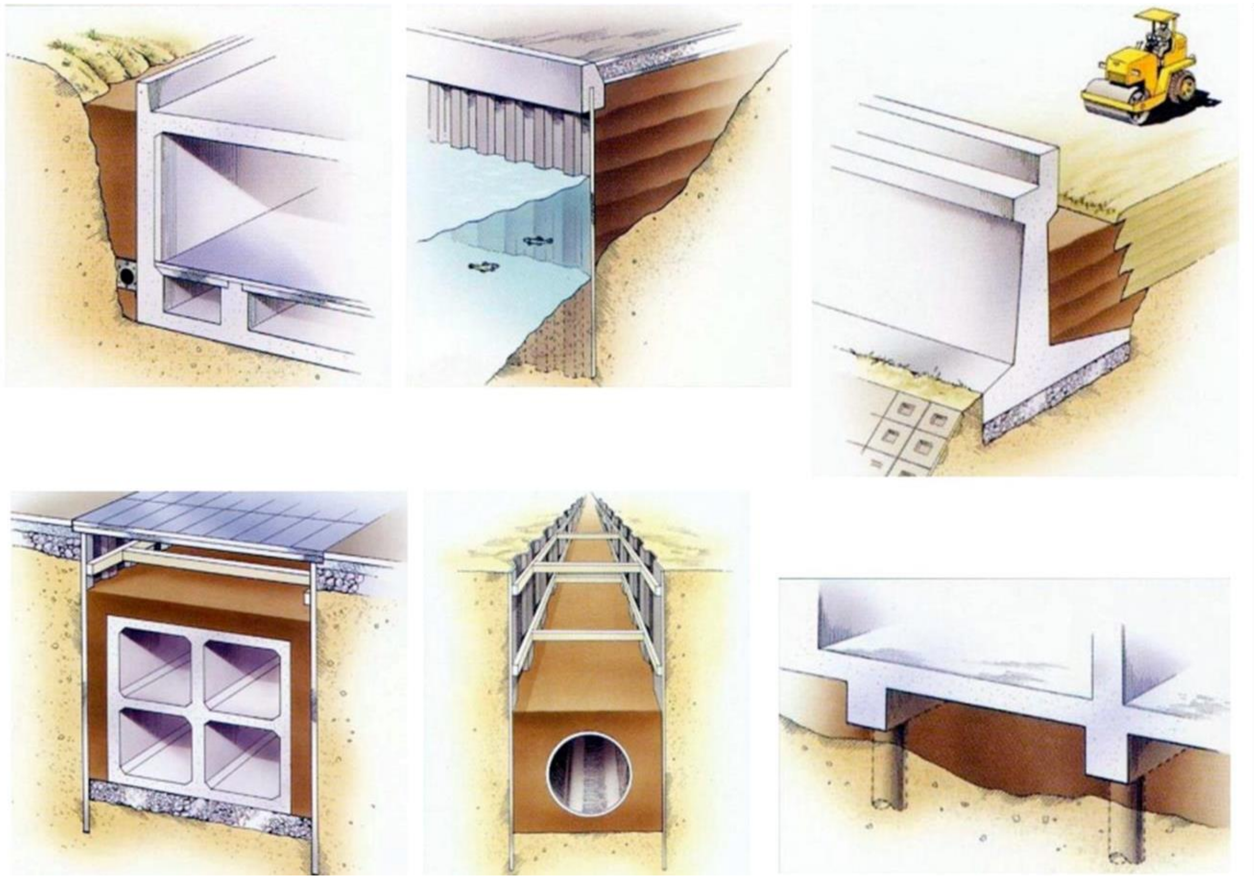

Figure 2-10 Using LSS for various backfilling works in Japan

2.4.1. Infrastructure Construction

In infrastructure construction, liquefied stabilized soil (LSS) is widely used for foundation reinforcement and soil stabilization. Particularly in soft soil and liquefaction-prone areas, the bearing capacity of traditional soils is insufficient to meet engineering design requirements. By adding cement and other binding materials, LSS improves the compressive strength and stability of the soil. For example, in large infrastructure projects such as bridges, roads, and subways, LSS can effectively enhance the bearing capacity of foundations, preventing ground settlement and uneven subsidence.

In several engineering cases, LSS has been utilized for large-scale foundation construction, especially on soft soil foundations. The use of liquefied stabilized soil allows for rapid foundation reinforcement, increasing construction efficiency and reducing costs.

2.4.2. Dams and Hydraulic Engineering

LSS also plays a significant role in dams and hydraulic engineering. Since hydraulic projects are often located in moist or saturated soil layers, they are prone to liquefaction and settlement, posing safety hazards. Therefore, employing LSS for the reinforcement and stabilization of dams is one of the important measures to ensure the safety of hydraulic projects.

For instance, liquefied stabilized soil can be used as fill material for dams, enhancing their overall stability and impermeability while reducing the impact of water level fluctuations on dam safety. Additionally, the excellent impermeability of LSS effectively minimizes leakage from reservoirs and lakes, ensuring the rational use of water resources.

2.4.3. Environmental Remediation

The application of liquefied stabilized soil in environmental engineering is also increasing, particularly in soil remediation and pollution control. Due to its good impermeability and bearing capacity, LSS can be used in the construction and maintenance of landfills, enhancing landfill stability and preventing environmental pollution caused by leachate.

Moreover, LSS can improve the properties of contaminated soil by incorporating cement and other modifying materials to create a stable soil structure, reducing the migration of pollutants. At the same time, the application of LSS can decrease the demand for natural soil, achieving sustainable resource utilization.

2.4.4. Soft Soil Foundation Treatment

The application of liquefied stabilized soil (LSS) in the treatment of soft soil foundations is increasingly being recognized. Soft soil foundations are characterized by high moisture content and high compressibility, often leading to foundation settlement and uneven deformation. By using LSS for soil improvement, the bearing capacity and stability of the soil can be effectively enhanced, thereby reducing settlement risks.

In several engineering projects, LSS has been employed as a substitute for traditional foundation reinforcement methods, yielding positive results. For instance, in high-rise buildings and large-scale projects, using LSS for foundation treatment can significantly shorten construction periods and lower construction costs.

2.4.5. Transportation Engineering

In transportation engineering, liquefied stabilized soil serves as a material for subgrades and pavements, effectively improving the bearing capacity and durability of roads. Particularly in soft soil regions, the application of LSS enhances the settlement resistance and longevity of roadways, minimizing damage caused by soft soil settlement.

For example, in the construction of highways and railways, utilizing LSS as subgrade material can significantly improve the stability and service life of the pavement. Additionally, the construction process of liquefied stabilized soil is relatively straightforward, allowing for shorter construction cycles and improved economic efficiency.

2.4.6. Applications in Other Fields

Beyond the main application areas mentioned above, liquefied stabilized soil also demonstrates promising prospects in specific fields. For instance, in mining engineering, LSS can be used to reinforce mine slopes, preventing slope failures and collapses. In agricultural engineering, LSS can improve the compressive strength of soil, enhance soil structure, and promote crop growth.

With ongoing technological advancements, the application areas of liquefied stabilized soil are expected to expand further. Researchers are exploring the integration of new materials and technologies with LSS to enhance its performance and adaptability, catering to a broader range of engineering needs.

2.4.7. Summary

In summary, liquefied stabilized soil exhibits significant application potential across various fields, including infrastructure, dams, hydraulic engineering, environmental remediation, soft soil foundation treatment, and transportation engineering. Its superior physical and mechanical properties, along with its adaptability, make it an effective solution for addressing soft soil and liquefaction risks. In the future, as research deepens and technologies advance, the application fields of liquefied stabilized soil are expected to broaden further, contributing to the development of civil and environmental engineering.

2.5. Current Research of The Liquefied Stabilized Soil

Liquefied stabilized soil (LSS) refers to soil that has undergone changes to its physical properties through physical, chemical, or biological methods, enabling it to exhibit flowability and plasticity in engineering applications.

Liquefied Stabilized Soil materials can be divided into two types: traditional solidified materials and new solidified materials. Initially, the research object of traditional solidified materials was limited to cement and quicklime.

Yuji Maeno (1996) considered that the slag passed the compaction test, unconfined compression test, CBR value test, consolidation compression test under the conditions of different, single solidified materials (such as cement, quick lime) and their dosage. He Comparatively systematically analyzed and studied the reasons that influenced the unconfined compressive strength, optimal water content, CBR value, and change trend of the treated soil, which provided a basis for future research and engineering practice.

Researchers have developed different slag solidification materials for different soil qualities, such as Medina reinforced red clay with phosphoric acid. Tomohisa (1997) believes that the use of fine recycled powder, pulp slag, fly ash, and volcanic ash soil for high moisture content and high organic matter content Slag soil. Bobrowski (1997) developed an ionic curing agent to strengthen soft foundation soil. Zalihe (1998) used fly ash and lime to solidify expansive calcareous clay.

When scholars study the slag solidifying agent, the research objects and ideas are broader, including not only the research on the various additives of cement and lime, and the recycling of waste, but also the in-depth study of fungus reinforcement and insect reinforcement technology.

Shirazi (1998) believes that the mixture of lime and fly ash can avoid cracking caused by the shrinkage of cement soil. Bell (1999) added PFA (an additive) to cement and lime to strengthen the effect of clay reinforcement Research. Miller (2000) studied the performance of cement pit dust (CKD) reinforcement treatment of slag. Kohata (2001) had considered a method of adding crushed old newspapers as a fibrous material to add Liquefied Stabilized Soil Reinforcement methods. Robert (2001) studied a highly concentrated liquid slag solidification material (CLS). Saboundjian (2002) reported on the application of an organic slag solidification material (EMC2) in roadbed reinforcement. Attom (2002) It has been reported that burned olive waste can be used as a new material for the solidification of dregs. Thecan (2003) studied basidiomycetes in the decomposition of lignin by saprophytic organisms. He believed that it has an essential role in the solidification of dregs Function. Nene (2004) studied the method of natural termites using clay to solidify and build nests and proposed the concept of geotechnical entomology.

Now muck-solidified materials have been widely used in water conservancy projects, high-speed railways, highways, airport runways, the benefits are very obvious. It was named as one of the great inventions of the 20th century by the United States "engineering news." In Japan, it was also called the new materials of the 21st century.

In many countries, slag solidified specialized companies produce materials as a branded product, such as Parma curing enzymes, Soilrock, EN-1 slag solid materials produced in the United States. Roadbond Roadpacker was developed in Australia. Moreover, the UKC company in Japan Produced various brands of slag solidification materials.

Mechanism of solidified soil

The research on the solidification mechanism of treated soil is mainly carried out from theory and experiment, and its research methods are various. In the experiments, chemical analysis, scanning electron microscope (SEM), differential thermal analysis, or X-diffraction (XIM) methods are generally used to study the solidified matter generated in the solidified soil. The mechanism is to perform ion adsorption and exchange of the curing agent and the components of the slag. It is to reduce the surface electricity of the slag micelle and the thickness of the electric double layer of the slag micelle. It can make the slag particles tend to agglomerate. The chemical reaction generates new substances to strengthen the links between the muck particles. The volume expansion of the product improves and fills the pores between the muck particles. The distance between the muck particles is shortened under the action of external squeezing force, and the muck structure is compact, making the solidified soil easy to compact Become one, to obtain excellent macro mechanical properties.

Supabj Nontananalldhn (1996) used X-rays to irradiate the treated soil, studied the reasons that affected the strength change of the reinforced soil at different ages, and observed the changes in the microstructure and morphology of the reinforced soil through an electron microscope. From a micro perspective, they are more scientific and reasonable.

Linda Hills and Vagn C. Johansen (1996) proposed the formation model of the structure of solidified soil according to the actual solidification process of solidified soil. The structure of solidified soil is composed of the solidification agent hydrates fully surrounding the soil particles and filling the pores between the soil particles. Experiments and theoretical calculations with cement-solidified soil show that the amount of cementing agent corresponding to the cemented soil particles and the pore filling is quite consistent. The model reflects the relationship between the structure of the compacted soil filled with the cement-filled pores and the strength growth of the solidified soil.

Masashi Kaman (1996) studied the role of liquid curing agent in cement-based composite consolidated soil. He determined that the consolidation of cement-based composite consolidated soil is the interaction of curing agent, cement, and clay, which promote each other to form dense, stable, Higher strength structure. The chemical bonding of the hydration of the curing agent and the cementation of the cementing material can form the early strength of the solidified soil. In contrast, the performance of the solidified soil of the slag curing agent continues to improve for a long time. It depends on the interaction of the composite slag cement and the slag.

Mechanical properties of solidified soil

At present, the commonly used curing agents are cement and quicklime, which are evenly distributed in the sludge by manual or mechanical stirring. Therefore, the mechanical properties of the solidified soil of the sludge are similar to the cement soil. Many scholars have used the method of the indoor geotechnical experiment to study the characteristics and influencing factors of reinforced soil more systematically.

MA Khan, A. Usmani, SS Shah, and H. Abbas et al. (1996) conducted indoor geotechnical tests on solidified soil and found that the unconfined compressive strength increases with the increase of cement content. The dry density increases with the cement content Under the same conditions, the compressive strength of the mixed curing agent is increased by a maximum of 10 to 138 % compared with the non-mixed, and the dry density is increased by 0.01 to 0.07 g / cm3. Good anti-seepage performance. Coefficient of permeability can reach the order of 10-8 cm / s. The slow freezing method was used to conduct the anti-freeze test. After 50 freeze-thaw cycles, the strength loss was 13.5-21.07 %. For the slag soil, the curing effect is remarkable; first, the curing agent and the soil are mixed and placed, and then the cement or lime is added to obtain a better curing effect. First, after mixing the curing agent with the soil for a while, the optimal moisture content of the soil will decrease, and the soil will feel wet and viscous, and the cohesion of the soil will increase. At this time, adding cement or lime can obtain a higher degree of compaction and dry density.

Kohata (2000) conducted a series of unconfined and triaxial compression tests after it was discovered that crushed old newspapers were incorporated as fiber material. The results show that the peak value of the brittle characteristic curve of the slag is higher than that of the ordinary curing agent after the fiber material is mixed by this method.

2.5.1. Future Research Directions for LSS

Despite the good application results of liquefied stabilized soil in engineering practices, there are still challenges and future development directions in research.

Exploration of New Materials: Future research can continue to explore the application of new cement-based materials and fiber materials in LSS, especially the utilization of renewable materials to enhance LSS's performance and environmental friendliness.

Research on Composite Materials: The study of composite materials will emerge as a new direction in liquefied stabilized soil research. By combining LSS with other geotechnical materials, it is possible to further enhance its mechanical properties and adaptability.

Long-term Performance Monitoring: Long-term performance monitoring of LSS in engineering applications will also become an important research area in the future. Monitoring the LSS after construction can provide actual application data for further research.

Model Testing and Numerical Simulation: A combined approach using model testing and numerical simulation can provide a more comprehensive understanding of the mechanical behavior and engineering performance of LSS, improving the scientific basis for design and construction.

2.5.2. Summary

In summary, liquefied stabilized soil, as a novel engineering material, has achieved significant research outcomes and application effects in multiple fields. Studies on its composition, mechanical properties, application technologies, and future development directions provide a crucial foundation for a deeper understanding and application of liquefied stabilized soil. As scientific and technological advancements continue and application demands increase, the research and application prospects for liquefied stabilized soil will become even broader.

2.6. Research on Permeability of The Liquefied Stabilized Soil

Liquefied Stabilized Soil (LSS) in engineering applications not only needs to possess good mechanical properties but also must exhibit appropriate impermeability to meet the diverse requirements of civil and environmental engineering. Permeability is essential for evaluating the water flow characteristics of soil and is a key factor influencing the application of LSS in fields like hydraulic engineering, infrastructure, and environmental protection. In recent years, researchers have conducted extensive studies on the permeability of liquefied stabilized soil, focusing primarily on factors affecting permeability, testing methods, and improvement techniques. The following sections provide a multi-perspective review of the current research status on LSS permeability.

2.6.1. Factors Affecting Permeability

The permeability of liquefied stabilized soil is influenced by various factors, including substrate characteristics, the properties of cement-based materials, fiber additives, and environmental conditions.

Substrate Characteristics The characteristics of the substrate are among the primary factors influencing LSS permeability. Features such as particle size distribution, plasticity index, and water content of the substrate directly affect the permeability of LSS. For instance, substrates with larger particle sizes typically result in higher permeability, while smaller particle sizes may lead to lower permeability. Additionally, the plasticity index of the substrate has a significant impact on its ability to absorb and retain water. Thus, substrate selection must consider its effect on permeability to achieve the desired results in engineering applications.

Properties of Cement-Based Materials The type, amount, and proportion of cement-based materials also affect the permeability of LSS. Research shows that different types of cement exhibit varied hydration reactions and pore structures, which in turn impact soil permeability. Ordinary Portland cement and slag cement have different effects in LSS applications: the former may lead to higher permeability while enhancing strength, whereas the latter typically provides better impermeability. Increasing the amount of cement usually reduces permeability, but excessive cement content may also increase material brittleness, so a balance must be found for practical applications.

Effects of Fiber Materials The addition of fiber materials can significantly alter the permeability characteristics of LSS. Studies have found that fiber type, length, shape, and amount influence permeability. The addition of a suitable amount of fiber can improve the microstructure of the soil, forming a more stable network structure that effectively reduces permeability. However, excessive fiber addition may lead to an uneven pore structure in the soil, affecting permeability. Therefore, the use of fiber materials should be carefully designed according to engineering requirements.

Environmental Conditions Environmental factors, such as temperature, humidity, and atmospheric pressure, can also impact the permeability of LSS. Studies indicate that changes in environmental humidity lead to water migration within the soil, thereby influencing permeability. Under high humidity conditions, soil pores may be filled with moisture, reducing permeability, whereas low humidity conditions cause water evaporation, potentially increasing permeability. Consequently, when evaluating LSS permeability, the effects of environmental factors must be comprehensively considered.

2.6.2. Permeability Testing Methods

Various methods are used to test the permeability of liquefied stabilized soil, generally divided into laboratory and field tests.

Laboratory Tests In laboratories, researchers typically use permeability testing equipment (e.g., constant-head permeability apparatus, variable-head permeability apparatus) to test LSS permeability. Common permeability test methods include the constant-head method and the variable-head method. In the constant-head method, a stable water head is applied to the specimen, and the rate of water flow through the specimen is measured to calculate the coefficient of permeability; in the variable-head method, the water head is gradually increased, and the changes in water flow rate are observed to obtain the coefficient of permeability. These experimental methods provide foundational data for studying LSS permeability.

Field Tests In practical engineering, field permeability testing is an effective means of evaluating LSS permeability. Field tests typically include pumping tests, injection tests, and infiltration tests. Pumping tests measure groundwater level changes under certain pumping conditions to assess soil permeability, while injection tests inject water into the soil and observe water infiltration to evaluate permeability. These field testing methods provide reliable data for the practical application of liquefied stabilized soil.

2.6.3. Permeability Improvement Techniques

To enhance the permeability of liquefied stabilized soil, researchers have developed various improvement techniques aimed at adjusting the composition and structure of LSS to achieve better permeability performance.

Substrate Improvement Treating the substrate can effectively increase the permeability of LSS. For example, adding a suitable amount of organic or biological material can improve the pore structure of the substrate, thereby enhancing its permeability. Additionally, chemical improvement methods (such as adding modifiers) can alter the physical and chemical properties of the soil, leading to improved permeability.

Optimization of Cement-Based Materials Optimizing the type and proportion of cement-based materials is also an effective way to enhance permeability. Researchers can explore combinations of different cements and additives to optimize the permeability of LSS. For example, incorporating materials such as slag and fly ash can enhance impermeability while reducing permeability. Adjusting the water-to-cement ratio can also effectively reduce permeability while enhancing strength.

Adjustment of Fiber Materials Adding an appropriate amount of fiber material can effectively improve the permeability of LSS. Researchers have found that adjusting fiber length and amount can enhance the overall stability and permeability of LSS. Future research may further explore the potential of novel fiber materials (such as composite fibers) in improving permeability.

2.6.4. Engineering Applications of Permeability

The permeability of liquefied stabilized soil holds significant importance in practical engineering applications, especially in fields like hydraulic engineering, environmental protection, and civil engineering.

Hydraulic Engineering In hydraulic engineering, the permeability of LSS is crucial for the safety and stability of structures like dams and canals. Studies have shown that appropriate permeability can effectively reduce the impact of water level fluctuations on soil, lower the pressure of seepage water, and ensure structural stability.

Environmental Management The permeability of liquefied stabilized soil is increasingly valued in environmental management. Controlling soil permeability in soil remediation and pollution control can effectively reduce the migration of pollutants and achieve effective treatment outcomes. Researchers are optimizing LSS permeability to enhance its application potential in environmental protection.

Infrastructure Construction In infrastructure construction, the permeability of LSS aids in improving soil moisture conditions and reducing variations in subgrade soil humidity, thereby enhancing the safety and stability of foundations. Appropriate permeability helps prevent subgrade soil liquefaction and improves soil compressive strength.

2.6.5. Summary

In summary, research on the permeability of liquefied stabilized soil has received extensive attention in various fields, covering factors influencing permeability, testing methods, improvement techniques, and engineering applications. By deeply understanding the permeability characteristics of LSS, theoretical and practical guidance can be provided for its effective application in civil and environmental engineering. Future research can continue to explore new materials and techniques to further enhance the permeability and application performance of liquefied stabilized soil.

CHAPTER 3

MATERIALS AND PREPARATION METHOD OF SPECIMEN

3. Materials and Preparation Method of Specimen

3.1. Introduction

In China and Vietnam, rapid urban development has led to large-scale excavation of soil on construction sites, presenting significant disposal challenges. Traditionally, excavated soil has been compacted with sand sourced from mountainous or river valley areas for backfilling. However, due to the current volume of excavated soil, urban disposal sites have become severely overloaded. To address this issue, the recycling and reuse of excavated soil have emerged as a sustainable solution that promotes environmental protection and aligns with broader sustainable development goals.

As a type of cement-treated soil, Liquefied Stabilized Soil (LSS) exhibits properties similar to cement-stabilized materials, where increasing cement content leads to greater strength but also increased brittleness, which can reduce seismic resistance. Kohata et al. (2002, 2004, and 2007) proposed a method to mitigate this brittleness by reinforcing LSS with fiber materials from crushed waste newspaper. They conducted unconfined and triaxial compression tests, demonstrating improved ductility after the peak strength.

To address the challenges of topsoil reuse, there is ongoing exploration of LSS prepared at lower slurry densities as a substitute for conventional high-density formulations. However, research on the consolidation and permeability behavior of low-density LSS remains limited, particularly regarding its permeability characteristics and fiber reinforcement effects.

To investigate the effects of slurry density, curing time, and fiber content on the consolidation and permeability characteristics of liquefied stabilized soil (LSS), this study prepared specimens under varying conditions of slurry density, curing time, and fiber content. The impact of these factors on LSS structure and engineering performance was analyzed. As an improved soil material, LSS is commonly used in soft soil treatment and foundation engineering, offering advantages such as enhanced stability and reduced permeability.

To ensure homogeneity and standardize the experimental process, we carefully selected and prepared the base materials, cement-based stabilizers, and fiber additives. LSS specimens were produced through specific mixing and preparation methods for use in one-dimensional consolidation performance testing. By strictly controlling the specimen preparation and testing process, this study aims to obtain experimental data with significant reference value.

3.2. Test Material

In this study, we selected the following three primary materials:

Base Material: New Snow Fine Clay (NSF-Clay), a commercially available cohesive soil, was chosen as the base material, which is a fine-grained clay known for its good plasticity. NSF-Clay exhibits a uniform particle gradation and pore distribution, making it easy to mix with cement-based solidifiers and fibrous materials. Its basic physical properties, including liquid limit, plastic limit, plasticity index, specific gravity, and particle size distribution, are presented in Table 3-1. These physical characteristics determine their suitability and reactivity when mixed with cement and fibers.

Table 3-1 Physical parameters of NSF-Clay

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

Solidifier: The cement-based solidification agent, Geoset 200, was supplied by Taiheiyo Cement Co., Ltd. was used as the solidifying agent. This cement is specifically designed for soft soil treatment, offering strong consolidation and cohesion properties, which can significantly enhance the strength and stability of the soil over a certain curing period. The amount of cement was controlled at 100 kg/m³ to ensure effective solidification while avoiding volumetric changes or swelling due to excessive solidifier.

