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Laboratory Investigation of Creep Behavior in High-Plasticity Loose Soils under Constant Shear Stress

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***Abstract*:** This study examines the creep behavior of loose, high-plasticity soils under constant shear stress through a comprehensive laboratory investigation. High-plasticity loose soils, characterized by their substantial water retention capacity and susceptibility to significant deformation, pose critical challenges in engineering applications due to their time-dependent behavior under sustained loads. To analyze these behaviors, we conducted 25 laboratory tests, including Atterberg limits, particle size distribution, direct shear tests, and oedometer analysis. The results indicate that creep deformation in high-plasticity soils progresses in three stages (i.e. primary, secondary, and tertiary) with the rate and magnitude of deformation significantly influenced by factors such as applied stress levels, moisture content, and soil structure. Observations reveal that increased water content and higher stress levels accelerate creep deformation, while the soil's mineralogical composition governs its overall response. The findings also highlight the necessity of incorporating time-dependent behavior into the design and analysis of geotechnical projects involving high-plasticity soils.

Keywords: Creep behavior, Loose soils, High plasticity, Shear stress, Laboratory evaluation.

I. INTRODUCTION

The study of soil behavior under various stress conditions is crucial in geotechnical engineering to ensure the stability and safety of infrastructure (Nikbakht et al., 2022). Among the various soil properties, the creep behavior of loose soils, particularly those with high plasticity, plays a significant role in long-term deformations (Olek, 2022). Creep, defined as time-dependent deformation under sustained stress, is a common phenomenon in soils subjected to prolonged loading, such as foundations, embankments, and slopes. Understanding the creep behavior of high-plasticity soils is vital for accurate prediction and mitigation of settlement and deformation-related issues in engineering projects (Aung et al., 2019).

High-plasticity soils are characterized by their significant ability to retain water and deform under stress. These soils often exhibit complex mechanical behaviors due to their unique mineralogical composition and structure (Olek, 2022). When subjected to constant shear stress, high-plasticity soils can experience gradual deformation over time, which may compromise the structural integrity of overlying or adjacent structures (Bi et al., 2022). Despite the importance of this phenomenon, research on the creep behavior of high-plasticity soils, especially under controlled laboratory conditions, remains limited and demands further exploration (Havel, 2004).

Loose soils with high plasticity are typically associated with problematic engineering behavior, including high compressibility and low shear strength (Olek, 2022). These soils are often encountered in natural and man-made environments, such as alluvial deposits, floodplains, and backfill materials. The challenges posed by these soils in construction projects necessitate a comprehensive understanding of their mechanical properties and long-term performance under various loading conditions. Investigating their creep behavior provides valuable insights into their deformation characteristics and helps in developing effective design and stabilization strategies (Kavvadas & Kalos, 2019).

Creep behavior in soils is influenced by various factors, including soil type, plasticity index, moisture content, and stress level (Graham et al., 1983). High-plasticity soils, in particular, exhibit pronounced creep due to their ability to accommodate stress redistribution over time (Brandes & Nakayama, 2010). Laboratory investigations provide a controlled environment to study these factors in detail, enabling researchers to isolate specific influences and establish correlations. These studies are essential for validating theoretical models and enhancing predictive tools used in geotechnical practice (Havel, 2004). Constant shear stress conditions are a common scenario in many real-world applications, such as slopes and retaining structures. The behavior of soils under such stress regimes is critical for assessing long-term stability and performance (Sanchez et al., 2017). While traditional geotechnical investigations focus on immediate shear strength, the time-dependent deformation behavior under constant stress has gained attention in recent years (Luo & Chen, 2014).

The need for reliable data on soil creep behavior extends beyond academic interest to practical implications (Aung et al., 2019). Accurate assessment of time-dependent deformations is integral to designing structures that can withstand prolonged loading without excessive settlement or failure (Bi et al., 2022). For example, in foundation engineering, overlooking creep effects can result in underestimating settlement, leading to structural damage or even collapse (Olek, 2022). By focusing on high-plasticity soils, this study contributes to the broader understanding of soil behavior under challenging conditions (Havel, 2004). The laboratory evaluation of soil creep involves subjecting soil samples to constant shear stress and monitoring their deformation over time (Graham et al., 1983). This approach provides direct insights into the time-dependent properties of soils and allows for the development of empirical models. By incorporating advanced testing techniques and standardized procedures, researchers can achieve reproducible and reliable results (Kuhn & Mitchell, 1993). The findings from such investigations are instrumental in refining geotechnical design codes and guidelines.

