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EFFECT OF STRAIN RATE ON CONSOLIDATION CHARACTERISTICS OF ARTIFICIAL SILTY CLAY: INSIGHTS FROM MODIFIED CONSTANT RATE OF STRAIN TESTS

Tran The Viet[1], Pham Huy Dung[1]*

[1]Department of Civil Engineering, Thuyloi University, Vietnam

*Corresponding Author, Received: 28 Aug. 2024, Revised: 21 Oct. 2024, Accepted: 29 Oct. 2024

ABSTRACT: Soil consolidation behavior is crucial in civil engineering, particularly for construction and foundation design, where settlement and stiffness affect structural stability. However, the effect of strain rate on consolidation, especially in artificial silty clay, remains challenging. This study addresses this by investigating the impact of strain rate using modified constant rate of strain (MCRS) tests. The sample, a mixture of 35% kaolinite clay and 65% fine Baskarp sand, was classified as CL (clay with low plasticity) with a bulk density of 2.062 g/cm³ and a plasticity index of 11.25. MCRS tests were conducted using both a triaxial apparatus and an oedometric cell, applying continuous loading at strain rates ranging from 0.001 mm/min to 0.16 mm/min. Results show that the modulus of stiffness increases with both vertical stress and strain rate, with significant effects observed in stress ranges between 70 kPa and 200 kPa and strain rates between 0.0025 mm/min and 0.064 mm/min. Compared to conventional oedometer tests, higher strain rates lead to smaller settlements and greater stiffness, while lower strain rates result in larger settlements and lower stiffness. MCRS tests align well with conventional oedometer results when strain rates are between 0.012 mm/min and 0.021 mm/min. The findings show that MCRS tests offer more precise consolidation data within specific strain rate ranges, improving engineers' ability to predict settlement in artificial silty clay. This enhances understanding of strain rate effects and underscores the need for further research on clay mineral content sensitivity.

Keywords: *Consolidation behavior, Modified constant rate of strain (MCRS), Kaolinite clay, Modulus of stiffness, Strain rate.*

1. INTRODUCTION

The consolidation behavior of soils is vital in geotechnical engineering as it impacts the stability and performance of structures like foundations and embankments [1-3]. Understanding how soils consolidate under various conditions is crucial for predicting settlement and structural integrity [1, 4-6]. Strain rate-the rate at which deformation occurs under loads is a key factor influencing soil consolidation. Studying strain rate effects is essential for accurate predictions, especially in varying loading scenarios [7]. According to Yu và Liu [8], artificial silty clay, which is made by blending kaolinite clay with fine Baskarp sand, offers a controlled medium for examining consolidation behavior.

This well-defined material allows researchers to analyze how strain rate and stress levels affect soil mechanics. This detailed understanding provides crucial insights and significantly enhances the accuracy and reliability of predictive models for practical engineering applications.

Soil consolidation tests are essential in geotechnical engineering for predicting soil behavior under load. Key tests include the conventional oedometer test and the constant rate of strain (CRS) test. The conventional oedometer test measures soil settlement and compressibility under incremental loads, which helps in designing foundations that can manage expected movements [9]. In contrast, the CRS test applies continuous loads at various strain rates, offering a dynamic perspective on how soil stiffness changes under different conditions. This test is particularly useful for evaluating rapid loading effects and refining soil models for real-world scenarios [10]. Both tests are crucial for designing and assessing structures like buildings, bridges, and embankments, ensuring their stability and safety by accurately predicting soil behavior. Understanding these tests empowers engineers to make informed decisions about soil stabilization and design strategies, thereby effectively addressing and mitigating potential settlement issues and ensuring the stability of structures.

The conventional methods for assessing soil consolidation, such as oedometer tests, have provided valuable insights into soil behavior under vertical stress [11-14]. However, these methods often operate under static load that may not fully capture the dynamic behavior of soils in real-world conditions [9, 15, 16]. To address this gap, CRS tests have emerged as a more flexible approach, allowing for a range of strain rates to be applied and studied [17-19]. CRS tests are employed in geotechnical engineering to assess the consolidation behavior of soils under controlled and variable strain rates. These tests provide a better understanding of soil response than traditional methods by applying constant load at incremental steps [20, 21].