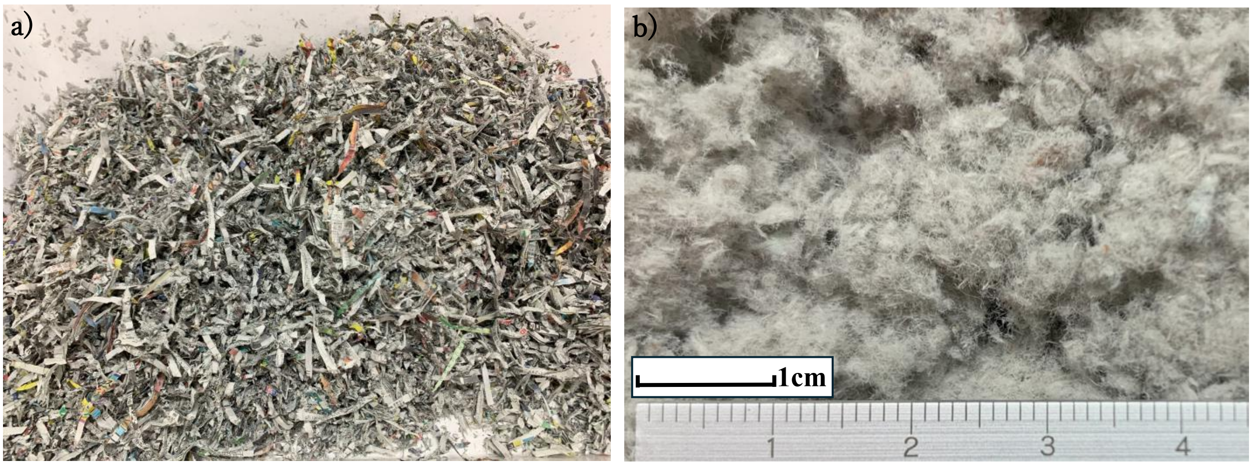

Figure 3-1 a) Pulverized newspaper; **b)** Fiber material made by pulverized newspaper (with scale: cm)

Fibrous Material: To improve the tensile strength and crack control performance of LSS and to simulate the application of reusable waste materials, this study selected waste newspapers as the fibrous material. The newspapers were first shredded into appropriate sizes using an office shredder. Then, the shredded newspapers were mixed with water in a food processor for further breakdown. After drying in an oven, they were manually separated and crushed again into a cotton-like consistency. The final fiber length was controlled to be between 0.5 and 3 millimeters as shown in Figure 3-1. The newspaper fibers contain a high cellulose content, which can be effectively distributed within the matrix, increasing the internal friction of the soil and enhancing the stability of LSS under loading conditions.

The Liquefied Stabilized Soil used in this research is intended as a backfill material primarily placed below the groundwater level. Therefore, it is expected to remain in a stable, inactive state.

3.3. Mixing Method

LSS can be mixed using two methods: the “slurry method” and the “adjusted slurry method.” In this study, LSS was prepared using the “slurry method,” where NSF-Clay is first mixed with a specific amount of water to create a density-controlled slurry, which is then combined with a cement-based solidification material and fiber material. This method is relatively simple and ensures the uniformity of the slurry. During the mixing process, the ratio of water to clay is adjusted to achieve the desired density, which is then uniformly mixed with the solidification and fiber materials.

The slurry density is determined based on the results of flow tests, breathing tests, and unconfined compressive tests after 28 days of curing, and a usable range of slurry density was plotted according to the flow values and unconfined compressive strength, as shown in Figure 3-2. This range was established using a cement content of 100 kg/m³ and the unconfined compressive strength after 28 days of curing. The usable range of unconfined compressive strength is between 200 and 500 kPa, with flow values ranging from 160 to 300 mm. In this study, the basic slurry density was selected as 1.280 g/cm³, and the change rate of slurry density Dρf is defined as (Actual slurry density) / (Basic slurry density) × 100 %.

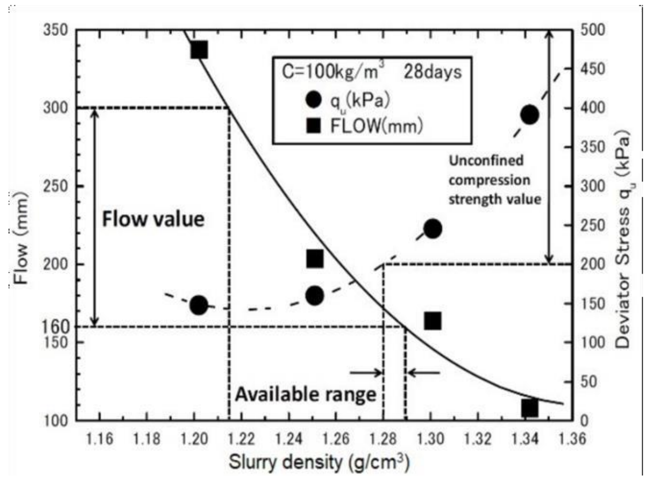

Figure 3-2 Available range of slurry density

The specific steps for preparing LSS using the “slurry method” are as follows:

Slurry Preparation: NSF-Clay is mixed with a certain amount of water to control the density to reach the target value. The slurry density is maintained at three levels: 1.216 × 10³ kg/m³ (Dρf = 95%), 1.280 × 10³ kg/m³ (Dρf = 100%), and 1.344 × 10³ kg/m³ (Dρf = 105%). During the mixing process, the water-to-clay ratio is adjusted to ensure the slurry density is precisely controlled within the specified range.

Addition of Cement and Fibers: After the slurry density is stabilized, the solidification material (Geoset 200 cement) and fiber material are added. The ratios of cement and fibers are controlled at 100 kg/m³ and either 0 or 10 kg/m³, respectively. The mixing process continues for about 10 minutes to ensure thorough and uniform blending of the materials. Pulverized newspaper and LSS slurry shown in Figure 3-3.

Deaeration Treatment: After mixing, the mixture is placed in a vacuum chamber for deaeration treatment, with the pressure controlled at -90 kN/m² for 30 minutes to remove any remaining air bubbles in the slurry. This deaeration treatment helps to improve the density of the specimens, preventing voids within the specimens and ensuring the reliability of the test results.

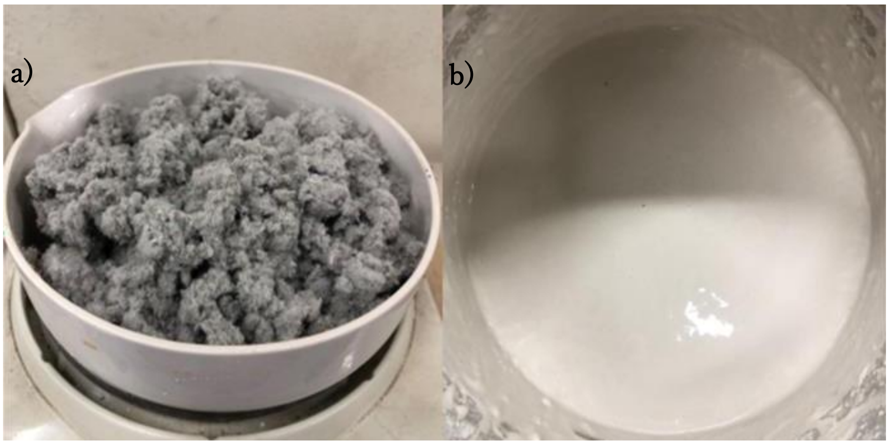

Figure 3-3 a) Pulverized newspaper; **b)** LSS slurry

3.4. Specimen Preparation

In order to investigate the effects of different slurry densities on the strength and deformation of LSS reinforced fiber materials under monotonic and cyclic loading, the basic slurry density was determined to be 1.280 g/cm³, based on the standard mix design figure from Kohata et al. (2011) and the variations in slurry density.

The density change rate Dρf (actual slurry density) / (basic slurry density) × 100% was defined as follows: Dρf = 100% (ρf = 1.280 g/cm³), Dρf = 105% (ρf = 1.344 g/cm³), and Dρf = 95% (ρf = 1.216 g/cm³). To achieve the desired slurry density, the density was tested by measuring the mass of the slurry poured into a stainless-steel container (AE mortar container) with a volume of 400 cm³, and the excess material was trimmed with a glass plate. After adjusting the slurry multiple times to obtain the required density, solidification material at a rate of 100 kg/m³ was added to the slurry. The amount of fiber material added was based on previous research, set at 10 kg/m³ (1.963 g/specimen). After the fiber material was incorporated, the LSS was mixed using a portable mixer.

To ensure standardized specimen preparation, after mixing the fiber material into the LSS slurry, a negative pressure deaeration treatment was applied at -90 kN/m² for 30 minutes. The mixture was then poured into commercial plastic molds measuring 60 × 60 mm, sealed with plastic wrap on top, and cured in moist air at a temperature of 20 ± 3 °C. The specimens were kept in the molds for prescribed days (7, 28, 56, and 120 days). in a standard curing room to ensure structural integrity and homogeneity. The test conditions for each specimen are shown in Table 3-2.

After a prescribed days curing period, the specimen is trimmed to dimensions of 20 mm in height and 60 mm in diameter to meet the specifications of the consolidation apparatus (Figure 3-4). The specimen is then placed in the apparatus for a one-dimensional consolidation test under fully confined conditions. The consolidation test procedure involves multi-step incremental loading, with the specimen's compression displacement recorded at each loading step to obtain the consolidation rate under different pressure levels.

Table 3-2 Test condition for each specimen

<table>
<tr><th>Test number</th><th>Cement content (kg/m3)</th><th>Slurry density (g/cm3)</th><th>Curing days</th><th>Fiber content (kg/m3)</th></tr>
<tr><td>1</td><td rowspan="10">100</td><td>1.216</td><td>28</td><td>Pc=0</td></tr>
<tr><td>2</td><td>1.216</td><td>28</td><td>Pc=10</td></tr>
<tr><td>3</td><td>1.344</td><td>28</td><td>Pc=0</td></tr>
<tr><td>4</td><td>1.344</td><td>28</td><td>Pc=10</td></tr>
<tr><td>5</td><td rowspan="6">1.280</td><td>28</td><td>Pc=0</td></tr>
<tr><td>6</td><td>28</td><td>Pc=10</td></tr>
<tr><td>7</td><td>7</td><td>Pc=0</td></tr>
<tr><td>8</td><td>56</td><td>Pc=0</td></tr>
<tr><td>9</td><td>120</td><td>Pc=0</td></tr>
<tr><td>10</td><td>120</td><td>Pc=10</td></tr>
</table>

Figure 3-4 Trimmed specimen

3.5. Variable Control and Impact Analysis

Slurry Density: The density of the slurry has a direct impact on the mechanical properties and permeability characteristics of LSS. Specimens with different slurry densities will exhibit variations in consolidation and permeability rates due to these density differences. In low-density slurries, there are more internal voids in the soil, leading to higher permeability but lower compressive strength. Conversely, high-density slurries increase the compactness and compressive capacity of the soil while reducing the likelihood of moisture permeability. This experiment compares specimens of different densities to investigate the specific effects of slurry density on the properties of LSS.

Fiber Content: Fiber materials play a role in enhancing the tensile strength and controlling cracks within LSS. The presence of fibers can improve the toughness and ductility of the specimens, reduce crack formation, and enhance the overall stability of LSS. Additionally, an increase in fiber content may influence consolidation characteristics and improve compressive strength. This study sets fiber contents at 0 and 10 kg/m^3 to compare the effects of fibers under different slurry density conditions.

Curing Time: Curing time is one of the key factors affecting the mechanical properties and permeability characteristics of LSS. During the curing process, the hydration reaction of the cement gradually proceeds, continuously strengthening and solidifying the internal structure of the soil. This study selects four different curing times: 7 days, 28 days, 56 days, and 120 days, to evaluate the impact of curing duration on consolidation strength and permeability performance. Short curing times (such as 7 days) lead to lower soil strength and higher permeability; as the curing time increases, the soil gradually densifies, resulting in decreased permeability and significantly increased compressive strength. This variable control is crucial for understanding the long-term stability of LSS.

Through the systematic control of these variables, this study provides a more comprehensive analysis of the combined effects of slurry density, fiber content, and curing time on the mechanical properties and permeability characteristics of LSS, offering a basis for the optimized design of LSS in various application scenarios.

3.6. Detailed Preparation Steps

1. Weigh the Bucket: Place the water bucket on the scale, weigh it, record the weight, and then zero the scale. (Figure 3-5)

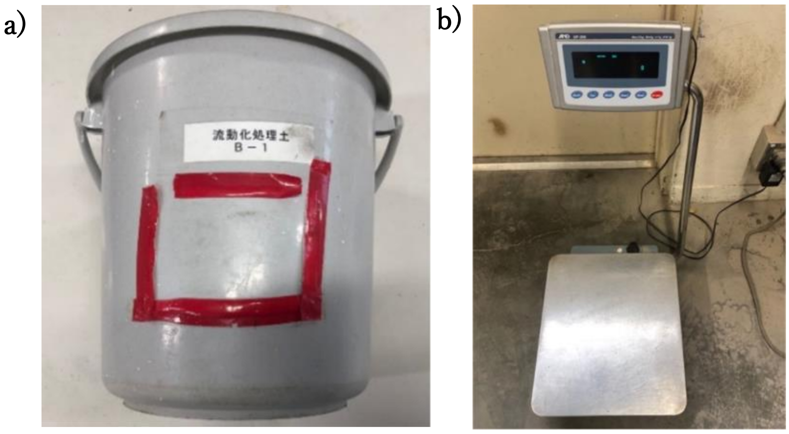

Figure 3-5 a) Bucket; **b)** Electronic scale

2. Add Water: Add water to the bucket as needed, weigh, and record the value.
3. Add Clay: Add clay according to the calculation table, ensuring it does not stick to the walls of the bucket, and mix thoroughly to form a slurry.
4. Adjust Slurry Density: Check the density of the slurry in a metal container; if it differs significantly from the target value, make adjustments. (Figure 3-6 a))
5. Add Cement and Fiber Material and Mix: After adjusting the slurry density to the target value, add cement and fiber material according to the preset ratios, and continue mixing until fully blended to ensure uniformity.
6. Deairing Treatment: Place the mixture in a sealed container and deair it under a negative pressure of -98 kPa for one hour. (Figure 3-6 b), c))

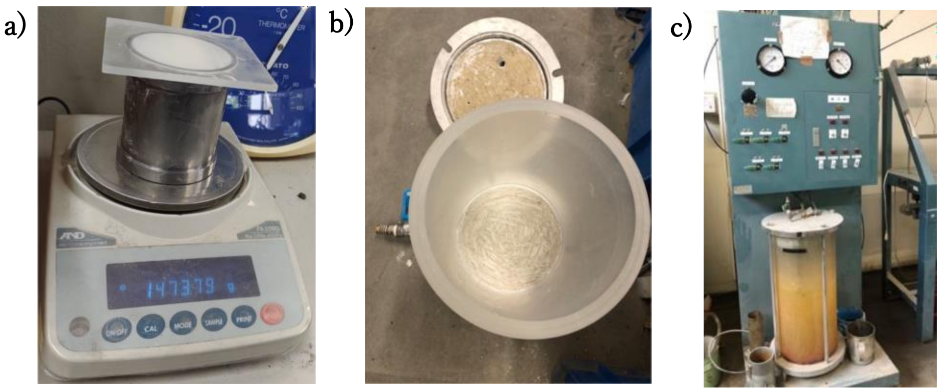

Figure 3-6 a) Metal container; **b)** Deair container; **c)** Negative pressure generator

7. Fill the Mold: Pour the uniformly mixed material into a plastic mold sized 60×60 mm. Fill the mold halfway, gently

vibrate it to eliminate air bubbles, and then continue filling the mold. After filling, seal the top with plastic wrap to maintain the specimen's moisture. (Figure 3-7 a)

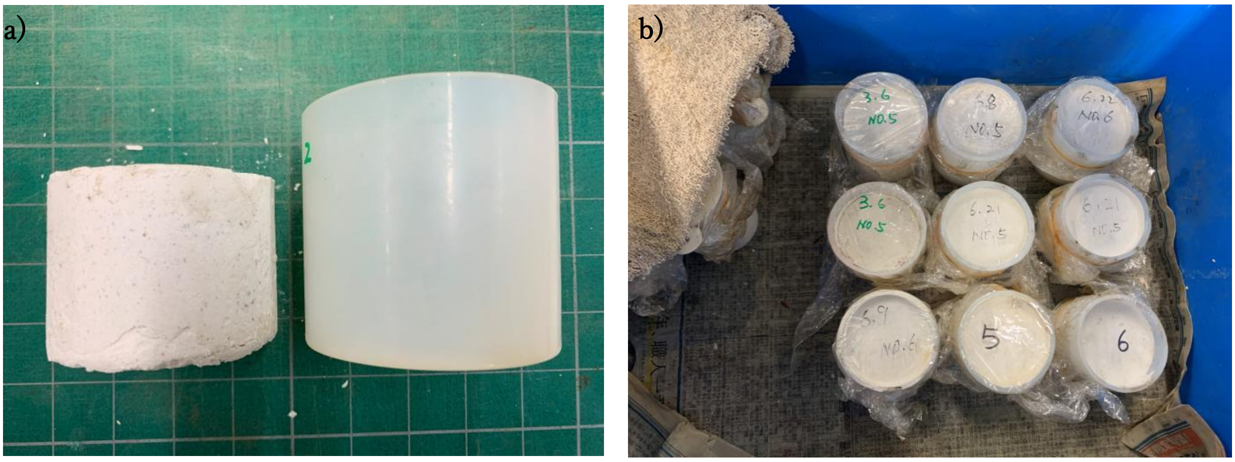

Figure 3-7 a) Plastic mold, **b)** Curing specimen

8. Curing Process: Place the sealed mold in a constant temperature chamber at 20± 3°C for curing, setting the curing time to prescribed days (7, 28, 56, and 120 days). During this period, do not remove the mold to prevent moisture evaporation or specimen deformation. (Figure 3-7 b))

Through these systematic preparation methods, the LSS specimens produced under different slurry density and fiber content conditions can be ensured to have consistency, providing reliable data support for subsequent tests analyzing their consolidation and permeability characteristics.

CHAPTER 4

APPARATUS AND TESTING PROCEDURES

4. Apparatus And Testing Procedures

4.1. Introduction

This chapter provides a detailed description of the equipment, methods, and specific operational steps used in the experiments. The study follows the "Test method for one-dimensional consolidation properties of soils using incremental loading" (JIS A 1217:2009) standard to conduct a series of standardized consolidation tests on LSS specimens. By conducting experiments on multiple specimens with varying densities and fiber contents, the consolidation properties of LSS are investigated, revealing its deformation and permeability characteristics under different conditions.

In this chapter, the experimental setup and procedures used to evaluate the consolidation characteristics of liquefied stabilized soil (LSS) are presented. A traditional one-dimensional consolidation apparatus was employed to accurately monitor soil consolidation under incremental loading conditions. This apparatus is equipped with dual drainage capability, high-precision loading mechanisms, and a displacement gauge, allowing detailed tracking of compressive deformation over time.

The consolidation test was conducted using an incremental loading approach, where specific loads were applied for set durations, replicating real-world conditions for foundation settlement in soft soil. Additionally, to determine the coefficient of consolidation c_v - a key indicator of soil behavior under stress - the time square root method was applied, recording the time to reach 90% consolidation for each pressure level. This method enables a reliable understanding of the relationship between applied pressure and consolidation rate, which is critical for designing effective soil stabilization and foundation treatments.

The chapter also provides an overview of the equipment components, including the consolidation cell, loading cap, and porous stones, detailing their construction and roles in maintaining measurement precision. The preparation, loading, measurement, and dismantling steps for the test specimens are discussed in detail to ensure experimental reproducibility.

4.2. Test Apparatus

In this experiment, a traditional one-dimensional consolidation apparatus was used (shown in Figure 4-1), meeting the requirements of the JIS A 1217:2009 standard for testing the consolidation properties of various soils. The apparatus consists of a loading device, porous plates, a dial gauge, and includes the following features:

Dual Drainage Capability: With porous plates on both the top and bottom, the apparatus enables dual drainage of the specimen, effectively accelerating the consolidation process.

Loading Precision: Using a precise loading device, the apparatus can perform incremental loading in the range of 9.8 to 1256 kN/m², ensuring a consistent load ratio of 1 for each increment.

Displacement Measurement: A dial gauge is used to monitor displacement with high accuracy, allowing for the recording of minute deformations and facilitating an accurate analysis of compressive displacement.

At each loading step, the applied load is gradually transferred to the specimen, with compressive displacement measurements taken at specific time intervals. This ensures that the specimen remains well-constrained throughout the loading process.

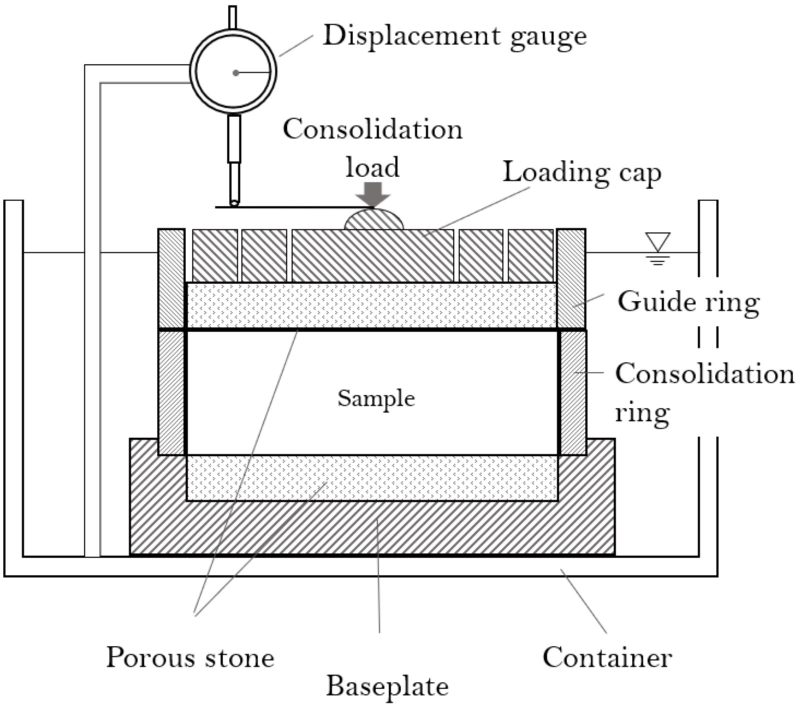

Figure 4-1 Schematic diagram of test apparatus

4.2.1. Test Equipment and Tools

1. Consolidation Cell

The consolidation cell consists of components that provide adequate rigidity to prevent deformation under consolidation pressure. An example of the consolidation cell is shown in Figure 4-2.

Figure 4-2 Consolidation Cell

1) Consolidation Ring

The consolidation ring is a smooth, stainless-steel ring with an inner diameter of 6 cm and a height of 2 cm as standard. It has low friction with the soil, is made of corrosion-resistant materials, and allows an inner diameter change of no more than 0.05% under maximum consolidation pressure. (Figure 4-3 a))

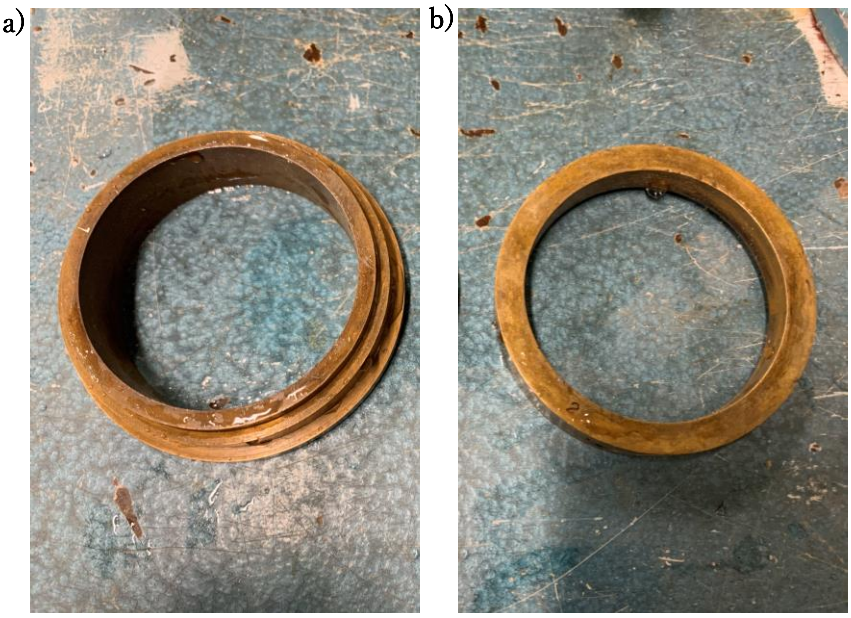

Figure 4-3 a) Consolidation Ring; **b)** Guide Ring

2) Guide Ring

The guide ring has the same inner diameter as the consolidation ring, with a height matching that of the outer edge of the loading plate. (Figure 4-3 b))

3) Loading Cap

The loading cap is a rigid circular plate with a loading point at its center. It has a porous surface and moves smoothly within the guide and consolidation rings. The loading cap's diameter is approximately 0.2 mm smaller than the consolidation ring's, with a smooth outer edge and a height between 10 mm and 15 mm.