Previous studies on soil creep have primarily focused on granular soils or soft soils with low to moderate plasticity. Recently, high-plasticity soils are became more highlighted. However, the behavior of high-plasticity soils under similar conditions remains underexplored. This research aims to stress this gap by conducting a comprehensive laboratory evaluation of high-plasticity loose soils. By doing so, it addresses the unique challenges posed by these soils and contributes to the body of knowledge in geotechnical engineering. This study not only advances theoretical understanding but also has practical significance. Such insights are valuable for both practitioners and researchers working to enhance the reliability and sustainability of geotechnical systems.

II. HIGH-PLASTIC LOOSE SOILS

High-plasticity loose soils are characterized by their significant plasticity, which arises from the presence of clay minerals capable of absorbing and retaining water (Graham et al., 1983). This water retention leads to high deformability and low shear strength, making these soils particularly susceptible to long-term time-dependent deformations under sustained loads (Moreno-Maroto & Alonso-Azcárate, 2017). Such behavior, known as creep, poses challenges in geotechnical applications, such as foundations, embankments, and slopes. The combination of their loose structure and high plasticity results in unique mechanical properties that require detailed analysis and testing to understand and mitigate potential risks (Efthymiou and Kavvadas, 2019). The behavior of high-plasticity soils is primarily governed by their composition and water content. These soils exhibit high compressibility due to their loosely packed particles and are prone to settlement under static loads. Under sustained shear stress, they exhibit creep deformation, which occurs in three stages (Krage et al., 2020): primary (instantaneous deformation), secondary (steady-state deformation), and tertiary (accelerated deformation leading to failure). The rate of creep depends on factors such as the applied stress, the soil's plasticity index, and the moisture content (Surjandari & Dananjaya, 2018).

As known, creep behavior in high-plasticity soils refers to the time-dependent deformation that occurs when these soils are subjected to sustained loads or stress over a prolonged period. This phenomenon is particularly significant in high-plasticity soils due to their unique mineralogical composition, which includes clay minerals like montmorillonite and illite (Sivasithamparam et al., 2015). These minerals have a high affinity for water, allowing the soil structure to undergo gradual rearrangements under stress were illustrated in Figure 1. The creep process typically progresses in three stages (Havel, 2004): primary creep, which involves an initial rapid deformation; secondary creep, where deformation continues at a relatively steady rate; and tertiary creep, marked by accelerated deformation leading to potential failure (Graham et al., 1983).

The inherent properties of high-plasticity soils, such as their high plasticity index and water retention capacity, make them especially susceptible to creep (Olek, 2022). These soils tend to have low shear strength and high compressibility, which contribute to their deformation under sustained loads (Sanchez et al., 2017). The rate of creep is influenced by various factors, including the magnitude of applied stress, water content, and soil structure (Moreno-Maroto and Alonso-Azcárate, 2017). Higher stress levels and water content often lead to faster and more pronounced creep, as the soil particles lose interparticle friction and cohesion were presented in Figures 2 and 3 (Havel, 2004).

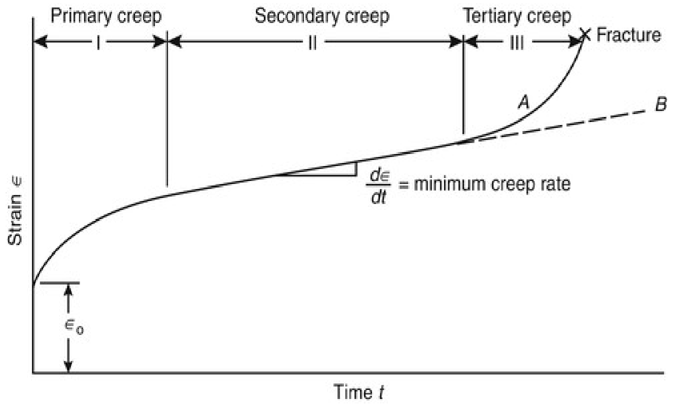

Fig. 1 An overview of creep stages (Havel, 2004)

