Assessing the Influence of Displacement Rates on the Failure Behavior and Undrained Shear Strength Characteristics of Reconstituted Varve Laminae Prepared at Different Moisture Contents

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Abstract

The geotechnical behavior of varved clays in cold regions remains inadequately understood despite their widespread occurrence. This study addresses this gap by investigating the behavior of homogeneous and reconstituted varved clay samples through Unconfined Compressive Strength (UCS) testing. Homogeneous samples consist of Red Soil (RS) and Black Soil (BS), while reconstituted varved clays are prepared by layering RS and BS in configurations of 2, 4, 8, and 16 layers. UCS tests are conducted at displacement rates of 1.25, 0.24, and 0.024 mm/min, hypothesized to simulate the velocity of glacial override on soils. Samples are prepared at five moisture contents ranging from 0.8 to 1.2 OMC. Results indicate that as moisture content decreases below OMC, undrained shear strength increases for all samples, accompanied by a reduction in strain, while the opposite trend is observed for samples on the wet side of OMC. For reconstituted varved clays, undrained shear strength increases as number of laminae rises from 2 to 8, but decreases in the 16-laminae sample, which suggests a threshold exists for the number of laminae beyond which strength reduces. Displacement rate significantly influences failure modes and patterns, with samples exhibiting more ductile behavior at lower displacement rates and higher moisture contents.

Keywords: Reconstituted Varve Laminae, Unconfined Compressive Strength Test, Undrained Shear Strength, Displacement Rate, Moisture Content

1. Introduction

Varved clays are a common type of laminated soil deposit found in glacial environments. These soils are characterized by distinct light and dark-colored bands arranged alternately and repetitively. The dark bands constitute clay-dominant laminae deposited during the winter season, while the light bands constitute silt-dominant laminae deposited during the summer season (Hang, 2003; Ehlers, 2022). These laminae form due to the unique interaction of the turbulence and temperature of the lake water with the density distribution of sediment particles transported by moving and melting glaciers during the summer season. As winter begins and temperatures drop below freezing, the melting of glaciers stops, their movement slows down, and no fresh debris is added to the lake. In the still water conditions, the leftover fine particles from the summer settle on top of the coarser layer. This alternating settlement of coarse and fine particles creates a clear division, with visible light-colored and dark-colored laminae. One pair of light and dark-colored bands together forms a couplet. When these couplets repeat year after year, the deposits are known as varves or varved clays (Lamoureux and Bradley, 1996; Lindqvist and Lee, 2009).

The engineering properties of the two soils that constitute the laminae in varves exhibit significantly different mechanical and infiltration responses under varying stress conditions, making these soils inherently anisotropic (Leroueil et al., 1990; Tankiewicz, 2015; Dobak et al., 2018; Schneider et al., 2022; Tornborg et al., 2023; Philippe et al., 2023). The darker lamina contains more clay-sized particles, has a higher natural moisture content in field conditions, lower hydraulic conductivity, higher plasticity, lower strength, and exhibits greater volumetric changes under load compared to the lighter-colored lamina (Florkiewicz et al., 2014; Flieger-Szymanska et al., 2019). Despite these contrasting properties between the two soils forming the laminae, the anisotropic behavior of varved clays is often overlooked due to the complexity of measuring various anisotropic parameters (Lacasse et al., 1977). This study addresses this gap by investigating the undrained shear strength and failure pattern characteristics of both homogenous and reconstituted varved clays with varying numbers of laminae using Unconfined Compressive Strength (UCS) tests.

UCS represents the load at which soil fails under axial compressive stress without lateral confinement and is influenced by factors such as soil type, displacement rate, temperature, and moisture content (Hampton and Yoder, 1958). There are very few studies that have explored the variation in shear strength behavior of soils with changes in these parameters, and even fewer studies specifically focus on varved clays or layered soil structures. Lo and Milligan (1967) conducted a comparative study on homogeneous and stratified clays and reported that the shear behavior of these two soil types differed considerably. The undrained strength of stratified clays was found to depend on the orientation of the stratification relative to the applied principal stresses. Awoleye et al. (1991) conducted UCS tests on clays at strain rates ranging from 0.08 mm/min to 2 mm/min and reported an increase in strength with a decrease in strain rate. Sabatini et al. (2002) found that even small variations in moisture content significantly affect soil strength under unconfined loading. Lydzba and Tankiewicz (2012) performed UCS tests on varved clays with bedding planes oriented at angles between 0° and 90° and reported that the resulting shear strength varied significantly, with the maximum strength being 14 times higher than the minimum. However, no clear trend was established between soil strength and bedding plane orientation. Alzubaidi and Lafta (2013) conducted triaxial tests under consolidation conditions by varying strain rates between 0.1% and 7% per minute on soil samples with lime contents ranging from 0% to 12%. Strength increased with higher lime content and strain rate; however, further increase in these variables led to a decrease in strength. Du et al. (2016) conducted UCS tests on frozen silty sands by varying negative temperature, moisture content, and applied strain rate. Brittle failure and a non-linear increase in strength at low moisture content and higher strain rates as the sample temperature decreased was reported. At lower strain rates, an increase in moisture content resulted in decreased strength. Tyagi et al. (2019) performed UCS tests on soil at different strain rates by mixing it with various proportions of cement and reported an increase in unconfined compressive strength with higher strain rates.