4) Base Plate

The base plate is a rigid plate that holds the consolidation ring in place and includes a porous section.

5) Porous Stone

The porous stones are rigid, with a coefficient of permeability of at least 1 x 10^{-6} m/s and a gap size small enough to prevent soil particles from entering. The porous stone must cover at least 85% of the specimen's cross-sectional area. If soil particles may penetrate the plate, a hydrophilic, low-compression, permeable membrane can be used as a filter. Before testing, ensure the porous plate is free from blockages. (Figure 4-3 a))

2. Water Container

The water container maintains the specimen in a saturated state within the consolidation cell. (Figure 4-3 b))

a)

b)


Figure 4-3 a) Porous Stone; **b)** Water Container

3. Loading Device

The loading device supports the consolidation cell horizontally, applying the specified load to the specimen quickly and without impact or eccentricity. It should apply incremental consolidation pressure to the specimen, using either a deadweight lever system or an air-pressure system. For pressure fluctuations, it must maintain precision within ±1 kN/m² for loads under 100 kN/m² and within ±1% for loads over 100 kN/m². In a deadweight lever system, there should be a mechanism for adjusting the lever angle. (Figure 4-4 a))

a) b)

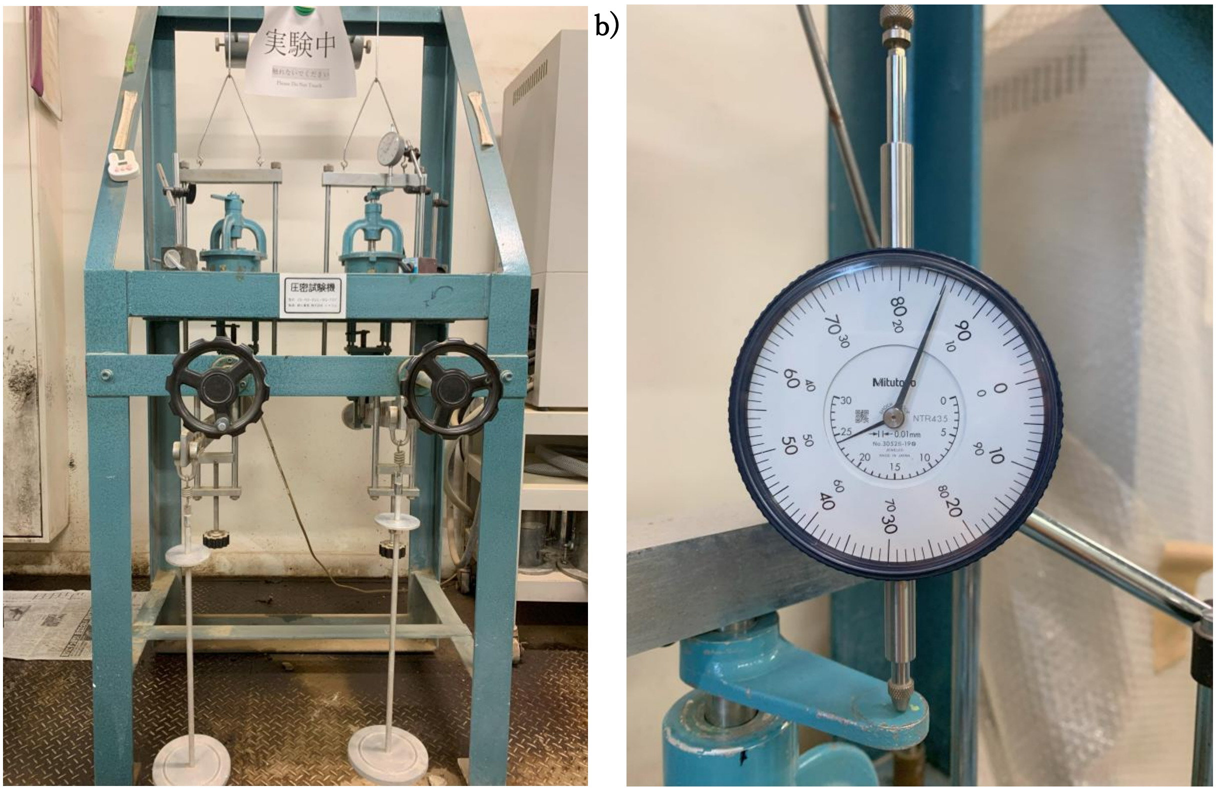

Figure 4-4 a) Loading Device; **b)** Displacement Gauge

4. Displacement Gauge

The displacement gauge should measure to 0.002 mm for total consolidation amounts less than 10 mm, and to 0.01 mm for amounts 10 mm or greater. Use a dial gauge or an electric displacement gauge with equivalent or higher accuracy. (Figure 4-4 b))

4.3. Test Method

4.3.1. Consolidation

Consolidation is the process by which excess pore water pressure dissipates and effective stress increases underload. The coefficient of consolidation cv 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 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 (t90). The coefficient of consolidation at this pressure level is calculated as follows:

$$c_v = \frac{0.848\bar{h}^2}{60t_{90}}$$

In the Equation:

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*.

4.3.2. Incremental Loading Consolidation Test

The incremental loading consolidation test is based on the method first adopted by Terzaghi, the founder of consolidation theory, and later established by Casagrande. This method is widely used around the world and is commonly referred to as the “standard consolidation test,” although this is not entirely accurate. It is specifically designed to determine consolidation characteristics under certain conditions.

Unlike continuous loading consolidation tests, such as the constant strain rate loading test or the constant hydraulic gradient test, this method uses an incremental loading approach. In this procedure, a set pressure p is applied for a standard duration of 24 hours. After this, an incremental pressure Δp, equal in magnitude to p (with a load increment ratio $\Delta p / p = 1$), is instantly applied and held for another 24 hours. This sequence is repeated for subsequent steps. 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.

Under a constant pressure p, primary consolidation occurs due to the dissipation of excess pore water pressure, followed by secondary consolidation under a constant effective stress $\sigma' = p$. The relationship between compression and time during the primary consolidation stage is fitted to an algebraic solution (for the above loading conditions) to calculate the coefficient of consolidation c_v. By determining the c_v value for each step, the relationship between c_v and pressure p can be established. If primary consolidation is observed to complete within 24 hours at each step, a compression curve $e \sim \log \sigma'$ can be plotted, from which the consolidation yield stress p_c, the compression index C_c ($= -\Delta e / \Delta \log \sigma'$), and the relationship between the volumetric compressibility m_v ($= (-\Delta e / \Delta \sigma') / (1 + e)$)) and effective stress σ' can be derived.

4.3.3. Preparation

In the preparation phase, the specimen is placed in a curing environment for 28 days, with temperature and humidity strictly controlled to ensure material stability. After curing, the specimen is trimmed to a standard size of 20 mm in height and 60 mm in diameter, ensuring precision and consistency during device operation. Before placing the specimen in the consolidation apparatus, the equipment is cleaned to eliminate impurities and avoid any influence on measurement results.

Preparation involves the following steps:

a) Place the consolidation ring containing the test specimen on the base plate of the consolidation cell and attach the guide ring to the consolidation ring. Place the loading plate on the top surface of the specimen, then assemble the consolidation cell. Note that a porous plate in an air-dried state is used. If using a permeable membrane, attach it to the top and bottom surfaces of the specimen while dry.

b) Insert the consolidation cell into an empty water-filled container and set it up on the loading device, attaching the displacement gauge. Take care to align the loading point with the central axis of the specimen when setting up the cell. The displacement gauge should be installed vertically on the end surface of the specimen, close to the central axis. Additionally, ensure that the specimen does not absorb water before or during loading.

4.3.4. Loading and Measurement

After loading begins, the specimen undergoes incremental loading cycles every 24 hours, with displacement changes recorded at the initial loading stage, particularly the compression displacement at each time point, to accurately measure the consolidation behavior. The displacement data recorded after each increment is used to plot the time-displacement curve, analyzing consolidation rate and stabilization time of the material.

To minimize experimental error, the state of both the device and the specimen is kept constant during each load application. After each test cycle, the equipment is checked and calibrated.

The loading and measurement of consolidation amount involve the following steps:

a) Use a load increment ratio of 1 for consolidation pressure p (kN/m²). The standard number of loading stages is

8, and the range for p is 10~1600 kN/m². Adjust the initial consolidation pressure and the number of stages based on soil hardness or test objectives. Additional pressures outside this range may be applied if necessary. To determine consolidation yield stress p_c (kN/m²), loading is typically conducted across three or more stages before and after p_c.

b) Apply the consolidation pressure without impact, reaching the specified pressure within either 2 seconds or 0.05 times t_{50}, whichever is shorter. t_{50} is the time corresponding to 50% theoretical consolidation for that stage. If primary consolidation has not concluded after 24 hours, the consolidation time is extended until completion. In over-consolidated areas where consolidation is observed to end quickly, the next stage may proceed before 24 hours.

c) Record the displacement gauge reading d_i (mm) just before each loading stage.

d) Record the displacement gauge reading d (mm) at regular time intervals to create a smooth compression-time relationship curve. Refer to examples for suitable time intervals. 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.

e) When the consolidation yield stress is reached, fill the container with water to saturate the specimen. Until this point, cover the consolidation cell with a damp cloth to prevent drying. For specimens with low saturation, avoid water immersion and ensure the specimen does not dry.

f) Record the highest and lowest room temperatures from the start o2f the first loading stage to the end of the final measurement stage.

4.3.5. Dismantling

After the test is completed, dismantle the specimen and conduct a structural examination to check for fiber distribution and crack formation during loading and curing (Figure 4-5). This dismantling process can include microscopic examination of internal changes, providing supplementary evidence for data validation.

Figure 4-5 Dismantling

Upon completing the final measurement stage, remove the entire specimen from the consolidation cell and place it on an evaporating dish. Oven-dry it at (110±5)◦C until the weight stabilizes and measure the oven-dried mass m_s (g) of the specimen. For specimens with low saturation, to determine post-test saturation, dismantle and remove the specimen without absorbing water, measure the wet mass, and then oven-dry it to determine the post-test water content (Figure 4-6).

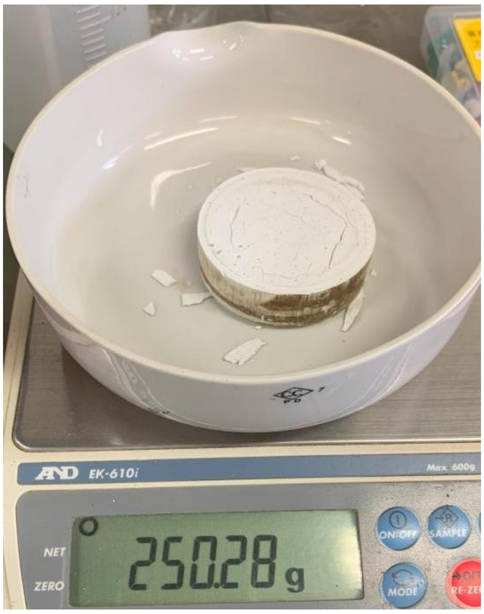

Figure 4-6 Specimen after Oven-dried

CHAPTER 5

RESULTS AND DISCUSSION OF CONSOLIDATION TESTS ON LIQUEFIED STABILIZED SOIL UNDER DIFFERENT CONDITIONS

5. Results and Discussion of Consolidation Tests on Liquefied Stabilized Soil Under Different Conditions

5.1. Introduction

This chapter analyzes the consolidation test data of liquefied stabilized soil under different conditions, aiming to reveal the effects of factors such as slurry density, curing time, and the addition of fiber materials on consolidation characteristics. The mechanisms by which these influencing factors affect parameters such as consolidation amount, coefficient of consolidation, and void ratio are first introduced, followed by a discussion and explanation of these relationships based on the experimental results.

5.2. Coefficient of Consolidation

Consolidation is the process where excess pore water pressure dissipates, leading to an increase in effective stress under applied load. The coefficient of consolidation, c_v, is a key parameter in Terzaghi's one-dimensional consolidation theory [38], representing the rate at which consolidation occurs in soft soils. A higher c_v value indicates that the soil layer consolidates more quickly. Essentially, this coefficient reflects the soil's consolidation characteristics and is a fundamental factor in soil testing as well as in designing soft ground foundation treatments. When applying drainage consolidation methods on soft ground, the coefficient of consolidation becomes particularly crucial. Precise determination of c_v is critical for accurately forecasting foundation settlement and ensuring the stability of soil-based structures.

There are four primary methods for determining the coefficient of consolidation: indoor consolidation 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 (t90). The coefficient of consolidation at this pressure level is calculated as follows:

$$c_v = \frac{0.848\bar{h}^2}{60t_{90}}$$

In the Equation:

c_v: Coefficient of consolidation, cm^2/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.

5.3. Coefficient of Permeability

The coefficient of permeability, denoted as k, is a crucial parameter that indicates the soil's capacity for water transmission. This coefficient is strongly influenced by factors such as slurry density, curing time, and fiber content in the soil. Understanding how these factors affect k is essential for optimizing the engineering applications of LSS, particularly in soft ground improvement.

The coefficient of permeability is calculated by the following formula:

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

In the Equation:

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/m^3)

5.4. Results Organization

5.4.1. Calculation Method

The experimental data are processed using the Log-Time Method and the Square Root Method to calculate the compression coefficient and coefficient of consolidation of LSS. These methods help analyze the compressibility and permeability characteristics of specimens under different densities, fiber contents, and curing times.

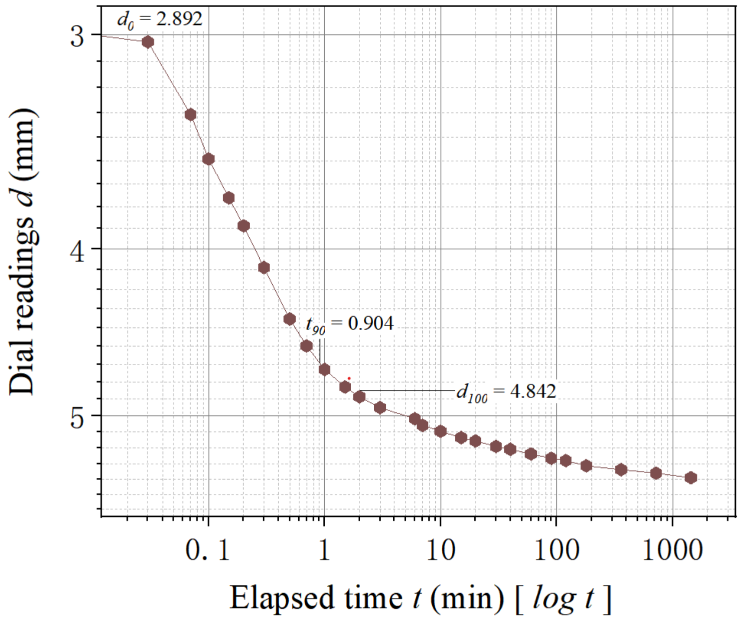

Figure 5-1 Log-Time Method Calculation

Log-Time Method: According to the Log-Time Method, the distribution of data points can be used to determine the initial compression stage and secondary compression stage, facilitating the analysis of the compression rate and final consolidation value.

Square Root Method: The Square Root Method allows for a more intuitive observation of the consolidation rate of the soil and the changes in the shrinkage process, helping to correct errors caused by initial deformation during the experiment.

Finally, a comparative analysis of the data obtained from the Log-Time Method and the Square Root Method with theoretical values is conducted to understand the specific performance of LSS consolidation characteristics under various experimental conditions, providing a basis for parameter selection in engineering applications. In this study, Square Root Method was used to results organization.

5.4.2. Square Root Method Calculation

1. Initial State of the Specimen

The initial state of the specimen, including water content w_o (%), void ratio e_0, and degree of saturation S_{r0} (%), is calculated using the following equations.

$$w_0 = \frac{(m_T - m_R) - m_s}{m_s} \times 100$$

$$e_0 = \frac{H_0}{H_s} - 1$$

$$S_{r0} = \frac{w_0 \rho_s}{e_0 \rho_w}$$

$$Hs = \frac{m_s}{\rho_s A} = \frac{m_s}{\rho_s \pi D^2 / 4}$$

In the Equation:

w_0: Initial moisture content, %.

e_0: Initial void ratio.

S_{r0}: degree of saturation, %.

m_T: Mass of the specimen and consolidation ring before consolidation, *g*.

m_R: Mass of the consolidation ring, *g*.

m_S: Oven-dry mass of the specimen, *g*.

H_0: Initial height of the specimen, *cm*.

H_S: Actual height of the specimen, *cm*.

A: Cross-sectional area of the specimen, cm^2.

D: Diameter of the specimen, *cm*.

ρ_S : Density of soil particles, g/cm^3.

ρ_W : Density of water, g/cm^3.

5.4.3. Relationship Between Consolidation Amount and Time

1. Relationship Between Consolidation Amount and Time at Each Loading Stage

The relationship between the consolidation amount and time at each loading stage is organized using the following steps:

a) Using the following methods, determine the dial readings corresponding to theoretical consolidation densities of 0% (d_0 in mm), 100% (d_{100} in mm), and 90% (t_{90} in min) or 50% (t_{50} in min).

1) Square Root Method

1.1) Plot the dial readings (d in mm) on the vertical axis using an arithmetic scale and the elapsed time (t in min) on the horizontal axis using a square root scale to draw the $d - \sqrt{t}$ curve.

1.2) Extend the straight portion appearing in the initial part of the $d - \sqrt{t}$ curve to intersect with $t = 0$, designating this point's dial reading as d_0 (mm).

1.3) Through the initial correction point, draw a straight line that has 1.15 times the horizontal distance of the straight line calculated in 1.2) and mark the intersection with the $d-\sqrt{t}$ curve as the theoretical consolidation density point at 90%. Obtain the dial readings d_{90} (mm) and time t_{90} (min) at this point.

1.4) Calculate $d100$ using the following equation:

$$d_{100}=\frac{10}{9}(d_{90}-d_0)+d_0$$

In the Equation:

d_{100}: Dial reading corresponding to theoretical consolidation density of 100%, *mm.*

d_{90}: Dial reading corresponding to theoretical consolidation density of 90%, *mm.*

d_0: Dial reading corresponding to theoretical consolidation density of 0%, *mm.*

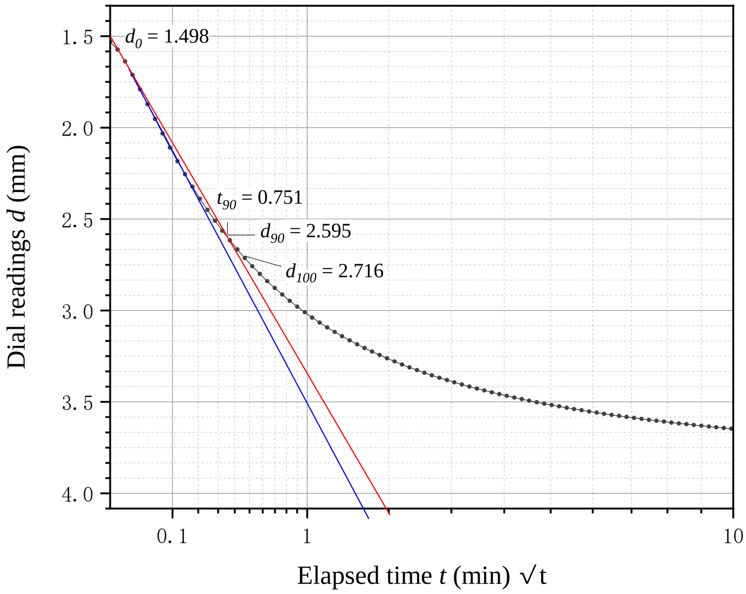

Figure 5-2 Square Root Method

5.4.4. Consolidation Amount, Specimen Height, and Average Specimen Height at Each Loading Stage

The consolidation amount ΔH (cm), specimen height H (cm), and average specimen height $\overline{H}$ (cm) at each loading stage are calculated using the following procedure.

a) The consolidation amount ΔH (cm) at each loading stage is calculated using the following equation. However, for the first loading stage, replace d_0 with d_i.

$$\Delta H=\frac{d_f-d_i}{10}$$

In the Equation:

ΔH: Consolidation amount at each loading stage*, cm.*

d_f: Final dial reading at each loading stage*, mm.*

d_i: Dial reading immediately before loading at each loading stage*, mm.*

To obtain the primary consolidation amountΔH_1 (cm) and the primary consolidation ratio r for each loading stage, use the following equation.

$$\Delta H_1 = \frac{d_{100} - d_0}{10}$$

In the Equation:

ΔH_1: Primary consolidation amount at each loading stage*, cm.*

r: Primary consolidation ratio for each loading stage

b) The specimen height H (cm) at the end of consolidation for each loading stage and the average specimen height $\overline{H}$ (cm) are calculated using the following equation. However, for the first loading stage, set $H' = H_0$:

$$H = H' - \Delta H$$
$$\overline{H} = \frac{H + H'}{2}$$

In the Equation:

H: Specimen height at the end of consolidation for each loading stage*, cm.*

$\overline{H}$: Average specimen height at each loading stage*, cm.*

H': Specimen height at the end of consolidation for the previous loading stage*, cm.*

5.4.5. Coefficient of consolidation at Each Loading Stage

a) If t_{90} were obtained in 4.5.3, the coefficient of consolidation c_v (cm²/d) at each loading stage is calculated using the following equations:

$$c_v = \frac{0.848\overline{h}^2}{60t_{90}}$$

In the Equation:

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

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

b) Plot c_v on the vertical axis using a logarithmic scale and the average consolidation pressure p (kN/m²) calculated using the following equation on the horizontal axis using a logarithmic scale to show the relationship between $\log c_v$ and $\log \bar{p}$. However, for the first loading stage, use $p/2$ as $\bar{p}$.

$$\bar{p} = \sqrt{p \times p'}$$

In the Equation:

$\bar{p}$: Coefficient of consolidation, *kN/m²*.

p: Coefficient of consolidation, *kN/m²*.

p' : Coefficient of consolidation, *kN/m²*.

5.4.6. Relationship Between Consolidation Amount and Pressure

1. Compression Curve, Compression Index, and Consolidation Yield Stress

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. The compression curve, compression index, and consolidation yield stress are determined using the following steps. a) The void ratio e at the end of consolidation for each loading stage is calculated using the following equation.

$$e = \frac{H}{H_S} - 1$$

In the Equation:

e: Void ratio at the end of consolidation for each loading stage

b) Plot the void ratio e obtained in a) on the vertical axis using an arithmetic scale and the consolidation pressure p (kN/m) for that loading stage on the horizontal axis using a logarithmic scale to draw the compression curve.

The compression curve for each loading stage can also be drawn using the following equation for volume ratio f instead of e.

$$f = \frac{H}{H_S}$$

In the Equation:

f: Volume ratio at the end of consolidation for each loading stage

c) Select two points a and b from the linear portion of the normal consolidation region of the compression curve to calculate the compression index Cc using the following equation .

$$C_c = \frac{e_a - e_b}{\log(p_b / p_a)}$$

In the Equation:

C_c: Compression index

However, if the compression curve is drawn using f, then C_c is calculated using the following equation.

$$C_c = \frac{f_a - f_b}{\log(p_b / p_a)}$$

If a clear linear portion cannot be recognized in the compression curve, approximate the line of the steepest slope in the normal consolidation region to obtain C_c. Additionally, based on the objective, derive C_c from the average slope of the compression curve within the necessary pressure range, noting the corresponding pressure range.

d) The consolidation yield stress p_c (kN/m²) is obtained using the following method. However, if it is difficult to obtain p_c (kN/m²), plot p using an arithmetic scale and draw the $e - p$ curve or $f - p$ curve. If it does not possess a convex portion, it is not necessary to obtain p_c.

1) Determine the intersection point A where the line with a slope of $C_c' = 0.1 + 0.25C_c$ meets the compression curve.