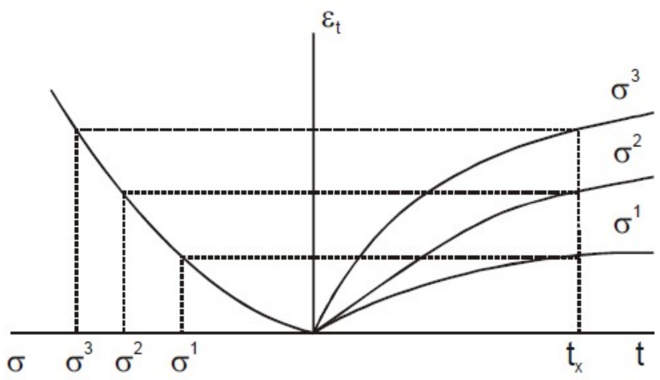

Fig. 2 Examples of the stress-strain behavior under different loading (Havel, 2004)

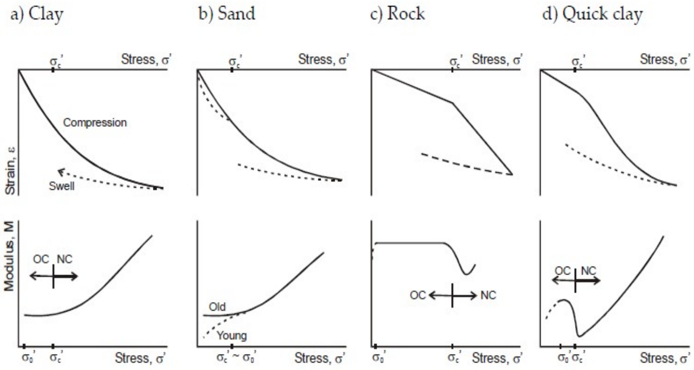

Fig. 3 Typical stress-strain curves for different soils (Havel, 2004)

Several laboratory tests are commonly employed to evaluate the mechanical behavior and creep characteristics of high-plasticity loose soils which can be classified as (Havel, 2004):

- *Atterberg limits*: Determines the plasticity index (PI), which is a measure of soil plasticity and its susceptibility to deformation.
- *Proctor Compaction*: Evaluates the maximum dry density and optimum moisture content.
- Direct-shear: Measures shear strength under varying normal stresses.
- *Consolidated undrained triaxial*: Assesses stress-strain behavior and water pore-pressure response under controlled drainage conditions.
- *Creep test*: Monitors time-dependent deformation under constant stress.

Laboratory tests, such as direct shear tests and triaxial creep tests, are commonly used to study the creep behavior of high-plasticity soils (Havel, 2004). These tests involve subjecting soil samples to constant stress conditions while monitoring their deformation over time (Mesri & Choi, 1979). The data obtained from these tests are crucial for understanding the time-dependent properties of the soil and for developing empirical models to predict long-term performance (Lo, 1961). Such models often incorporate parameters like the creep coefficient and exponent, which describe the rate and nature of deformation. From an engineering perspective, the creep behavior of high-plasticity soils poses significant challenges, especially in projects involving foundations, embankments, and slopes (Kavvadas & Kalos, 2019). Overlooking creep effects can result in underestimated settlement predictions, leading to structural instability or failure (Kaczmarek & Dobak, 2017). Therefore, accounting for time-dependent deformations in the design phase is essential for ensuring the long-term stability and safety of structures built on or with high-plasticity soils (Heimsath et al., 2002). Incorporating appropriate safety factors and ground improvement techniques can help mitigate these risks.

The existence of creep in high-plasticity soils has been recognized in verity of time, based on observations of old structures and natural slopes (Perisic et al., 2019). However, a serious investigation into this phenomenon began in the mid-19th century, coinciding with the rise in construction activities. Creep in clay soils gained attention from scientists and specialists after observing significant long-term deformations. The phenomenon was first prominently addressed in Karlovich's work Foundations and Footings in 1869 (Havel, 2004). Over the past century, and particularly in recent decades, creep deformation in clay soils has emerged as one of the most critical issues in soil mechanics. Most studies on creep were conducted during the latter half of the 20th century and the early years of the current century (Pawlik & Šamonil, 2018). Badalyan & Meschyan (1976) introduced a method to determine creep parameters for semi-saturated clay soils based on undrained test results. The deformation characteristics of soils are typically determined through laboratory testing, which can sometimes extend for up to a month. Their work presented a technique to reduce test duration to approximately one to two days. This method involved undrained creep tests conducted under uniaxial stress and lateral strain-free conditions (Culling, 1963).

