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Triaxial Testing of Mixed and Layered Speswhite and Polwhite Kaolin

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Acknowledgments

This project marks my final days at City, University of London. I would like to start by expressing my sincere gratitude to the entire institution for shaping the person I am today. I will always carry with me the memories of the people I've met here and the experiences that we shared. I would like to particularly thank Professor Sarah Stallebrass for her invaluable supervision and support throughout this study. Your expertise in soil mechanics and thoughtful guidance were instrumental in this project. You were always available to help and offer detailed and insightful feedback. And for that, I would simply like to say: thank you. I also wish to thank the technical staff in the geotechnical laboratory for their assistance during specimen preparation, especially Dr. Sam Divall. Your support was essential in carrying out the experimental work efficiently. Finally, I want to extend heartfelt thanks to my family and friends. Your encouragement, patience, and belief in me provided me with motivation.

Table of Contents

Acknowledgments 2
Abstract 5
1. Introduction 6
2. Background 7
3. Literature Review 8
    3.2 Layered and Mixed Soils: Behavioural Complexity 8
    3.1 Speswhite and Polwhite Kaolin in Soil Mechanics Research 8
    3.3 Critical State Framework and the Normal Compression Line (NCL) 8
    3.4 Summary and Research Gaps 9
4. Objectives 9
5. Research Methodology 10
    5.1 Calibration and Presentation of the Hydraulic Triaxial Apparatus 10
    5.2 Sample Preparation of Mixed and Layered Clay 13
        5.2.1 Preparation of Mixed Specimens 13
        5.2.2 Preparation of Layered Specimens 13
    5.3 Sample Testing Method 14
        5.3.1 Water Content Measurement 14
        5.3.2 Mounting of the Specimen in the Triaxial Cell 15
        5.3.3 Consolidation Phase 16
        5.3.4 Undrained Shearing 16
6. Results 17
    6.1 Calculations 17
        6.1.1 Specific Volume 17
        6.1.2 Deviator Stress 17
        6.1.3 Mean Effective Stress 18
    6.2 Stress–Strain Behaviour 18
        6.2.1 Mixed Specimens: Current and Previous Tests 18
        6.2.2 Layered Specimens: Current and Previous Tests 19
        6.2.2 Stress Ratio Evolution with Axial Strain 20
    6.3 Pore Pressure Response 21
        6.3.1 Mixed Specimens: Current and Previous Tests 21
        6.3.2 Layered Specimens: Current and Previous Tests 21
    6.4 Effective stress path 22
        6.4.1 Mixed Specimens: Effective Stress Paths 22
        6.4.2 Layered Specimens: Effective Stress Paths 23
    6.5 Specific Volume and Critical State Framework 23
7. Discussion 26
    7.1 Stress–Strain Behaviour 26
    7.2 Pore Pressure Behaviour 26
    7.3 Effective Stress Paths 27
    7.4 Specific Volume and Critical State Framework 27
    7.5 Experimental Limitations and Sources of Error 28
8. Conclusion 29
9. Recommendations 29
References 30

Table of Figures

Figure 1: Schematic of a typical hydraulic triaxial apparatus (Lu, Hickey and Sabatier, 2004) 10
Figure 2: Micrometer used for calibration 11
Figure 3: Calibration curve for the LVDT displacement transducer 11
Figure 4: Digital Pressure Indicator 12
Figure 5: Calibration curve for radial stress 12
Figure 6: Calibration curve for volume strain 12
Figure 7: Compaction of mixed specimens 13
Figure 8: Compaction of layered specimens 13
Figure 9: Sequence of water content measurements 14
Figure 10: Sequence of specimen mounting in the triaxial apparatus 15
Figure 11: Stress–strain curves for mixed specimens from the current and previous study under various confining pressures 18
Figure 12: Stress–strain curves for layered specimens tested in the current and the previous study 19
Figure 13: Stress ratio q/p′ versus axial strain for all mixed and layered specimens from 2025 tests 20
Figure 14: Pore pressure vs axial strain for mixed specimens 21
Figure 14: Pore pressure vs axial strain for mixed specimens 21
Figure 15: Pore pressure vs axial strain for mixed specimens 21
Figure 16: Deviator stress vs mean effective stress for mixed specimens 22
Figure 17: Specific volume vs ln(p') for layered (2025) and mixed (2024) specimens 24

Abstract

Understanding how soil structure influences mechanical behaviour is critical for the design of safe and efficient of geotechnical systems. This study explores role of internal configuration in clay soils by investigating the behaviour of kaolin specimens. It seeks to uncover how the arrangement of identical materials can lead to different responses under stress. Specimens composed of 70% Speswhite and 30% Polwhite were prepared and tested in two forms (mixed and layered). Specimens were subjected to controlled loading across a range of confining pressures. The results were then interpreted in regard to critical state soil mechanics.

Even if all specimens were composed of the same kaolin blend, the layered configurations consistently retained higher specific volumes than the mixed ones. Moreover, both had parallel Normal Compression and Critical State Lines. Additionally, effective stress paths and stress ratio curves also showed clear differences in strength behaviour.

Overall, the findings of this research offer a deeper understanding of how the internal structure affect critical state behaviour. The outcomes have implications for the interpretation of sedimented and layered deposits in both laboratory and real-world conditions.

1. Introduction

The mechanical behaviour of fine-grained soils is of critical importance in geotechnical engineering. Accurate prediction of their stress–strain response is essential for the efficient design of infrastructures. Among these soils, kaolin clays are widely used in laboratory research. Particularly, clays like Speswhite and Polwhite are suitable for controlled experimental investigations due to their uniformity, mineralogical stability, and reproducibility. For instance, Speswhite is well-suited for advanced constitutive modelling and critical state analysis. Its consistent behaviour under different stress paths makes it a good candidate for evaluating theoretical frameworks such as critical state soil mechanics (Stallebrass and Taylor, 1997).

Although numerous studies have concentrated on the behavior of specific types of kaolin, the interplay between different kinds of kaolins remains unexamined. In reality, soils are almost never uniform. Natural ground often exhibits layers of different materials or a blend of several materials within a single layer. Therefore, understanding the influence of structure and composition on the mechanical properties of clay systems remains a significant area of geotechnical research.

This project examines the behavior of a particular mix of homogeneously blended and horizontally layered kaolin (70% Speswhite and 30% Polwhite) under hydraulic triaxial loading conditions. Its goal is to determine how the internal structure (either mixed or layered) of the test material affects key parameters like peak deviator stress, excess pore pressure development, and volumetric response. It also aims to compare results with previous triaxial tests run by the student Akash to check the validity of those results and determine the position of the Normal Compression Line for the specified kaolin blends. The tests use consolidated undrained triaxial test with pore pressure measurement to assess undrained strength and effective stress paths.

This investigation aims to further the understanding of the composite clay system's behaviour at the macro level as a function of their microstructural arrangement. It aims to add to the ongoing effort to establish a consistent reference framework in the sedimentology of clays. It is hoped that the findings will have implications both for experimental modelling of artificial clay systems and for practical geotechnical design.

The structure of the report follows the logical progression of the study. It begins with the explanation of the broader engineering context. Then, relevant literatures are reviewed providing an overview of existing work on kaolin clays and layered soils. After that, it clearly lays out the research objectives. Subsequently, it moves on to a detailed explanation of the research and test methodology. Additionally, the results are presented and discussed in relation to important geotechnical concepts. Finally, the report finishes with a summary of the main findings and recommendations for further studies.

2. Background

As global populations grow and urban infrastructure expands, civil engineers are increasingly challenged. In environments where subsoil conditions are naturally highly variable, it can be difficult to deliver solutions that are safe, efficient, and sustainable at the same time. Understanding the mechanical behaviour of clays is essential as they are widely encountered in natural ground profiles. In fact, this will enable to enhance existing weak soils or to replicate natural conditions in controlled settings. The shift to simulations in engineering has placed a important focus on accurate soil characterisation. In fact, the numerical models used heavily rely on parameters that are obtained from laboratory tests, an accurate characterisation is therefore needed. Materials like Speswhite and Polwhite kaolin play an important role in this situation. Their properties make them valuable in exploring soil behaviours under controlled conditions.

Despite advances in modelling, the influence of structure remains a source of uncertainty. In reality, soils are rarely homogeneous. In fact, they often exhibit layering and variations in composition. These characteristics affect parameters like strength, stiffness, and pore pressure response. In design, failure to account for such heterogeneities can result in overconservative estimates (affecting efficiency) or underpredicted risks of instability (affecting safety). One area where this becomes critical is in the behaviour of layered and mixed clay systems. Numerous studies have investigated the response of uniform kaolin specimens but far less is known about how specific combinations with different structural arrangement behave. This is even more significant when considering applications in which material contrasts in stiffness can strongly influence global behaviour (e.g.engineered barriers or reinforced ground).

The current study aims to contribute to this gap by investigating a controlled blend of 70% Speswhite and 30% Polwhite kaolin. Two structural configurations are examined: one that is homogeneously mixed and the other composed of horizontal layers. These experiments aim to understand how these arrangements affect the mechanical response. It also seeks to validate and expand upon previous test data.

The following section presents a review of the relevant literature. It includes contributions that have informed the current state of understanding in kaolin-based soil behaviour and the effects of arrangement structure.

3. Literature Review

As explained in the background section, in the field of geotechnical engineering, an in-depth understanding of soil behaviour is essential for safe and efficient design. Laboratory-based experimental research plays a central role in this understanding. This is even more critical when using reconstituted soils that offer a high degree of control over initial conditions. Due to their mineralogical purity and consistent grain structure, Kaolin clays are frequently employed as model materials in such studies.

3.1 Speswhite and Polwhite Kaolin in Soil Mechanics Research

Among different type of kaolin clays, Speswhite has been widely adopted in experimental soil mechanics. It has a uniform particle size distribution and repeatable mechanical behaviour. In a study conducted by Stallebrass and Taylor (1997), they used Speswhite to develop a kinematic hardening soil model. It has been demonstrated that this clay is suitable for simulating critical state behaviour and stress path dependency. Their research highlighted the importance of capturing small-strain stiffness and anisotropic hardening which Speswhite was able to do under controlled loading conditions. On the other hand, Polwhite kaolin has been less studied. Therefore, predicting the response of combinations of Speswhite and Polwhite clays in different forms is even more challenging. To date, there is a significant knowledge gap when it comes to understanding the mechanical behaviour of Speswhite–Polwhite mixtures.