Given the increasing construction in permafrost regions over the past few decades, understanding the strength properties of glacial soils has become crucial (Du et al., 2016). Glacial override, the process of glaciers moving over existing soils, influences its strength, deformation, and stability. This behavior is further complicated by moisture content variations during the glacial overriding. This study addresses these aspects by conducting UCS tests on six different soil samples, which include homogeneous and reconstituted varved clay samples prepared at five moisture contents. Red Soil (RS) and Black Soil (BS) were selected based on laboratory geotechnical characterization to represent the laminae in actual varved clays. Two homogeneous soil samples are composed separately of RS and BS, while for the reconstituted varved clays, RS and BS are alternated in a repeating pattern to form four different samples with 2, 4, 8, and 16 layers. The five moisture contents at which these samples are prepared include the moisture content corresponding to Optimum Moisture Content (OMC), two on the drier side of OMC (0.8 OMC and 0.9 OMC), and two on the wetter side of OMC (1.1 OMC and 1.2 OMC). To simulate glacial override, UCS tests in this study are conducted at three displacement rates of 1.25 mm/min, 0.24 mm/min, and 0.024 mm/min. The behavior of soils under different displacement rates provides a simplified simulation of how soils with varying compositions might respond to different loading rates, which, in this study, is considered analogous to the varying velocities of glacial movement on the soil. Although the absolute magnitudes of displacement rates used in the present study might be different from the actual glacial override velocities, the general trends observed through the study regarding the undrained shear strength of the soil and its failure patterns provide insights into the way in which the soil may respond to glacial override.

2. Materials and Methodology

The two soils, RS and BS, used in the present study were obtained from the vicinity of the IIT Guwahati campus. Various preliminary geotechnical investigations were carried out to determine the suitability of these soils to replicate the soils that constitute the laminae of actual varved clays. These geotechnical investigations are discussed in Section 2.1, and the methods of testing and sample preparation are discussed in Section 2.2.

2.1 Material Characterization of RS and BS used as Constituent Laminae

Figure 1 shows the deposition sites of RS and BS. This figure also includes an image of the soils collected in a tray and dried. It can be observed that RS has a coarser texture, while BS has a finer texture. The preliminary geotechnical investigations conducted for selecting these soils include determining the Atterberg limits (IS: 2720 Part 5-1985) and Particle Size Distribution (PSD) (IS: 2720 Part 4-1980). These analyses revealed that RS can effectively represent the light-colored, silt-dominant laminae, while BS can represent the darker, clay-dominant laminae of actual varved clays. The laboratory tests, including these parameters of RS and BS along with other important geotechnical parameters that help in assessing their engineering behavior, are listed in Table 1.

Figure 1. Representative samples of (a) RS and (b) BS collected in the vicinity of IIT Guwahati campus

Table 1. Geotechnical properties of RS and BS

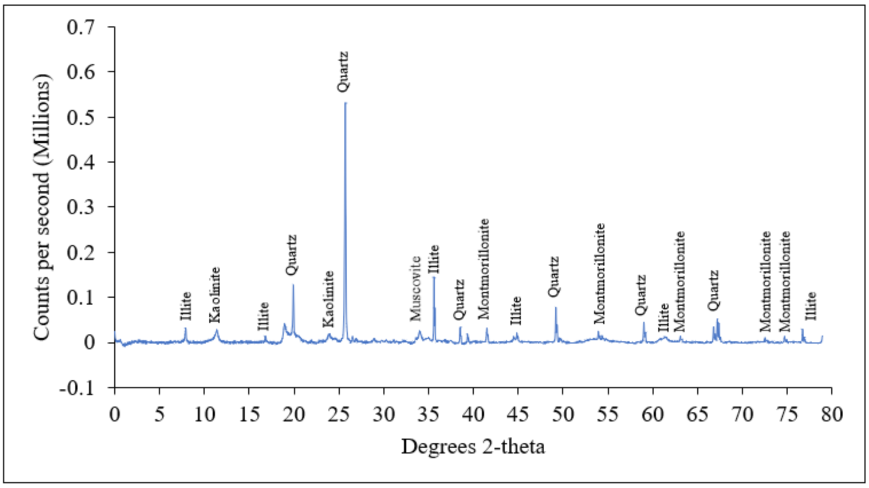
Geotechnical Parameters	Red Soil (RS)	Black Soil (BS)
Specific Gravity	2.7	2.6
Atterberg Limit (%)		
Liquid Limit	45	95
Plastic Limit	19	30
Plasticity Index	26	65
Compaction Characteristics		
Maximum Dry Density (g/cc)	1.77	1.59
Optimum Moisture Content (%)	19.5	21.5
Grain Size Distribution (%)		
Sand	23.2	8.4
Silt	54.4	6.7
Clay	22.4	84.9
Soil Classification	ML	CH
Shear Strength Parameters		
Effective friction angle (°)	17.53	13.0
Cohesion (kPa)	12.4	6.1

From Table 1, it is observed that the liquid limits of RS and BS are 45% and 95%, respectively. The liquid limit is often associated with the clay content in soils, with soils that have higher clay content tending to have a higher liquid limit. This aligns well with the findings of the PSD, which show that BS has a significantly higher clay content of 84.9%, compared to RS, which has a lower clay content of 22.4%. The plastic limits of RS and BS are 19% and 30%, respectively. In comparison to RS, the higher plastic limit of BS indicates that it requires more moisture to make transition from a plastic to a semi-solid state. Practically, this means that BS has a greater ability to retain water while maintaining a plastic consistency. Additionally, the plasticity index of 26% for RS reflects its moderate plasticity, whereas BS demonstrates significantly higher plasticity with an index of 65%. The plasticity index values provide insight into the range of moisture over which each soil exhibits plastic behavior. In this case, BS exhibits plastic behavior over a wider range of moisture content compared to RS. From the grain size distribution, RS is found to have a composition of 23.2% sand, 54.4% silt, and 22.4% clay, while BS is characterized by 8.4% sand, 6.7% silt, and a predominant 84.9% clay content. These variations in grain size distribution and Atterberg limits contribute to the divergent engineering behavior of the soils when placed in layers to form the laminae of varved clays. The dominance of clay in BS and the higher silt content in RS are noteworthy and explain the differences in Atterberg limits. Furthermore, according to the classification system, RS is classified as ML (silt with low to medium plasticity), while BS is classified as CH (clay with high plasticity). These parameters of RS and BS are consistent with the characteristics of actual varved clays documented in the literature by Eden (1955), Kazi (1967), Eigenbrod and Burak (1991), Lydzba and Tankiewicz (2012), Florkiewicz et al. (2014), Tankiewicz (2016), Krawczyk and Szymanska (2018), and Flieger-Szymanska et al. (2019). Table 1 also lists other parameters obtained from laboratory tests, such as specific gravity (IS: 2720 Part 3/Sec-2-1980), compaction characteristics (IS: 2720 Part-7-1983), and shear strength parameters. The shear strength parameters were obtained from Direct Shear Tests (DST) conducted according to ASTM D3080/D3080M (ASTM 2012).