III. CREEP AND CONSOLIDATION

Loose high-plasticity soils exhibit complex time-dependent deformation behaviors, primarily categorized as creep and consolidation. Creep refers to the gradual, continuous deformation of soil under a constant load over time, while consolidation involves the expulsion of water from soil pores under sustained pressure, leading to a reduction in volume (Yin & Feng, 2017). These behaviors are particularly pronounced in high-plasticity soils due to their unique mineralogical composition and high water-retention capacity, which influence their mechanical and hydraulic properties (Murad et al., 2001). The creep behavior in high-plasticity soils is governed by the rearrangement of soil particles and the viscoelastic properties of the soil structure (Yin & Feng, 2017). When subjected to a constant load, such soils deform initially at a rapid rate (primary creep), followed by a slower and more consistent rate (secondary creep), and eventually, an accelerated deformation phase (tertiary creep) that may lead to failure which is illustrated in Figure 1. This progression depends on factors such as the magnitude of applied stress, water content, and temperature. High water content and stress levels exacerbate creep by reducing interparticle friction and weakening soil bonds (Chen et al., 2021).

Consolidation in high-plasticity soils, on the other hand, involves the gradual expulsion of pore water under sustained load (Crawford, 1986). This process is time-dependent and occurs due to the low permeability of these soils, which impedes water movement. During consolidation, the soil experiences settlement as pore water pressure dissipates and the effective stress within the soil structure increases. Figure 4 is providing an explanation about creep and consolidation relation. Unlike creep, consolidation is directly related to the hydraulic properties of the soil, such as permeability and saturation level (Radhika et al., 2010). The interplay between creep and consolidation is crucial in high-plasticity soils, as these processes often occur simultaneously (Crawford, 1986). For instance, during long-term loading, the gradual reduction in pore water pressure (consolidation) can alter the stress distribution within the soil, which in turn influences creep deformation (Yin et al., 2022). This interaction makes it challenging to isolate and analyze the effects of each process independently in practical engineering scenarios (Radhika et al., 2010). Laboratory tests, such as oedometer tests for consolidation and triaxial or direct shear creep tests, are critical for understanding these behaviors (Mesri

& Choi, 1979). Oedometer tests help determine consolidation parameters like the coefficient of consolidation and compression index, while creep tests provide insights into the rate and magnitude of time-dependent deformation were illustrated in Figure 5 (Havel, 2004). These tests reveal that high-plasticity soils exhibit prolonged consolidation times and significant creep deformations, emphasizing the need for careful design considerations in engineering projects (Heimsath et al., 2002). The standard laboratory procedure for analyzing soil consolidation is the oedometer test (Wang & Abriak, 2015). In this test, a cylindrical soil sample, confined laterally, is placed in a ring and subjected to incremental vertical loads. After each load increment, the volume change due to water expulsion is recorded over time until equilibrium is reached. Key parameters measured during the test include:

- *Settlement (deformation)*: Vertical displacement of the soil sample.
- *Time intervals*: The duration required for each load increment to achieve equilibrium.
- The test progresses through several loading increments to replicate different stress levels a soil layer might experience in situ. Data collected during the test are used to plot settlement versus time curves and stress-strain relationships.

Terzaghi's one-dimensional consolidation theory is the foundation for interpreting consolidation test results.

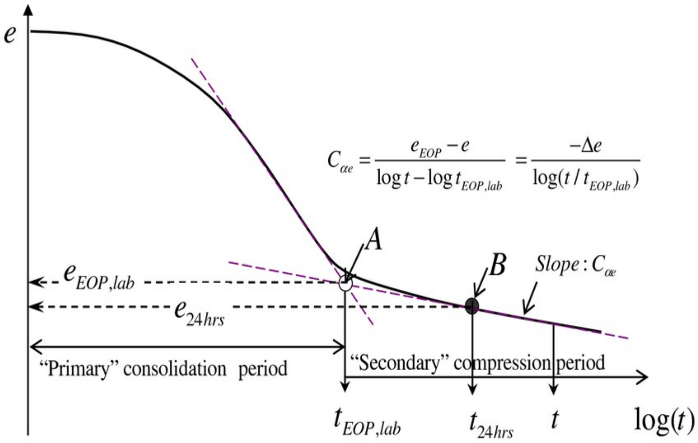

Fig. 4 Typical consolidation curves in plastic soils (Yin et al., 2022)