3.2 Layered and Mixed Soils: Behavioural Complexity

Natural soils are almost never homogeneous. In real-world situations, clays are deposited in stratified layers. The influence of layering on mechanical behaviour has been explored in several studies. A study conducted by Zhang et al. (2017) on artificially layered clays reported that interfaces between contrasting materials could lead to localised shear zones and pore pressure build-up. In contrast with the homogeneous samples, this shows the potential for non-uniform stress distribution in layered systems. Similarly, Lade and Yamamuro (1996) and Lo and Morin (1972) explored the mechanical response of stratified clays and silts under undrained conditions. Their results indicated that strength and pore pressure behaviour in layered samples can deviate significantly from that predicted by models calibrated on homogeneous specimens. However, the materials used in many of these studies were natural clays with heterogeneous microstructures. This makes it difficult to isolate the effects of layering. Whereas kaolin clays allow to study layering effects under highly controlled conditions. In fact, when two kaolins with distinct properties like Speswhite and Polwhite are used different configurations, the mechanical behaviour can be examined in detail with minimal interference from unknown material factors. Yet, this approach remains underexplored in the literature specially when it comes to pore pressure response and critical state behaviour.

3.3 Critical State Framework and the Normal Compression Line (NCL)

The critical state framework is one of the most recognised approaches for interpreting the behaviour of fine-grained soils subjected to shear loading. This is because It offers a coherent basis for defining ultimate failure, grounded in volumetric strain and effective stress path analysis. For a given clay type, the Normal Compression Line (NCL) represents the boundary separating elastic from plastic consolidation behaviour and is essential for determining parameters such as yield stress ratio and the degree of overconsolidation.

Researchers have established NCLs for reconstituted clays. For instance, Coop and Atkinson (1993) and Gasparre (2005) have successfully applied this framework to reconstituted London Clay. They were able to derive critical state parameters and inform constitutive modelling. Also, with regard to, the works of Stallebrass and Taylor (1997) and Gasparre et al. (2007) have produced strong frameworks for interpreting triaxial test data with Speswhite clay. Nevertheless, it remains uncertain whether these established lines remain valid when two kaolins are combined and arranged in different forms. The presence of material interfaces may influence the overall behaviour and this could potentially cause the NCL to shift from standard reference lines.

3.4 Summary and Research Gaps

The literature reviewed shows critical observations. Firstly, the characteristics of Speswhite kaolin are well documented. The material has been proven reliable in experimental testing and also numerical simulation. Secondly, layering and mixing between kaolins introduces behavioural complexities which are not captured by traditional models. Moreover, there exists a notable absence of focused investigations into the effects of combining kaolins such as Speswhite and Polwhite. These findings show the importance of further research into engineered kaolin systems featuring internal heterogeneity. The behaviour of homogeneous clays and the foundations of critical state theory are well understood but the response of prepared Speswhite–Polwhite specimens remains relatively unexplored. The proposed investigation offers an opportunity to address this research gap by employing consolidated undrained triaxial testing on both mixed and layered configurations. The resulting data will contribute to enhancing predictive models for layered and engineered soil systems. Also, It may support the validation of previous findings and improve the understanding of interface effects and anisotropy.

4. Objectives

The main objective of this research is to investigate the mechanical behaviour of a reconstituted clay composed of 70% Speswhite and 30% Polwhite kaolin under triaxial loading. A central focus of the study is the influence of internal material configuration (mixed or layers) on the soil's mechanical response. The aim is to understand how structural arrangement affects key parameters such as stress–strain behaviour and pore pressure generation during undrained testing. This has practical implications because almost all natural soils exhibit a non-uniform composition. Understanding this effect could lead to more accurate predictive models.

In addition, the study also seeks to validate and extend previous experimental data collected in 2024 by Akash on a series of triaxial tests with similarly prepared specimens. By comparing the results obtained with the earlier dataset, it will allow to further strengthen the experimental foundation required for advanced constitutive modelling.

Furthermore, this research also seeks to investigate how the Normal Compression Line (NCL) and the Critical State Line (CSL) varies depending on the material configuration. This is significant in understanding the potential influence of structure on consolidation. The identification of the NCL for the 70/30 Speswhite–Polwhite mixture would contribute to establishing it as a reference material for future laboratory studies involving composite and stratified clays.

Ultimately, through a series of consolidated undrained triaxial tests, this study aims to contribute to the refinement of laboratory procedures and modelling strategies used in the analysis of composite clays.

5. Research Methodology

5.1 Calibration and Presentation of the Hydraulic Triaxial Apparatus

All triaxial tests conducted in this study were performed using a fully automated hydraulic triaxial apparatus as illustrated in figure 1. It is equipped with a computer-controlled loading and pore pressure monitoring systems. The apparatus also includes a load transducer for axial force measurement and an LVDT displacement transducer for axial strain recording. The fluid pressure changing within the specimen and the confining chamber is monitored by the pore and cell pressure transducers respectively. The specimen is enclosed within a cylinder and is confined by de-aired water. Additionally, the loading ram applies vertical stress from the bottom and the top cap allow this load to be uniformly transferred. This configuration ensures accurate consolidation and shearing processes under undrained conditions. It is critical for determining the effective stress paths and the interpretation of critical state parameters.

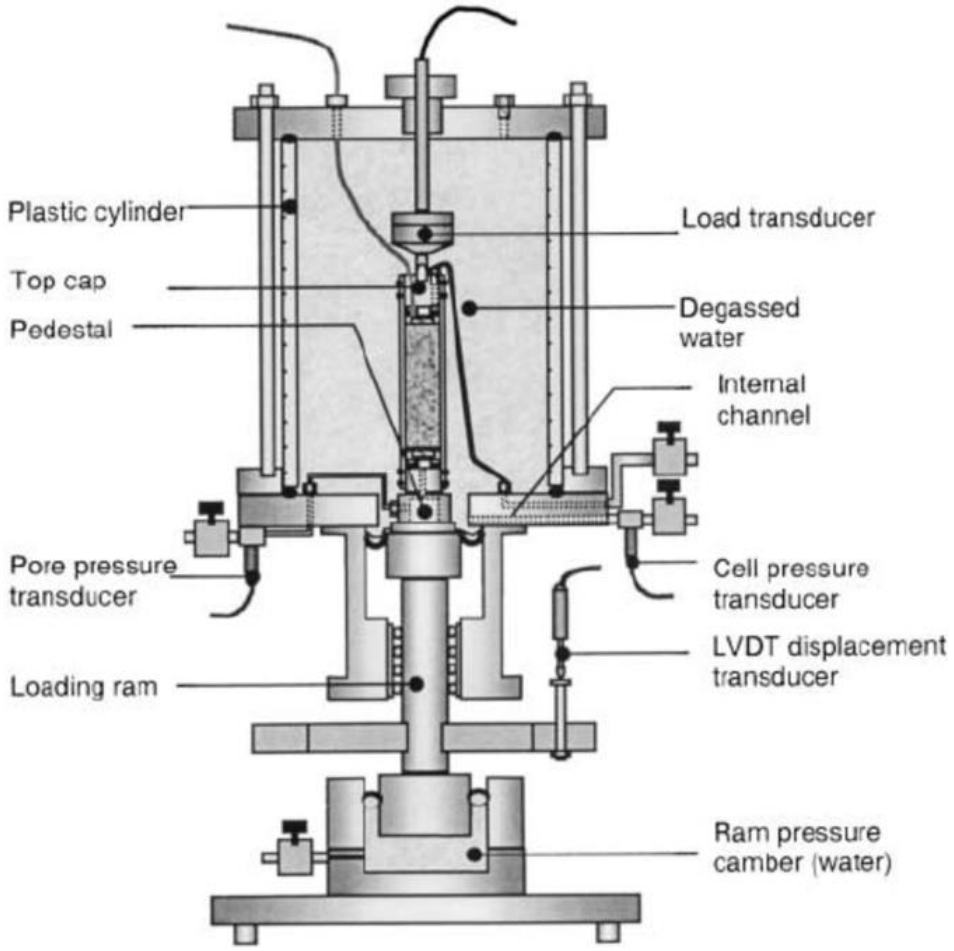


Figure 1: Schematic of a typical hydraulic triaxial apparatus (Lu, Hickey and Sabatier, 2004)

Before testing, a calibration of these instruments was carried out to ensure the reliability of the results. The calibration of the LVDT (Linear Variable Differential Transformer) displacement transducer was carried out to verify the accuracy of axial displacement measurements recorded. To do so, the transducer's output was compared with known displacements applied using a precision micrometer (figure 2). A series of incremental displacements were manually imposed and the corresponding outputs from the LVDT were recorded.

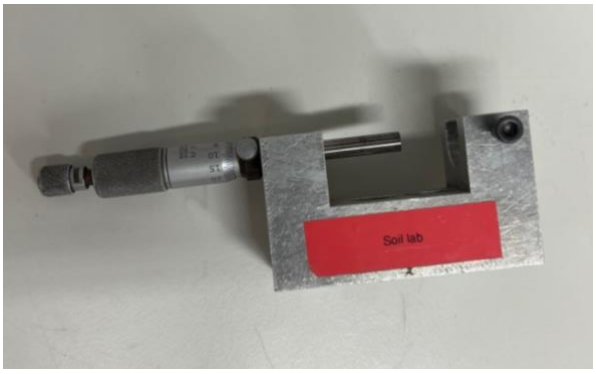


Figure 2: Micrometer used for calibration

These recorded values were then plotted against the actual imposed displacements. The relationship between the physical displacement and the recorded one is expected to be linear with a slope of unity. In this case, it can be seen that the deviation from linearity and offset from the origin was negligible (figure 3). In the opposite case, it would mean that the instrument was not correctly calibrated. A corrective factor should have been applied to ensure accurate measurements.