This study aims to clarify the effect of strain rate on soil stiffness. Additionally, it recommends an appropriate strain rate for artificial silty clay by comparing results from Modified Constant Rate of Strain (MCRS) tests with those from conventional oedometer tests. For this purpose, a series of MCRS tests are carried out, in which the soil sample is loaded continuously using a triaxial apparatus and an oedometric cell at a constant rate of strain. The sample, classified as CL (clay with low plasticity), was consolidated in a Rowe cell, and its properties, including bulk density and plasticity index, were carefully measured. The findings underscore the relevance of MCRS tests in accurately assessing consolidation behavior and offer practical recommendations for their application. Additionally, the study proposes further exploration into the impact of clay mineral content on strain rate sensitivity, aiming to enhance the understanding of soil behavior under diverse conditions.

2. RESEARCH SIGNIFICANCE

The significance of this study lies in its detailed investigation of the consolidation behavior of artificial silty clay under varying strain rates, which has implications for both theoretical understanding and practical applications in geotechnical engineering. By employing modified constant rate of strain (MCRS) tests, this research provides valuable insights into how strain rate influences the modulus of stiffness and settlement characteristics of silty clay, which is crucial for accurately predicting and managing soil behavior under different loading conditions.

3. METHODS AND MATERIALS

3.1 Methodology

As previously indicated, a series of MCRS tests were conducted on artificial silty clay using both a triaxial apparatus and an oedometer cell. The artificial silty clay was prepared by mixing a clay mineral (WBB Vingerling kaolinite) with fine Baskarp sand. The resulting slurry was consolidated in a Rowe-cell until it achieved sufficient solidity. Subsequently, it was subjected to a standard oedometer and multiple MCRS tests. The laboratory analyses conducted to define the properties of the soil samples included: a sieving test to determine the grain size distribution of the fine Baskarp sand (as presented in Fig. 1), Atterberg limits for soil classification, density tests for bulk and particle density, a Rowe-cell test for fabricating the artificial samples, conventional oedometer tests, and MCRS tests using a triaxial apparatus. Fig. 1 illustrates the key steps for conducting the study. All test procedures and their results will be detailed in the following sections.

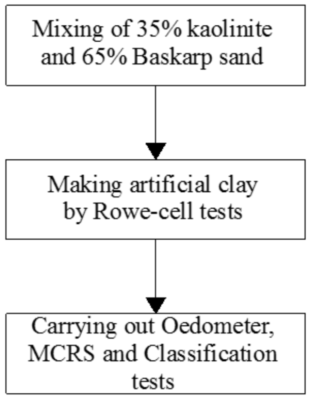

Fig. 1 Key Steps for Conducting the Study

3.2 Laboratory tests

3.2.1 Sieving tests

The selection of fine Baskarp sand for the creation of artificial silty clay necessitates the determination of its grain size distribution. To this end, sieving tests are conducted. Initially, dry sieving is performed, followed by wet sieving to verify the initial findings. Both procedures adhere strictly to the standards outlined in BS 1377-2:2022 [22].

The outcomes of the dry and wet sieving tests are delineated in Fig. 2. It is observed that the percentage of material passing through the final sieve is marginally lower in the dry sieving compared to the wet sieving, suggesting potential clogging issues during the dry process. Nonetheless, the observed variance is minimal, with differences of less than 1%. This small degree of variability suggests that the test results are consistently reliable in a qualitative sense. The minimal variance indicates that despite any minor fluctuations, the outcomes of the tests maintain a high level of accuracy and dependability, reinforcing the validity of the findings. According to BS 1377-2:2022 [22], this sand is classified as uniformly graded fine sand.