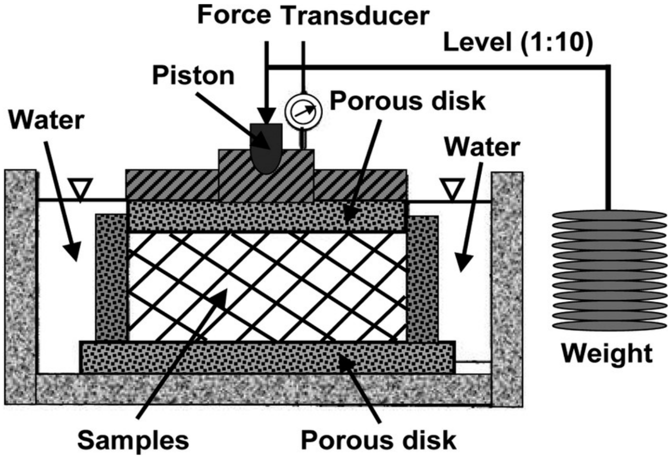

Fig. 5 A schematic of a oedometer test (Wang & Abriak, 2015)

The theory assumes:

- Soil deformation occurs in one dimension (vertical direction).
- Soil is fully saturated, and water pore-pressure dissipation governs consolidation.
- Soil grains are incompressible, and the flow of pore water obeys Darcy's law.

From an engineering perspective, the creep and consolidation behaviors of high-plasticity soils pose challenges for long-term stability and settlement predictions in structures such as foundations, embankments, and slopes. Ignoring these time-dependent processes can result in underestimating deformation and settlement, leading to structural damage or failure. To address these issues, geotechnical designs must incorporate appropriate safety factors, account for both immediate and delayed settlements, and, where necessary, employ ground improvement techniques to mitigate adverse effects.

The analysis of consolidation tests and theory is fundamental in understanding the time-dependent settlement and deformation behavior of fine-grained soils, particularly high-plasticity clays. The purpose of consolidation testing is to evaluate soil compressibility and permeability properties under sustained loads. This is achieved using laboratory experiments, primarily the oedometer test, combined with theoretical frameworks, such as Terzaghi's one-dimensional consolidation theory.

IV. MATERIALS AND METHODS

To investigate the creep behavior of loose, high-plasticity soils under constant shear stress, a systematic methodology was adopted, comprising 25 detailed laboratory tests. These tests aimed to characterize the physical and mechanical properties of the soils and to evaluate their time-dependent deformation under controlled conditions. The following paragraphs outline the tests conducted and their roles in the study:

- Soil samples were collected from various sites known for high-plasticity soils. Care was taken to ensure minimal disturbance during sampling. The collected samples were air-dried, homogenized, and sieved to remove large particles or organic matter, ensuring consistency in the laboratory experiments.
- The Atterberg limits (liquid limit, plastic limit, and shrinkage limit) were determined to classify the soils and assess their plasticity. These tests provided insights into the water content range over which the soil behaves plastically, crucial for understanding deformation behavior under varying moisture conditions.
- A combination of sieve analysis and hydrometer tests was conducted to determine the particle size distribution. This analysis helped classify the soil texture and evaluate the proportion of fines, which significantly influences water retention and creep behavior.
- Specific gravity tests were performed to identify the density of soil particles, a critical factor for understanding the soil's mineralogical composition and its impact on deformation characteristics.

- Standard Proctor compaction tests were conducted to determine the soil's optimum moisture content and maximum dry density. These parameters were essential for preparing samples at controlled conditions during subsequent testing.
- Direct shear tests were carried out to measure the soil's shear strength parameters such as cohesion (c) and internal friction angle (ϕ). These parameters are fundamental in understanding the stress-strain behavior of the soil under constant shear stress conditions.
- Oedometer tests were performed to analyze the soil's consolidation behavior. The tests measured the time-dependent settlement under vertical loading and provided data on the soil's compressibility and permeability, which are critical for evaluating its long-term performance.
- Moisture content and degree of saturation were measured for all samples before and after testing. These parameters were correlated with the observed creep behavior to assess the influence of water content on deformation rates.