2) The horizontal coordinate of the intersection point B of the line through point A with a slope of $C_c'' = C_c / 2$ and the extension of the straight line representing the steepest slope portion of the normal consolidation region is designated as p_c. If a clear maximum curvature point can be identified using the vertical axis scale corresponding to a void ratio of 0.1 and a horizontal logarithmic scale with a cycle length of 0.1 - 0.25, then p_c can be calculated using the following method 2.1) Identify the maximum curvature point A on the compression curve and draw a horizontal line AB and a tangent AC at this point.

2.2) The horizontal coordinate of the intersection point E of the bisector AD of the two lines and the extension of the straight line representing the steepest slope portion of the normal consolidation region is designated as p.

調査件名	流動化処理土No.5-3 10.13		
試験年月日	2023.10.13		
試料番号	No.5-3		
試料配合	100%, Pc=0		
試料作成日	2023.9.15	養生日数	28

試験機		
試験機	試験機No.	2
	変位計No.	2
	圧密リングNo.	1
	圧密リング質量m_R g	249

供試体		
	試験前	
	高さ H_0 cm	2
	直径 D cm	6
	供試体+リング質量 m_T g	328.07
	供試体質量 m_0 g	79.07
	初期含水比 w_0 %	126.69%
	炉乾燥後	
	容器 No.	60
	供試体+容器質量 g	392.27
	容器質量 g	357.39
	供試体質量 m_s g	34.88

初期含水比（削りくずによる）			
容器No.	CC-14	N19	N54
m_a g	77.14	93.61	85.36
m_b g	60.85	77.98	71.57
m_c g	47.51	65.32	60.49
w %	122.11%	123.46%	124.46%
平均値w%	122.79%		

載荷段階	①	圧力p KN/m^2	9.8
試験日	10/13	室温 ℃	21.5
時 刻	経過時間	変位計の読みdmm	
10:20	0	0	
	2 s	0.048	
	4 s	0.052	
	6 s	0.053	
	9 s	0.057	
	12 s	0.058	
	18 s	0.058	
	30 s	0.058	
	42 s	0.058	
	1 min	0.058	
	1.5	0.058	
	2	0.058	
	3	0.059	
	5	0.06	
	7	0.06	
0:10	10	0.06	
0:15	15	0.06	
0:20	20	0.0605	
0:30	30	0.061	
0:40	40	0.061	
1:00	1 h	0.061	
1:30	1.5 h	0.061	
2:00	2 h	0.061	
3:00	3 h	0.061	
6:00	6 h	0.061	
12:00	12 h	0.061	
0:00	24 h	0.061	

載荷段階	②	圧力p KN/m^2	19.6
試験日	10/14	室温 ℃	21.3
時 刻	経過時間	変位計の読みdmm	
10:30	0	0.051	
	2 s	0.081	
	4 s	0.084	
	6 s	0.088	
	9 s	0.089	
	12 s	0.089	
	18 s	0.089	
	30 s	0.089	
	42 s	0.089	
	1 min	0.089	
	1.5	0.0895	
	2	0.09	
	3	0.09	
	5	0.09	
	7	0.09	
10:40	10	0.09	
10:45	15	0.09	
10:50	20	0.09	
11:00	30	0.09	
11:10	40	0.09	
11:30	1 h	0.09	
12:00	1.5 h	0.09	
12:30	2 h	0.09	
13:30	3 h	0.09	
16:30	6 h	0.09	
22:30	12 h	0.09	
10:30	24 h	0.09	

Figure 5-3 Calculation Results 1

試験機No.	2	供試体	直径 D cm	6	初期状態	含水比 w_0 %	122.79%
最低～最高室温 ℃			断面積 A cm^2	28.274		間隙比 e_0, 体積比 f_0	3.478 / 4.478
土質名称	NSF clay		高さ H_0 cm	2		湿潤密度 ρ_t g/cm^3	1.398
土粒子の密度ρ_s g/cm^3	2.762		質量 m_0 g	79.07		飽和度 S_{r0} %	70%
液性限界w_L %	60.15%		炉乾燥質量 m_s g	34.88	圧縮指数 C_c		1.74150194
塑性限界w_P %	35.69%		実質高さ H_s cm	0.447	圧密降伏応力 Pc kN/m^2		389.24

載荷段階	圧密圧力p kN/m^2	圧力増分ΔP kN/m^2	圧密量ΔH cm	供試体高さH cm	平均供試体高さ $\bar{H}$ cm	圧縮ひずみ $\Delta\varepsilon=\frac{\Delta H}{\bar{H}}\times 100\%$	体積圧縮係数m_v m^2/kN	間隙比 $e=H/H_s-1$ 体積比$f=H/H_s$
0	0			2				3.478
		9.8	0.006		1.997	30.55%	0.0003117	
1	9.8			1.994				3.464
		9.8	0.004		1.992	19.58%	0.000199784	
2	19.6			1.990				3.455
		19.6	0.005		1.988	23.14%	0.000118073	
3	39.2			1.985				3.445
		39.2	0.008		1.982	39.36%	0.000100419	
4	78.4			1.978				3.428
		78.4	0.014		1.971	70.03%	8.93187E-05	
5	156.8			1.964				3.397
		156.8	0.039		1.944	200.59%	0.000127925	
6	313.6			1.925				3.309
		313.6	0.196		1.827	1074.64%	0.00034268	
7	627.2			1.729				2.870
		627.2	0.272		1.593	1708.01%	0.000272322	
8	1254.4			1.457				2.261

Figure 5-4 Calculation Results 2

載荷段階		1	2	3	4	5	6	7	8
圧密圧力	p kN/m^2	9.8	19.6	39.2	78.4	156.8	313.6	627.2	1254.4
載荷直前読み	d_i mm	0	0.051	0.073	0.096	0.121	0.18	0.526	2.478
圧密度 0 % 読み	d_0 mm	0.0014	0.05167	0.07387	0.0971	0.1229	0.1835	0.524	2.491
最終読み	d_f mm	0.061	0.09	0.119	0.174	0.259	0.57	2.489	5.198
圧密度 100 % 読み	d_{100} mm	0.064	0.093126	0.121014	0.161322	0.2419	0.416167	1.785111	4.509889
圧密量	ΔH cm	0.006	0.004	0.005	0.008	0.014	0.039	0.196	0.272
一次圧密量	ΔH_1 cm	0.00626	0.00415	0.00471	0.00642	0.01190	0.02327	0.12611	0.20189
圧密度 90% 時間	t_{90} min	0.2017	0.2079	0.2142	0.1956	0.1997	0.2038	0.3846	0.79472

載荷段階	圧力p	間隙比 e
0	0	3.478
1	9.8	3.464
2	19.6	3.455
3	39.2	3.445
4	78.4	3.428
5	156.8	3.397
6	313.6	3.309
7	627.2	2.870
8	1254.4	2.261

圧縮指数 Cc	1.741502
e_a	3.309
e_b	2.261
p_a	313.6
p_b	1254.4
Cc'	0.535375
Cc''	0.267688

Cc'線	x	y	k	b
1	30	3.5	0.535375	-12.5613
2	90	35.62253		

Cc''線	x	y	k	b
接点	30	3.5	0.267688	-4.53063
2	90	19.56126		

Pc	x
交点	389.24

Figure 5-5 Calculation Results 3

5.4.7. Results report

The test results report the following, As shown in Figure 5-3, 5-4 and 5-5:

a) The diameter (cm) and initial height (cm) of the specimen.

b) Initial state of the specimen including water content (%), void ratio or volume ratio, and degree of saturation (%).

c) Consolidation amount for each loading stage (cm) and specimen height at the end of consolidation (cm).

d) Average specimen height (cm) for each loading stage.

e) Coefficient of consolidation c_v (cm²/d) for each loading stage.

f) Relationship between void ratio e and consolidation pressure p (kN/m²) or relationship between volume ratio f and consolidation pressure p (kN/m²)

g) Compression index C_c and consolidation yield stress p_c (kN/m²)

5.5. Comparison of Consolidation and Coefficient of Permeability Between Liquefied Stabilized Soil and Basic Material NSF-Clay

NSF-Clay, as the foundational material for liquefied stabilized soil (LSS), plays a crucial role in defining the mechanical and permeability properties that make LSS suitable for engineering applications. LSS is designed by modifying NSF-Clay with additional components such as cement and fibers to achieve enhanced consolidation and permeability characteristics, which are critical for ground improvement and stability in construction projects. NSF-Clay itself has certain structural and compositional properties that contribute to LSS's strength and permeability control, making it an essential element in achieving a balance between compressibility and resistance to water infiltration.

In this study, we compare the base material NSF-Clay with LSS under varying conditions, specifically examining differences in coefficient of consolidation, void ratio, and coefficient of permeability to highlight how NSF-Clay contributes to the performance of the modified LSS. This analysis provides insights into how modifying NSF-Clay through the addition of stabilizing agents like cement and reinforcing fibers can alter its behavior, enhancing compressive strength, reducing permeability, and improving the material's durability.

One of the primary motivations behind using NSF-Clay as a base material for LSS lies in its inherent ability to hold water while also exhibiting a relatively high compressibility under pressure. When combined with cement, NSF-Clay undergoes a chemical transformation that increases particle bonding, reducing the soil's volume change under stress and improving structural integrity. Additionally, fibers are often incorporated to provide internal reinforcement, helping distribute stress and reduce cracking or shear deformations. The resulting LSS material gains both strength and reduced permeability, which is especially beneficial in foundations, embankments, and other earthworks where stability under load and minimal water infiltration are required.

Through this comparison, we aim to elucidate how NSF-Clay's properties are modified in LSS to offer significant advantages over the unmodified clay material. By adjusting factors such as slurry density, curing time, and fiber content, LSS can be tailored to meet specific engineering needs, offering a versatile solution for projects in soft soil improvement. The modifications improve not only load-bearing capacity and resistance to deformation but also long-term durability, making LSS a promising material for sustainable ground engineering applications.

Furthermore, understanding the specific role of NSF-Clay within LSS supports advancements in soft ground improvement techniques by providing a foundation for optimizing the composition of LSS. This optimization can enhance its application in challenging environments, such as coastal or low-lying areas prone to water saturation. The systematic evaluation of NSF-Clay's role in LSS also sets the stage for future research into the synergistic effects of different additives and varying preparation methods, ultimately contributing to the development of more resilient and adaptable soil stabilization technologies.

5.5.1. Comparison of Coefficient of Consolidations between LSS and NSF-Clay

In this study, the consolidation-permeability characteristics of LSS were investigated to understand how NSF-Clay, as the base material, influences these critical properties under controlled conditions. Specifically, experiments were conducted on saturated soft soil specimens composed solely of the NSF-Clay base material, prepared at a slurry density of 1.28 g/cm³ with no fiber additives and subjected to incremental loading up to 200 kN/m² and cured for 7 days. This baseline setup provides insight into the fundamental behavior of the base material before any further stabilization or reinforcement modifications. By isolating the NSF-Clay's natural consolidation and permeability responses, we gain a clearer perspective on how subsequent additions of cement and fiber may alter these properties in LSS.

The experimental setup aimed to mimic typical field conditions where LSS is applied for soil stabilization. By examining NSF-Clay in its unmodified state, the study establishes a performance benchmark, allowing for a more direct comparison with LSS specimens that include stabilizers. Figure 5-6 presents the results, highlighting the differences between the pure NSF-Clay specimens and LSS specimens prepared under identical conditions. This comparison provides a valuable reference for assessing the role of slurry density and the unmodified clay structure on consolidation characteristics such as compression behavior, rate of consolidation, and permeability.

The observed coefficient of consolidations and permeability characteristics of NSF-Clay at this density level serve as a baseline for interpreting changes introduced by LSS modifications. Key findings indicate that the natural Void ratio and compressibility of NSF-Clay influence both the consolidation rate and water permeability, essential parameters for determining the material's load-bearing capacity and stability under saturation. The results in Figure 5-6 reveal the fundamental response of the soil matrix before any enhancement through cement or fiber reinforcement, offering a comparative view of how stabilization processes alter the consolidation behavior.

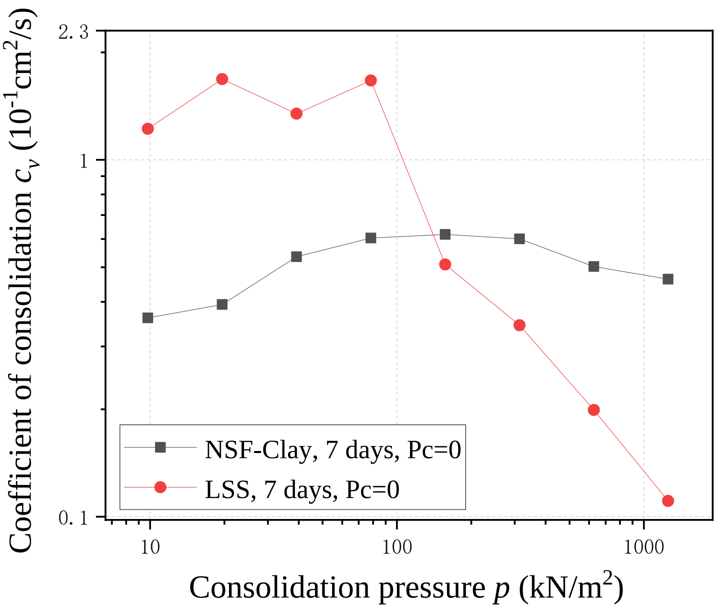

Figure 5-6 Variation of coefficient of consolidation with consolidation pressure (LSS and NSF-Clay)

From Figures 5-6 and related data, it is evident that NSF-Clay and LSS exhibit significant differences in consolidation behavior at different consolidation pressures. These differences arise from the varying compressibility and stability characteristics of their soil structures during the consolidation process. For NSF-Clay, the coefficient of consolidation initially increases with consolidation pressure, demonstrating typical compressive behavior. This indicates that NSF-Clay has higher compressibility at lower pressures, and as the pressure increases, the soil becomes more compact, increasing the coefficient of consolidation. However, after applying a higher pre-consolidation pressure 200 kN/m², the soil has already undergone some compression in the initial stage, which reduces its compressibility. As a result, the increase in consolidation coefficient slows down in subsequent stages. This could explain why NSF-Clay has a lower initial consolidation coefficient compared to LSS.

In contrast, LSS shows a decreasing trend in consolidation coefficient with increasing consolidation pressure, particularly after an initial rapid stabilization. This suggests that LSS, after stabilization treatment, forms a stronger soil structure, making it less sensitive to consolidation pressure. The inclusion of stabilizing materials reduces the soil's further compressibility, resulting in a more stable consolidation process.

Pre-consolidation pressure impacts NSF-Clay and LSS differently. NSF-Clay, when subjected to a pre-consolidation pressure of 200 kN/m², has already undergone some initial compression, reducing its compressibility during subsequent consolidation and leading to a slower increase in the consolidation coefficient over time. This behavior explains why NSF-Clay initially exhibits a lower consolidation coefficient compared to LSS, which hasn't undergone the same level of pre-consolidation. For LSS, the soil structure is relatively loose before consolidation, allowing it to undergo consolidation more readily and show a higher initial consolidation coefficient. As pressure increases, the consolidation coefficient of LSS decreases, possibly due to the stabilizing agents hardening the soil, limiting further compression.

Regarding consolidation rate and stability, LSS reaches a peak consolidation coefficient of about 1.35×10^{-1}cm²/s in the first loading stage, indicating faster stabilization. This rapid stabilization is attributed to the effects of cement and fibers, which improve the soil structure and make it less susceptible to further compression under increasing loads. Therefore, LSS is well-suited for applications requiring rapid consolidation and stability. In comparison, NSF-Clay reaches a maximum consolidation coefficient of 0.41×10^{-1}cm²/s only in the second loading stage, exhibiting a slower stabilization process. This slower consolidation rate is due to NSF-Clay's natural composition, which lacks the strengthening elements found in LSS.

When the consolidation pressure exceeds 600 kN/m², LSS's consolidation coefficient decreases with increasing pressure and then stabilizes. This indicates that at higher pressures, pore space decreases, and particle mobility is limited, restricting further compression and slowing the consolidation rate. This behavior suggests that LSS maintains steady consolidation under high pressure after an initial rapid stabilization, making it suitable for applications requiring both initial load-bearing capacity and long-term stability. In contrast, NSF-Clay exhibits a lower overall consolidation coefficient with slower compaction, making it more suitable for applications requiring lower load-bearing capacity or where longer consolidation periods are acceptable.

Conclusion:

NSF-Clay's consolidation coefficient is initially low and increases slowly after pre-consolidation pressure is applied, indicating a slower consolidation response. Without stabilizing additives, NSF-Clay shows more significant changes in the consolidation coefficient. In contrast, LSS shows a higher initial consolidation coefficient, which decreases with increasing pressure. The strengthened soil structure from stabilizing materials makes LSS less sensitive to further compression, making it ideal for high-pressure applications that demand both rapid consolidation and long-term stability.

5.5.2. Comparison of Coefficient of Permeability between LSS and NSF-Clay

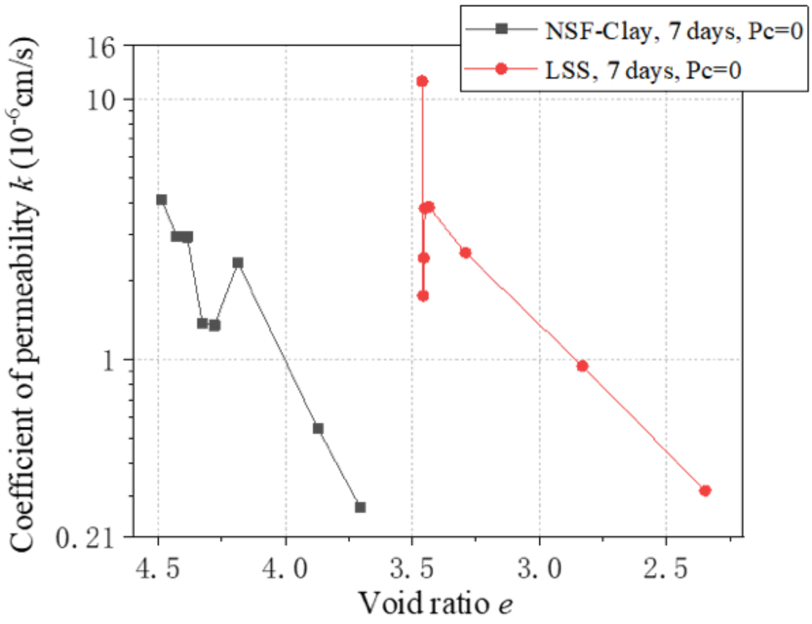

Figure 5-7 Variation of coefficient of permeability with void ratio (LSS and NSF-Clay)

Figures 5-7 present a comparative analysis of the relationship between the permeability coefficient and void ratio for NSF clay and LSS. The data highlight significant differences between the two materials under varying loading conditions, particularly regarding permeability and void ratio.

The permeability coefficient, reflecting the ease of water flow through the material, varies notably between LSS and NSF clay. Despite NSF clay having a relatively large void ratio, its permeability remains low. This is due to preloading pressure disrupting continuous water flow paths, limiting water movement even with ample pore space.

1. Relationship Between Permeability Coefficient and Void Ratio:

NSF clay shows a sharp decline in permeability as the void ratio decreases, indicating high sensitivity to compaction. At higher void ratios, its looser structure permits greater water flow, but as the soil compacts, permeability decreases rapidly.

LSS maintains relatively high permeability even at lower void ratios, with a more gradual decline. The stabilizing agents in LSS help preserve the soil structure, reducing sensitivity to compaction and consolidation.

2. Effect of Preloading Pressure on NSF Clay:

Applying 200 kN/m² preloading pressure partially compacts NSF clay, resulting in lower initial permeability during testing. Compared to LSS without preloading, NSF clay exhibits a reduced permeability coefficient from the outset.

The absence of stabilizing agents makes NSF clay highly sensitive to further consolidation, especially in denser conditions where permeability decreases rapidly under increased pressure.

3. Comparison Between LSS and NSF Clay:

LSS displays a more stable permeability profile, with gradual changes under increasing pressure. The stabilizing materials strengthen the soil structure, preventing sharp declines in permeability, making LSS ideal for applications needing consistent permeability under high pressures.

NSF clay, even after preloading, is more prone to significant permeability changes under higher consolidation pressures. Its sensitivity to compaction results in rapid permeability reductions, particularly at lower void ratios.

4. Conclusion:

NSF clay initially shows lower permeability than LSS after preloading but experiences rapid permeability reductions as consolidation pressure increases. Its permeability is highly influenced by compaction and consolidation.

LSS demonstrates greater permeability stability, retaining higher permeability even after compaction. The stabilizing materials reduce sensitivity to pressure changes, making it suitable for engineering applications demanding consistent permeability.

Summary:

NSF clay is highly sensitive to compaction, with permeability decreasing sharply under consolidation, while LSS maintains stable permeability due to its stabilizing agents. This makes LSS more suitable for conditions requiring steady water flow, even under high pressure.

5.5.3. Comparison of e-log p Curves between LSS and NSF-Clay

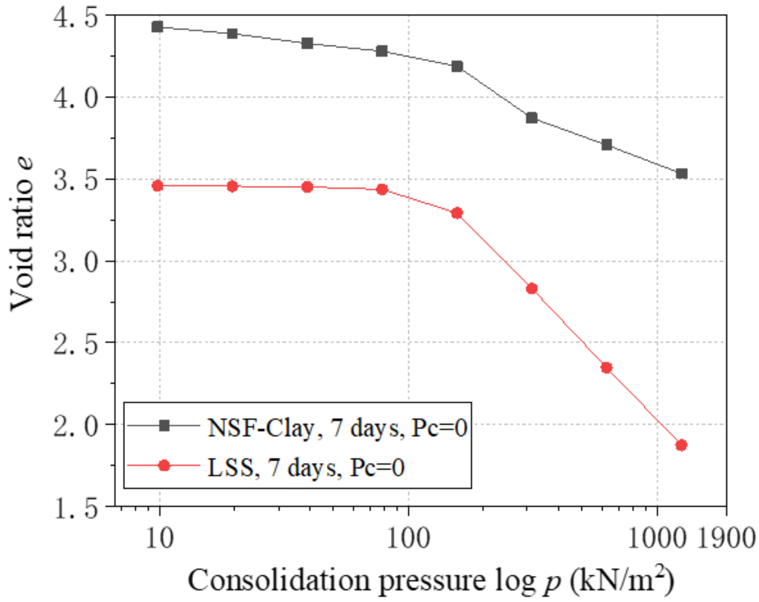

Figure 5-8 Variation of void ratio with consolidation pressure (LSS and NSF-Clay)

Figures 5-8 show the e-log p curves, illustrating the variation in the void ratio of NSF clay and LSS with respect to the applied load. It was observed that, compared to NSF clay, the void ratio of LSS changes less at low pressures, with cement-modified LSS exhibiting a more stable void ratio under low pressure. This can be attributed to the presence of cement, which binds the particles together, reducing the compressibility of the material. As a result, LSS exhibits enhanced structural stability and is less prone to volume reduction under low load conditions. The cement treatment in LSS significantly alters the soil structure by increasing the bonding between particles, forming a more rigid network that resists compression and maintains a relatively constant void ratio under low pressure.

As shown in the e-log p curves, the differences in behavior between NSF clay and LSS highlight the importance of modifying the base material to improve its performance in engineering applications. By incorporating cement and other stabilizers, LSS exhibits higher load-bearing capacity and lower compressibility, making it more suitable for applications such as foundation construction, embankment stabilization, and soil reinforcement. Additionally, this comparison provides valuable insights into how structural changes induced by binders affect the behavior of materials under load, ultimately contributing to the development of more durable and reliable geotechnical engineering materials.

Basic Observations from the e-log p Curve: The void ratio of NSF clay significantly decreases with increasing consolidation pressure, indicating that NSF clay is highly compressible. At lower pressures, the void ratio is larger, and as consolidation pressure increases, the voids within the soil are compressed, causing the void ratio to gradually decrease. This suggests that NSF clay responds more sensitively to pressure, particularly in the early stages, where increases in consolidation pressure result in significant compression. Similarly, the curve for LSS shows that the void ratio decreases with increasing consolidation pressure, but the change in the initial stages is relatively small.

This indicates that the soil structure of LSS responds more gently to consolidation pressure and does not experience significant compression at lower pressures like NSF clay.

Effect of Preloading on NSF Clay: The application of preload pressure (200 kPa) affects the e-log p curve of NSF clay. After applying a 200 kPa preload, the NSF clay may have undergone partial compaction in the initial stages, resulting in a smaller change in the void ratio compared to LSS, which did not undergo preloading. Due to the effect of the preload, NSF clay may show a more gradual change in void ratio during subsequent consolidation, especially at lower pressures. The effect of preloading is to reduce the voids in the soil, making it denser. Therefore, during the consolidation test, NSF clay subjected to preloading may not undergo significant compression in the initial stages, and the decrease in the void ratio may be more gradual.