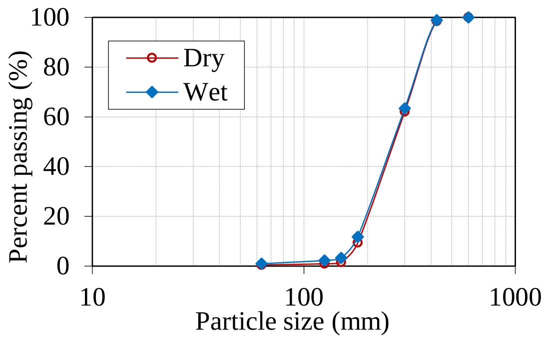

Fig. 2 Grain size distribution of fine Baskarp sand

3.2.2 Fabricating artificial sample

In this study, artificial silty clay was meticulously synthesized by blending a specific clay mineral, WBB Vingerling kaolinite, with fine Baskarp sand. The process involved carefully measuring and mixing these two materials in a predetermined ratio to create a composite soil sample with defined properties. The composition of the mixture was 35% clay mineral and 65% sand by dry weight. Subsequently, water was incorporated to form a slurry, which was then placed in the Rowe-cell. The mixture was subjected to a specified pressure until the majority of the consolidation process was completed.

The Rowe-cell is an apparatus utilized for conducting consolidation tests. Unlike a traditional oedometer, the cell is uniquely designed to load the specimen hydraulically through water pressure exerted on a flexible diaphragm rather than a mechanical system. This design facilitates the testing of samples with a larger diameter. For these tests, we employed a Rowe-cell with a diameter of 150 mm and a functional height of 65 mm. The test facilitates both vertical and horizontal drainage. It is capable of executing tests under constant strain or constant stress conditions. However, the primary objective of employing the Rowe-cell in our study was solely to fabricate the artificial silty clay sample. Therefore, we imposed a constant stress of 100 kPa and utilized a flexible porous disk to envelop the top of the sample.

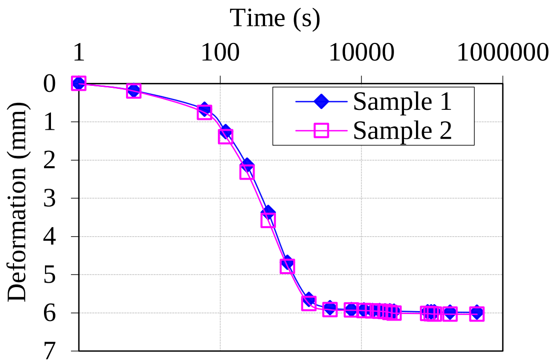

Fig. 3 Settlement of artificial samples in Rowe-cell

Fig. 3 displays the consolidation test results obtained using a Rowe-cell. It is evident that the consolidation of the artificial silty clay sample is almost completed after 4 days, as indicated by the plateauing of the settlement curve. An additional sample was tested to ensure the consistency of the results. The data reveals only a negligible difference in deformation under identical conditions. Overall, the Rowe-cell test results demonstrate commendable repeatability and consistency. Upon completion of the Rowe-cell tests, these artificial samples were utilized for subsequent testing.

3.2.3 Physical properties of artificial samples

A series of tests are carried out to identify and classify the physical properties of artificial samples including bulk and particle density, atterberg limits, and water content. The results are presented in Table 1. According to BS 1377-2:2022 [22], this artificial silty clay is classified as CL with plastic state.

3.2.4 Conventional oedometer tests

The main purpose of this test for the present study is to check the consistency of the artificial sample and the reliability of MCRS tests. Subsequently, a proper strain rate is suggested for this type of soil. The Oedometer is controlled manually. At every loading step, based on these relations after 24 hours we can decide whether or not to apply the next loading step. If the dial reading versus log-time shows a flattening out from the steep part of the curve, it means that the primary consolidation phase is completed then the next step can be applied. Otherwise, we must wait until the curve is flat before applying the next step.