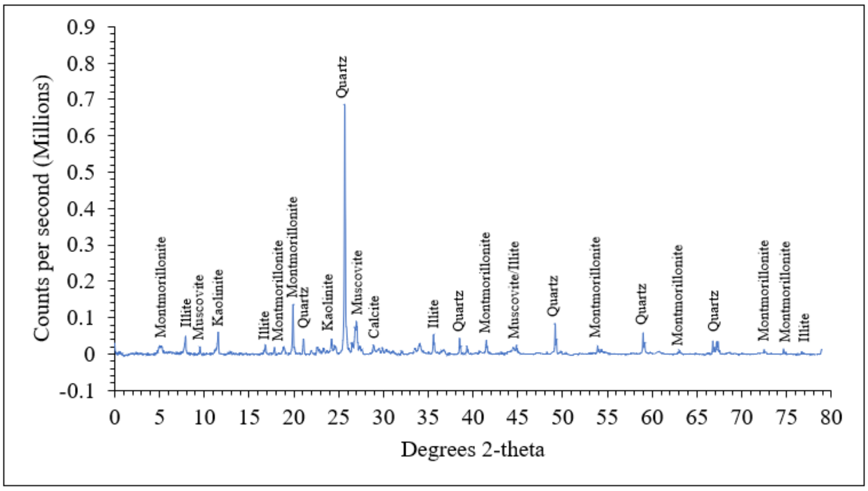
2.1.1 Mineralogical and morphological characteristics of RS and BS

To further ensure that RS and BS, used as representative soils in reconstituted varved clays, are mineralogically similar to the two laminae in actual varved clays, X-ray Diffraction (XRD) and Field Emission Scanning Electron Microscopy (FESEM) were conducted. Figures 2(a) and 2(b) present the results of the XRD analysis, while Figures 3(a) and 3(b) show the outcome of the FESEM analysis for RS and BS, respectively. The difference between these analyses is that the XRD technique examines the crystal structure of the soil, while the FESEM technique focuses on the microstructure of the soil. XRD works by illuminating the soil samples with X-ray beams and then measuring the angles and intensities of the beams scattered by the crystal lattice of the soil grains. On the other hand, in FESEM, electron beams are directed onto the samples, which creates an image of the surface and topography of the sample. This electron beam is focused on the sample with the help of electromagnetic lenses.

For conducting XRD analysis of RS and BS, the soils were finely ground and dried in the oven for 24 hours. The soils were then taken out of the oven, and the samples were placed on a glass sample holder. To ensure that the powdered sample didn't blow away and stayed in place, the soil was gently pressed with a glass slide. The excess soil powder was removed with the same glass slide, and care was taken to ensure that the surface of the soil sample was smooth. This process was done separately for RS and BS. The prepared soil samples were then placed in a sample holder inside the XRD instrument, which consists of a detector. When the X-ray beams interact with the crystal lattice of the minerals in the soils, diffraction patterns are obtained. The X-ray diffraction patterns are produced by varying the angle at which X-rays strike the soil samples. The intensity of diffracted X-rays at different angles is used to create XRD patterns. The peak positions and intensities of the XRD patterns are compared with reference patterns available in literature or a database to identify the mineral composition in RS and BS, as shown in Figures 2(a) and 2(b). The XRD patterns clearly indicate that BS contains a significant amount of the clay mineral montmorillonite compared to RS. A similar observation was reported by Ringberg and Erlström (1999). In this study, the researchers performed XRD by separating the summer layer (the lighter lamina) and the winter layer (the darker lamina) of varved clay. A significant difference was found between the XRD diffractograms of the two soils, particularly in the clay mineral peaks, with the winter layers showing higher magnitudes of these peaks. Blondeau (1975) also reported that when the dark and light laminae were X-rayed separately, they were found to be mineralogically identical, except for the higher clay content in the dark-colored laminae compared to the light-colored laminae. The author further reported the dominance of illite in the light-colored laminae with minor montmorillonite, whereas montmorillonite dominated the dark-colored laminae. This finding aligns with the XRD results of RS and BS obtained in the present study.



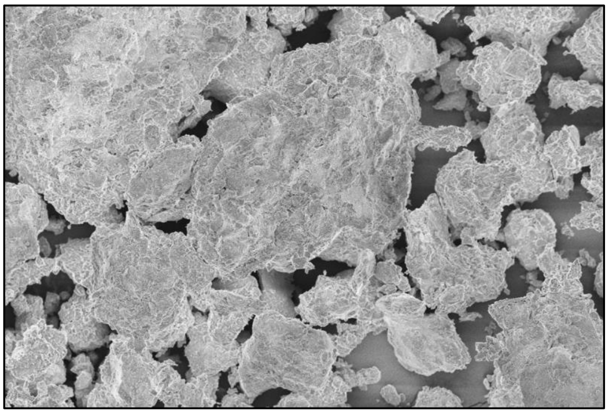
(a)



(b)