Comparison between LSS and NSF Clay: The e-log p curve for LSS shows a more gradual initial decrease, indicating that the void ratio changes less during consolidation. The response of LSS to pressure is more stable, likely because the stabilizing materials added to LSS make the soil more rigid and reduce its sensitivity to consolidation pressure. This smooth curve indicates that LSS exhibits stable consolidation behavior and is less prone to significant compression under pressure.

NSF clay shows a larger change in void ratio at low consolidation pressures, indicating that its soil is more compressible at lower pressures. As pressure increases, the compaction effect on the soil becomes more pronounced. In contrast, the compressibility of LSS is smaller at the initial pressure, with less noticeable changes in the void ratio compared to NSF clay.

After applying a 200 kPa preload to NSF clay, the soil may have undergone partial compaction in the initial stages, which leads to a more gradual decrease in the void ratio during subsequent consolidation. This could result in a smoother e-log p curve for NSF clay compared to LSS. For LSS, the initial curve at low pressure is relatively flat, suggesting that the stabilizing materials help the soil to resist compression under pressure. The void ratio changes in LSS show that its structure adapts well to pressure variations.

Conclusion:

After applying a 200 kPa preload to NSF clay, the void ratio change under consolidation pressure may become more gradual, indicating that the preload effect makes the soil less prone to significant compression during subsequent consolidation. Lower pre-consolidation pressure in further experiments may yield more accurate results. The void ratio of LSS decreases gradually with increasing consolidation pressure, but the change is smaller initially, suggesting that LSS responds more stably to consolidation pressure, especially under higher consolidation pressures, where it maintains low compressibility.

5.5.4. Practical Applications of Experimental Results

Compared to NSF clay, LSS exhibits enhanced load-bearing capacity and stability. In contrast, the cement-modified structure of LSS resists deformation and maintains its integrity even under higher loads. This characteristic is crucial for applications requiring low compressibility and high stability, such as in foundation engineering and embankment construction.

The e-log p curve further demonstrates that while NSF clay may be effective in some cases, its ability to maintain structural integrity under substantial loads is limited. Adding stabilizers to LSS not only improves its mechanical properties but also reduces the likelihood of long-term settlement, ensuring better performance in geotechnical engineering applications. These insights help guide the design and optimization of soil stabilization technologies to meet specific engineering requirements.

5.6. Relationship between void ratio and consolidation pressure

5.6.1. The e-log p Curve

In consolidation tests, the e-log p curve typically represents the relationship between the void ratio (e) and the effective stress (log p). This curve is a critical tool in geotechnical engineering, reflecting the compressibility and consolidation behavior of soil under various loading conditions. The key implications of the curve are as follows:

1. Compressibility Characteristics

Initial compression stage: The initial part of the curve represents compression under low-stress levels, primarily dominated by elastic deformation. Primary compression stage: At higher stress levels, the curve generally exhibits a steeper linear decline, indicating the primary consolidation process is dominated by plastic deformation. Over-consolidation behavior: The shape of the e-log p curve can reveal whether the soil is normally consolidated (NC) or over-consolidated (OC), with over-consolidated soils exhibiting a distinct yield point.

2. Compression and Recompression Indices

The slopes of specific segments of the curve are used to calculate: 1). Compression index (Cc): The slope of the linear segment in the primary consolidation phase, representing the soil's compressibility. 2). Recompression index (Cr): The slope of the unloading segment, reflecting the soil's rebound capability.

3. Pre-consolidation Pressure

The shape of the e-log p curve helps identify the pre-consolidation pressure ($\sigma p'$), which can be estimated using methods such as Casagrande's procedure or the logarithmic method. This parameter is critical for distinguishing between normally consolidated and over-consolidated soils.

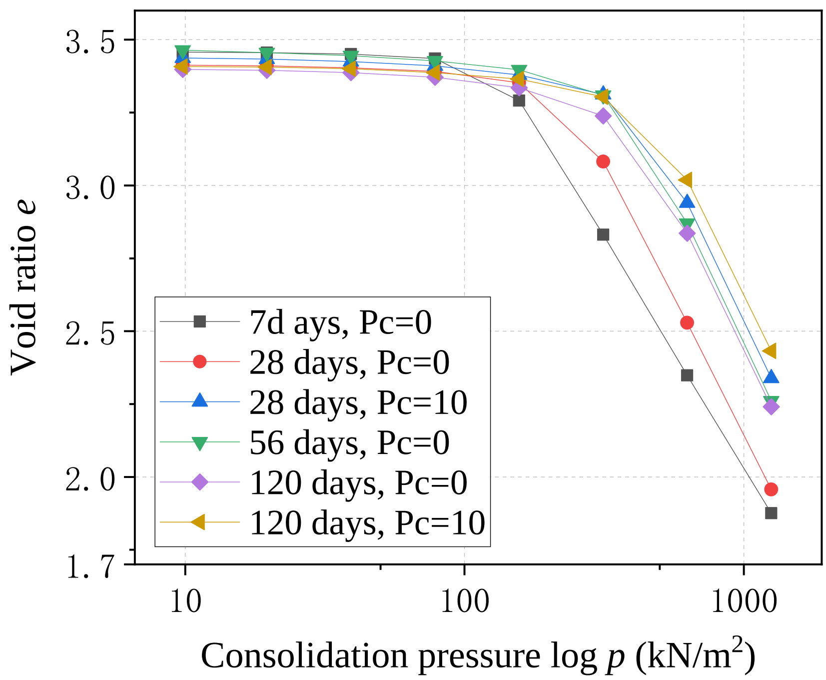

Figure 5-9 Relationship between void ratio and consolidation pressure

4. Void Ratio Variation

The curve directly illustrates the trend of void ratio changes with increasing stress, providing insights into the compressibility and consolidation characteristics of the soil.

Figure 5-9 shows the e-log p curves for specimens with 7, 28, 56, and 120 days of curing and fiber content of 0 and 10 kg/m³ respectively. From the trend of the e-log p relationship, it can be observed that the void ratio of LSS varies from 1.9 to 3.5 at consolidation pressures ranging from 9.8 to 1256 kN/m². The e-log p curves show a gradual decrease in the void ratio of LSS as the consolidation pressure increases. In addition, at lower consolidation pressures, the variations in the void ratio of LSS were not significant, and the void ratio of LSS with different curing days was almost the same for the same initial void ratio.

Figure 5-10 shows the e-log p curves for specimens with 7, 28, 56, and 120 days of curing, under the condition of no fiber material addition.

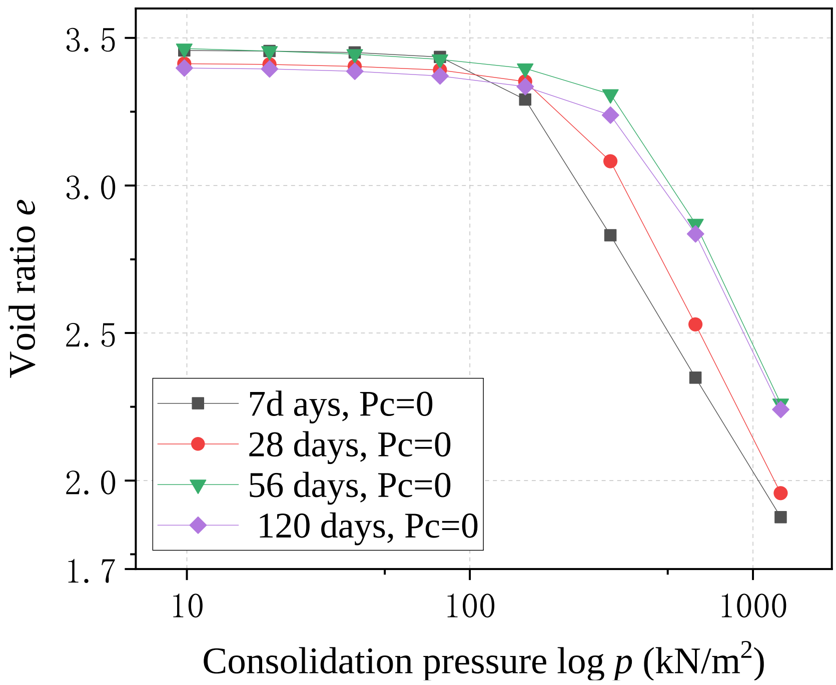

Figure 5-10 Relationship between void ratio and consolidation pressure (Pc=0)

From the figure, it can be seen that the void ratio of LSS with different curing days remains almost the same as the initial void ratio in the range of consolidation pressure is low. With the increase in the curing days, the void ratio shows a decreasing trend. After the consolidation pressure reaches 78.4 and 156.8, the LSS with shorter curing days shows a rapidly decreasing trend. The void ratio of the specimen with 7 days of curing was the first to decrease, followed by the specimen with 28 days, and the specimens with other curing days decreased more slowly. The LSS considered as having a lower curing day and large initial void ratio are more prone to change their void ratio under pressure.

Figure 5-11 shows the relationship between void ratio and consolidation pressure for specimens with 28 and 120 days of curing and 0 and 10 kg/m³ of fiber content. It can be observed from the figure that for the same curing days, the decrease in the void ratio of the specimens with the addition of fiber material is significantly slower compared to the specimens without fiber material. It can be found that the addition of fiber material improves the stability of LSS well under pressure.

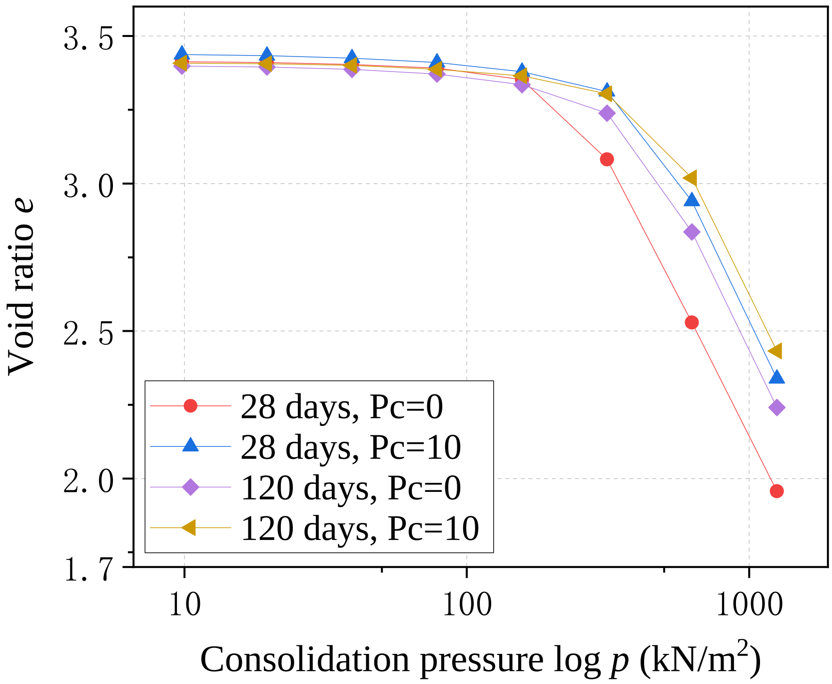

Figure 5-11 Relationship between void ratio and consolidation pressure (Pc=0,10)

5.6.2. Unloading

In the e-log p diagram, the unloading process is primarily used to analyze the rebound characteristics of soil, which plays a significant role in engineering design, foundation settlement assessment, and soil behavior prediction. The main applications and implications of the unloading process are as follows:

1. Determining the Soil's Recompression Index (Cr)

The slope of the unloading curve reflects the compressibility of soil during the unloading stage, referred to as the recompression index (Cr).

Calculation formula:
$$Cr = -\frac{\Delta e}{\Delta \log p}$$

Where Δe is the change in void ratio, and $\Delta \log p$ is the change in the logarithm of effective stress.

Significance: The recompression index (Cr) is a critical parameter for evaluating the elastic recovery potential of soil under stress reduction.

2. Simulating Unloading Conditions in Foundations

In practical engineering, soil may undergo stress reduction due to excavation, dewatering, or the removal of structures. The unloading curve in the e-log p diagram simulates these conditions, illustrating the transition of soil from plastic deformation to elastic deformation.

3. Evaluating Recoverable Settlement

In foundation settlement analysis, the unloading segment helps estimate the recoverable settlement of soil. After unloading, part of the settlement may be recovered (elastic rebound), while the plastic deformation remains irreversible. The e-log p diagram aids in distinguishing between recoverable and permanent settlements.

4. Studying Soil Elastic-Plastic Behavior

The unloading path in the e-log p diagram is useful for studying the elastic-plastic behavior of soil, particularly in understanding whether deformation during stress reduction is purely elastic or includes residual plastic deformation. This is important for analyzing soil deformation under repeated loading and unloading cycles.

5. Verifying the Behavior of Over consolidated Soils

For over-consolidated soils (OC), the unloading path in the e-log p diagram is particularly significant: Over-consolidated soils exhibit notable elastic recovery during unloading. The unloading curve helps validate the over-consolidation ratio (OCR) and provides insight into subsequent loading behavior.

1. Changes in Void ratio

Loading Phase:

All samples exhibited a significant decrease in void ratio when loaded to 1256 kN/m², indicating considerable compression behavior. The sample with a lower slurry density (95%) experienced the greatest compression, with a Void ratio decrease from 4.4 to 2.441, resulting in a compression of 1.959. The sample with a higher slurry density (105%) showed less compression, with void ratio decreasing from 2.75 to 2.002, resulting in a compression of 0.748. The sample with a slurry density of 100% showed a moderate compression of 1.288, with void ratio decreasing from 3.45 to 2.162 (As shown in Figure 5-12, 5-13).

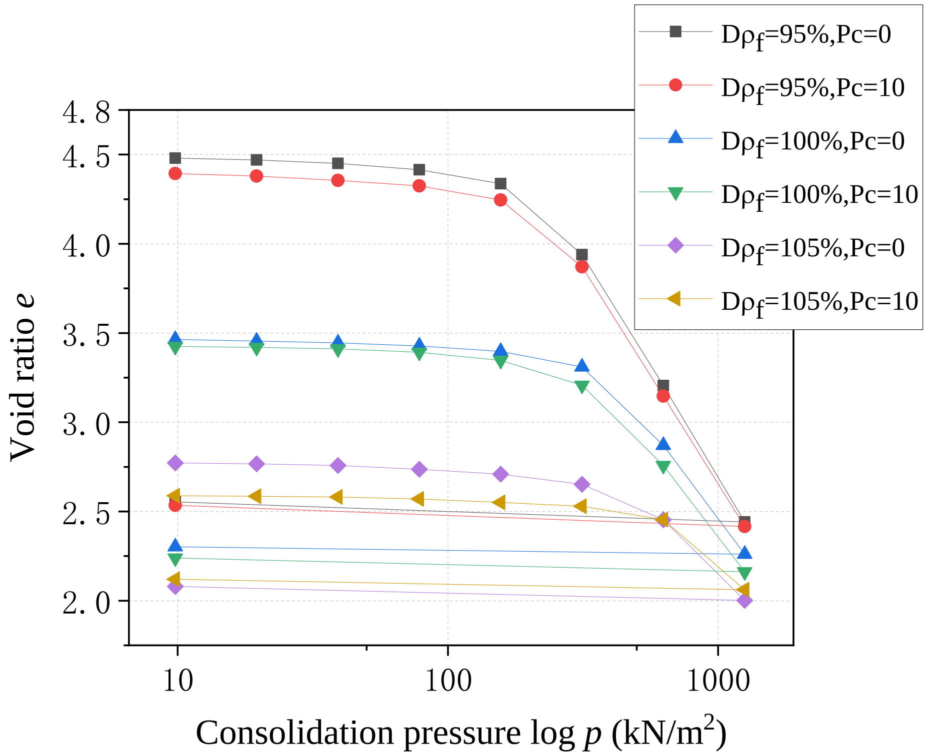

Figure 5-12 Relationship between void ratio and consolidation pressure (with unloading)

Unloading Phase:

After unloading to 9.8 kN/m² and resting for 24 hours, the samples exhibited a slight increase in void ratio. The sample with a slurry density of 95% showed the greatest rebound, with a rebound of 0.113, indicating a higher elastic recovery. The samples with slurry densities of 100% and 105% showed smaller rebound amounts, 0.087 and 0.078, respectively, indicating weaker rebound capabilities.

2. Effect of Slurry Density on Sample Behavior

Compression Behavior:

The sample with a lower slurry density (95%) showed a larger compression deformation, suggesting that higher initial Void ratio makes the material more compressible under pressure. The sample with a higher slurry density (105%) exhibited less compression, indicating that the lower initial Void ratio results in lower compressibility. The sample with a slurry density of 100% showed intermediate compression between the 95% and 105% samples.

Rebound Behavior:

After unloading, the sample with a lower slurry density (95%) exhibited a larger rebound, indicating a looser pore structure with a stronger elastic recovery ability. The sample with a higher slurry density (105%) showed a smaller rebound, suggesting a more compact structure with weaker rebound capacity. The sample with a slurry density of 100% had a rebound value between the two.

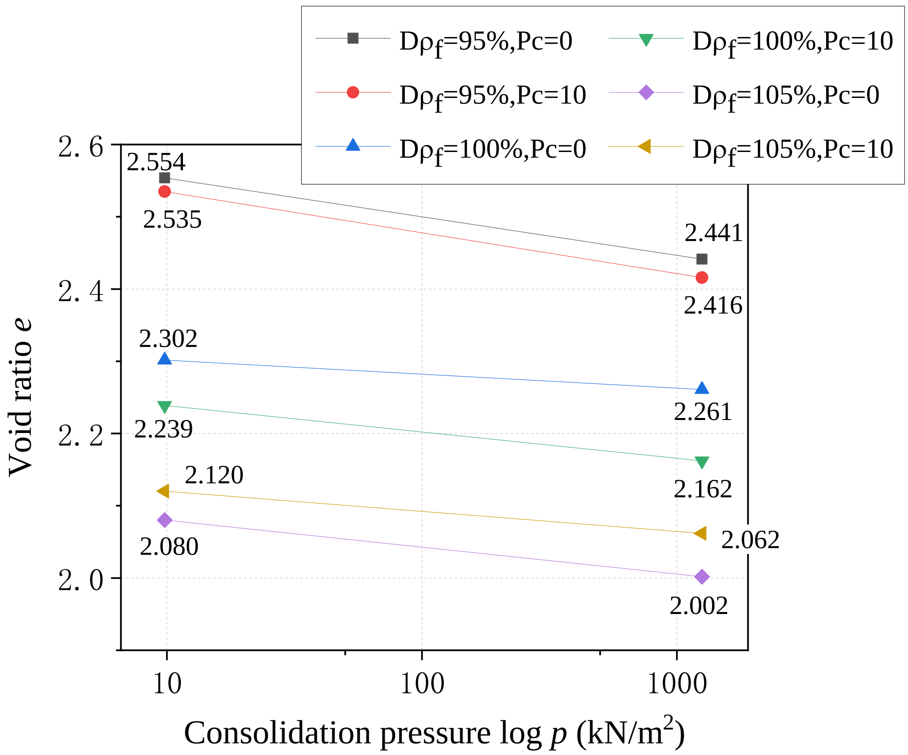

Figure 5-13 Relationship between void ratio and consolidation pressure (p=1256 kN/m² and unloading)

3. Behavior in Loading and Unloading Phases

After Loading:

All samples showed significant decreases in Void ratio during the loading phase, indicating irreversible compression of the soil. The sample with a lower slurry density exhibited greater compression, while the sample with a higher slurry density showed less compression.

After Unloading:

Following unloading, all samples showed some degree of rebound, but the rebound was relatively small, suggesting significant plastic deformation during the loading phase. The sample with a lower slurry density exhibited stronger elastic recovery, while the sample with a higher slurry density had a weaker rebound.

Effect of Slurry Density on Compression and Rebound Behavior:

Lower slurry density results in a sample with a higher initial Void ratio, leading to greater compression and stronger rebound. Conversely, higher slurry density results in a sample with lower initial Void ratio, leading to smaller compression and weaker rebound.

Impact of Initial Void ratio on Compression Potential:

Samples with higher initial Void ratio (such as those with 95% slurry density) experience larger compression and exhibit stronger rebound. In contrast, samples with higher slurry density (105%) show smaller compression and weaker rebound.

5.6.3. Consolidation Yield Stress of LSS

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 5-1.

Table 5-1 Consolidation yields stress of LSS

Specimen ID	Yield stress (kN/m^2)
$D\rho_f$ = 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

Effect of Slurry Density on Yield Stress

As shown in figure 5-14, as the slurry density increased from 95% to 105%, the yield stress of both fiber-reinforced and non-fiber-reinforced samples showed significant improvement. Specifically: The yield stress of fiber-reinforced samples increased from 231.6 kN/m² to 478.6 kN/m². The yield stress of non-fiber-reinforced samples increased from 199.5 kN/m² to 447.5 kN/m². This trend indicates that an increase in slurry density enhances the soil's resistance to compression.

Effect of Fiber Materials on Yield Stress

Under the same slurry density conditions, the yield stress of fiber-reinforced samples was higher than that of non-fiber-reinforced samples. For instance: At a slurry density of 95%, the yield stress of fiber-reinforced samples was approximately 32.1 kN/m² higher than that of non-fiber-reinforced samples. At a slurry density of 105%, this difference increased to 31.1 kN/m². This suggests that the addition of fiber materials enhances the soil's yield resistance, although its impact is relatively smaller compared to the influence of slurry density.

Relationship Between Void Ratio and Yield Stress

In the e-logp curve, significant changes in the void ratio consistently occur near the yield stress, indicating that yield stress is the critical point were soil transitions from elastic deformation to plastic deformation. Within this pressure range, the soil structure compresses rapidly, resulting in a notable reduction in the void ratio.

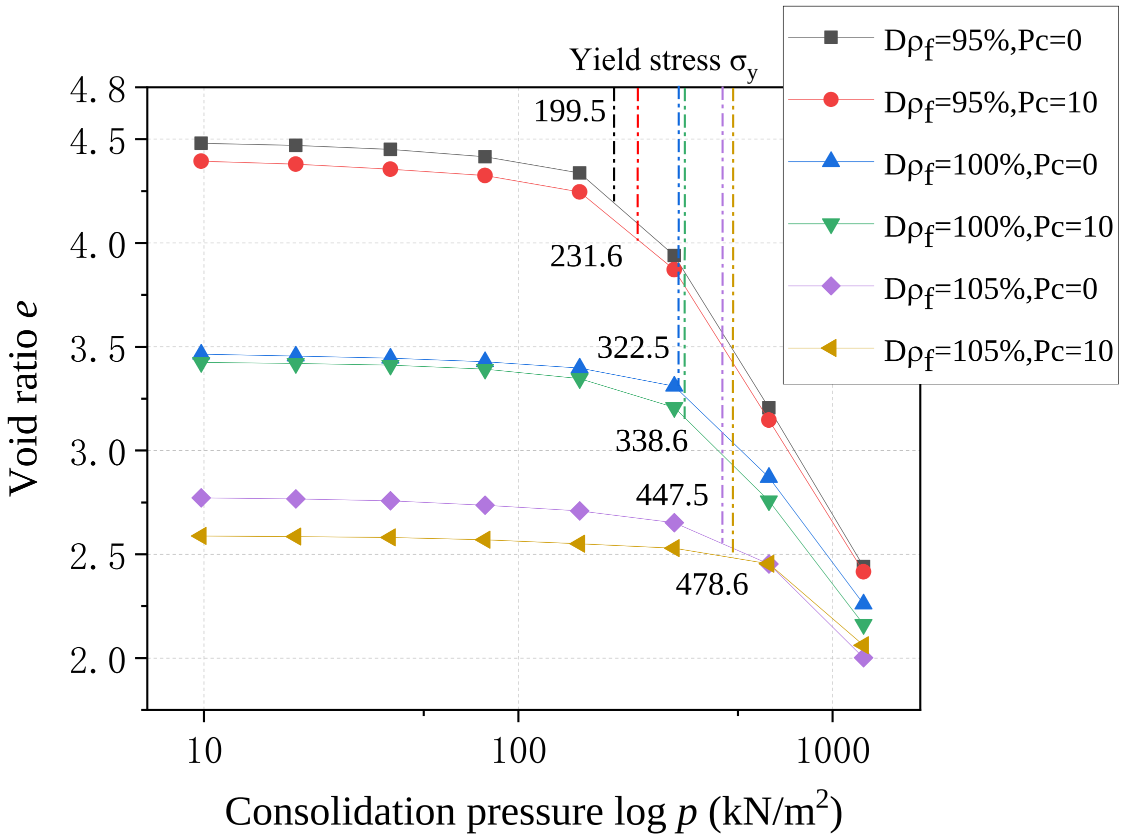

Figure 5-14 Relationship between void ratio and consolidation pressure (with yield stress)

Increasing slurry density significantly enhances the yield stress and compression resistance of the samples. The addition of fiber materials also contributes to the improvement of yield stress, though its effect is less pronounced compared to slurry density. The evident changes in the void ratio are closely related to yielding stress, making yielding stress a key indicator for evaluating the compression resistance of soils.