3.2.5 Modified constant rate of strain tests

The Constant Rate of Strain (CRS) test was developed to overcome the limitations of the conventional test, particularly their time-consuming nature and the issue of secondary settlement. In the CRS tests, the soil sample is loaded continuously, rather than incrementally so that it produces a desired constant rate of strain. Throughout the test, continuous measurements are taken for various parameters, including the applied load, the resulting strain, and the pore water pressure. These measurements are systematically recorded and used to analyze the behavior of the soil. From the collected data, several key soil properties are determined. These include the pre-consolidation stress, the coefficients of consolidation, and the permeability.

Due to the lack of apparatus for a real CRS test, the modified constant rate of strain consolidation tests are carried out by using a triaxial apparatus and an oedometric cell. Similar to the conventional oedometer test, the sample is placed in a circular ring, which prevents horizontal soil movements. The ring is placed in a plastic tray that is filled with water. This design ensures that the water movement is controlled and confined to vertical flow, allowing for accurate measurement of the soil's consolidation behavior.

Table 1. Physical properties of artificial samples

Bulk density (g/cm^3)	Particle density (g/cm^3)	Water content (%)	Liquid limit (%)	Plastic limit (%)	Liquid index (-)
1.962 – 2.101	2.651 – 2.657	19.28 – 19.12	22.80 – 23.11	10.82 – 12.81	0.71 – 0.69

However, in the MCRS test, the sample is loaded increasingly under a selected strain rate rather than step by step. Only the load and the corresponding settlement are measured whilst the pore water pressure does not need to be recorded for this application. Subsequently, this study aims to clarify the effect of strain rate on the stiffness of soils. Also, an appropriate strain rate for the artificial silty clay is also recommended by comparing MCRS' results and those from a conventional oedometer test.

4. RESULTS AND DISCUSSIONS

4.1 Results of conventional oedometer tests

Table 2 presents the results obtained from two conventional oedometer tests, detailing the settlements recorded in response to applied vertical stress. Additionally, vertical strain values are calculated from these settlement measurements to provide a comprehensive understanding of the material's behavior under stress.

Table 2. Results of conventional oedometer tests

Vertical stress (kPa)	Oedometer 1		Oedometer 2	
	Settlement (mm)	Vertical strain (%)	Settlement (mm)	Vertical strain (%)
0	0	0	0	0
27.6	0.432	2.262	0.452	2.366
55.2	0.610	3.194	0.680	3.560
110.4	0.852	4.461	0.918	4.806
220.8	1.140	5.969	1.218	6.377
441.6	1.454	7.613	1.540	8.063
883.2	1.794	9.382	1.860	9.738

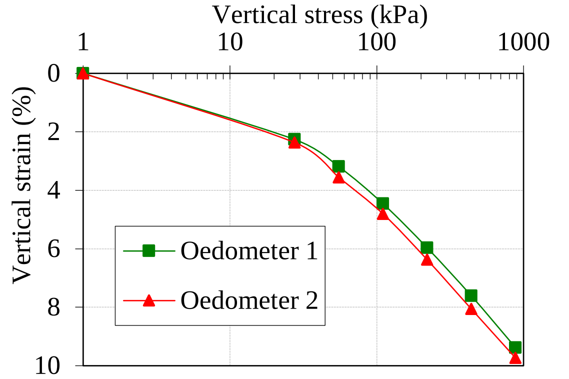

Fig. 4 Vertical stress and strain in conventional oedometer tests

The outcomes of these tests are further illustrated in Fig. 4, which visually represents the data collected. An analysis of the results reveals that the two samples exhibit qualitatively similar behavior, indicating consistent performance between them. However, it is noted that the discrepancy between the samples tends to increase as vertical stress is applied more intensely. Despite this, the variation observed is considered acceptable, as the maximum difference between the two samples does not exceed 1%. At the end of the tests, the vertical strains reach approximately 10% while the vertical stresses are around 900 kPa.

The artificial silty clays used in these tests have been carefully constructed to ensure reliability. These findings are crucial for determining the most appropriate strain rate for this type of artificial silty clay. Accurate strain rate selection will be vital in effectively assessing and predicting the performance of these materials in practical applications.