Figure 2. X-ray Diffraction spectra of (a) RS (b) BS samples

Figure 3 displays the microstructure of RS and BS using FESEM analysis. FESEM analysis requires even more careful sample preparation than XRD. For FESEM, just like in XRD, both RS and BS were finely ground and oven-dried for 24 hours. Also, testing soils for FESEM is more difficult than conducting XRD analysis because, in FESEM analysis, the soil sample can absorb moisture from the atmosphere during the sample preparation stage and can simultaneously develop electric charges on its surface. If this occurs, the images obtained through FESEM may not be clear, and many white patches can appear in the images. To avoid moisture exposure, both RS and BS samples were immediately transferred to an airtight box filled with silica beads after being removed from the oven. For the FESEM analysis, both samples were mounted on the same stub using sticky carbon tape. To prevent the buildup of charges on the surface of the soil sample due to moisture in the environment, once the samples were placed on the stub, they were coated with gold. The samples were then inserted into the FESEM machine, and images were captured at 1000X magnification, as this magnification provided the clearest images. From the captured images, it was observed that the particles of RS appeared larger and more rounded (Figure 3a), while BS exhibited flaky-shaped particles (Figure 3b). Clay particles are generally flaky in shape. Moreover, comparing the network of pores between the particles of both soils, higher porosity was observed in BS compared to RS. This can be attributed to the presence of clay minerals with a highly flocculated structure, leading to a larger number of inter-floc voids. Therefore, based on the mineralogical compositions and microstructure of the chosen RS and BS, it is concluded that the light-colored and dark-colored laminae of actual varves from glaciated regions can be suitably represented by RS and BS, respectively.


(a)

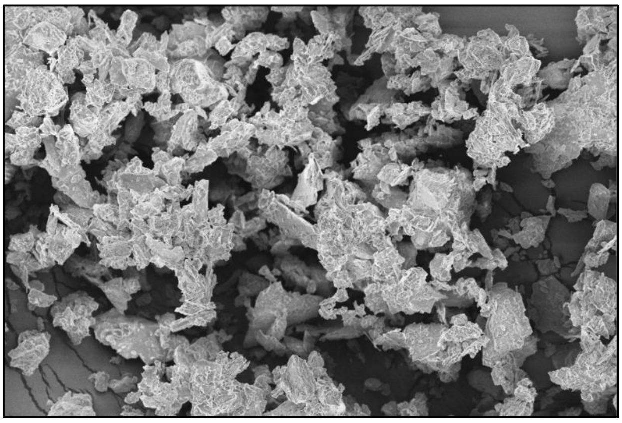
 (b)

Figure 3. Field Emission Scanning Electron Microscopy (FE-SEM) showing microstructure of (a) RS (b) BS at 1000X magnification

2.2 Methodology

All the soil samples for UCS testing are prepared by weighing the soil according to its Maximum Dry Density (MDD). The water content used for preparing these samples is based on the OMC. The five water contents selected for sample preparation are OMC, 1.2 OMC, 1.1 OMC, 0.9 OMC, and 0.8 OMC. The MDD and OMC were obtained by conducting the Standard Proctor Test (IS: 2720 Part-7-1983) on both soils. The MDD and OMC for RS are found to be 1.77 Mg/m³ and 19.5%, respectively, while for BS, the corresponding values are 1.59 Mg/m³ and 21.5% (Table 1). The lower OMC of RS is attributed to the high presence of silt-sized particles, which allows better packing and helps in achieving MDD at a lower moisture content compared to BS. The higher OMC of BS is attributed to its high clay content, which requires a substantial amount of water for proper compaction.

The standard stainless-steel UCS mould, with a volume of 86,192.74 mm³, is used to prepare samples with a diameter of 38 mm and a length of 76 mm. The homogeneous soil samples are prepared by following routine sample preparation steps for UCS testing. First, the required weight of soil is calculated by multiplying the MDD of the soil with the volume of the standard mould used for preparing the sample for testing. The soil is then placed in a bowl and mixed with the designated moisture content. The mixture is transferred into the mould, and the mould is screwed from the ends. This standard mould is also illustrated in Figure 4. Afterward, the sample is extruded using a sample extruding machine and immediately placed in the UCS machine by positioning it between metal plates. The axial load is then applied to the sample at a specific displacement rate. For the reconstituted varved clay samples, the sample extrusion process remains the same, but the amount of RS and BS used varies. Since the proportion of RS and BS is consistent for the standard dimensions of UCS samples, regardless of the number of laminae in the reconstituted varved clay samples, the weight of each soil (RS and BS) also remains unchanged for all reconstituted varved clay samples. Figure 4 illustrates the preparation of the 4-layered reconstituted varved clay sample used in the UCS test. To achieve this, half of the total volume of the mould is considered to calculate the weight of each soil type, with the appropriate amount of water added based on the desired moisture content relative to the OMC. In this example, the weights of RS and BS are measured to fill half of the volume of the mould, which is approximately 43,096.37 mm³ for each soil. The unit weights of RS and BS are 1.77 Mg/m³ and 1.59 Mg/m³, respectively (as shown in Table 1). Therefore, 76.28 g of RS and 68.52 g of BS are weighed separately into two containers, and the soil-water mixture is prepared. For the 4-layered reconstituted sample, these soils are further divided into two equal portions of 36.63 g of RS and 34.47 g of BS. The soils are then alternately transferred, layer by layer, into the UCS mould to form a 4-layered sample. Once the layers are placed, the mould is sealed with caps on both ends, and the sample is extruded for testing. This process is repeated for other varved clay samples, prepared at different water contents and with varying numbers of layers, following the same methodology.