5.6.4. Practical Applications of Experimental Results

Impact of Excavation: In underground excavation or foundation pit projects, the unloading process may cause deformation in surrounding soils. The unloading segment in the e-log p diagram assists in evaluating the recoverability of such deformations.

Cyclic Loading Effects: Under cyclic loading, such as traffic or seismic loads, soils experience multiple loading-unloading cycles. The e-log p diagram is instrumental in analyzing the effects of cyclic loading on soil compressibility.

The unloading segment in the e-log p diagram provides valuable insights into the rebound behavior of soil, enabling the evaluation of elastic recovery, foundation settlement, and over-consolidated soil characteristics. By analyzing the unloading curve, engineers can more accurately predict soil deformation under unloading conditions and optimize design and construction strategies accordingly.

In this experiment, the unloading process was conducted as follows: after the test reached the final loading stage, the specimen was unloaded to an effective stress of 9.8 kN/m^2. The specimen was then allowed to rest under this stress for 24 hours to ensure that the deformation had fully stabilized. After the resting period, the final height of the specimen was measured and recorded. This unloading procedure was designed to simulate the rebound and deformation behavior of soil under unloading conditions in practical engineering, providing reliable data for analyzing the specimen's rebound and compressibility characteristics.

Engineering Recommendations:

Based on the slurry density and Void ratio of the soil, soil compression and rebound behavior can be adjusted for specific engineering applications. Soils with lower slurry density are suitable for scenarios where larger deformations and stronger rebound are required, while soils with higher slurry density are suitable for applications where smaller deformations and weaker rebound are desired.

5.7. Relationship Between Coefficient of Consolidation and Pressure of LSS

5.7.1. The Influence of Slurry Density on Consolidation Characteristics

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. Figure 5-15 shows the correlation between the coefficients of consolidation and consolidation pressures in consolidation tests. The legend illustrates the different slurry densities (Dρf = 95 %, 100 %, and 105 %) and fiber contents (0 and 10 kg/m3) for the specimens.

As shown in Figure 5-15, the experimental results reveal that the coefficient of consolidation of LSS varies between 0.1 and 1.9 × 10^{-1} cm^2/s under the consolidation pressure ranges from 9.8 to 1256 kN/m^2. 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/m^2, the coefficient of consolidation starts to decrease. After 200 kN/m^2, 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/m^2, the specimen with a slurry density of 95 % already exhibits cv = 0.4 × 10^{-1} cm^2/s, while the specimens with slurry densities of 100 % and 105 % show cv = 1.2 × 10^{-1} cm^2/s and 1.7 × 10^{-1} cm^2/s, respectively. After 600 kN/m^2, the difference between the coefficients of consolidation of LSS with different slurry densities becomes smaller gradually.

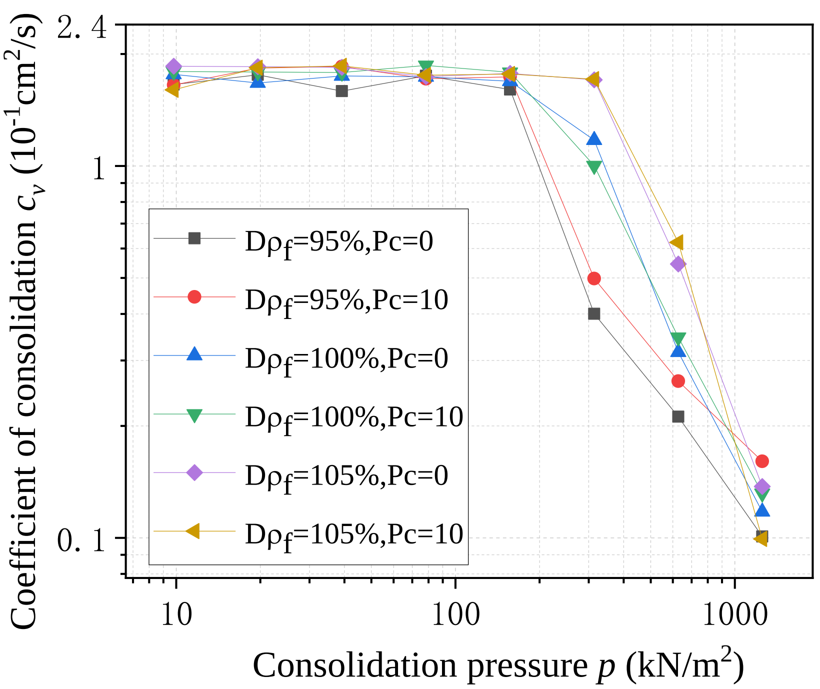

Figure 5-15 Relationship between the coefficient of consolidation and pressure (slurry density)

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 Figure 5-16, 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 Dρf =95 % and Dρf =100 % decrease rapidly, while the decrease in the coefficient of consolidation for specimens with Dρf =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 Dρf =95 % and 200 to 600 kN/m² for Dρf =100 %. When the consolidation pressure exceeds 400 kN/m², the coefficient of consolidation of the Dρf =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.

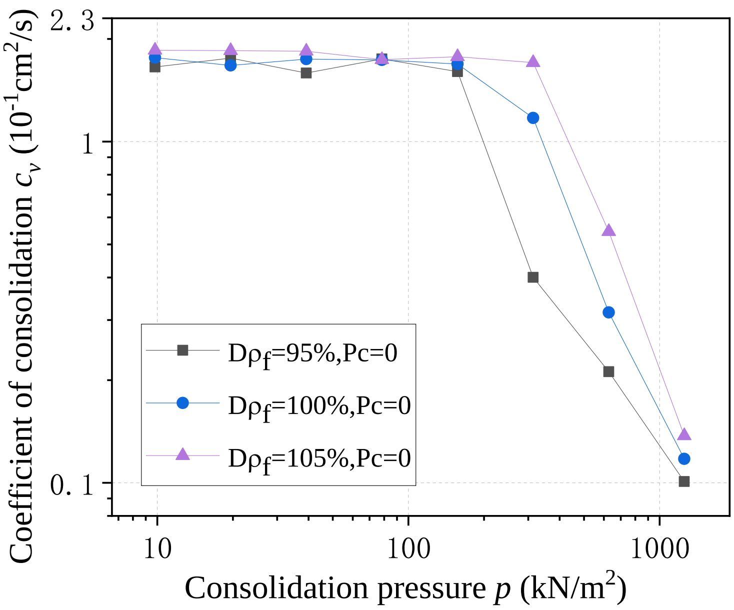

Figure 5-16 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0)

Considering the consolidation yield stress presented in Table 5-1, 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, as seen in Figure 5-16, for Dρf =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 Dρf =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.

5.7.2. The Influence of Curing Days on Consolidation Characteristics

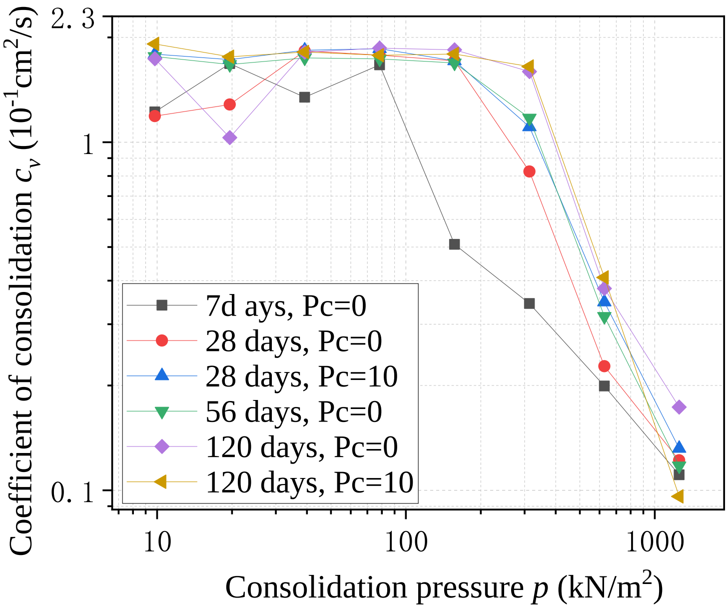

Figure 5-17 Relationship between the coefficient of consolidation and consolidation pressure (curing days)

By analyzing the relationship between the consolidation pressure applied to the specimen and the coefficient of consolidation, we can observe the variation coefficient of consolidation of the LSS varied for different curing days and fiber content. Figure 5-17 shows the correlation between the coefficient of consolidation and the consolidation pressures in the consolidation test. The legend of the figure indicates the different curing periods (7, 28, 56, and 120 days) and fiber contents (0 and 10 kg/m3) of the specimens.

As shown in Figure 5-17, the experimental data indicate that the coefficient of consolidation of LSS varies between 0.09 and 1.9 × 10^{-1} cm²/s in the consolidation pressure range of 9.8 to 1256 kN/m². The observed results show that the coefficient of consolidation of LSS decreases with increasing pressure. For the general trend, the coefficient of consolidation of the specimens was relatively stable in the lower pressure region, but when the consolidation pressure reached 156.8 kN/m², the coefficient of consolidations began to show a significant decrease. At a consolidation pressure of 313.6 kN/m², the coefficient of consolidation of the specimens with 7 days of curing was about 0.3 × 10^-1 cm²/s, whereas those of the specimens with 28, 56 and 120 days of curing were 0.8 × 10^{-1} cm²/s, 1.2 × 10^{-1} cm²/s, and 1.6 × 10^{-1} cm²/s, respectively. when the consolidation pressure reached above 627.2 kN/m², the differences in the coefficient of consolidation of LSS specimens with different curing days were gradually reduced.

Figure 5-18 illustrates the relationship between the coefficient of consolidation and consolidation pressure for specimens with curing days of 7, 28, 56, and 120, under the condition of no fiber material addition.

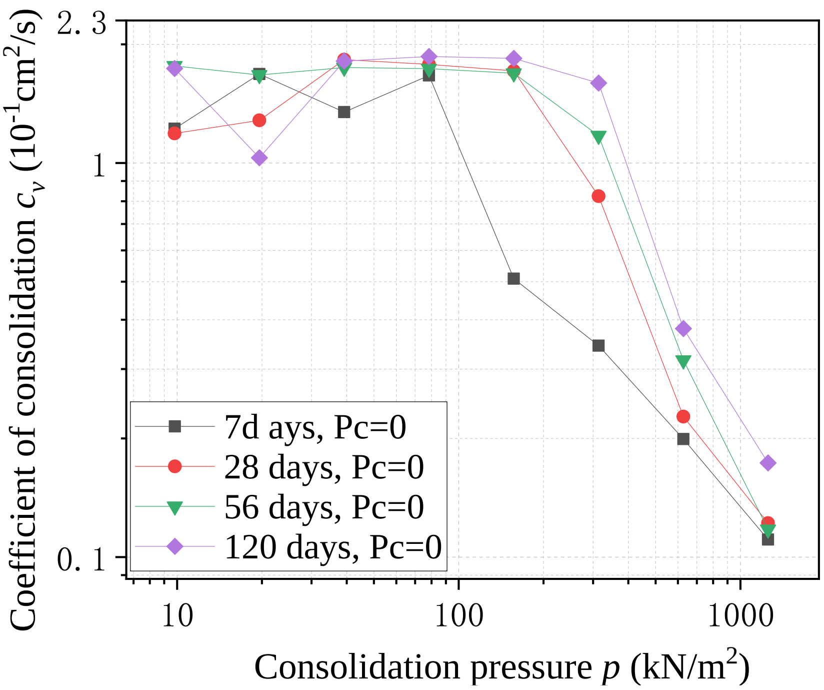

Figure 5-18 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0, curing days)

Without the addition of fiber material, it can be observed by comparing the curing days that the coefficient of consolidation of LSS increases with the curing days. The individual specimens at the beginning of the loading stage showed slightly different fluctuations, but all of them were in the range of 1~ 2 × 10^{-1} cm^2/s. The LSSs were also found to have a higher coefficient of consolidation at the beginning of the loading stage. At a consolidation pressure of 78.4 kN/m^2, the coefficient of consolidations of the individual specimens showed similar values. At a consolidation pressure of 156.8 kN/m^2, the coefficient of consolidation of the 28 and 56-day curing specimens decreases more rapidly, while the coefficient of consolidation of the 120-day curing specimens decreases slightly more slowly. In particular, the 7-day curing specimens show more significant fluctuations. At a pressure of 156.8 kN/m^2, the coefficient of consolidation is about an order of magnitude lower than for the other specimens.

Without the addition of fiber material, it can be observed by comparing the curing days that the coefficient of consolidation of LSS increases with the curing days. The individual specimens at the beginning of the loading stage showed slightly different fluctuations, but all of them were in the range of 1~ 2 × 10^{-1} cm^2/s. The LSSs were also found to have a higher coefficient of consolidation at the beginning of the loading stage. At a consolidation pressure of 78.4 kN/m^2, the coefficient of consolidations of the individual specimens showed similar values. At a consolidation pressure of 156.8 kN/m^2, the coefficient of consolidation of the 28 and 56-day curing specimens decreases more rapidly, while the coefficient of consolidation of the 120-day curing specimens decreases slightly more slowly. In particular, the 7-day curing specimens show more significant fluctuations. At a pressure of 156.8 kN/m^2, the coefficient of consolidation is about an order of magnitude lower than for the other specimens.

5.7.3. The Influence of Fiber Content on Consolidation Characteristics

The relationship between the coefficient of consolidation and consolidation pressure for specimens is shown in Figure 5-19, with slurry densities of 95 %, with fiber content of 0 and 10 kg/m³. From Figure 5-19, 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.

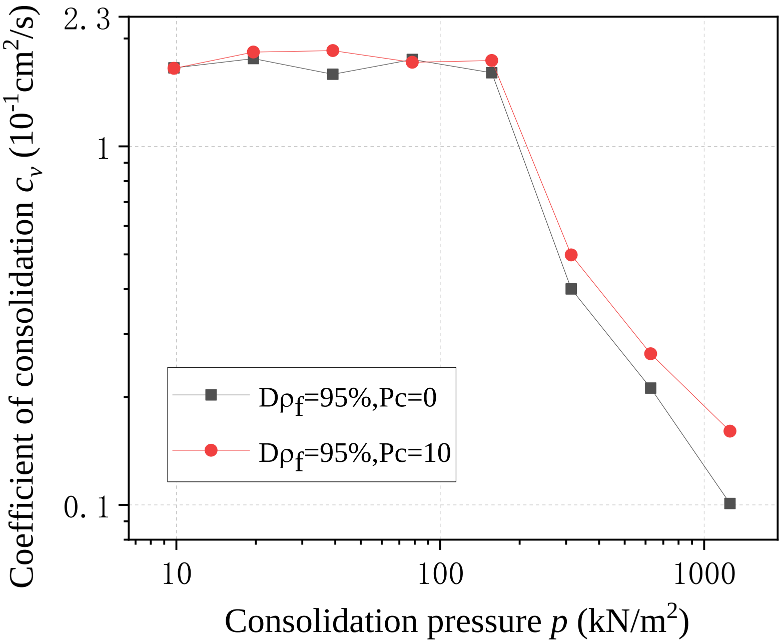

Figure 5-19 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0,10,Dρf =95%)

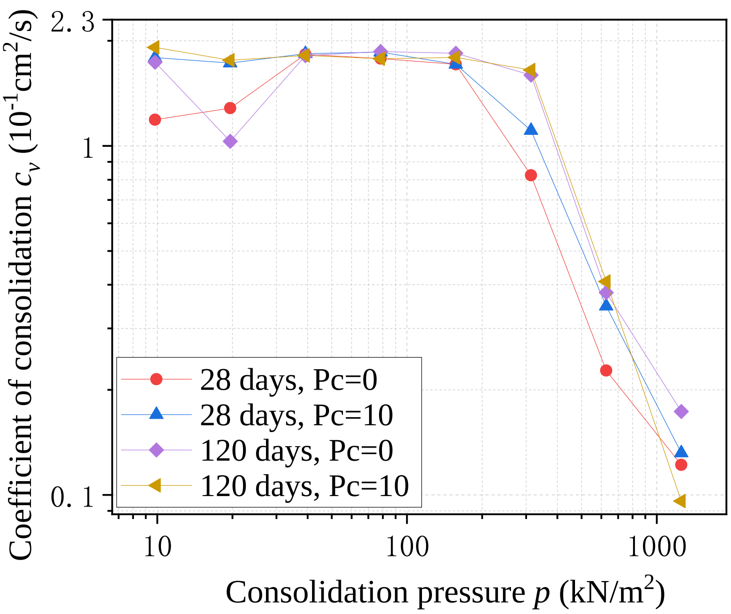

Figure 5-20 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0,10, curing days)

Figure 5-20 shows the relationship between the coefficient of consolidation and consolidation pressure for specimens with curing days of 28 and 120, with a fiber content of 0 and 10 kg/m³.

From Figure 5-20, it can be observed that the coefficient of consolidations of LSS with different fiber contents is very close for the same curing days. However, the coefficient of consolidation of the specimens with added fiber material is slightly higher compared to the specimens without fiber material, especially at 28 days when curing days are not too long.

5.7.4. Practical Applications of Experimental Results

1. Influence of Slurry Density

The experimental results highlight the significant impact of slurry density on the coefficient of consolidation. As the slurry density increases, LSS specimens demonstrate greater stability under higher consolidation pressures, with a slower decline in the coefficient of consolidation. This suggests that higher slurry densities contribute to enhanced structural integrity and resistance to deformation under loading.

In practical applications, such as in embankments or backfill materials, optimizing slurry density can improve the settlement control and load-bearing capacity of LSS. For instance, areas requiring rapid construction may benefit from using higher slurry densities to minimize excessive settlement during the early stages of loading.

2. Influence of Curing Days

The curing period significantly affects the consolidation behavior of LSS. Specimens cured for longer durations exhibit higher coefficients of consolidation and more gradual decreases under higher consolidation pressures. This indicates that extended curing enhances the strength and stability of LSS.

In real-world engineering projects, this implies that allowing sufficient curing time can improve the long-term performance of LSS, especially in applications requiring sustained load-bearing capacity. For example, in soft soil foundation improvements, ensuring adequate curing periods can mitigate excessive settlement and improve the durability of the treated soil.

3. Influence of Fiber Content

The addition of fiber material slightly increases the coefficient of consolidation, particularly during early curing stages. This indicates that fibers help reinforce the soil structure, leading to better load distribution and reduced compressibility.

For practical applications, adding fibers to LSS can enhance its resistance to deformation, making it suitable for scenarios involving repeated or dynamic loading, such as road construction or airport runways. Moreover, the use of fibers could be a sustainable solution for improving soil properties while reducing the reliance on cement.

Overall Significance

The study's findings underscore the importance of optimizing slurry density, curing time, and fiber content for tailoring the consolidation characteristics of LSS to specific engineering requirements. These factors play a crucial role in ensuring the stability, durability, and performance of LSS in various geotechnical applications, making the material a versatile and sustainable choice for soil stabilization and improvement projects.

5.8. Variation of coefficient of consolidation with void ratio

5.8.1. Variation of coefficient of consolidation with void ratio

The cv -e relations for specimens with slurry densities of 95 %, 100 %, and 105 %, and fiber content of 0 and 10 kg/m³ are shown in Figure 5-21. At the low-pressure level, as the consolidation pressure increases, the void ratio decreases rapidly, leading to a sharp decline in cv. However, when the void ratio reaches a certain value, a decreasing tendency of cv decreases. For the specimens of Dρf = 95 %, the inflection points where cv 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 Dρf = 95 % specimen is in a relatively dense state. Similarly, for the specimens of Dρf = 100 %, the inflection point is around 600 kN/m², suggesting a relatively dense state when the consolidation pressure exceeds 600 kN/m².

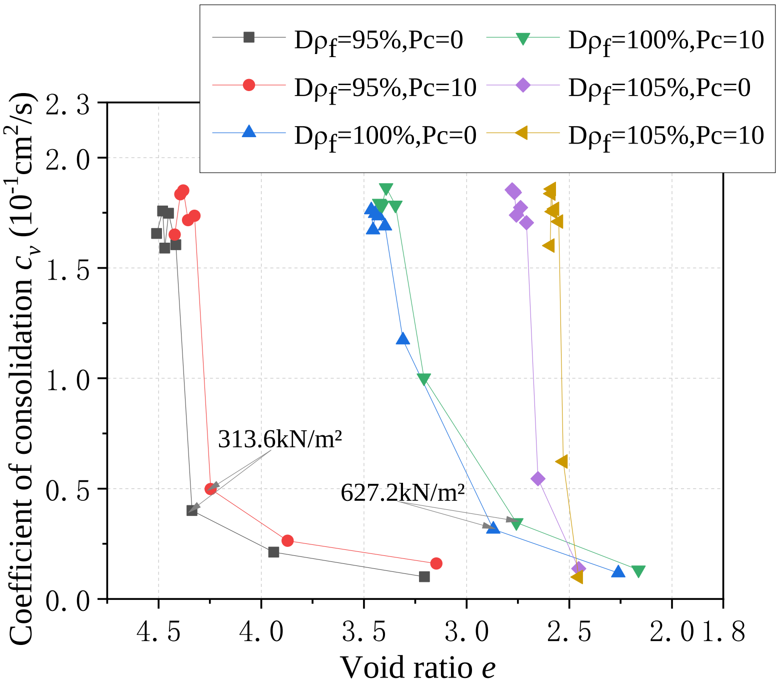

Figure 5-21 Relationship between the coefficient of consolidation and void ratio

The relationship between compression height and consolidation pressure is presented in Figure 5-22. 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.

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 specimens 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.

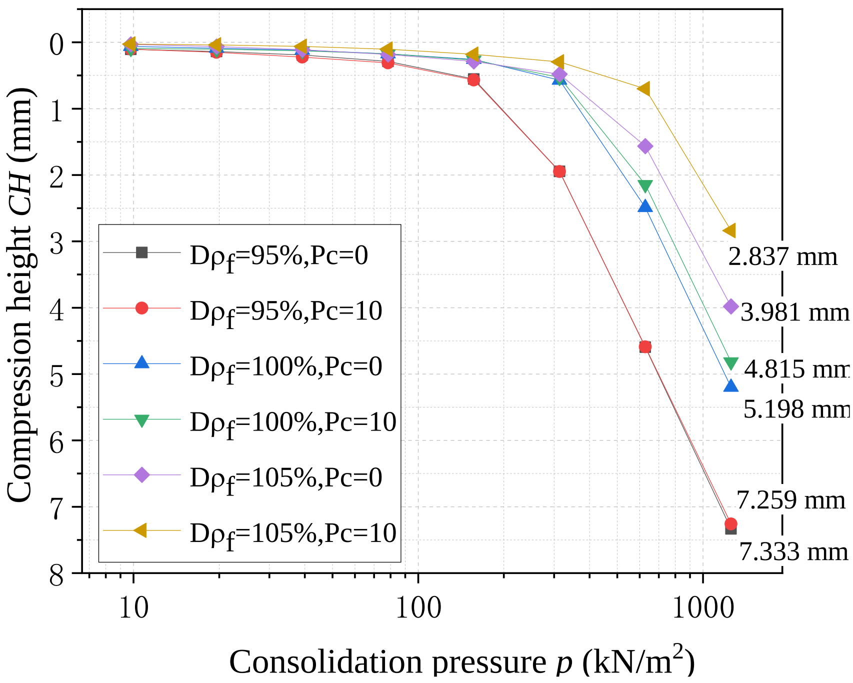

Figure 5-22 Relationship between the compression height and consolidation pressure

5.8.2. Practical Applications of Experimental Results

The relationship between the coefficient of consolidation (cv) and void ratio (e) highlights critical insights for practical engineering applications. The observed inflection points in cv-e relationships for specimens with varying slurry densities provide valuable benchmarks for estimating soil densification behavior under increasing consolidation pressures:

Densification Thresholds and Soil Stability:

For the Dρf = 95 % specimens, the inflection point occurs at approximately 300 kN/m², indicating that soils with lower slurry density reach a relatively dense state at lower pressures. This implies that in engineering practices involving soft soil foundations with lower slurry densities, careful attention should be given to consolidation pressures exceeding this threshold to ensure stability and prevent excessive settlement.