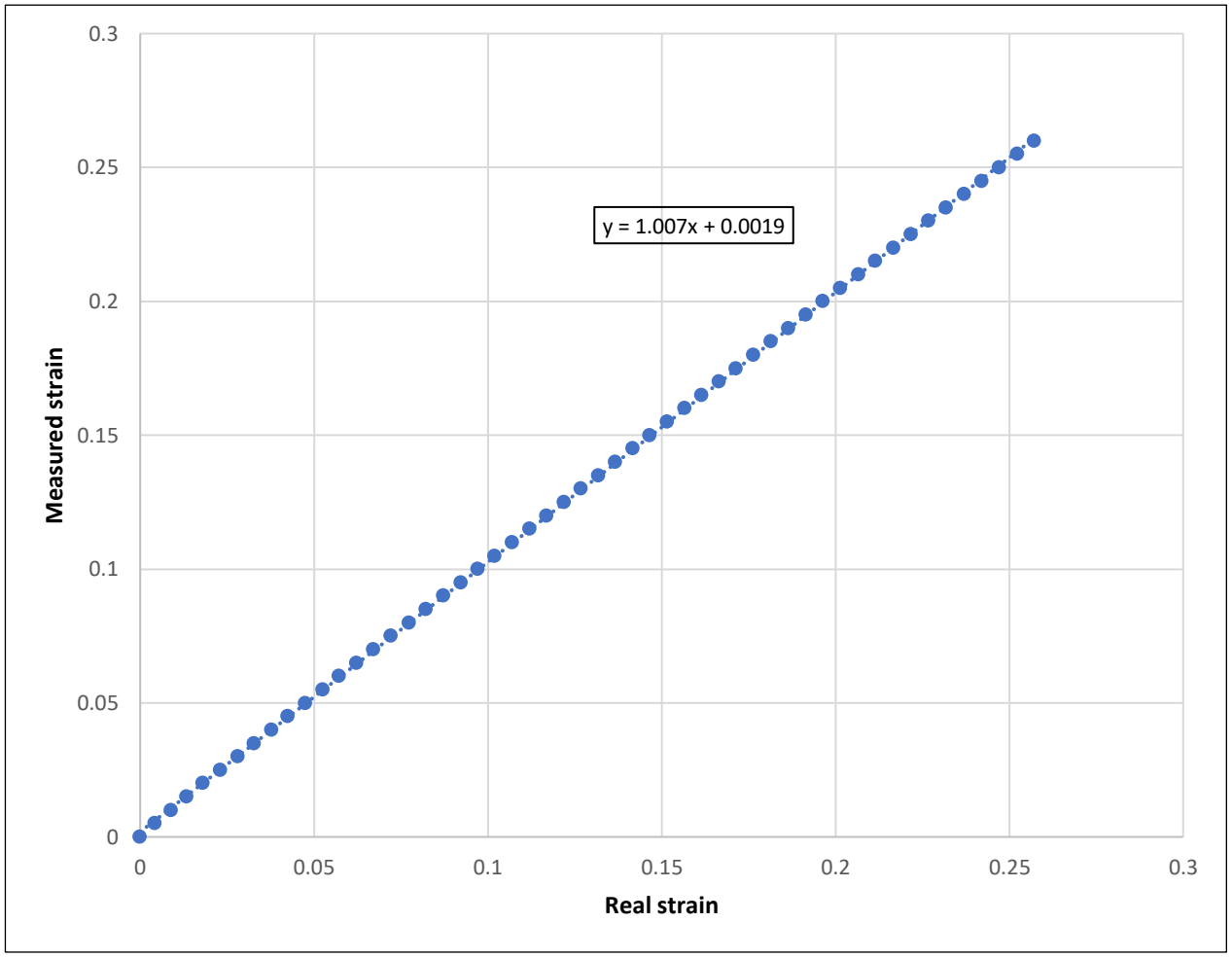


Figure 3: Calibration curve for the LVDT displacement transducer

Similar calibration procedures were conducted for the other instruments. Calibration of radial stress was performed using a Digital Pressure Indicator (figure 5.4) and the corresponding readings from the pressure transducer were recorded. The relationship was plotted to confirm linearity (Figure 5.5). It can be seen that the results demonstrated strong agreement with negligible deviation. Accurate measurement of radial stress was essential to maintain the desired effective stress. Moreover, the volume change device connected to the back pressure controller records the amount of water entering and exiting the specimen. In order to calibrate it, a series of known water volumes were introduced into the system using a bishop ram. A graph of the actual volume applied against the corresponding digital readings was then plotted. As shown in Figure 5.6, the calibration confirmed a consistent linear response.



Figure 4: Digital Pressure Indicator

Furthermore, the apparatus was connected to a digital control interface that allowed real-time monitoring of axial stress, pore water pressure, and volumetric strain. The base pedestal was fitted with porous discs to allow even distribution of back pressure. Additionally, the top cap included a central hole for drainage and pore pressure measurement. De-aired water was used to preserve the accuracy of the volume change readings and pore pressure. The apparatus was thoroughly cleaned and flushed between tests.

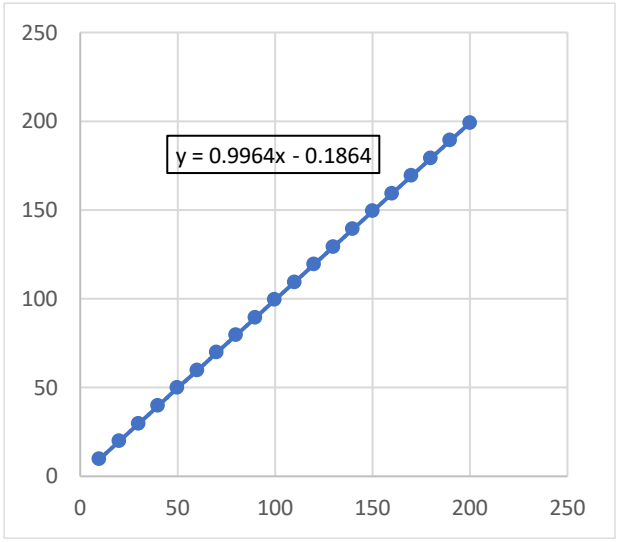


Figure 5: Calibration curve for radial stress

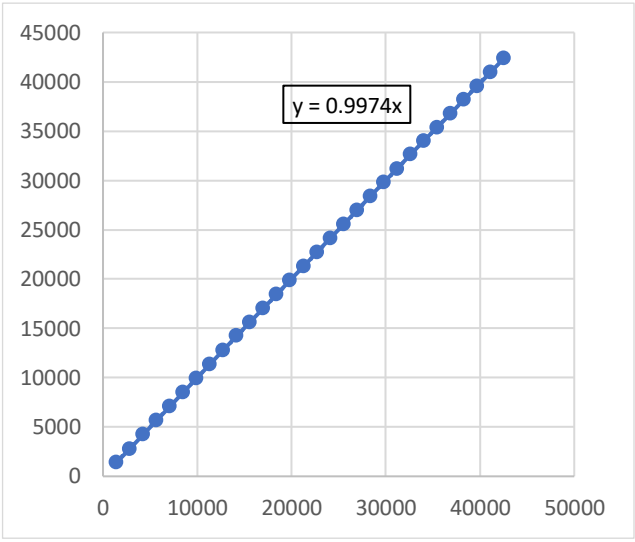


Figure 6: Calibration curve for volume strain

This apparatus, once calibrated, provided the control and sensitivity necessary to capture the complex pore pressure response and stress–strain behaviour of the mixed and layered Speswhite–Polwhite specimens under undrained loading conditions. The following sections describe the procedures followed in specimen preparation and testing.

5.2 Sample Preparation of Mixed and Layered Clay

The quality of specimen preparation is crucial to ensure the reliability of the triaxial test results. In this study, homogeneously mixed and horizontally layered specimens were prepared. One mixed and two layered samples were tested. All of them were composed of a 70% Speswhite and 30% Polwhite kaolin. Both Speswhite and Polwhite kaolin were supplied in dry powder form and stored in sealed containers to prevent moisture absorption.

5.2.1 Preparation of Mixed Specimens

For the mixed specimens, Speswhite and Polwhite kaolin clays were weighed using a digital precision balance (+- 0.01g) to achieve the required 70/30 dry mass proportion. The two clays were combined with de-aired distilled water in a mechanical mixer. During the mixing process, the water was added gradually to the dry mixture in order to achieve an even slurry consistency and avoid the formation of dry pockets. Mixing was continued for approximately of 10 minutes until the slurry appeared homogeneous in colour and texture. Once the blending was completed, the slurry was sealed in a cylindrical container shaped to resemble the final specimen dimensions. The container was lightly loaded with weights to shape and compact it (figure 7). It was then left for at least 72 hours to saturate it and fully hydrate the clay particles.



Figure 7: Compaction of mixed specimens

5.2.2 Preparation of Layered Specimens



Figure 8: Compaction of layered specimens

The layered specimens in this study were prepared by Dr. Sam Divall by adapting the principles described by Ritchie et al. (2021). They developed a centrifuge-based method to produce anisotropic clay models with layers. To form distinct sedimented layers similar to natural ones, high-water-content slurries composed of Speswhite and Polwhite kaolin were consolidated in a centrifuge. A slurry consisting of 70% Speswhite and 30% Polwhite kaolin was prepared using de-aired distilled water to reach an initial water content of approximately 1200%. The high-water content facilitated particle mobility which enable the natural segregation of the Speswhite and Polwhite particles during sedimentation. The dry materials were first weighed, and then combined with water in a paddle mixer until a homogeneous slurry was obtained. The slurry was then poured horizontally in a geotechnical centrifuge strongbox.

Under the elevated gravity field, the particles settled according to size and density resulting in a layered profile. Moreover, after sedimentation, the samples were vertically compacted to reach saturation (figure 8). Specimens were then trimmed from the sedimented block using a 38 mm internal diameter cutter. This method allowed for the formation of layered specimens with clearly defined stratification to reflect the structural features found in natural soils.

5.3 Sample Testing Method

The testing of all samples was done following a structured sequence. Each specimen underwent water content measurement and then precise mounting within the triaxial apparatus. Following that, they went through isotropic consolidation and finally undrained shearing. At the end of each test the water content was measured again using the middle third of the specimens. All tests were performed using a computer-controlled hydraulic triaxial system with a continuous data logging. This sequence is designed to capture their mechanical response under consolidated undrained conditions.

5.3.1 Water Content Measurement

In order to determine the initial water content of each specimen, a slice was carefully taken from the extremity prior to mounting. In fact, the sample was cut from of the specimen using a fine steel wire and was then placed in a pre-labelled aluminium tin to ensure traceability.

The tin was weighted alone (1) and then together with the wet sample (2) using a digital precision balance (±0.01 g). After that, they were placed in a drying oven. After drying, the tin and sample were reweighed (3) to determine the mass of water lost during the drying process. This water content was later used to calculate the specimen's initial specific volume (section 6.1.1).



Figure 9: Sequence of water content measurements

5.3.2 Mounting of the Specimen in the Triaxial Cell

The process of mounting the specimen into the triaxial cell was carried out with particular care (figure 10). It is essential for the overall performance of the test to ensure correct alignment, membrane integrity, and reliable sealing. First, the base pedestal of the triaxial cell has been lubricated with silicone grease (1). Then, a porous stone and a filter paper disk were dipped into de-aired water and placed on top of the base. After that, the prepared specimen was carefully transferred onto the base pedestal of the triaxial cell (2). Next, the top cap along with another porous stone and a filter paper disc were placed on top of the specimen. Additionally, a filter paper was placed around the specimen to ensure continuity of the sample (3).