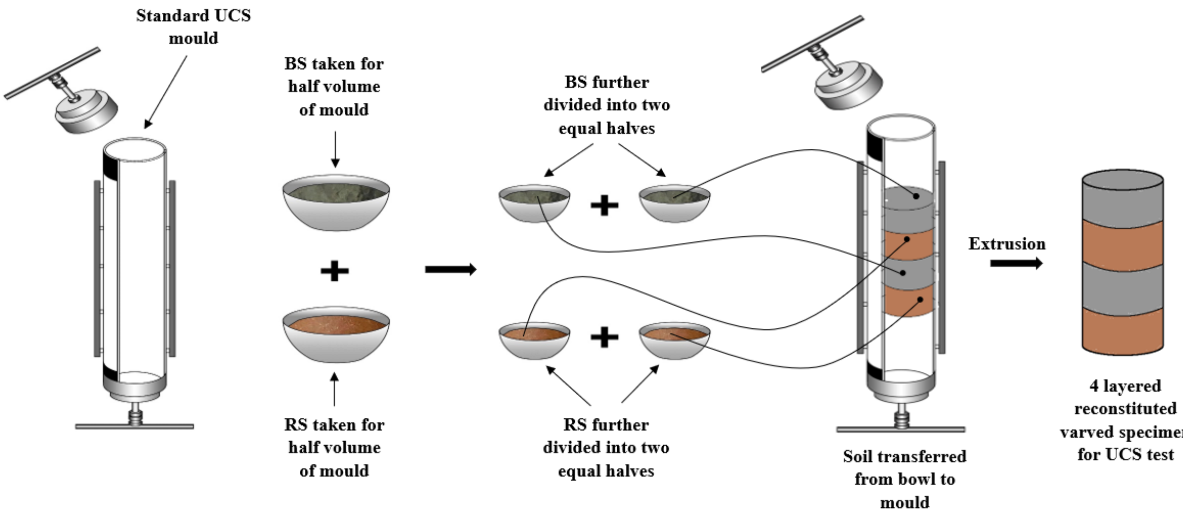


Figure 4. Illustration of the sample preparation process for 4-layered reconstituted varved clays used in UCS testing

For all the reconstituted varved clay samples, the soil samples are extruded and placed for UCS testing such that the lowermost lamina, which rests on the bottom plate, always consists of RS. With the layers arranged alternately, the top layer is always BS, in contact with the top plate attached to the loading cell. The reconstituted varved clays are designated as 2L, 4L, 8L, and 16L in the study, where the numeric digits indicate the number of laminae, and 'L' stands for 'Laminae'.

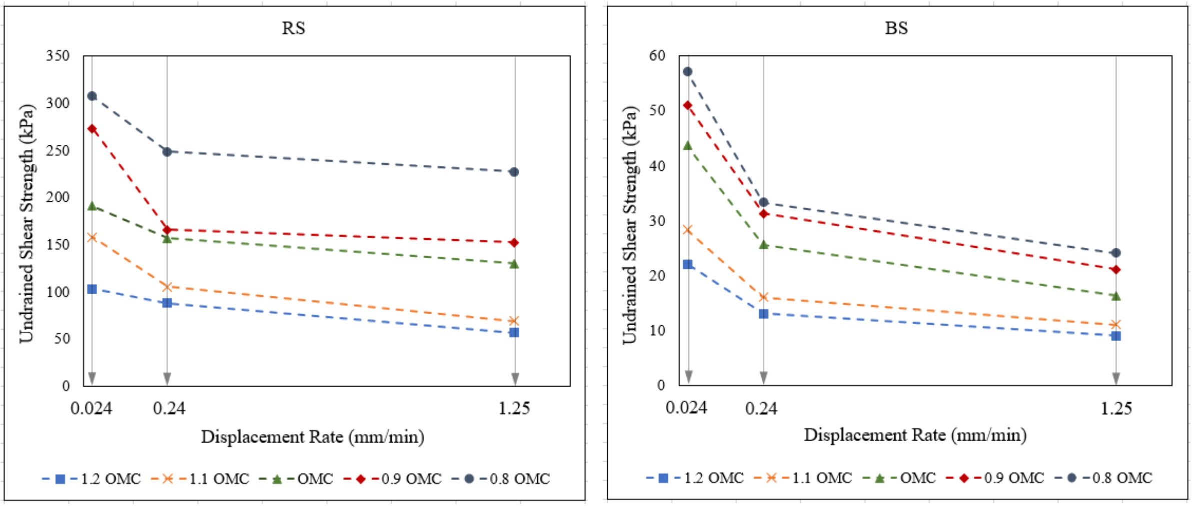
3. Results and Discussions

This section discusses the variation in undrained shear strength with respect to variables such as applied displacement rate and moisture content in both homogeneous and reconstituted varved clays, with additional consideration given to the varying number of laminae in the reconstituted samples. Additionally, different failure patterns under UCS loading for samples prepared and tested considering different combinations of these variables are also explored in this study. In Sections 3.1 and 3.2, the variation of undrained shear strength with respect to the chosen variables is discussed. Shear strength is an important property of soil that maintains equilibrium when the surface is uneven, such as in the case of slopes, or when loading on the soil induces shear stresses. In the UCS test, the applied axial stress generates shear stresses in the samples. The peak axial stress at which the soil sample fails is referred to as the unconfined compressive strength of the soil. According to the Mohr-Coulomb criterion, the unconfined compressive strength is related to the undrained shear strength, with undrained shear strength being half of the unconfined compressive strength. Since the study is conducted in the context of a glacial environment, where glacial override and hilly terrain prevail, the discussion focuses on the undrained shear strength across different soil profiles.

3.1 Variation of Undrained shear strength with displacement rate and moisture content

Figures 5(a) to 5(f) show the variation of undrained shear strength with displacement rate for RS, BS, and reconstituted varved clay samples with 2, 4, 8, and 16 laminae, that are tested at different moisture contents. The general trend observed in all these graphs indicates that undrained shear strength decreases as the displacement rate increases for all soil profiles at different moisture contents. This demonstrates that when the axial loading rate on the soil decreases, its ability to resist shear stress increases. The increase in undrained shear strength of soils with the decrease in displacement rate is more pronounced when the rate lowers from 0.24 mm/min to 0.024 mm/min, compared to when it decreases from 1.25 mm/min to 0.24 mm/min. This non-linear behaviour suggests that soil samples exhibit greater sensitivity to undrained shear strength at lower displacement rates. This sensitivity occurs because slower displacement rates allow more time for the soil structure to mobilize its internal strength to resist loading. The mobilization at low displacement rates occurs through the rearrangement and redistribution of internal stresses within the soil that result in increased undrained shear strength. In contrast, when the displacement rate is higher, soils exhibit more brittle behaviour with less opportunity for internal adjustment, which leads to failure at lower axial compressive loads. This suggests that in the actual field conditions, the rate of glacial movement governs the strength and stability of both layered and homogeneous soils. This behaviour is further supported by visual observations of the failed soil samples after UCS testing shown in Figures 9 to 14. These figures show that samples subjected to higher displacement rates experience shear-dominated, abrupt failure with sharp failure planes, indicating a brittle nature compared to those subjected to lower displacement rates. Since displacement rate is analogous to the velocity of glacial movement, it can be inferred that rapid glacial override on soils in cold regions leads to brittle, abrupt, and early failure of the underlying soils.