Conversely, for Dρf = 100 % and 105 %, the higher inflection points (600 kN/m² and beyond) suggest that these soils can withstand higher consolidation pressures before achieving a dense state. This behavior makes higher-density LSS suitable for applications requiring higher load-bearing capacities, such as highway embankments or heavy structural foundations.

Optimized Soil Improvement Strategies:

The cv-e trends indicate that soils with higher slurry densities exhibit slower rates of void ratio reduction. This aligns with practical measures to reduce settlement risks in construction projects. For instance, preloading or vacuum consolidation techniques could effectively accelerate the compression process for lower-density LSS, ensuring the desired soil properties are achieved before construction begins.

The data 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/m^2, the compression height begins to increase, though the rate of consolidation remains relatively slow. However, at pressures above 300 kN/m^2, there is a significant increase in compression height, indicating an acceleration of the consolidation process.

The compression height in specimens 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.

Summary

The experimental results provide important references for the application of liquefied stabilized soil (LSS) with different slurry densities in practical engineering. Combining the analysis of the cv-e relationship and CH-p relationship, high-density LSS is suitable for high-load, low-settlement conditions, while low-density LSS offers the advantage of quickly reaching a dense state. These findings can optimize material selection and construction processes in engineering design, improving the safety and cost-effectiveness of infrastructure construction.

5.9. The Influence of coefficient of volume compressibility on Consolidation Characteristics

The coefficient of volume compressibility (denoted as m_v) is a parameter in soil mechanics used to describe the volume compressibility of soil under applied pressure. It represents the volume change per unit volume of soil due to a unit change in pressure. Common units for m_v are m^2/MN or cm^2/kN.

Formula

The coefficient of volume compressibility m_v is defined as:

$$m_v = \frac{\Delta V / V}{\Delta \sigma}$$

where:

ΔV is the change in volume,

V is the original volume of the soil,

$\Delta \sigma$ is the change in effective stress.

Calculation Method

In a compression test, the coefficient of volume compressibility m_v can be determined by calculating the slope of the compression curve:

$$m_v = \frac{\Delta e}{\Delta \sigma} \cdot (1 + e_0)$$

where:

Δe is the change in void ratio,

e_0 is the initial void ratio,

$\Delta \sigma$ is the change in effective stress.

Physical Significance

A larger m_v value indicates that the soil experiences a greater volume change under the same stress change, meaning it is more compressible.

A smaller m_v value means the soil is less compressible and resists volume changes more effectively.

The coefficient of volume compressibility is crucial in soil consolidation analysis, especially for predicting settlement and analyzing ground deformation in foundation and geotechnical engineering.

The coefficient of volume compressibility (mv) and the coefficient of consolidation (c_v) are two key parameters in soil mechanics, and they are closely related. The coefficient of consolidation c_v is an indicator that describes the rate of soil consolidation and is related to the volume compressibility, the soil's permeability (coefficient of permeability k), and the unit weight of water (γ_w) through the following equation:

$$c_v = \frac{k}{m_v \cdot \gamma_w}$$

Explanation of Parameters

Coefficient of Volume Compressibility m_v: Describes the degree of volume deformation of soil under unit pressure. A larger m_v indicates that the soil is more compressible.

Coefficient of Permeability k: Describes the flowability of water within the soil. Higher permeability allows water to drain out more easily.

Coefficient of Consolidation c_v: Represents the rate of consolidation. A larger c_v value implies a faster consolidation rate.

Relationship Analysis

From the formula, we see that the coefficient of consolidation c_v is influenced by both the volume compressibility m_v and the permeability k:

1) When the volume compressibility c_v increases (indicating that the soil is more compressible), the coefficient of consolidation c_v decreases. This is because higher compressibility results in greater volume deformation requirements, which means the consolidation process takes longer under the same permeability conditions, leading to a slower consolidation rate.
2) When the coefficient of permeability k increases (indicating that water can be expelled more easily), the coefficient of consolidation c_v increases. This means that water drains out more quickly, accelerating the consolidation rate, allowing the soil to reach a stable state faster.

Engineering Significance

In practical engineering applications, controlling the volume compressibility and permeability allows adjustment of the consolidation rate of soil. For foundations where rapid consolidation is desired, choosing soil with lower volume compressibility or enhancing its permeability can increase consolidation efficiency.

In cement-stabilized clay, specimens with higher initial mud-water density typically have a lower coefficient of consolidation. Here's an analysis of the reasons:

Reduced Void ratio: A higher initial mud-water density indicates lower water content in the soil at the start of consolidation, which means smaller gaps between particles. This lower Void ratio reduces the channels for water to drain, thereby decreasing the permeability of the soil.

Decreased Coefficient of permeability: High mud-water density usually makes the soil more compact, which reduces its permeability (k). Since the coefficient of permeability is an important component of the coefficient of consolidation (c_v), a lower permeability will also result in a lower coefficient of consolidation.

Enhanced Structural Stability: A higher-density mud-water slurry helps form a more stable soil structure, which tends to resist compression and water discharge. This resistance slows down the rate of water expulsion and thus prolongs the consolidation process.

When the coefficient of volume compressibility (m_v) also changes significantly, the situation becomes slightly more complex. Since the coefficient of consolidation (c_v) is determined by both permeability and compressibility, a significant increase or decrease in compressibility can affect the consolidation rate.

1. When the Volume Compressibility Coefficient Increases Significantly

If m_v increases significantly (indicating the soil is more compressible), then the volume deformation of the soil underload will increase. This has the following effects:

Possible Decrease in the Coefficient of Consolidation: With higher compressibility, the soil's demand for compression increases, extending the consolidation process and potentially slowing down the overall consolidation rate. As a result, even with high permeability, the consolidation rate might be restricted by the increase in compressibility, reducing c_v

Increased Significance of Permeability: In this scenario, permeability more directly impacts the rate of water discharge. If permeability is low (slow drainage), the increased demand for compression can further slow down the consolidation rate.

2. When the Volume Compressibility Coefficient Decreases Significantly

If mv decreases significantly (indicating the soil is less compressible), the compression required is reduced, which can facilitate faster consolidation. The effects include:

Possible Increase in the Coefficient of consolidation: With lower volume deformation demand, the consolidation process can be faster, potentially increasing the coefficient of consolidation c_v as long as the water discharge rate is sufficient.

Continued Importance of Permeability: However, if permeability is low, even with decreased compressibility, the slow water discharge rate can still delay consolidation, leading to a coefficient of consolidation that may remain lower than expected.

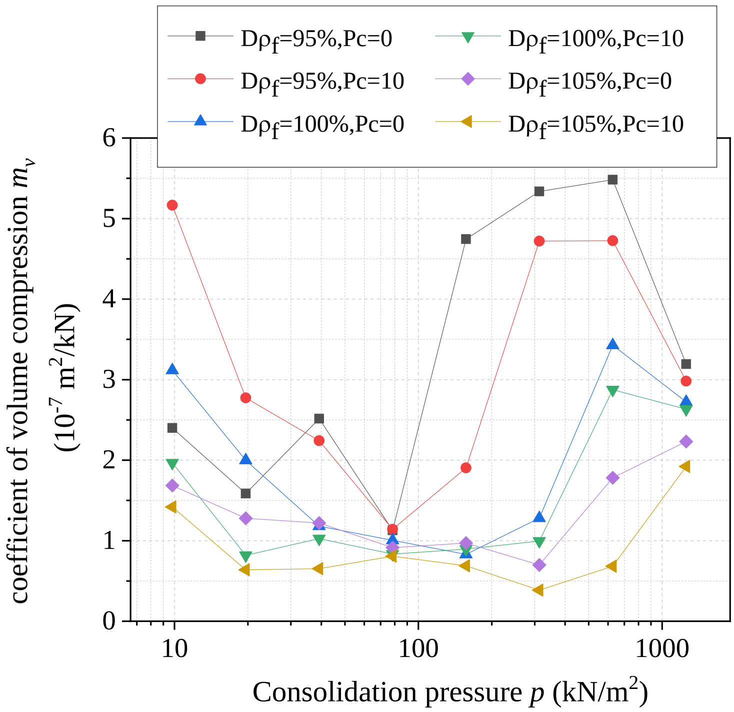

Figure 5-23 Relationship between the coefficient of volume compression and consolidation pressure

As shown in the figure, in this experiment, the coefficient of volume compressibility shows a significant decreasing trend with the increase in slurry density and fiber content. Therefore, in this experiment, specimens with higher mud-water density exhibit a higher coefficient of consolidation compared to those with lower slurry density.

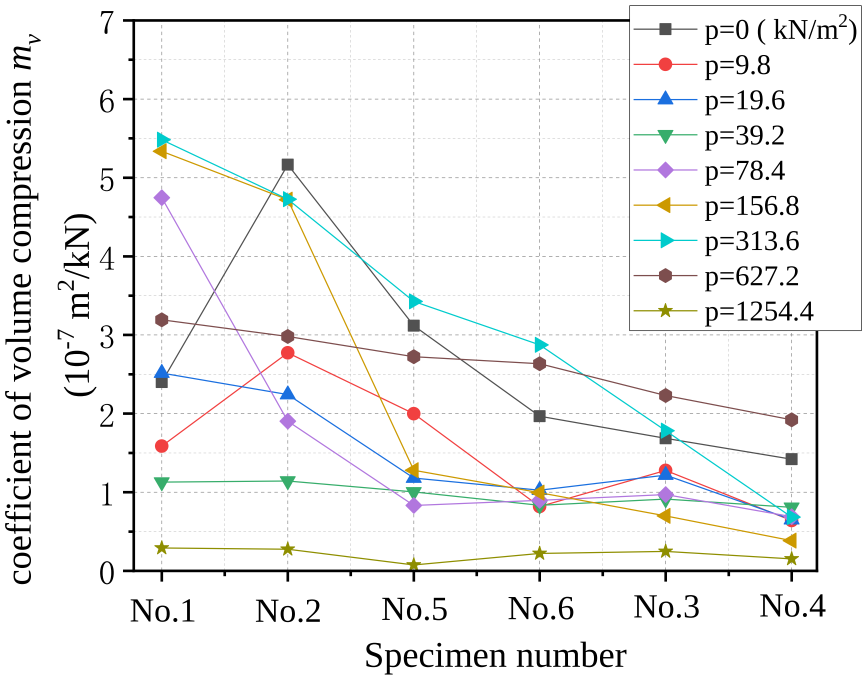

Figure 5-24 Relationship between the coefficient of consolidation and consolidation pressure (Pc=0)

The notable change in the coefficient of volume compressibility further impacts the consolidation rate, with a decrease in compressibility leading to an increase in the coefficient of consolidation. When compressibility is low, the consolidation rate tends to accelerate, potentially increasing the coefficient of consolidation, as seen in Specimens No.3 and 4 (slurry density is 105%, Pc = 0, 10). Conversely, when compressibility is high, as observed in Specimens No.1 and 2 (slurry density is 95%, Pc = 0, 10), the consolidation rate slows down further, and the coefficient of consolidation decreases.

CHAPTER 6

RESULTS AND DISCUSSION OF THE PERMEABILITY PROPERTY OF LIQUEFIED STABILIZED SOIL PREPARED BY VARIOUS CONDITIONS

6. Results And Discussion of The Permeability Property of Liquefied Stabilized Soil Prepared by Various Conditions

6.1. Introduction

This chapter investigates the permeability characteristics of liquefied stabilized soil (LSS) under various conditions using permeability tests. The coefficient of permeability, denoted as k, is a crucial parameter that indicates the soil's capacity for water transmission. This coefficient is strongly influenced by factors such as slurry density, curing time, and fiber content in the soil. Understanding how these factors affect k is essential for optimizing the engineering applications of LSS, particularly in soft ground improvement.

In this study, a one-dimensional permeability test was conducted to analyze the relationships between the coefficient of permeability, consolidation pressure, and void ratio. The results reveal how the permeability of LSS changes with varying slurry densities, curing times, and fiber content. It was found that increased curing time and higher slurry density typically lead to a reduction in permeability, enhancing the material's water resistance and making it more suitable for applications in soft soil stabilization.

The findings offer valuable insights into the suitability of LSS for applications in soft soil stabilization, where effective water drainage is necessary for structural stability and longevity. Understanding the permeability of LSS under different conditions is essential for determining its effectiveness as a material for improving the load-bearing capacity of soft soils, preventing water infiltration, and ensuring long-term stability in civil engineering projects.

The results are intended to inform practical approaches to improve the design and performance of LSS as a backfill and stabilization material. By studying the interactions of consolidation pressure, void ratio, and permeability in LSS, this chapter provides a scientific basis for advancing the use of LSS in engineering practice. The optimization of these factors can contribute to the development of more effective and durable ground improvement solutions, particularly in challenging environments where water infiltration and soil instability are concerns.

Overall, the study contributes to the understanding of how various factors influence the permeability of LSS, providing key information that can be applied in future research and practical engineering applications to enhance the use of LSS in soil stabilization.

6.2. Relationship between Coefficient of Permeability and 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:

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

In the Equation:

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/m^3)

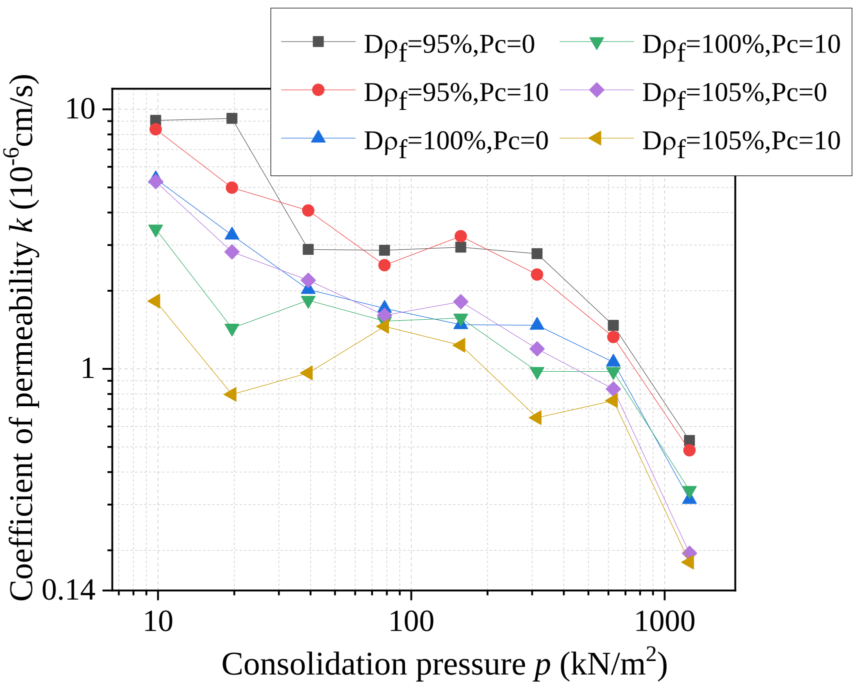

Figure 6-1 Variation of coefficient of permeability with consolidation pressure

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 Figure 6-1. As can be seen from the figure, 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.

6.2.1. 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 %.

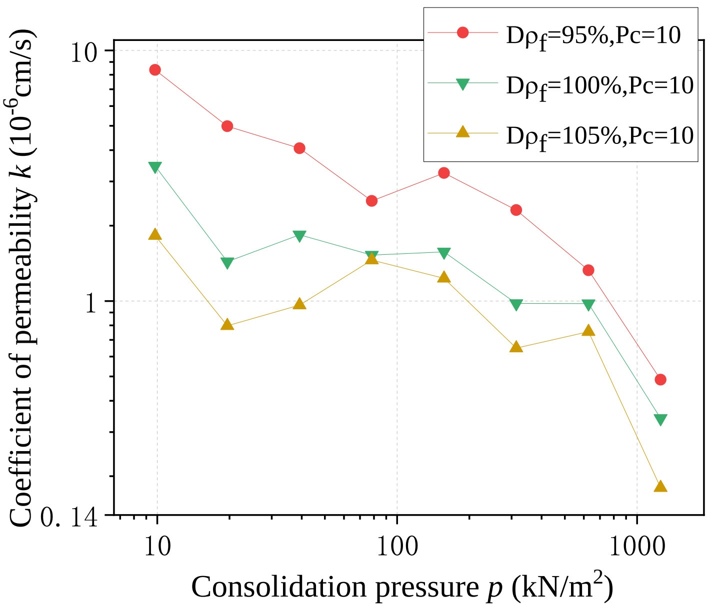

Figure 6-2 Variation of coefficient of permeability with consolidation pressure (Pc=10)

As shown in Figure 6-2, the coefficient of permeability initially maintains a steady trend around a consolidation pressure of 100 kN/m², and then gradually decreases, ultimately reaching values on the order of 10^{-7} cm/s. This behavior suggests that, with increasing consolidation pressure, the specimens become denser, reducing the permeability specifically, under high pressure, the pore structure of the LSS is compressed, which diminishes the connectivity between the pores and limits the flow of water through the material. Consequently, LSS is considered to have been transformed into an impermeable material under these high-pressure conditions.

For the LSS specimens used in this study, which were cured for 28 days, the coefficient of permeability is on the order of 1×10^{-6} cm/s. This value indicates that, after curing, the LSS achieves a level of permeability that is generally suitable for common engineering applications, such as foundation stabilization, embankments, and water-retention structures, where low permeability is essential to prevent water infiltration and enhance the material's long-term stability.

The observed reduction in permeability under consolidation pressure and overtime highlights the ability of LSS to become increasingly impermeable as the material densifies, making it suitable for a wide range of construction and stabilization applications. The 28-day curing period provides a balance between achieving low permeability and maintaining manageable processing times for practical use in engineering projects.

6.2.2. The Influence of Curing Days on Permeability Characteristics

Figure 6-3 shows the relationship between the coefficient of permeability and consolidation pressure for specimens with 7, 28, 56, and 120 days of curing and fiber content of 0 and 10 kg/m³ respectively. From Figure 10, the coefficient of permeability of LSS decreases with the increase of consolidation pressure. The trend of the coefficient of permeability is more sensitive at lower pressures and decreases rapidly at the beginning of loading. It is considered that the high compressibility of LSS. During the initial loading, the large and medium pores in the LSS decrease, and the small pores, which are difficult to permeate, increase. As the pressure increases, the change becomes less obvious and stabilizes around 100 kN/m² consolidation pressure. The coefficient of permeability of the LSS with 7 days of curing was the most affected by the consolidation pressure, with a change of 1 to 2 orders of magnitude.

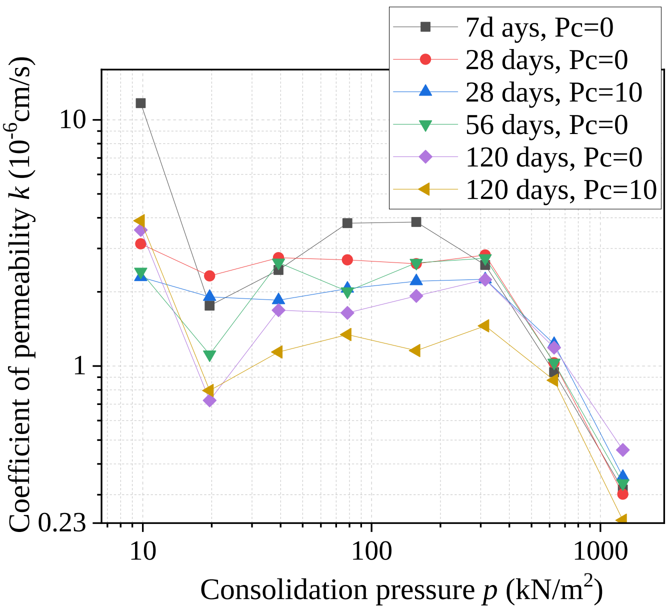

Figure 6-3 Variation of coefficient of permeability with consolidation pressure

Figure 6-4 depicts the relationship between the coefficient of permeability and consolidation pressure of the LSS specimens cured for 7, 28, 56, and 120 days. A comparison of the results for different curing periods reveals a clear trend: the coefficient of permeability of LSS decreases as the curing time increases. Specifically, the average coefficient of permeability for the LSS is 3.4×10^{-6} cm/s after 7 days of curing, 2.2×10^{-6} cm/s after 28 days, 1.9×10^{-6} cm/s after 56 days, and 1.7×10^{-6} cm/s after 120 days.

The decrease in permeability over time can be attributed to the chemical and physical processes occurring during curing. As the curing period increases, cementitious reactions in the LSS mix continue to solidify and bond the soil particles more effectively, reducing the overall pore volume and the connectivity of the pore network. This results in a tighter, more compact structure, which inhibits water flow through the material.

The overall coefficient of permeability of the LSS, after curing for 28, 56, and 120 days, tends to stabilize at values close to 1×10^{-6} cm/s, indicating relatively high permeability resistance. This demonstrates that, over time, LSS becomes increasingly effective at resisting water infiltration, which is a critical property for its use in geotechnical applications where low permeability is required, such as in foundation improvement, embankments, and water-retention structures.

In summary, the curing time plays a significant role in enhancing the impermeability of LSS. The longer the curing period, the lower the permeability, which improves the material's suitability for applications that demand high resistance to water flow. The decrease in permeability over time highlights the importance of curing conditions in optimizing the performance of LSS for construction and stabilization projects.

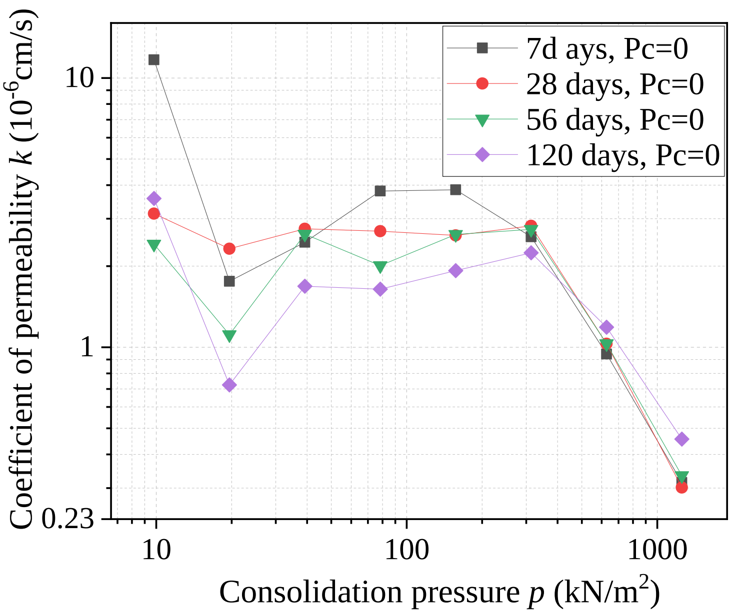

Figure 6-4 Variation of coefficient of permeability with consolidation pressure with consolidation pressure (Pc=0)

6.2.3. The Influence of Fiber Content on Permeability Characteristics

As shown in Figure 6-5, under the same slurry density conditions, a comparison of different fiber contents reveals a significant impact on the coefficient of permeability specifically, for LSS without fiber material (Pc =

0), the coefficient of permeability is approximately 5.3×10^{-6} cm/s. In contrast, when 10 kg/m³ of fiber material is incorporated into the LSS, the coefficient of permeability drops to between 1.8×10^{-6} cm/s. This indicates a clear reduction in permeability upon the addition of fiber material, highlighting the beneficial effect of fibers in improving the impermeability of LSS.

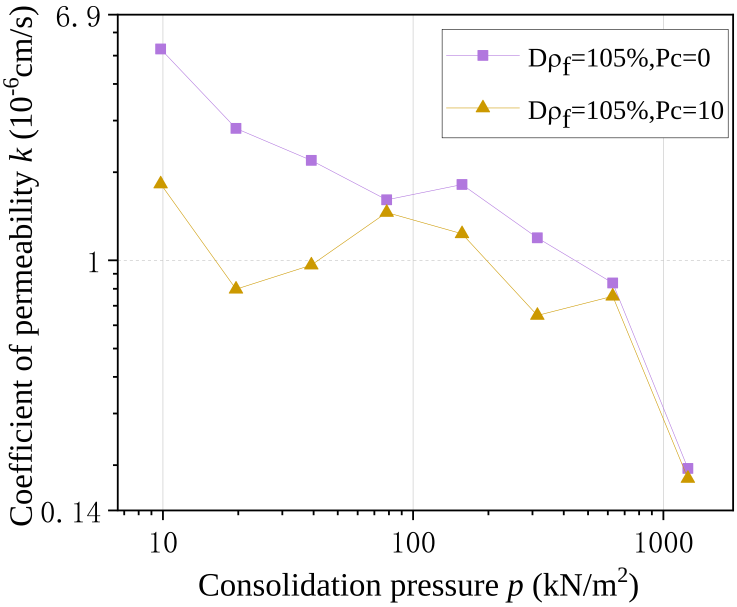

Figure 6-5 Variation of coefficient of permeability with consolidation pressure ($D\rho_f$ =105 %)

Mechanism Behind Reduced Permeability with Fiber Addition:

The addition of fiber materials to LSS plays a significant role in modifying its permeability characteristics. Fibers can improve the structure of the soil matrix by providing internal reinforcement. This reinforcement helps to distribute stress more evenly across the soil, filling some of the void spaces and reducing the overall flow paths for water. The result is a denser network of soil particles, which reduces the overall permeability of the material.