Moreover, a latex membrane was lubricated with magnesium silicate hydroxide (talcum powder). To place it around the specimen without damaging it, a membrane stretcher was used to expand the membrane outward (4). By inhaling air from within the tube and blocking one end with a finger, it created negative pressure inside the membrane which cause it to expand. The membrane was then smoothly placed around covering the entire body of the specimen. Once correctly positioned, the membrane was sealed at both ends using two O-rings placed at the pedestal and top cap (5). After that, the cell wall was installed and the chamber was filled with distilled water (6). Finally, the cell was inspected for leaks and the sample was ready to consolidate.

This mounting procedure was repeated for each specimen to ensure consistency between tests. Correct specimen installation is critical for the success of subsequent phases (consolidation and undrained shearing).



Figure 10: Sequence of specimen mounting in the triaxial apparatus

5.3.3 Consolidation Phase

This stage involved the application of an isotropic cell pressure to the specimen under drained conditions. This allows the excess pore water to escape and the sample to consolidate under effective stress. Consolidation was carried out using the automated control of the triaxial system.

The target cell pressure (depending on the test) was set using the system's control computer. It automatically regulated the cell pressure in small increments to avoid specimen disturbance. Moreover, in order to maintain the effective stress condition during consolidation, the back pressure applied was kept constant. During this period, no axial load was applied apart from the small seating load required to maintain top cap contact. The system was configured to log the following parameters in real time: axial stress, pore pressure, radial stress, axial strain, and volume strain. The specimen was considered fully consolidated when there was no more volume change and the drainage valves were then closed to begin the undrained phase. A final system inspection was performed to ensure that all pressures, displacements, and volumes had stabilised and were accurately logged.

5.3.4 Undrained Shearing

After consolidation, the specimen was subjected to undrained shearing. This phase aim to simulate loading conditions where drainage is not permitted. It allows the measurement of excess pore water pressures and their effect on effective stress. Once the drainage valves were closed, the shearing phase was programmed through the computer. As the specimens deformed, the axial load response was continuously recorded. The test was continued until the specimen showed a distinct peak strength followed by softening. After completion of shearing, the system was paused and the final readings were recorded. The specimen was then carefully removed from the triaxial cell and a sample (from the middle third of the specimen) was cut off to measure the water content after the test (using the same technique explained in 5.3.1).

This phase concluded the mechanical testing process. The recorded data formed the basis of the analysis presented in the following results and discussion chapters.

6. Results

6.1 Calculations

This subsection shows the key calculations performed to derive the mechanical parameters required from the raw data. These calculations were done in Microsoft Excel based on measurements taken during the tests. The parameters calculated are the specific volume, deviator stress, and effective stresses. These parameters were subsequently used to plot the graphs in the following sections.

6.1.1 Specific Volume

The specific volume v is defined as the ratio of the total volume of a soil to the volume of its solid particles. It represents how much space the soil occupies relative to its solid content. The initial specific volume v_0 was calculated from the initial water content w using the following expression:

$$v_0 = 1 + w * 2.65$$

Where 2.65 represent the assumed specific gravity of the soil and where the water content (w) was calculated as:

$$w = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

with m_{wet} being the mass of the wet sample and m_{dry} being the mass after oven drying.

Additionally, the specific volume was adjusted to account for changes in the specimen's volume at each time. It was calculated using the volumetric strain measured during the test. This is essential for interpreting consolidation characteristics with respect to the Normal Compression Line (NCL).

Given the high sensitivity of the $v - ln\,(p')$ relationship to the accuracy of water content, additional measures were taken to validate the reliability of the calculated specific volumes. The final water content was measured from the middle third of the specimen at the end of each test. This value was used to calculate the final specific volume. The aim was to verify the consistency of results by comparing them. This ensures that the specific volume evolution during the test corresponded with a physically realistic position relative to the NCL.

6.1.2 Deviator Stress

The deviator stress was calculated during the shearing phase based on the applied axial force and the cross-sectional area that evolved with axial strain. The initial cross-sectional area at the start of shearing was first calculated based on the final volume of the specimen at the end of the consolidation phase. This volume was derived using the measured volumetric strain during consolidation. During shearing, the change in area due to axial strain was accounted at each time increment as follows:

$$A = \frac{A_0}{1 - \varepsilon_a}$$

Where A_0 is the cross-sectional area after consolidation and where ε_a is the axial strain at each time increment.

The deviator stress was then calculated as: $q = \frac{F}{A}$

Where F is the axial load measured and A is the cross-sectional area.

6.1.3 Mean Effective Stress

The mean effective stress is used to describe the stress state of soil in triaxial testing. It was calculated in both the consolidation and shearing phases using appropriate measurements at each stage. At the consolidation phase, the test conditions were isotropic. This means that the total stress applied was equal in all directions. Because of this, the mean effective stress is simply: $p' = \sigma_c - u$

Where σ_c is the applied cell pressure and u is the measured pore pressure.

During the shearing phase, the mean effective stress was calculated using the following expression:

$$p' = \frac{q}{3} + (\sigma_c - u)$$

6.2 Stress–Strain Behaviour

6.2.1 Mixed Specimens: Current and Previous Tests

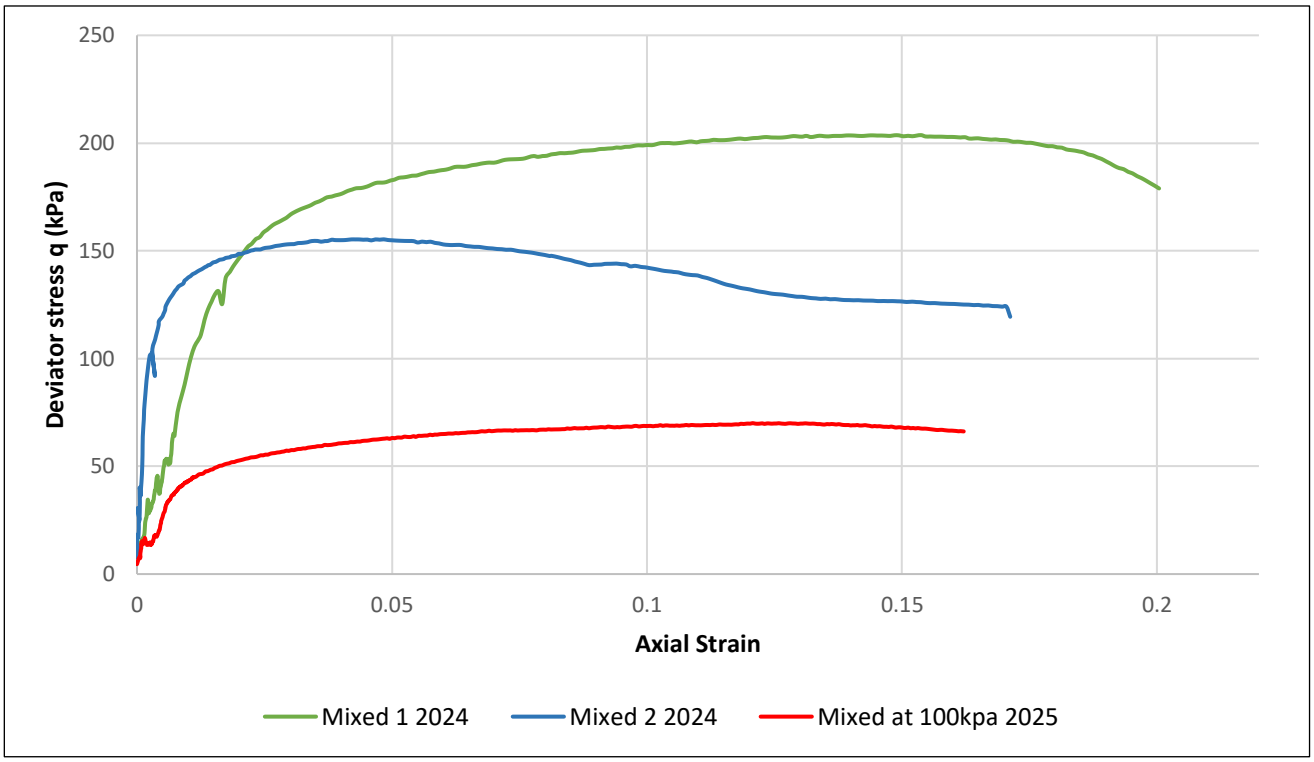


Figure 11: Stress–strain curves for mixed specimens from the current and previous study under various confining pressures

Figure 11 presents the deviator stress–axial strain response for three mixed specimens tested under consolidated undrained conditions. Two specimens (Mixed 1 and Mixed 2) correspond to the tests done in the previous year (2024) and the third specimen (Mixed at 100 kPa) represents a test conducted during the current study (2025) at a confining pressure of 100 kPa. All specimens exhibited a typical

stress–strain profile characterised by a rapid increase in deviator stress with axial strain and followed by a distinct peak and subsequent post-peak softening. Mixed 1 reached the highest deviator stress of approximately 205 kPa at an axial strain of about 14. Mixed 2 attained a peak of approximately 155 kPa with a slightly earlier peak and more pronounced post-peak softening. In opposite, the current specimen (Mixed at 100 kPa) reached a lower peak stress of approximately 70 kPa and exhibited a relatively flat post-peak response. These results provide a basis for comparing the stress–strain response of mixed specimens. Further interpretation of the mechanical behaviour is provided in Section 7.1.