Additionally, it is observed that, among all the soil samples tested (Figure 5), RS consistently exhibits the highest undrained shear strength (Figure 5a), whereas homogeneous BS shows the lowest undrained shear strength (Figure 5b). The reconstituted varved clay samples exhibit intermediate undrained shear strength, with values between those observed for homogenous RS and BS. This pattern holds true for all combinations of displacement rates and moisture contents for the reconstituted varved clays. The higher undrained shear strength of RS is attributed to its higher shear strength parameters, i.e., the angle of internal friction and cohesion, compared to BS (Table 1). The high angle of internal friction allows for more compact packing of soil grains during sample preparation, while the high cohesion provides additional strength in the absence of lateral confinement, resulting in higher undrained shear strength for RS under unconfined axial loading compared to BS.



(a) **(b)**

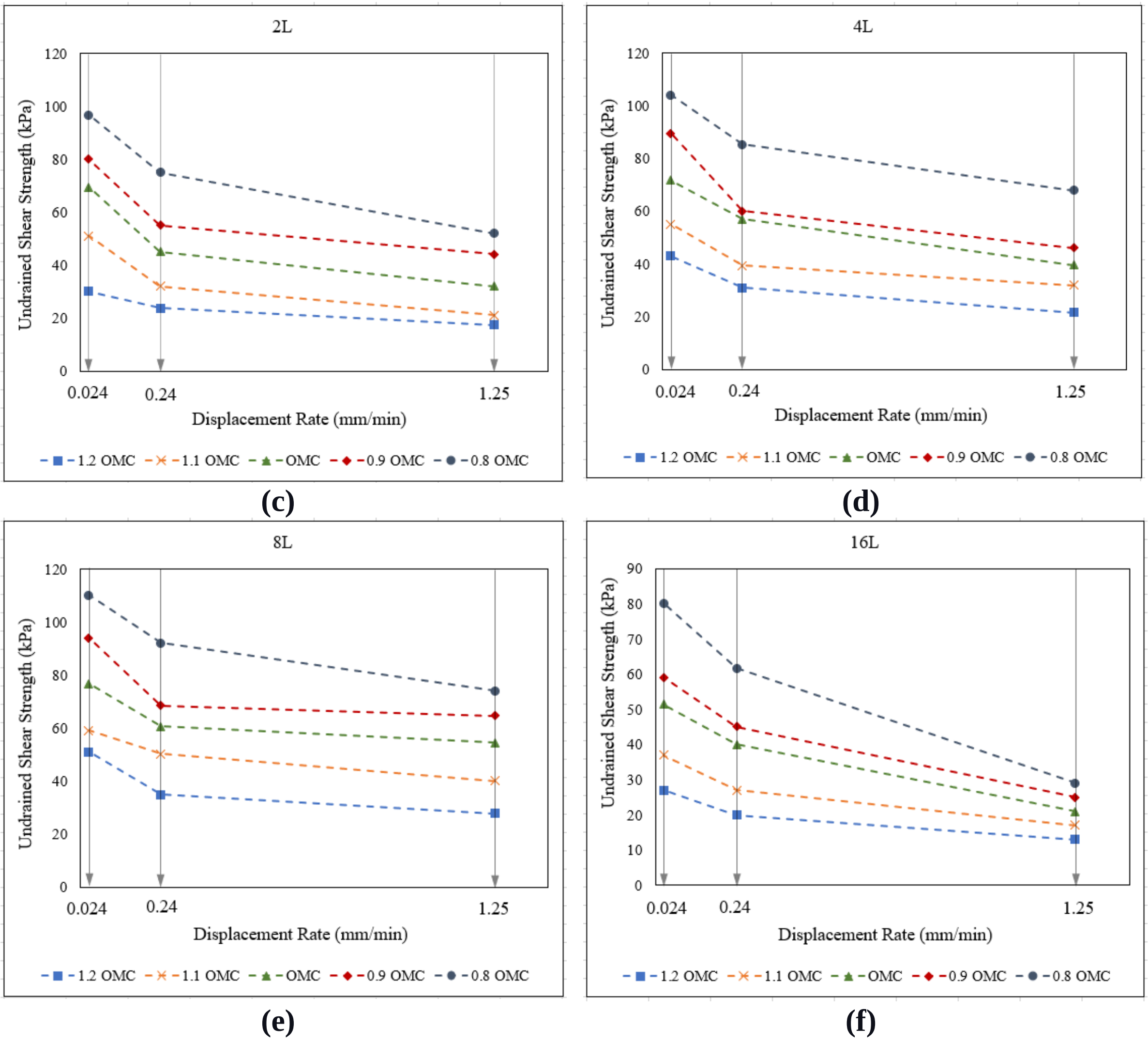


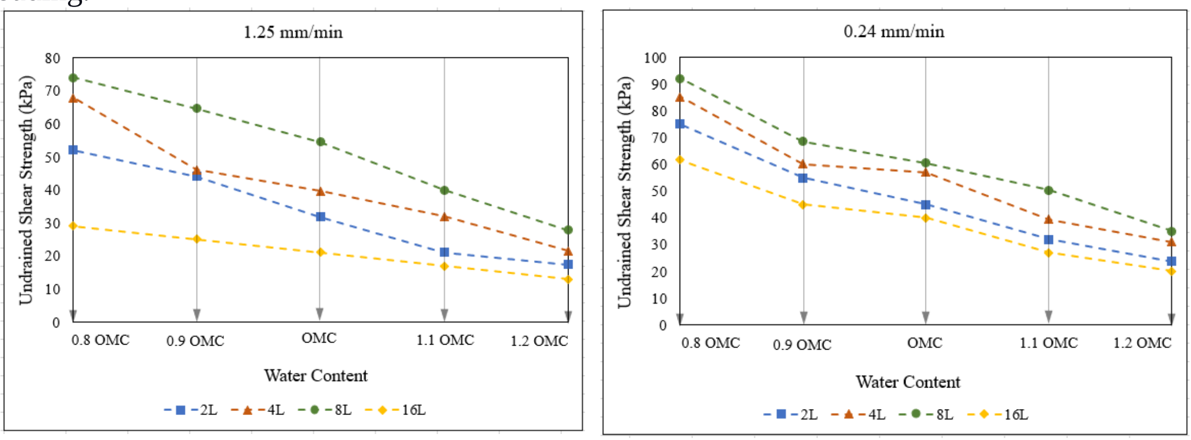
Figure 5. Variation of undrained shear strength with displacement rate at different moisture contents for samples of (a) homogeneous RS soil, (b) homogeneous BS soil, and reconstituted varved clay samples with (c) 2L, (d) 4L, (e) 8L, and (f) 16L

3.2 Variation of Undrained shear strength with displacement rate, moisture content and number of laminae in reconstituted varved clays

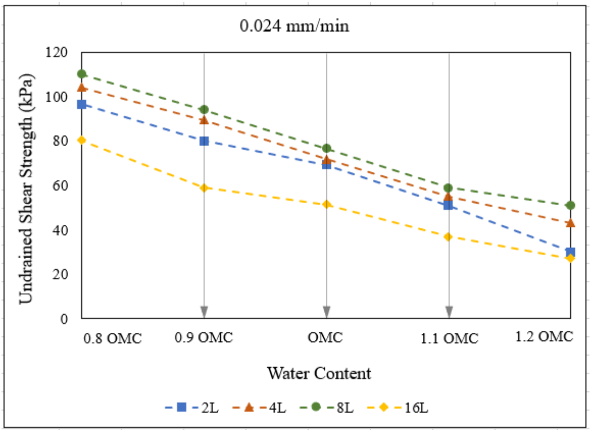
Figures 6 and 7 specifically focus on the variation in undrained shear strength for reconstituted varved clays with different moisture contents and numbers of laminae at a given displacement rate. The results from homogeneous RS and BS samples are not shown here, as the differences in undrained shear strength magnitudes between RS and BS would make the graphs difficult to interpret alongside the reconstituted varved clays. Moreover, the discussion on undrained shear strength for RS and BS has already been briefly covered in the previous section.

Figure 6 shows the variation in undrained shear strength with moisture content for reconstituted varved clay profiles at different displacement rates of 1.25 mm/min (Figure 6a), 0.24 mm/min (Figure 6b), and 0.024 mm/min (Figure 6c). From the graphs, it is observed that reducing the moisture content from OMC to 0.9 OMC and 0.8 OMC leads to an increase in undrained shear strength. Conversely, increasing the moisture content from OMC to 1.1 OMC and 1.2 OMC results in a decrease in undrained shear strength for all the soil profiles, irrespective of the applied displacement rates. However, the undrained shear strength values remain higher for samples tested at lower displacement rates, as discussed in Section 3.1. This decrease in undrained shear strength with increasing moisture content occurs because excess water acts as a lubricant between soil grains, which reduces friction and cohesion between particles and makes the soil fail more easily under load. A decrease in moisture content, up