4.2 Results of MCRS tests

In MCRS tests, seven samples were subjected to varying strain rates, ranging from 0.001 mm/min to 0.16 mm/min, ensuring a comprehensive coverage of the strain rate spectrum. Given that the triaxial machine's maximum load capacity is 2 kN, the allowable total stress is capped at approximately 1000 kPa.

Consequently, in these MCRS tests, the procedure is halted if the total vertical stress approaches the threshold of approximately 1000 kPa. With the rates selected, the duration required is merely 10 minutes and 24 hours for the shortest and longest tests, respectively. This is significantly more efficient than a traditional oedometer test, which typically takes about one week for clay samples. These tests yield measurements of total vertical stress and vertical deformation. Following this, Fig. 5 presents the displacement curves, illustrating the correlation between total vertical stress and vertical strain at a specified deformation rate. These findings will undergo a more thorough evaluation in the subsequent sections.

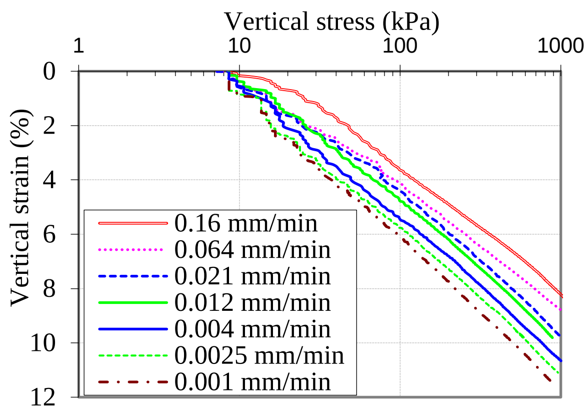

Fig. 5 Results of a series of MCRS tests

It is observable that, at a specific strain rate, the stress-strain curve is quite similar to the relation obtained from the conventional oedometer test. Interestingly, the soil's modulus of stiffness escalates in response to both the vertical stress and the duration of loading. This behavior can be attributed to the soil hardening as a result of the reduction in pore volume, which in turn diminishes the overall soil volume. Therefore, it becomes imperative to significantly increase the vertical stress to maintain a constant strain rate in the soil.

Fig. 5 also demonstrates that vertical deformation intensifies as the strain rate diminishes. Additionally, the disparity between the two curves widens in conjunction with the vertical stress. Regarding soil behavior, under a specified pressure, water pressure diminishes over time, culminating in an elevation of the effective stress and, consequently, an augmentation of deformation. Hence, a reduced strain rate is associated with an amplified deformation of the soil.

4.3 Rate-dependency of stiffness

This section clarifies the effect of strain rate on the stiffness of soils. Based on the results given in Fig. 5, the modulus of stiffness at a certain point is calculated as the following [23]:

$$E_i = \frac{\sigma_{i+1} - \sigma_{i-1}}{\varepsilon_{i+1} - \varepsilon_{i-1}} \quad (1)$$

where:

E_i being the modulus of stiffness at point i;

E_i being the modulus of stiffness at point i;

σ_{i-1} and σ_{i+1} being the vertical stress at point i-1 and i+1;

ε_{i-1} and ε_{i+1} being the vertical strain at point i-1 and i+1.

This study covers a wide range of stress levels, from 20 kPa to 800 kPa, to examine the effect of stress levels on the modulus of stiffness. Table 3 illustrates the results of the modulus of stiffness at the selected vertical stresses corresponding to the strain rates. Fig. 6 shows the dependency of stiffness on loading rates.