6.2.2 Layered Specimens: Current and Previous Tests

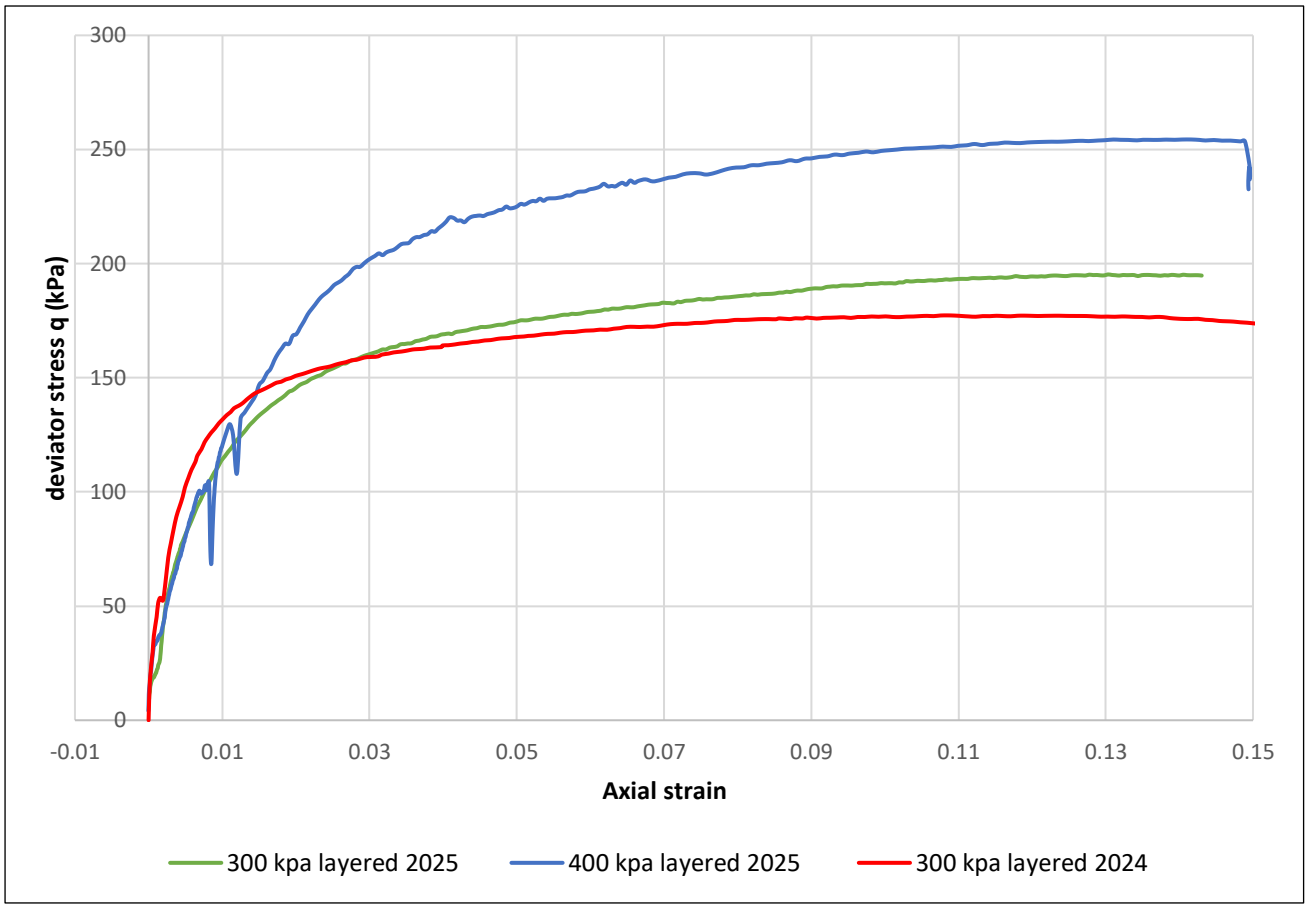


Figure 12: Stress–strain curves for layered specimens tested in the current and the previous study

Figure 12 presents the stress–strain behaviour of layered specimens tested under consolidated undrained conditions. Two specimens from the current study were tested at confining pressures of 300 kPa and 400 kPa and the third corresponds to the previous year's experiment tested at 300 kPa.

All specimens exhibited a rapid increase in deviator stress with axial strain. The specimen tested at 400 kPa (current study) developed the highest peak deviator stress of approximately 255 kPa. The specimen tested at 300 kPa this year achieved a peak deviator stress of around 195 kPa. In contrast, the 300 kPa layered specimen from the previous year peaked at a slightly lower deviator stress of approximately 180 kPa. Further interpretation is provided in Section 7.1.

6.2.2 Stress Ratio Evolution with Axial Strain

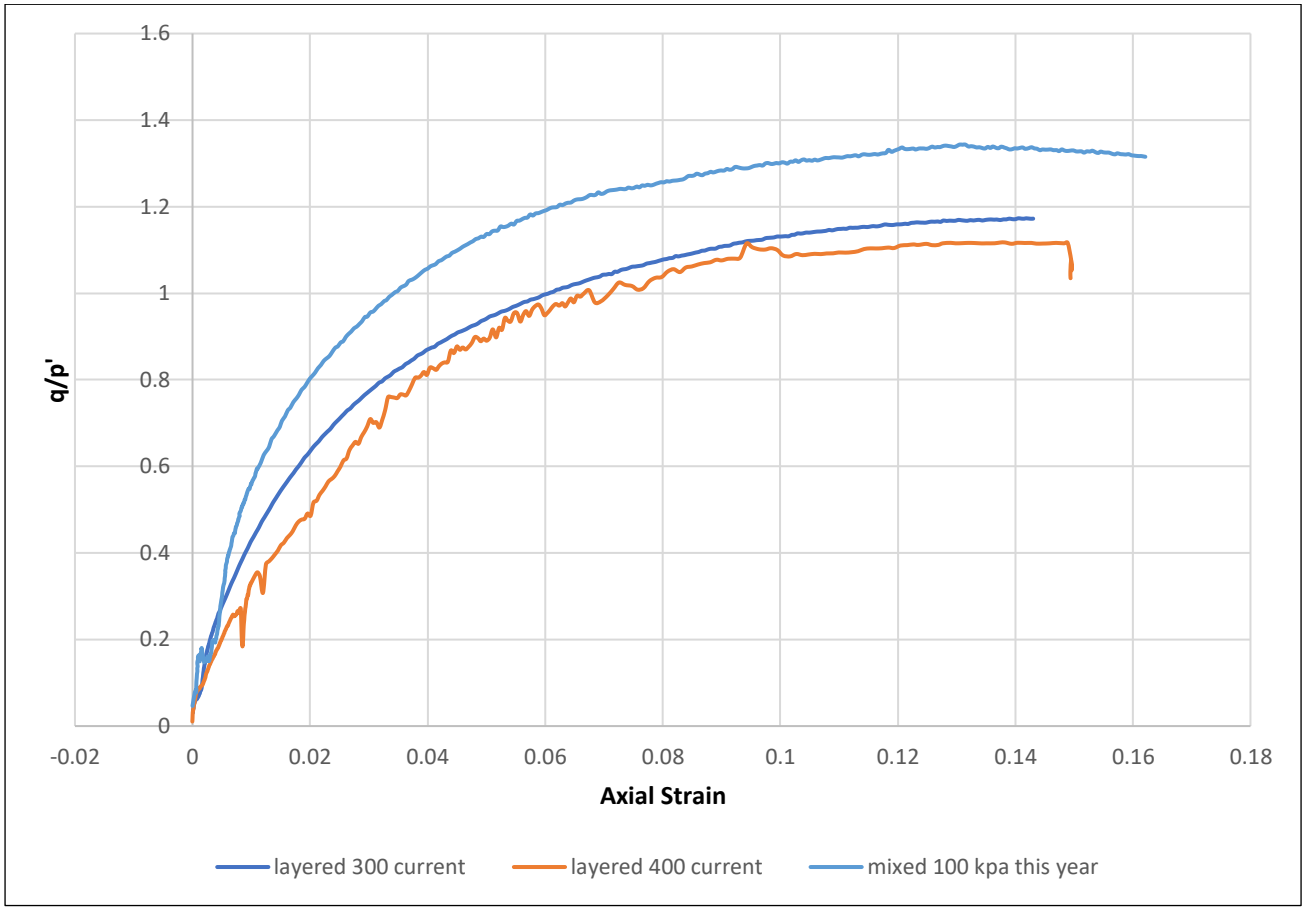


Figure 13: Stress ratio q/p′ versus axial strain for all mixed and layered specimens from 2025 tests

Figure 13 presents the variation of the stress ratio q/p' with axial strain for the current mixed and layered specimens. The stress ratio was computed at each time increment during undrained shearing. All specimens displayed a progressive increase in stress ratio with axial strain. The two layered specimens followed almost a similar trajectory throughout the shearing phase. Despite being tested under different confining pressures, the shapes and gradients of their curves remained closely aligned. In contrast, the mixed specimen tested at 100 kPa exhibited a distinctly higher stress ratio across the full strain range. Its curve rose more rapidly in the early stages and reached a peak value exceeding 1.3. This divergence in behaviour provides a reference point for evaluating structural influence on stress mobilisation, which is discussed further in Section 7.1.

6.3 Pore Pressure Response

6.3.1 Mixed Specimens: Current and Previous Tests

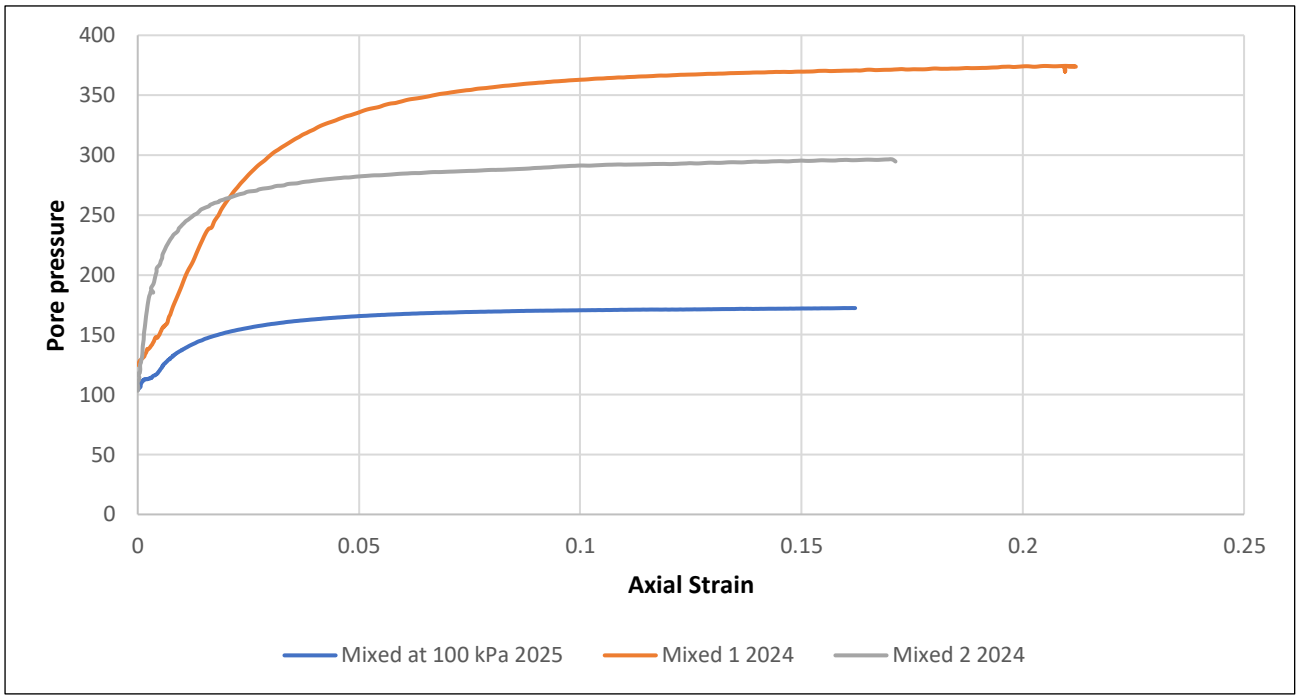


Figure 14: Pore pressure vs axial strain for mixed specimens

Figure 14 illustrates the pore pressure development during undrained shearing for three mixed specimens. Two specimens (Mixed 1 and Mixed 2) correspond to the previous year's test series and the third (Mixed at 100 kPa) was tested in the current study. All specimens exhibited a rapid build-up of pore pressure in the early stages of shearing. Mixed 1 and Mixed 2 generated respectively peak pore pressures of approximately 375 kPa and 300 kPa. The current specimen that tested at a lower confining pressure of 100 kPa reached a lower peak pore pressure of around 170 kPa.