to a certain limit, leads to greater frictional resistance between soil grains. At moisture contents of 0.9 OMC and 0.8 OMC, the undrained shear strength increases, which indicates that reduced moisture enhances interlocking between soil particles, leading to greater resistance to axial loading. The samples prepared at water contents lower than OMC also become more rigid, which is observed in their failure patterns shown in Figures 8 to 13. Also, for samples prepared at moisture content on the wetter side of OMC, significant challenges were encountered during the preparation phase. The samples frequently broke during the extrusion process due to their tendency to stick to the metal plates. Even after successful extrusion, the samples often became distorted while being placed between the two metal plates for UCS testing, making the samples prepared on the wet side of OMC difficult to handle. Due to these challenges, careful handling was required for samples prepared at moisture contents above OMC. These observations and experiences during the preparation and handling of soil samples with high water content highlight the adverse effects of excess moisture on the strength and stability of the samples.

Another important observation from Figure 6 is the asymmetry in the sensitivity of undrained shear strength to increases and decreases in moisture content relative to OMC. Notably, the decrease in undrained shear strength due to increase in moisture content (from OMC to 1.1 OMC and 1.2 OMC) is more pronounced than the increase in undrained shear strength for the same magnitude of moisture content decrease (from OMC to 0.9 OMC and 0.8 OMC) for all soil samples. For example, at a displacement rate of 1.25 mm/min for the 2L reconstituted varved clay sample, the undrained shear strength at OMC is 32 kPa. When the moisture content is reduced to 0.9 OMC and 0.8 OMC for this sample, the undrained shear strength increases to 44 kPa and 52 kPa, respectively. However, when the moisture content is increased to 1.1 OMC and 1.2 OMC, the undrained shear strength decreases to 21 kPa and 17 kPa, respectively. The increase in undrained shear strength due to the reduction in moisture content from OMC to 0.9 OMC and 0.8 OMC is 1.38 times and 1.63 times the undrained shear strength at OMC, respectively. Conversely, the decrease in undrained shear strength due to the increase in moisture content from OMC to 1.1 OMC and 1.2 OMC is 1.52 times and 1.83 times the undrained shear strength at OMC, respectively. This asymmetry suggests that soils are more sensitive to increases in moisture content compared to equivalent decreases in moisture content relative to OMC. This difference in sensitivity is due to increased pore water pressure at higher moisture contents, which significantly reduces the ability of soil to resist shear stresses, as discussed in Section 3.1. The higher pore water pressure lowers the effective stress within the soil, which weakens the bonds between particles and leading to earlier failure under axial loading.