The collected data from all tests were analyzed to establish correlations between soil properties and creep deformation. Statistical methods and regression analyses were employed to quantify the effects of stress levels, moisture content, and soil structure on creep rates. The results were used to identify trends and develop insights into the time-dependent behavior of loose, high-plasticity soils. This comprehensive methodology provided a robust framework for evaluating the creep behavior of high-plasticity soils under constant shear stress. The integration of multiple laboratory tests ensured a detailed understanding of the soil's physical, mechanical, and time-dependent properties, which is critical for geotechnical engineering applications.

V. RESULTS AND DISCUSSION

In this section, the results of the evaluation on the prepared and tested soil samples are presented. Figure 6 illustrates the grain size distribution curve, which characterizes the soil samples under investigation. The curve indicates that the majority of the evaluated soil belongs to the clay category, reflecting the high plasticity properties of these soils. Figure 7 presents the plasticity chart, derived from Atterberg limit tests. The results reveal that the tested soil falls within the range of medium to high plasticity, classified as CH (high plasticity clay) to CL (low plasticity clay) according to the Unified Soil Classification System (USCS). Figures 8 and 9 display the results of the direct shear test and the associated stress-strain curves. The maximum shear stress observed during the tests ranged between 20 to 40 kPa under axial and shear loading conditions, indicating that the soil exhibits medium to low density.

The strain at failure was calculated to be approximately 30%, highlighting significant deformation before reaching the point of rupture. This behavior is consistent with the properties of loose, high-plasticity soils, which tend to undergo substantial strain under sustained stress. These findings underscore the complex mechanical behavior of the tested soil and its implications for geotechnical applications. Understanding these characteristics is crucial for designing stable foundations and addressing potential deformation risks associated with such soils. Figures 10 to 13 illustrate the time-dependent creep behavior of the soil across its three distinct creep stages. The results indicate that during each stage, up to 6 mm of creep deformation was recorded, following an upward trend over time. In this study, an effort was made to maintain a constant applied load of 10 kPa, ensuring that the load remained stable and unchanged throughout the test. This approach allowed for a precise evaluation of the failure rate and creep deformation for each stage individually. The observed behavior highlights the gradual deformation of the soil under sustained stress, with each stage reflecting the progressive nature of creep in high-plasticity soils. This data is critical for understanding long-term soil performance and predicting settlement behavior in geotechnical projects.

The results of this study provide critical insights into the time-dependent creep behavior of loose, high-plasticity soils under constant shear stress. The creep deformation observed across the three distinct stages—primary, secondary, and tertiary—demonstrates the progressive nature of these soils under sustained loading. The maximum deformation recorded in each stage, up to 6 mm, reflects the soil's susceptibility to long-term deformation, emphasizing the importance of considering such behaviors in geotechnical designs. The upward trend in creep deformation highlights the impact of prolonged loading on the structural integrity of these soils. Maintaining a constant load of 10 kPa allowed for controlled observations, enabling a clear distinction between the different creep stages. This consistent loading condition proved valuable for evaluating the rate of deformation and failure mechanisms, providing practical insights into the time-dependent response of high-plasticity soils under realistic stress conditions. The stress-strain behavior captured during the direct shear tests complements the creep findings by offering a broader understanding of the soil's mechanical response. The shear stress values between 20 and 40 kPa suggest that the soil exhibits medium to low density, which correlates with the substantial strain of approximately 30% observed at failure. This significant deformation capacity is a hallmark of high-plasticity soils and poses challenges in applications requiring long-term stability. The plasticity characteristics identified through Atterberg limits testing further corroborate the soil classification (CH to CL). These findings indicate that the mineralogical composition and water retention properties are key factors influencing the creep response.