6.3.2 Layered Specimens: Current and Previous Tests

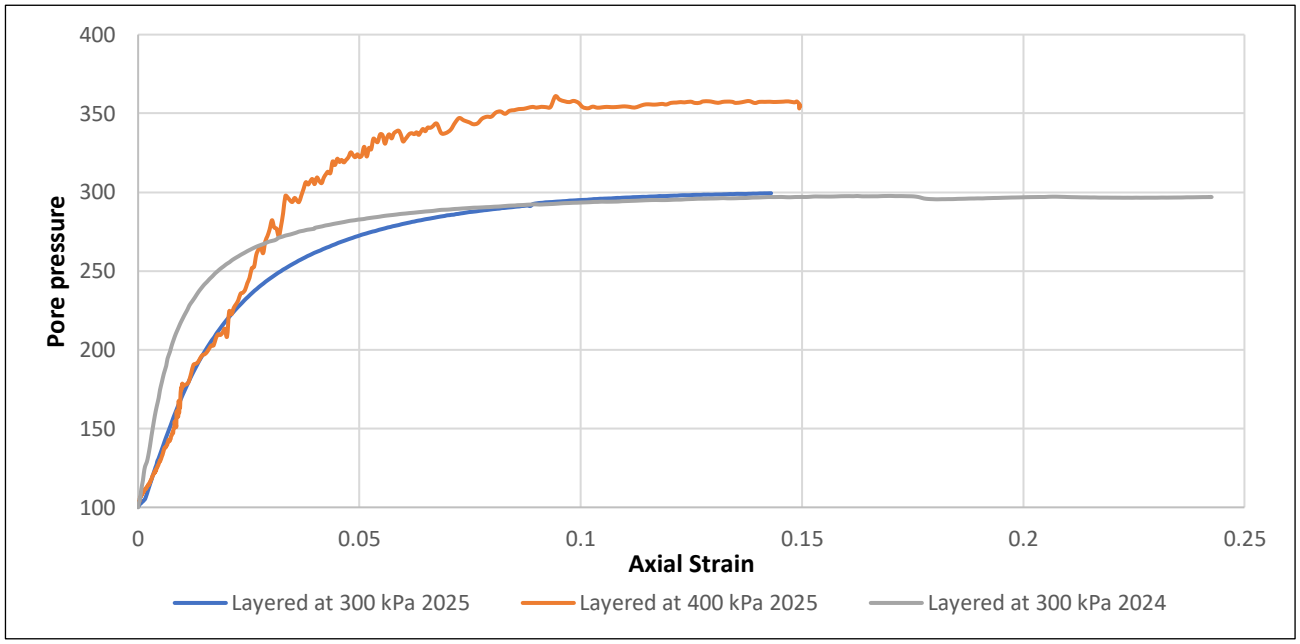


Figure 15: Pore pressure vs axial strain for mixed specimens

Figure 15 presents the pore pressure response for layered specimens tested at 300 kPa and 400 kPa in the current study and 300 kPa specimen from the previous year. All specimens displayed a rapid rise in pore pressure reaching peak values of 300 kPa and 350 kPa**.** The specimen tested at 400 kPa developed the highest pore pressure. The 300 kPa specimen from the current study closely matched the response of the previous year's specimen with both curves showing a plateau after reaching peak pore pressure.

6.4 Effective stress path

6.4.1 Mixed Specimens: Effective Stress Paths

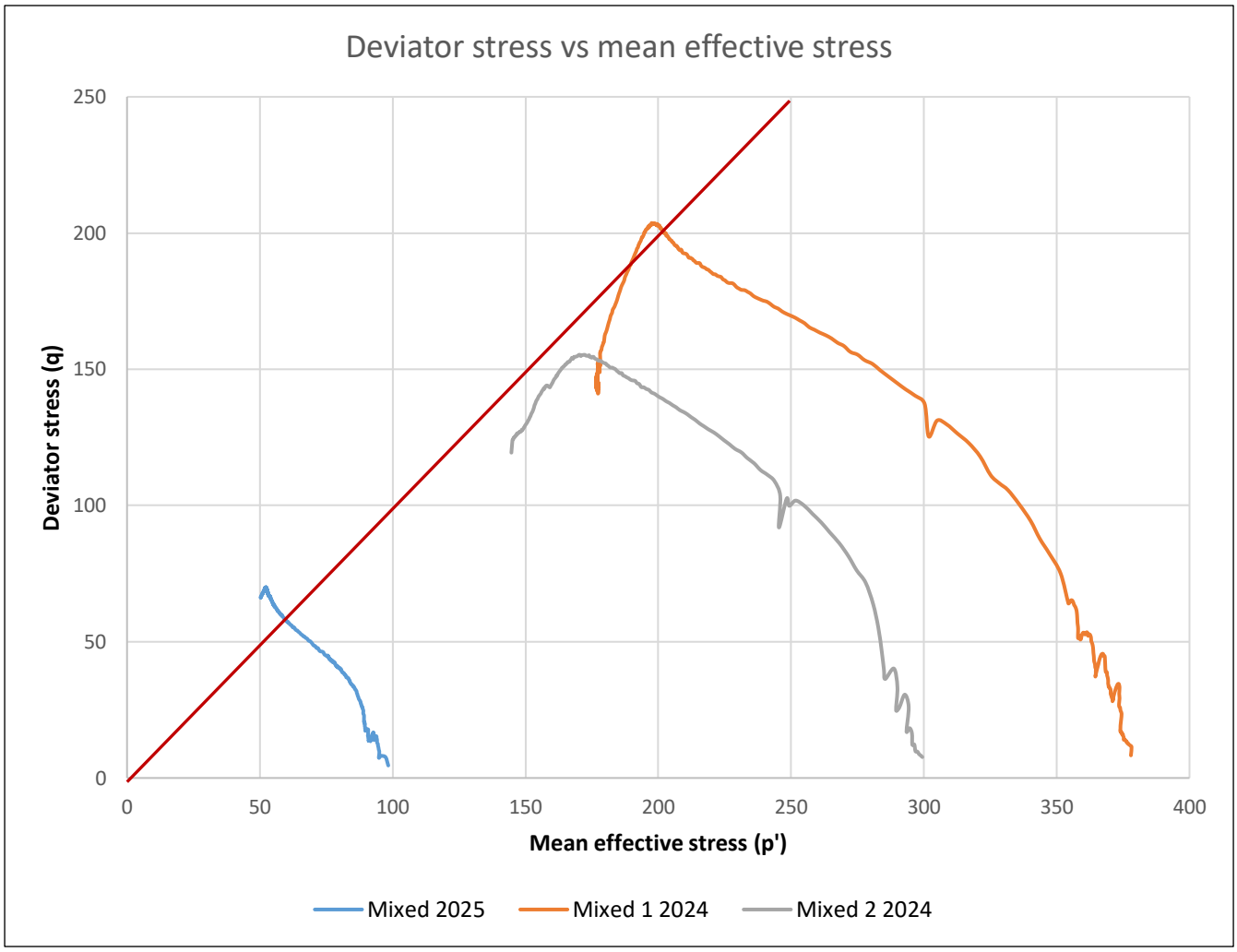


Figure 16: Deviator stress vs mean effective stress for mixed specimens

Figure 16 shows the effective stress paths in the $q-p'$ space for three mixed specimens: two from the previous year and one from the current study. A critical state line was drawn for reference, based on an estimated slope of $m = 1.0$. However, it is important to note that the line did not intersect all peak points.