Influence of Slurry Density on Permeability:

The coefficient of permeability is also closely related to the slurry density of the LSS. As the slurry density increases, the soil particles are more tightly packed, leading to a reduction in the size of voids and the number of interconnected pores. This densification effectively reduces the water pathways, further lowering the coefficient of permeability. Therefore, increasing slurry density not only enhances the material's overall strength but also plays a critical role in reducing its permeability, making it more effective in applications requiring low water infiltration.

Conclusion:

In summary, the addition of fiber material significantly decreases the permeability of LSS, demonstrating its role in improving impermeability. Additionally, increasing slurry density further enhances this effect by reducing void size and improving particle packing. This combination of factors is essential for optimizing LSS for various engineering applications, particularly in environments where water resistance and long-term durability are critical.

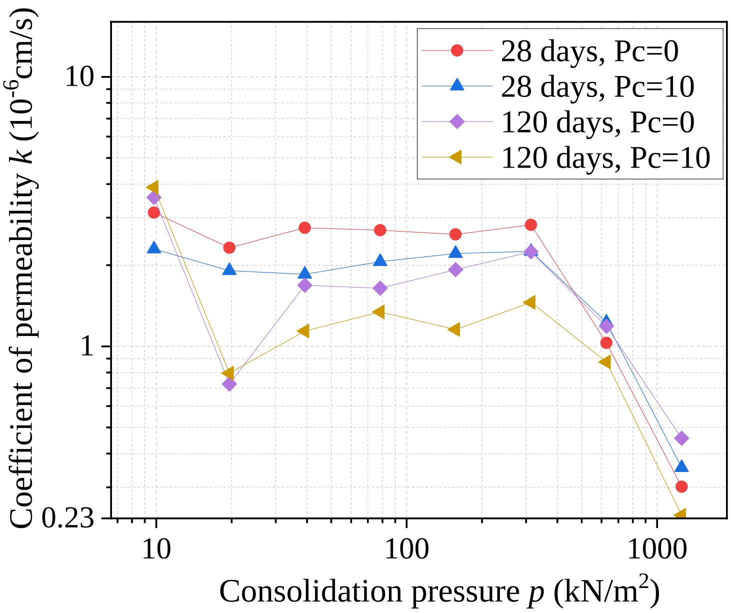

Figure 6-6 Variation of coefficient of permeability with consolidation pressure with consolidation pressure (Pc=0,10)

The curing time plays a crucial role in the performance of liquefied stabilized soil (LSS), particularly in terms of its consolidation and permeability characteristics. The results from Figure 6-6 show a clear comparison of the coefficient of permeability for specimens with different curing times of 28 and 120 days, under two different fiber contents (0 and 10 kg/m³). It is evident that as the curing time increases, the coefficient of permeability decreases for both fiber contents.

Impact of Curing Time on Permeability:

Chemical Binding and Cementation: As curing time increases, the chemical reactions between the cement and soil particles continue to progress. This leads to enhanced bonding and cementation, which results in a denser microstructure and smaller pore spaces within the LSS. This densification of the soil matrix significantly reduces the pathways available for water flow, thereby lowering the coefficient of permeability.

Long-Term Structural Development: With longer curing periods, the soil's structural integrity improves due to the development of stronger cementitious bonds. Over time, the LSS becomes more stable, and the permeability decreases further, contributing to enhanced resistance to water infiltration. This is especially beneficial in applications where long-term soil stability and water retention are critical, such as in embankments and foundations.

Effect of Fiber Content and Curing Time Interaction: When fiber content is added, the reduction in permeability becomes even more pronounced with extended curing time. The fibers, in combination with the cementing agent, help to improve the overall mechanical strength and connectivity within the soil matrix, further reducing the permeability. This interaction between fibers and curing time plays a crucial role in enhancing the overall performance of LSS, particularly in terms of its durability and resistance to water infiltration.

Conclusion:

The effect of curing time on the coefficient of permeability is significant, with longer curing times leading to lower permeability values. The chemical binding and cementation processes continue to improve the soil structure over time, enhancing its ability to resist water flow. The results indicate that extending the curing period not only improves the mechanical strength of LSS but also its resistance to water infiltration, making it a more durable and stable material for various engineering applications.

6.2.4. Practical Applications of Experimental Results

1. Impact of Reduced Permeability on Engineering Stability

The experimental results indicate that the permeability coefficient of LSS (Liquefied Stabilized Soil) decreases significantly with increasing consolidation pressure and curing time. This low permeability is critical for engineering projects, particularly in scenarios where water infiltration needs to be prevented, such as:

Foundation Reinforcement: In building or infrastructure projects, low permeability reduces groundwater erosion of the foundation, enhancing long-term stability.

Hydraulic Engineering: For applications such as dam bases and reservoir liners, low permeability effectively prevents leakage, preserving structural integrity.

2. Potential of Fiber Addition to Improve Material Performance

The inclusion of fiber materials in the experiments significantly reduced permeability, indicating that fibers enhance the compactness of the internal structure of LSS.

Crack Resistance: The reinforcing effect of fibers not only lowers permeability but also improves the crack resistance of the material, making it more durable in long-term use.

Application Scenarios: Fiber-reinforced LSS can be widely used in high-water-pressure environments, such as underground tunnels, subway construction, and floodwalls.

3. Effect of Slurry Density on Material Stability

The experimental results for different slurry densities show that higher slurry densities significantly reduce permeability coefficients. This suggests that higher-density LSS is suitable for engineering environments requiring high strength and low permeability.

Filling Material: In urban construction, high-density LSS can be used as backfill material, providing better foundation support.

Pollution Control: High-density LSS can be applied in landfill liner systems or contaminated soil containment projects to prevent hazardous substances from leaking.

4. Optimization of Long-Term Performance Through Curing Time

As curing time increases, the permeability coefficient decreases further, demonstrating the continuous improvement of LSS performance during chemical bonding and solidification.

Construction Planning: For projects requiring high performance, longer curing times can be employed to achieve optimal results.

Long-Term Stability: This time-dependent effect makes LSS highly suitable for projects requiring long-term impermeability, such as bridge foundations and port construction.

Practical Application:

Based on the above analysis, your experimental results have broad practical application potential in the following areas:

Ground Improvement: The low permeability and high density of LSS make it an ideal material for soft soil ground treatment.

Environmental Engineering: LSS can be used for landfill liners and pollution containment barriers to effectively prevent leakage and provide long-term protection.

Urban Underground Space Development: In high-water-pressure environments such as subways and underground parking lots, the low permeability and enhanced structural performance of LSS significantly improve construction safety and durability.

Hydraulic and Protective Engineering: LSS can serve as a reliable impermeable material in dams, slopes, and reservoir bases.

By promoting the application of these experimental results, LSS can demonstrate greater value in engineering fields while providing technical support for sustainable construction and resource reuse.

6.3. Variation of coefficient of permeability with void ratio

6.3.1. Variation of coefficient of permeability with void ratio

Figure 6-7 illustrates the relationship between the coefficient of permeability (k) and void ratio (e), showing the comparison of specimens with slurry densities of 95%, 100%, and 105%, and fiber contents of 0 and 10 kg/m³. The data reveals how variations in slurry density and fiber content can influence the permeability of the specimens. For cohesive soils, which are sensitive to changes in moisture content and pore structure, the water channels within the soil matrix are critical factors that govern the flow of water through the material. Small changes in the arrangement of soil particles, as influenced by variations in slurry density or fiber content, can significantly affect the connectivity of the pore spaces, thereby altering the permeability.

The relationship between slurry density and permeability is particularly important in understanding how soil behavior changes under different compaction conditions. At lower slurry densities (e.g., 95%), the soil tends to have more loosely packed particles, resulting in larger voids and a higher coefficient of permeability. As the slurry density increases (to 100% and 105%), the particles are more tightly packed, reducing the available void space and thereby decreasing the permeability. The addition of fibers also contributes to reducing permeability by improving the soil structure, enhancing its cohesion, and potentially decreasing the size and connectivity of the pores.

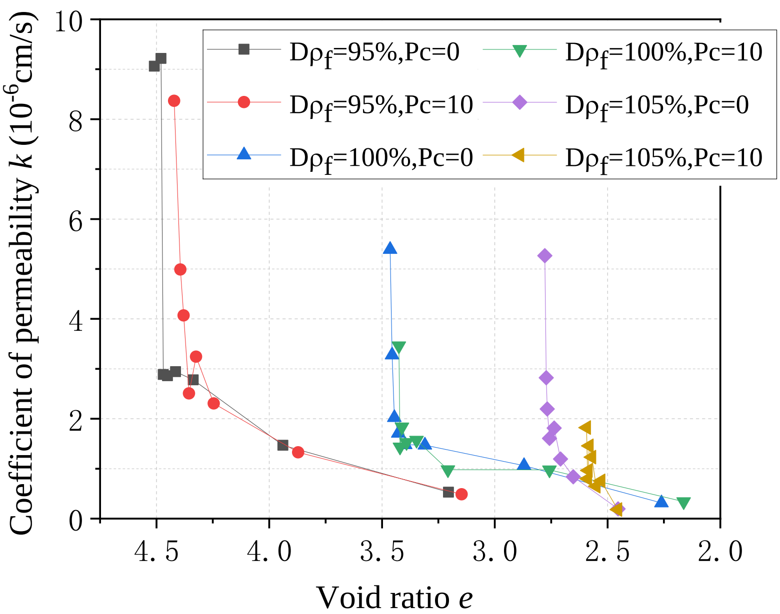

Figure 6-7 Variation of coefficient of permeability with void ratio

From Figure 6-8, it can be observed that the coefficient of permeability (k) decreases with the reduction in void ratio (e) in consolidation tests. This inverse relationship is a result of the changes in the pore structure during consolidation. As the consolidation pressure increases, liquid water in the soil pores is gradually replaced by air, leading to the compression of the soil particles and a reduction in the void ratio. This process also leads to the formation of a less connected pore network, with fewer pathways for water to flow through.

The reduced pore connectivity and the tighter packing of soil particles mean that the water flow through the soil is increasingly restricted. The consolidation pressure compacts the soil, diminishing the size and number of interconnected voids, which in turn reduces the coefficient of permeability. This process results in the formation of a denser, more impermeable material that is less likely to allow water infiltration.

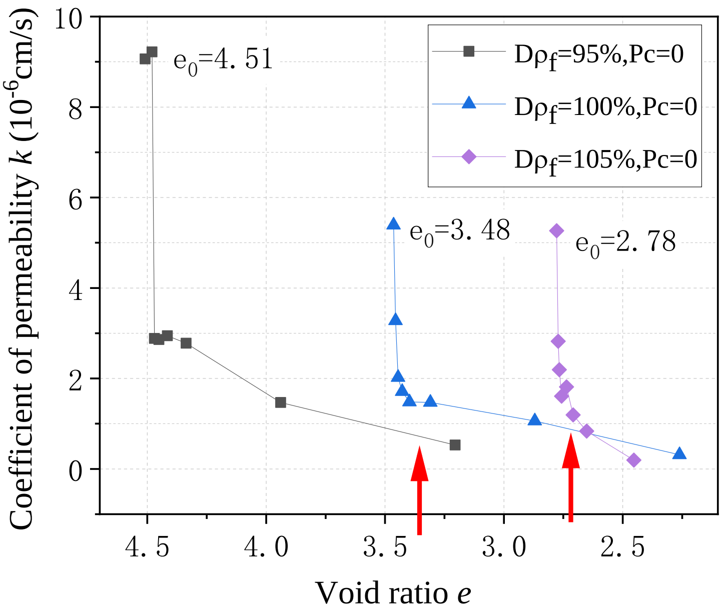

Figure 6-8 Variation of coefficient of permeability with void ratio with consolidation pressure (Pc=0)

This decreasing trend in permeability with decreasing void ratio is critical for applications where controlling the movement of water through soil is essential. For example, in embankments, foundations, or landfills, a low permeability is desirable to prevent water from migrating through the soil and to ensure stability under load. Understanding the relationship between void ratio and permeability allows to design and optimize soil treatments that meet the specific requirements of construction projects, such as ensuring adequate drainage or minimizing water ingress.

The gradual decrease in permeability with consolidation also underscores the importance of proper consolidation and compaction techniques to achieve desired soil properties. These techniques can be further enhanced with additives, such as cement or fibers, which modify the pore structure and improve the material’s resistance to water flow. By controlling the slurry density, curing time, and fiber content, can tailor the soil's permeability to fit the needs of the project, contributing to the long-term durability and stability of the structure. Figure 6-8, 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 6-8, the results indicate that after consolidation, under the same void ratio conditions, the coefficient of permeability decreases with the increase in initial void ratio e0. 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 Void ratio, and greater coefficient of permeability.

2. With a smaller initial void ratio e0, 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 extremely high permeability resistance.

6.3.2. Practical Applications of Experimental Results

The test results indicate that as slurry density increases (from 95% to 100% and 105%), soil particles are packed more tightly, reducing pore spaces and significantly lowering the permeability coefficient. Under higher slurry density conditions, the tighter particle arrangement diminishes the connectivity of water flow channels.

The addition of fibers (10 kg/m³) further reduces permeability through the following mechanisms: Improvement of Soil Structure: Fibers enhance soil cohesion, making the pore network less connected. Filling and Constraining Effect: Fibers may fill larger voids and restrict particle rearrangement, further reducing the pathways for water flow.

The test shows that the permeability coefficient (k) decreases as the void ratio (e) reduces. This trend indicates that under consolidation pressure, liquid water is gradually replaced by air in the pores, resulting in a denser pore structure and fewer pathways for water flow, thereby reducing permeability.

Practical Applications

Foundation Treatment and Stability Enhancement

The low permeability of LSS materials offers significant advantages in foundation engineering:

In collapsible or saturated soft soil regions, increasing slurry density and adding fibers can effectively enhance foundation stability and reduce settlement risks.

During consolidation, the reduced permeability helps improve the long-term bearing capacity of foundations.

Applications in Impermeability Engineering

Landfills and Contamination Barriers: The low permeability coefficient of LSS makes it suitable for impermeable layers to prevent contaminants from seeping into groundwater.

Dams and Hydraulic Structures: Adjusting slurry density and fiber content improves resistance to seepage, ensuring structural integrity and reducing leakage risks.

Optimization of Drainage and Erosion Resistance

In projects requiring control over water migration (e.g., slopes and retaining walls), the low permeability of LSS helps reduce surface water erosion. Additionally, the reinforcing effect of fibers enhances slope stability.

Urban Backfill and Underground Engineering

In underground tunnels and excavations, using fiber-reinforced, high-density LSS materials minimize water infiltration while improving the overall strength and durability of the backfill material.

Conclusion

By optimizing slurry density and fiber content, LSS materials demonstrate excellent performance in controlling permeability. These characteristics make them highly valuable in applications such as impermeable layers, foundation stabilization, and water and soil conservation. Furthermore, their low permeability contributes to environmental protection and engineering sustainability, offering a superior alternative to traditional soil treatment methods.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIO

7. Conclusions And Recommendation

7.1. Conclusions

This study conducted consolidation and permeability tests on liquefied stabilized soil (LSS) under varying conditions of initial slurry density, curing time, and fiber content, systematically exploring their effects on the mechanical and permeability characteristics of LSS. Based on experimental findings, the following key conclusions and corresponding recommendations are presented:

1) **Influence of Initial Slurry Density:** Initial slurry density has a notable effect on LSS. In general, the coefficient of consolidation of LSS shows an increasing trend with higher initial slurry density across different specimens.

   Influence in Practical Application: Changes in the initial slurry density directly affect the compression and permeability characteristics of LSS. High-density LSS is suitable for engineering applications that require resistance to large loads and low settlement, such as heavy structural foundations in infrastructure construction.

2) **Reduction in Pore Space and Increased Compressive Resistance:** Higher initial slurry density can effectively reduce Void ratio in LSS, thereby enhancing compressive resistance. When compressive resistance increases, the volume compressibility coefficient decreases, potentially leading to a faster consolidation process. In such cases, the coefficient of consolidation is likely to increase, as less compression is required for consolidation to be completed.

   Influence in Practical Application: This characteristic allows high-density LSS to more efficiently handle structural loads, improving construction efficiency and the long-term stability of infrastructure.

3) **Inverse Relationship with Volume Compressibility Coefficient:** The coefficient of consolidation is inversely related to the volume compressibility coefficient. In this study, as slurry density increased, the volume compressibility coefficient decreased, which resulted in higher coefficient of consolidations for specimens with higher slurry densities.

   Influence in Practical Application: In projects where consolidation efficiency needs to be improved, choosing high-density LSS can effectively reduce construction time and enhance construction quality.

4) **Coefficient of consolidation Decrease with Pressure Increase:** As applied pressure increases, the coefficient of consolidation of LSS tends to decrease, with a critical point related to the consolidation yield stress. By controlling pressure, it is possible to predict the compressive behavior of LSS and optimize its use in various applications.

   Influence in Practical Application: For different engineering load requirements, optimal design can be achieved by controlling consolidation pressure, ensuring the long-term stability and load-bearing capacity of the material.

5) **Effect of Fiber Content on Coefficient of consolidation:** The coefficient of consolidation of LSS increases with the addition of fiber, although the impact of fiber content is relatively minor overall.

   Influence in Practical Application: Although the effect of fiber content on the coefficient of consolidation is relatively minor, appropriately increasing the fiber content can improve the mechanical properties of LSS, particularly in engineering applications that require enhanced soil stability.

6) **Enhanced Structural Stability with Fiber Addition:** The addition of fibers helps to disperse stress, hinder particle movement, and improve the compressive resistance and structural stability of LSS.

   Influence in Practical Application: In soil improvement and foundation reinforcement, fibers can effectively enhance the compressive strength of the material, thereby improving the durability and seismic performance of infrastructure.

7) **Impact of Curing Time on Structural Stability:** With longer curing time, the internal structure of LSS becomes more stable, leading to a decrease in compressibility, a reduction in void ratio, and an increase in compressive resistance. Notably, after 28 days of curing, the compressive performance of LSS improves significantly.

   Influence in Practical Application: Extending the curing time can significantly improve the engineering performance of LSS. In projects that require enhanced long-term stability, a curing time of more than 28 days ensures higher compressive and permeability resistance.

8) **Effect of Slurry Density on Permeability:** Slurry density has a considerable influence on the permeability of LSS. As slurry density increases, the coefficient of permeability tends to decrease.

   Influence in Practical Application: High-density LSS has lower permeability, making it suitable for projects that require low permeability, such as the application of impermeable walls and foundation waterproof layers.

9) **Reduced Void ratio for Enhanced Permeability Resistance:** Higher slurry density effectively reduces Void ratio within LSS, thus enhancing its resistance to permeability.

   Influence in Practical Application: This characteristic makes LSS suitable for projects requiring waterproofing and impermeability, effectively preventing moisture penetration and ensuring the stability of the structure.

10) **Effect of Fiber Length on LSS Properties:** The fiber length in this study ranged from 0.5 mm to 3 mm. Although the effect of fiber length on the properties of LSS specimens was not directly addressed, it is important to acknowledge that fiber length can play a significant role in the mechanical behavior of soil mixtures. Previous studies have indicated that variations in fiber length can impact the reinforcement efficiency and overall performance of composite materials, including LSS.

    Influence in Practical Application: The selection of fiber length has a significant impact on soil reinforcement effectiveness. Therefore, in practical applications, fiber length should be optimized based on soil type and engineering requirements.

11) **Limited Impact of Fiber on Permeability:** The addition of fiber has a limited effect on permeability, possibly due to the small voids created by fibers, which do not significantly alter the overall permeability of LSS.

    Influence in Practical Application: Although the impact of fiber on permeability is minimal, its role in enhancing soil stability and compressive strength is still important, especially in projects that require high compressive performance.

12) **Exploration of Scale Effects**: Future research should also focus on understanding the scale effect of fiber length, examining how the variations in fiber length affect the overall behavior of LSS. This could provide

valuable insights into optimizing fiber length for improved soil stabilization and more efficient engineering applications.

Influence in Practical Application: Understanding the scale effect of fiber length helps make more informed material choices in soil reinforcement, further enhancing the performance of LSS.

13) **Stabilizing Effect of Extended Curing on Permeability:** With extended curing time, the internal structure of LSS stabilizes, reducing compressibility and void ratio, and significantly lowering the coefficient of permeability. After 28 days of curing, both compressive and permeability resistance of LSS improve markedly.

    Influence in Practical Application: Extending the curing time not only improves the compressive strength of LSS but also effectively reduces its permeability, which is crucial in projects requiring strict waterproofing and impermeability.

14) **Comparative Performance to NSF-CLAY Matrix:** Compared to the NSF-CLAY matrix, LSS demonstrates superior stability and permeability resistance, especially under high-pressure conditions.

    Influence in Practical Application: LSS exhibits better adaptability under high-pressure conditions, making it suitable for soil improvement and infrastructure construction in extreme pressure environments.

15) **Average Coefficient of Permeability:** The average coefficient of permeability of LSS is approximately 3×10^{-6} cm/s, indicating high impermeability.

    Influence in Practical Application: This characteristic makes LSS an ideal material for impermeability projects, especially in situations where effective water penetration prevention is required.

16) **Engineering Suitability through Cement and Fiber Modification:** The modifications achieved with cement and fiber make LSS well-suited for a variety of engineering applications, offering distinct advantages.

    Influence in Practical Application: The improvements in LSS give it broad potential for applications in soil stabilization, road construction, and infrastructure impermeability.

Based on experimental results, empirical relationships between the consolidation and coefficient of permeability of LSS and factors such as initial slurry density, fiber content, void ratio, and consolidation yield stress were established. These findings provide a foundation for the design and estimation of relevant parameters in LSS mixtures.

7.2. Recommendations

1) **Selection of Slurry Density According to Engineering Needs:** Choose an appropriate slurry density to balance the consolidation and permeability resistance of LSS according to specific engineering requirements. For projects requiring high compressive strength and low permeability, a higher slurry density is recommended.
2) **Optimization through Controlled Consolidation Pressure:** Consolidation pressure can be adjusted based on the yield stress threshold of LSS to optimize design for different compaction requirements. During construction, it is advised to set appropriate loading procedures to avoid pressures exceeding the yield stress, thus ensuring long-term stability of the material.
3) **Consideration of Extended Curing for Enhanced Stability:** Curing time significantly influences the compressive and permeability properties of LSS. Engineering practices should consider extending curing

time to ensure optimal stability and permeability resistance. For critical projects, a minimum curing time of 28 days is recommended.

4) **Incorporation of Fibers for Improved Compressive Strength:** The addition of fibers significantly enhances the compressive strength of LSS, though it has limited impact on permeability. For projects requiring higher compressive performance, a moderate increase in fiber content is recommended. Further studies on fiber length and morphology may help optimize the mechanical properties of LSS.
5) **Application Potential of NSF-CLAY and Modified Material Combinations:** The notable advantages of LSS in terms of permeability resistance and stability suggest that combining NSF-CLAY with modified materials has great potential for engineering projects. Promotion of this approach is recommended in various soft soil improvement projects, providing new solutions for soil treatment.
6) **Future Research on Fiber Length Impact:** The specific influence of fiber length on LSS properties remains unclear. Future research should systematically evaluate the effect of varying fiber lengths to gain a more comprehensive understanding of their impact on the consolidation and permeability performance of LSS.
7) **Importance of Fiber Length for Mechanical Behavior of Soil Mixtures:** While this study does not directly address the impact of fiber length on LSS specimens, it is important to recognize that fiber length can significantly influence the mechanical behavior of soil mixtures.
8) **Further Research on Material Modification Combinations and Loading Conditions:** Broader investigations into diverse material modifications and loading conditions will enhance the adaptability and engineering value of LSS.

These recommendations provide targeted guidance for the design and application of LSS, assisting engineering projects in optimizing soft soil improvement strategies and enhancing long-term stability.

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