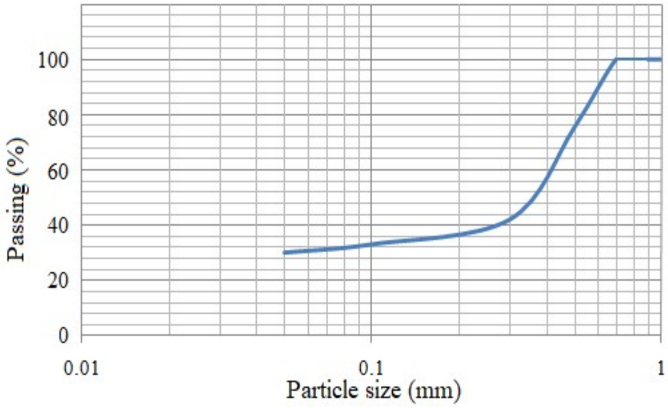

Fig. 6 Analysis of particle size distribution for studied soils

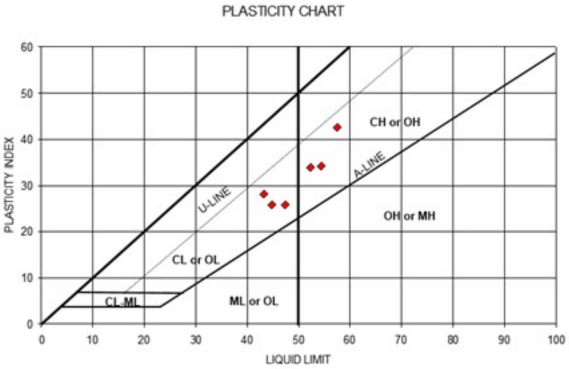

Fig. 7 A plasticity chart results for studied soils

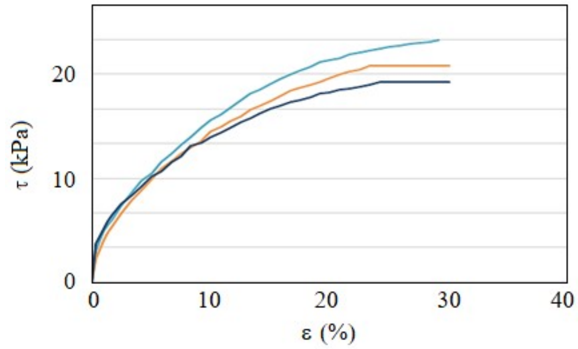

Fig. 8 A stress-strain curve obtain for studied soils

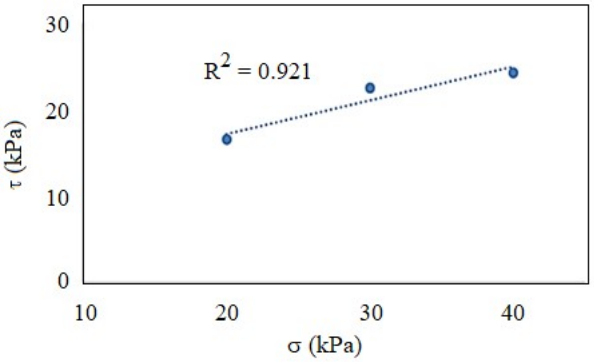

Fig. 9 A soil direct-shear test for stress condition

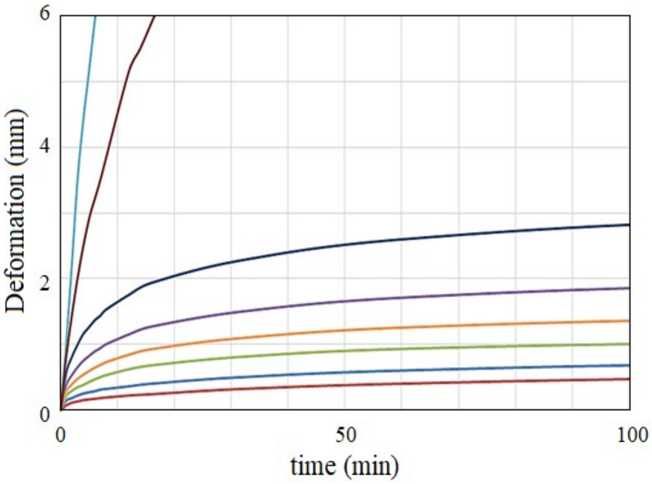

Fig. 10 Shear creep deformation behavior under direct-shear test

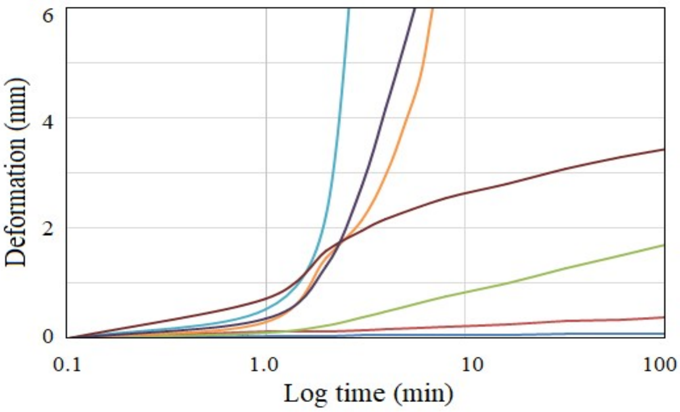

Fig. 11 Primary shear creep-time curves under direct-shear test

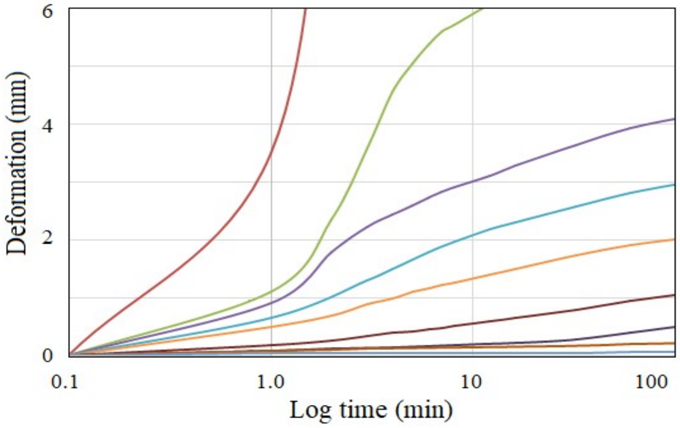

Fig. 12 Secondary shear creep-time curves under direct-shear test

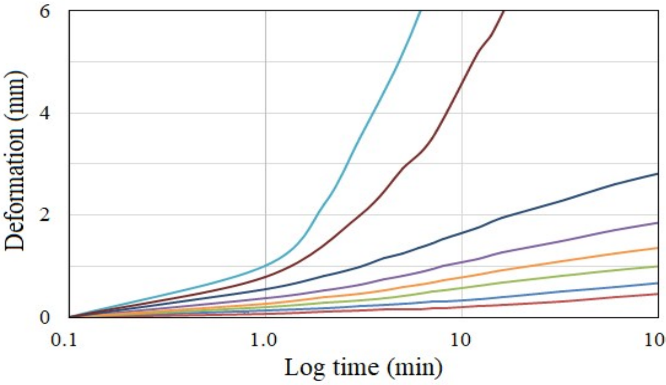

Fig. 13 Tertiary shear creep-time curves under direct-shear test

Soils with higher plasticity tend to exhibit more pronounced time-dependent deformation, particularly when subjected to sustained loading, making them critical in determining design parameters for foundations and slopes. The study emphasizes the need for incorporating time-dependent deformation behaviors, such as creep, into the design and analysis of geotechnical projects.

VI. CONCLUSION

This study explored the creep behavior of loose, high-plasticity soils under constant shear stress, offering significant insights into their time-dependent deformation characteristics. High-plasticity soils, with their notable water retention and deformation capacities, present unique challenges in engineering applications. Through a series of 25 laboratory tests, including Atterberg limits, particle size distribution, direct shear, and oedometer tests, the study successfully characterized the complex behavior of these soils under sustained loads. The findings reveal that creep deformation in high-plasticity soils occurs in three distinct stages: primary, secondary, and tertiary. The rate and magnitude of deformation are heavily influenced by factors such as applied stress levels, moisture content, and soil structure. Increased water content and higher stress levels were found to significantly accelerate creep deformation, while the mineralogical composition played a critical role in determining the soil's overall response to stress. This research underscores the importance of considering time-dependent behavior in the design and analysis of geotechnical projects involving high-plasticity soils. Incorporating these behaviors into engineering models is essential for predicting long-term settlement and ensuring the stability of structures built on or with such soils. In conclusion, this study contributes to the understanding of high-plasticity soil behavior, providing a foundation for future research and practical applications. Engineers and researchers are encouraged to integrate these findings into soil improvement techniques, foundation design, and predictive models to address the challenges posed by these complex soil types.

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AUTHORS' CONTRIBUTIONS

Nazila Danesh and Ali Taghizadeh conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Mohsen Valinejad performed checks and Mehdi Kouhdaragh provided supervision, conceptual guidance, and critical revision of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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