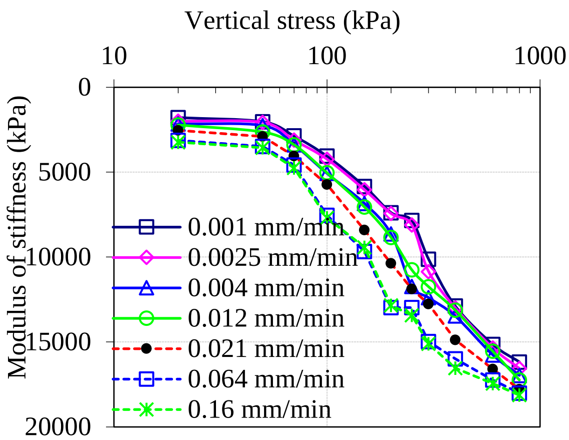

Fig. 6 Dependency of stiffness on loading rates

As shown in Fig. 6, for a given strain rate, the modulus of stiffness increases with vertical stress, as previously explained. However, this increase is not uniform across all levels of vertical stress. Specifically, the modulus of stiffness increases slowly at both low and high vertical stress values but rises more rapidly within a certain stress range.

Also, the modulus of stiffness increases with the strain rate. Similarly, this increment of the modulus of stiffness is more sensitive in a certain range of the strain rate while it is less affected at a low and high strain rate. The results show that the modulus of stiffness is more sensitive in a certain range of strain rate and stress. For this type of soil, the modulus of stiffness increases rapidly if the vertical stress varies from 70 kPa to 200 kPa and the strain rate varies from 0.0025 mm/min to 0.064 mm/min.

Table 3. Modulus stiffness for different rates and stress levels

Vertical stress (kPa)	Strain rate (mm/min)						
	0.001	0.0025	0.004	0.012	0.021	0.064	0.16
20	1783	1992	2155	2218	2536	3125	3231
50	2028	2066	2254	2635	2898	3481	3561
70	2868	3110	3381	3381	4057	4572	4742
100	4057	4232	5072	5037	5732	7545	7697
150	5836	6037	6837	7052	8414	9664	9420
200	7384	7434	8635	8846	10365	11980	12845
250	7845	8101	11734	10746	11876	12976	13422
300	9724	9852	12389	11746	12764	14968	15112
400	12879	12989	13472	13124	14876	15984	16542
600	15142	15347	15756	15543	15987	17245	17438
800	17173	17356	18163	18634	18849	19578	19732

The impact of strain rate is further illustrated in Fig. 7. It is reaffirmed that the stiffness modules are particularly responsive within specific ranges of strain rates and stress levels. Moreover, the smallest and largest of the selected rates may represent the lower and upper limits of strain rate, respectively, exerting a significant effect on the stiffness modulus of this soil type.

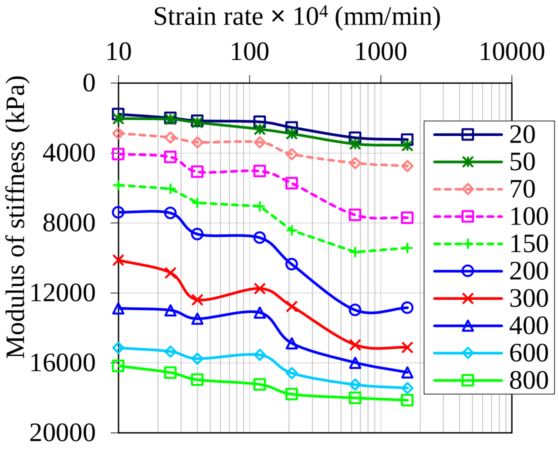

Fig. 7 Dependency of stiffness on stress levels

4.4 Rate selection

In both the CRS and MCRS tests, selecting strain rates that yield results comparable to a conventional oedometer test is crucial, as the latter is often used as a benchmark. If the chosen strain rate is too low, minimal or no pore pressure will be induced, resulting in greater settlement than observed in a conventional oedometer test. Conversely, a higher strain rate may produce excessive pore pressure, leading to a smaller settlement than anticipated due to transient state conditions. Therefore, it is essential to determine an optimal strain rate for both CRS and MCRS tests.