6.4.2 Layered Specimens: Effective Stress Paths

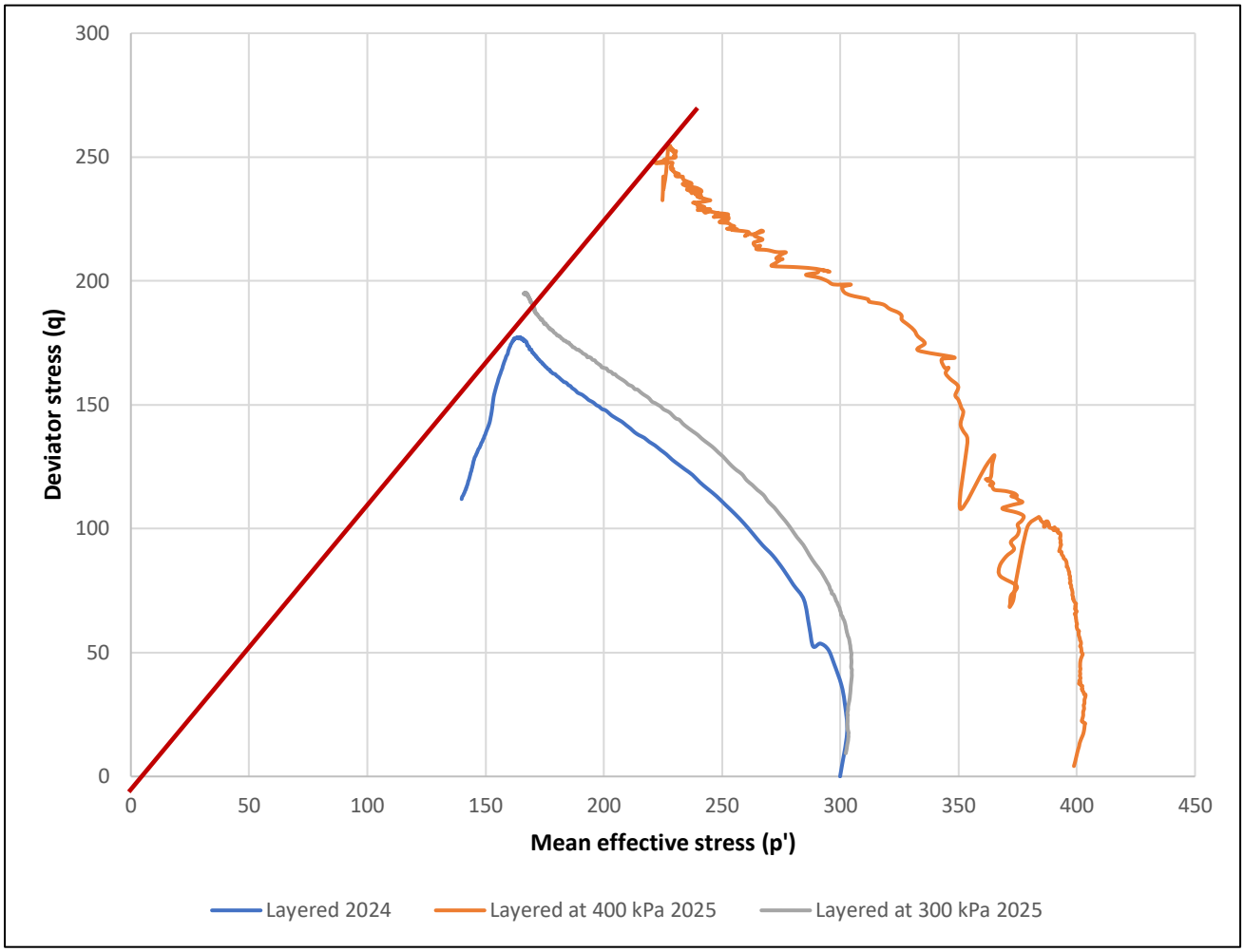


Figure 17: Deviator stress vs mean effective stress for layered specimens

Figure 17 presents the effective stress paths for the layered specimens tested under consolidated undrained conditions. The paths for the two 300 kPa specimens (current and previous years) were closely aligned in both shape and magnitude. As expected, the 400 kPa specimen reached the highest deviator stress and mean effective stress values. A critical state line with slope $m = 1.12$ was drawn. The line passed approximately through all the endpoints which indicate a well-defined critical state across the layered specimens.

6.5 Specific Volume and Critical State Framework

Figure 18 presents the relationship between specific volume v and the natural logarithm of mean effective stress $ln(p')$ for selected mixed and layered specimens. Two layered specimens tested during the current study (2025) and two mixed specimens from the previous year (2024) were selected for this comparison due to the observed reliability of their data. Based on these data, two lines were fitted for each specimen type (layered and mixed): one Normal Consolidation Line (NCL) through the consolidation phase points and one Critical State Line (CSL) through the end-of-shear values.

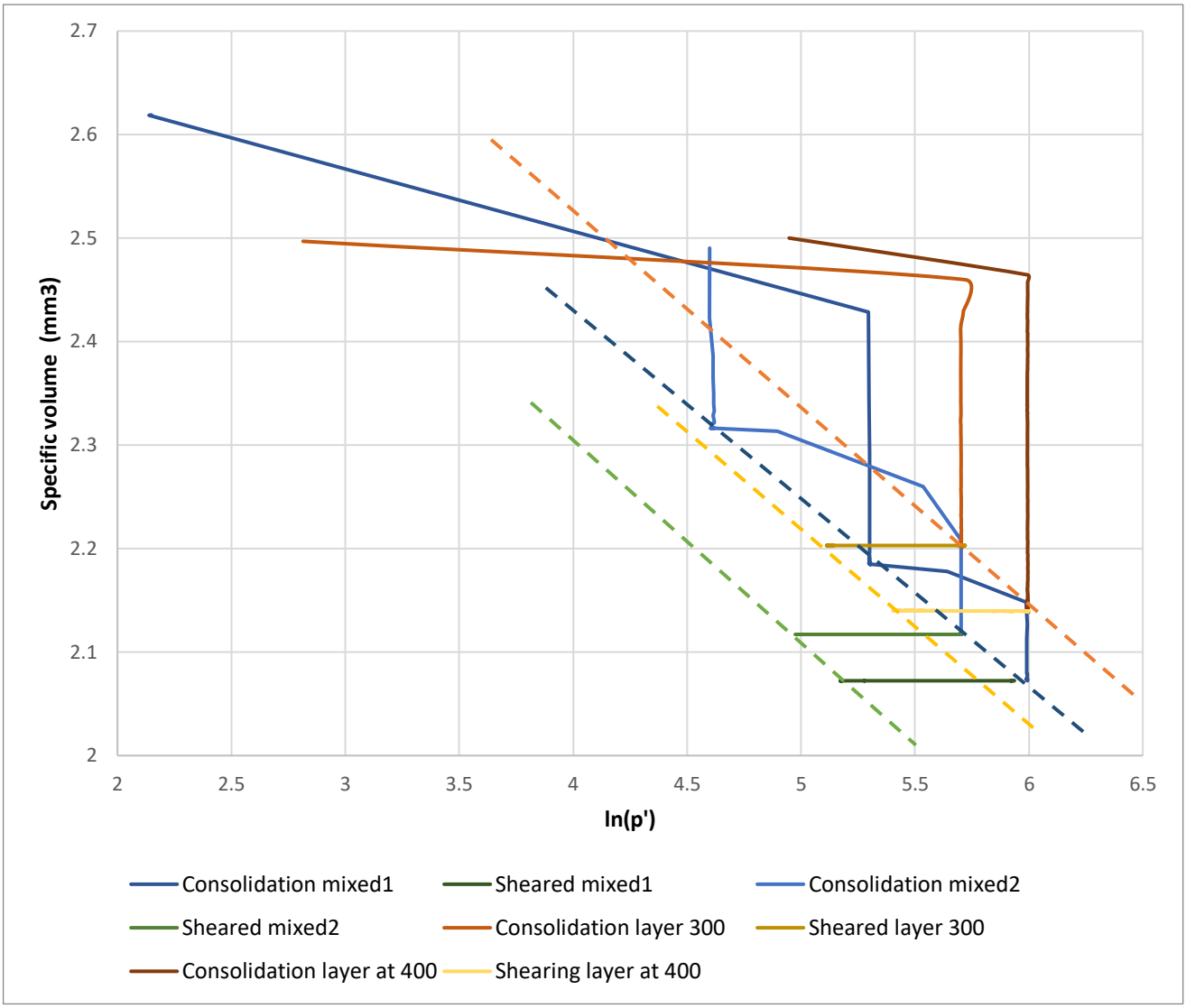


Figure 18: Specific volume vs ln(p') for layered (2025) and mixed (2024) specimens

The NCL and CSL plotted for the selected specimens appear to be approximately parallel which is consistent with established critical state soil mechanics theory. Also, it can be observed in the graph that the lines for the layered specimens lie consistently above those for the mixed specimens. This shift in position is evident in both the consolidation and shearing phases. The implication of this trend will be further explored in section 7.4.

The expression of each line has been worked out as follows:

NCL (Layered specimens)

$$v = N - \lambda \ln(p')$$

Two representative points were extracted using Excel by identifying values of specific volume and the natural logarithm of mean effective stress from the plotted curve:

Point A: $(ln\ (p') = 5.7,\ v = 2.2)$ Point B: $(ln\ (p') = 3.1,\ v = 2.7)$

Using these points, the slope λ was calculated as:

$$\lambda = \frac{v_B - v_A}{\ln (p')_B - \ln (p')_A} = \frac{2.7 - 2.2}{3.1 - 5.7} = -0.192$$

Substituting Point A into the standard form of the NCL equation, the constant N was found to be :

$$N = 3.29$$

Therefore, $v = 3.29 - 0.192 \cdot ln(p')$

Similar calculations were carried out to define the Normal Consolidation Line (NCL) and Critical State Line (CSL) for both mixed and layered specimens. The resulting expressions for each line are as follows:

CSL (Layered specimens) $v = 3.158 - 0.188 \cdot ln(p')$

NCL (Mixed specimens) $v = 3.15 - 0.182 \cdot ln(p')$

CSL (Mixed specimens) $v = 3.07 - 0.188 \cdot ln(p')$

7. Discussion

7.1 Stress–Strain Behaviour

The stress–strain behaviour observed across all tests highlights the distinct mechanical responses of mixed and layered kaolin specimens. It also shows as the effect of confining pressure and specimen preparation history. It can be seen that all specimens exhibited the expected general trend of increasing deviator stress with axial strain. In the mixed specimens, the comparison between current and previous tests revealed noticeable differences in both strength and ductility. The 2025 specimen tested at 100 kPa developed a significantly lower peak deviator stress than those tested in the previous year. This is what would have been expected as the confining pressure of the other ones was higher. Moreover, it showed a smoother curve and a more ductile post-peak behaviour. This suggests that the magnitude of confining pressure is a dominant factor in controlling peak strength. The two previous specimens showed a higher strength and more defined peak points. This could be attributed to a denser initial packing or a more pronounced particle alignment during preparation.

Moreover, the results obtained from the layered specimens show that the two tests conducted at 300 kPa (current and previous study) followed a very similar stress–strain path. This consistency is encouraging as it suggests a reproducible mechanical response under identical confining pressures. In fact, the proximity of the two curves in peak stress and overall shape indicates a robust behavioural pattern. Additionally, as expected, the layered specimen tested at 400 kPa developed a higher peak deviator stress due to the increased confinement. Minor variations in peak strength between the two 300 kPa specimens can be attributed to several inherent variabilities. Even if the same layering technique was applied, the specimens are not exactly identical. A relevant factor is the potential variation in the proportion of layers that were retained within each sample. In fact, it is likely that the 70–30 target ratio of Speswhite to Polwhite was not strictly preserved in every vertical cross-section. Small differences in the distribution of the layers could influence the internal interfaces along the shearing plane. Despite this, the stress–strain responses still remain consistent which reinforces confidence in the specimen preparation method used.

Furthermore, the analysis of the stress ratio q/p' against axial strain highlights clear distinctions between layered and mixed configurations. As shown in Figure 6.7, the layered specimens exhibit a consistent pattern. Despite being tested under different confining pressures, the similarities in shape, gradient, and peak values suggests that the mode of strength mobilisation in layered configurations is dominated by interface effects. In contrast, the mixed specimen tested at 100 kPa follows a different trajectory. Throughout the entire shearing phase, it maintains a higher q/p' value than the layered specimens. This indicates that the mixed specimen was able to mobilise greater deviator stress relative to the mean effective stress. In layered samples, the presence of internal boundaries may create early strain localisation which can reduce the development of high deviator stresses. However, the homogeneous structure of the mixed sample allows for a more uniform stress distribution and to reach a higher stress ratio. Collectively, these findings demonstrate the sensitivity of undrained strength behaviour to the fabric structure and the test conditions.

7.2 Pore Pressure Behaviour

Among the mixed specimens, a clear relationship was observed between the magnitude of the confining pressure and the peak pore pressure. The specimens tested in the previous year under higher consolidation pressures (Mixed 1 and Mixed 2) generated peak pore pressures of respectively 345 kPa and 300 kPa. The current specimen that was tested at a confining pressure of 100 kPa exhibited a

significantly lower peak pore pressure of around 165 kPa. This confirms the dependency of pore pressure generation on the initial effective stress level.

For the layered specimens, the pore pressure response was more consistent across test years. The specimens tested at 300 kPa in both the current and previous studies followed nearly identical trends and final peak values. The specimen tested at 400 kPa generated the highest pore pressure which is consistent with the increased confinement. Additionally, all the curves reached a plateau meaning that critical conditions were approached during shearing.

Overall, the pore pressure data underline the strong influence of confining pressure on the magnitude of excess pore pressure generation in both mixed and layered configurations. The close match between the layered tests at 300 kPa from different years also strengthens confidence in the reproducibility of the experimental procedure.

7.3 Effective Stress Paths

The effective stress paths observed in the space further clarify the shear behaviour and critical state of the tested specimens. The mixed specimens displayed trajectories characteristic of undrained shear behaviour in fine-grained soils. However, the critical state line drawn for these specimens with a slope of m=1.0 does not intersect all final points. This may be attributed to several factors. The current mixed specimen developed lower q and p' values which is consistent with its lower consolidation pressure. But, the fact that it is not passing exactly through the critical state lime may also reflect measurement uncertainties and differences in preparation quality.

In contrast, the layered specimens exhibited stress paths that were both more consistent and better aligned with a well-defined critical state. The critical state line with a slope of M=1.12 passed closely through the peak points of all specimens which indicate that a common critical state condition was achieved. This alignment suggests that the layered configuration produced a more coherent shear response across specimens. The slightly higher M value implies that the layered structure may have allowed for greater mobilisation of deviator stress relative to mean effective stress at failure. This could be due to the influence of anisotropic structuring and constrained shear paths imposed by the layering.

Overall, the contrast between mixed and layered specimens in effective stress space reinforces the broader observation that specimen configuration significantly influences mechanical behaviour. The variation in critical state line slopes between the two configurations further supports the fact that structural arrangement (even with identical material composition) affects the stress path evolution.

7.4 Specific Volume and Critical State Framework

The comparison of v against ln(p') provides important insights into the mechanical differences between mixed and layered specimens with the same composition. The Normal Consolidation Lines (NCLs) and Critical State Lines (CSLs) revealed two main findings: the parallelism of the lines and the vertical shift between the mixed and layered specimens. The fact that the NCL and CSL for both configurations are approximately parallel is consistent with the behaviour of soils with similar mineralogical composition. It suggests that despite structural differences, the fundamental characteristics of the Speswhite–Polwhite system remain governed by the same properties. However, the layered specimens exhibit both an NCL and a CSL that lie above those of the mixed specimens. This vertical shift indicates that the layered specimens maintain a higher specific volume than the mixed ones. An explanation for this difference lies in the heterogeneity of layer distribution. If fact, even if both configurations contain the same proportions of Speswhite and Polwhite, the arrangement of the

materials affects the evolution of internal structure during consolidation. The fact that the materials are arranged in discrete bands in the layered specimen can potentially lead to less efficient interparticle rearrangement and reduced densification. In contrast, the lending in the mixed specimens allows to reach higher densities. Furthermore, the fact that the lines are almost parallel reinforces the notion that the difference is not due to changes in mineralogy but reflects the impact of fabric structure on void ratio and compressibility. Indeed, the structural arrangement changes the way these materials respond to stress. Additionally, the preservation of the same gradient while shifting vertically suggests that the effective percentage of Speswhite and Polwhite within each sample remains valid.

7.5 Experimental Limitations and Sources of Error

In this study, multiple sources of uncertainty may have influenced the results. There are practical limitations that must be acknowledged even if care was taken in all the testing steps. One notable limitation relates to the layered specimens. In fact, it is difficult to ensure that this ratio of 70/30 Speswhite to Polwhite was maintained in the trimmed test specimens. Because the specimens were cut from the box, small variations in trimming could result in different layer proportions in the tested specimens.

Another important source of uncertainty comes from the determination of water content. In several cases, a discrepancy was observed between the water content determined from the small sample taken before the test and the one obtained from a middle-third sample at the end of the test. In order to address this, the post-test water content was used as the reference value in this report. However, the implications of this approach will be discussed further in the recommendations section.

Additionally, measurement errors should be acknowledged. Small inaccuracies in volume change readings and pore pressure response could influence the accuracy of calculated parameters such as mean effective stress or deviator stress. This could explain why the NCL and CSL were not passing exactly through all the point but taken as an approximation. Similarly, any residual air in the saturation system could introduce errors into the pore pressure measurements during shearing.

None of these limitations are expected to invalidate the general trends and findings reported. However, they highlight the importance of careful specimen handling and critical review of results when interpreting data.

8. Conclusion

This study investigated the mechanical behaviour of kaolin clay specimens composed of 70% Speswhite and 30% Polwhite. The specimens were prepared in mixed and layered configurations and were subjected to consolidated undrained triaxial testing. The primary objective was to examine how internal structural arrangement influences overall mechanical response of the soils. A series of tests was analysed across both current and previous datasets. This analysis focused on stress–strain response, effective stress paths, stress ratio evolution, and specific volume behaviour. The results demonstrate that all specimens followed similar mechanical trends but the structural configuration had a influence on their behaviour. Layered specimens for example exhibited higher peak deviator stresses under the same confining pressures. Effective stress path analysis confirmed that both configurations approached critical state conditions. Most Importantly, the analysis of specific volume versus ln p′ revealed parallel Normal Consolidation Lines (NCLs) and CSLs for both configurations which is consistent with critical state theory. But, the layered specimens consistently occupied a higher position in v–ln p′ space. This vertical shift suggests that the layered specimens were consistently less dense and more compressible than their mixed ones. This is due to the influence of internal interfaces and also variability in layer distribution during specimen trimming.

The differences observed between the mixed and layered configurations of the same composition shows the importance of structural arrangement in soil behaviour. It points out that assuming homogeneity in the analysis of natural and artificial soils is not ideal for safety and efficiency in design.

Overall, this research contributes to the understanding of structured clays and it provides experimental evidence that internal layering can significantly affect the compressibility and strength response of fine-grained soils. The insights gained here are directly relevant to the geotechnical assessment of stratified and engineered clay deposits. Finally, it offers guidance and data for further laboratory characterisation and modelling development.

9. Recommendations

Based on the findings and the limitations of this study, several recommendations can be made to improve the accuracy and scope of future research on mixed and layered clays.

First, a notable discrepancy was observed between the initial water content and the final water content measured measure at the beginning and at the end of the test respectively. These differences may have introduced error in the calculations. Therefore, it is recommended to use a more comprehensive approach by measuring the water content of the entire specimen at the end of the test. This will reduce the risk that moisture distribution within the sample affects the water content measurements.

Moreover, a key challenges in preparing layered specimens was ensuring that the targeted 70–30 distribution of was preserved in the trimmed test samples. In the future, layered samples could be prepared as full-height cylindrical moulds to avoid vertical trimming and therefore reduce uncertainty in the proportion composition. These cylindrical moulds could be placed inside the centrifuge box.

Furthermore, it is advised for future studies to explore other ratios and layer geometries. Investigating vertical layering or inclined interfaces for example could provide deeper insights into how structural anisotropy influences soil behaviour.

By addressing these areas, future research can build upon the findings of this study and therefore enhance their application in geotechnical engineering.

References

Clayton, C.R.I., Khatrush, S.A. and Stallebrass, S.E., 1992. *The influence of structure on the behaviour of a natural stiff clay*. Géotechnique, 42(2), pp.211–226.

Stallebrass, S.E. and Taylor, R.N., 1997. *The development and evaluation of a constitutive model for the prediction of ground movements in overconsolidated clay*. Géotechnique, 47(2), pp.235–253.

Stallebrass, S.E. and Woods, R.I., 1994. *Modelling the behaviour of structured clay*. In: *Predictive Modelling in Geomechanics: Proceedings of the British Geotechnical Association Conference*, pp.73–84.

Zhang, J., Zhang, L., Zhang, B. and Xu, C., 2017. *Anisotropic behaviour of layered clay under triaxial loading*. Engineering Geology, 221, pp.153–161.

Chandler, R.J., 1997. *The use of the Cam-Clay model in teaching and research*. Géotechnique, 47(2), pp.219–232.

Coop, M.R. and Atkinson, J.H., 1993. *The mechanics of reconstituted London Clay*. Géotechnique, 43(1), pp.53–67.

Gasparre, A., 2005. *Advanced laboratory characterisation of London Clay*. PhD thesis, Imperial College London.

Gasparre, A., Nishimura, S., Coop, M.R. and Jardine, R.J., 2007. *The influence of structure on the behaviour of London Clay*. Géotechnique, 57(1), pp.19–31.

Lade, P.V. and Yamamuro, J.A., 1996. *Undrained behaviour of sand under anisotropic stress conditions*. Géotechnique, 46(3), pp.435–456.

Lo, K.Y. and Morin, P., 1972. *Strength anisotropy and stress–strain behaviour of two sensitive clays*. Canadian Geotechnical Journal, 9(3), pp.261–277.

Stallebrass, S.E. and Taylor, R.N., 1997. *The development and evaluation of a constitutive model for the prediction of ground movements in overconsolidated clay*. Géotechnique, 47(2), pp.235–253.

Zhang, J., Zhang, L., Zhang, B. and Xu, C., 2017. *Anisotropic behaviour of layered clay under triaxial loading*. Engineering Geology, 221, pp.153–161.

Lu, Zhiqu & Hickey, Craig & Sabatier, James. (2004). Effects of Compaction on the Acoustic Velocity in Soils. Soil Science Society of America Journal. 68. 7-16. 10.2136/sssaj2004.7000.

Ritchie, E.P., Divall, S. and Goodey, R.J., 2021. A method for creating larger clay samples with permeability anisotropy for geotechnical centrifuge modelling. *In: Rahman, M. and Jaksa, M., eds. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*, Sydney, Australia, 1–5 May 2021. London: International Society for Soil Mechanics and Geotechnical Engineering, pp.1175–1180.