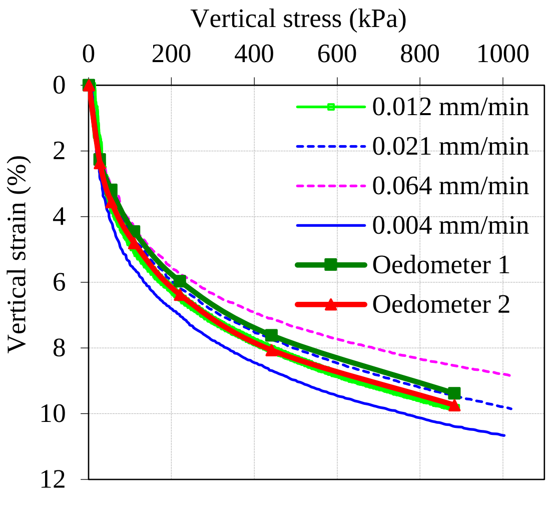

Fig. 8 Suggested rate selection

In conjunction with the oedometer tests, Fig. 8 displays a comparative analysis between the traditional oedometer tests and the series of MCRS tests. It is evident that the response curves from the oedometer tests closely resemble those from the MCRS tests in terms of curvature. However, there are notable differences in settlement. When the strain rate is excessively high, the resulting settlement is significantly smaller compared to the oedometer tests, which leads to an increased modulus of stiffness. Conversely, if the strain rate is exceedingly low, the settlement is considerably larger than that observed in oedometer tests, resulting in a reduced modulus of stiffness. The data indicate that the MCRS tests align well with the oedometer tests, producing congruent curves, particularly when the strain rate is within the range of 0.012 mm/min to 0.021 mm/min. Within this interval, the settlement and curvature correspond closely, yielding a robust correlation for assessing the consolidation behavior of soils.

5. CONCLUSIONS

This research investigates the consolidation properties of artificial silty clay, focusing on strain rate effects through modified constant rate of strain tests. The artificial sample, made by blending kaolinite and fine Baskarp sand, was compacted and categorized according to British standards before testing with both standard oedometer and modified CRS methods.

A series of modified constant rate of strain consolidation tests (MCRS) is performed by using a triaxial apparatus and an oedometric cell. It is concluded that the modulus of stiffness increases with both vertical stress and strain rate, although the rate of increase varies depending on these factors. The modulus of stiffness rises slowly at very low and very high values of vertical stress but increases rapidly within a certain stress range. Similarly, the modulus of stiffness is more sensitive to changes in strain rate within a specific range, while it shows less variation at very low and very high strain rates. For this type of soil, the modulus of stiffness increases rapidly when vertical stress ranges from 70 kPa to 200 kPa and the strain rate ranges from 0.0025 mm/min to 0.064 mm/min.

Compared to conventional oedometer tests, MCRS tests show that when the strain rate is too high, the settlement is much smaller than in oedometer tests, resulting in a larger modulus of stiffness value. Conversely, if the strain rate is too low, the settlement is much greater than in oedometer tests, leading to a smaller modulus of stiffness value. The results indicate that MCRS tests provide curves that closely align with those from oedometer tests when the strain rate ranges from 0.012 mm/min to 0.021 mm/min. Therefore, it is recommended that MCRS tests with strain rates within this range be conducted to accurately determine the consolidation behavior of this type of soil.

Numerous common errors can impact our results during the tests, stemming from human factors and equipment issues. These errors can arise from simple tasks such as mixing minerals or from more complex procedures like trimming samples and setting up the test. To ensure consistency in the artificial clay samples, they must be prepared under uniform conditions, including the same proportions of mineral clay, the same amount of water added to the mixture, and the same consolidation time during the Rowe-cell test.

Finally, an in-depth study could be conducted to explore how variations in clay mineral content impact strain rate changes during MCRS tests. This research would offer valuable insights into the sensitivity of soil modulus of stiffness to different mineral compositions, enhancing our understanding of soil behavior under varying conditions. While the study was conducted under controlled laboratory conditions, future work could refine these findings through field investigations and by examining other soil compositions.

6. ACKNOWLEDGMENTS

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