(a) **(b)**



(c)

Figure 6. Undrained shear strength variation with moisture content for reconstituted varved clay profiles with different laminae at displacement rates of (a) 1.25 mm/min, (b) 0.24 mm/min, and (c) 0.024 mm/min

From Figure 6, it is evident that as the number of laminae in the reconstituted varved clay sample increases from 2 to 4 and then to 8, the undrained shear strength increases. However, when the number of laminae increases to 16, the undrained shear strength decreases significantly, with these values falling below those of the 2-layered reconstituted sample. The increase in undrained shear strength up to 8 layers suggests that adding laminae within a fixed length of soil enhances load resisting capacity up to a certain number of laminae. This improvement in strength is likely due to the interaction between RS and BS laminae, where the RS laminae act as reinforcement in the alternating arrangement with BS in the reconstituted varved clay profiles. This is evident from the fact that in homogeneous BS soil samples, where the entire sample consists of BS, the undrained shear strength is the lowest among all the soil profiles considered in this study at the given displacement rate and moisture content. However, when the same BS is alternated with RS to form a laminated structure, an increase in undrained shear strength is observed. The RS laminae in the reconstituted varved clays also provide a confinement effect, limiting the lateral expansion of the BS laminae when BS is sandwiched between RS laminae. This is particularly evident in the samples prepared at moisture contents above OMC, as shown in Figures 10 to 12, which depict the failure patterns in the reconstituted varved clay profiles. Therefore, as the number of laminae increases in the reconstituted varved clays, the alternating arrangement of RS and BS enhances interlayer bonding and friction, contributing to increased undrained shear strength. However, when the number of layers reaches 16, a sharp decline in undrained shear strength occurs. This suggests that an excessive number of laminae introduces too many RS-BS interfaces within the soil samples, which now act as planes of weakness, reducing the overall strength during UCS testing. As a result, the RS laminae can no longer compensate for the weaker BS laminae, and the increased number of laminae outweighs the benefits of interlayer bonding between RS and BS, which leads to a decrease in strength. Additionally, the weakness of the 16-layered soil was evident during the sample extrusion process, as the layers often began to separate, particularly in samples prepared on the wetter side of OMC. At water content greater than OMC, these samples, among all other reconstituted varved clays, were more difficult to handle and place between the plates of the UCS machine, indicating mechanical instability caused by excessive layering and high-water content.

3.3 Stress-strain curves for different combinations of soil profile, displacement rate and moisture content

Figure 7 presents the stress-strain curves for different types of soil samples prepared at the water content of OMC under the UCS test with the load applied at different displacement rates. From an initial observation, it is evident that in all the soil samples, the peak compressive stress is highest for the displacement rate of 0.024 mm/min, followed by 0.24 mm/min, with the lowest peak compressive stress observed for samples loaded at the displacement rate of 1.25 mm/min. The strains at which peak compressive stress is achieved are also highest for the soil sample loaded at the displacement rate of 0.024 mm/min, followed by 0.24 mm/min, and the lowest strain is observed for the displacement rate of 1.25 mm/min.

It is further observed that among all the six soil profiles and for all displacement rates, the homogeneous RS samples exhibit the highest peak strength (Figure 7a), while homogeneous BS samples exhibit lower peak strength (Figure 7b). However, the post-peak nature of the stress-strain curve for homogeneous RS indicates its brittle nature compared to BS at all applied displacement rates. The brittle behavior in homogeneous RS is particularly evident from its sharp stress-strain curve up to the peak stress at displacement rates of 1.25 mm/min and 0.24 mm/min. This is followed by a steep drop in the curve post-peak strength to very low magnitudes of compressive stress at these displacement rates. These characteristics of stress-strain curve for RS indicates a sharp fracture of the sample. As the displacement rate is reduced to 0.024 mm/min, RS exhibits a more gradual stress-strain curve with a higher peak strength attained at higher strain magnitude. In this case, the post-peak drop is less sharp and does not fall to as low magnitudes as seen in the previous two higher displacement rates. Therefore, as the displacement rate is lowers, failure in homogeneous RS transforms to a less brittle nature. Comparatively, the stress-strain curves for homogeneous BS exhibit a gentler slope when approaching the peak stress, with noticeable plastic deformation before failure. After reaching the peak, a gradual strain softening is observed.

The stress-strain curves for reconstituted varved clays with 2, 4, 8, and 16 layers are shown in Figures 7c, 7d, 7e, and 7f, respectively. Among the reconstituted varved clay profiles, as the number of laminae increases, the peak stress is achieved earlier, i.e., at smaller strains for a given applied displacement rate. For instance, at a displacement rate of 1.25 mm/min, the peak stress is reached at strains of around 0.012 and 0.0102 for the 2L and 4L reconstituted varved profiles, while for the 8L and 16L samples, it is approximately 0.009. At a displacement rate of 0.24 mm/min, the peak stress is attained at strains of 0.04, 0.034, 0.026, 0.024, and 0.021 for the 2L, 4L, 8L, and 16L samples, respectively. For the displacement rate of 0.024 mm/min, the strain at which the maximum stress is reached is 0.049, 0.044, 0.04, and 0.036 for the 2L, 4L, 8L, and 16L samples, respectively.

From the stress-strain curve for samples loaded at a displacement rate of 0.24 mm/min, it is observed that as the number of laminae increases, the curve becomes flatter near the peak stress, indicating enhanced ductility in the samples as the number of laminae increases. However, for the other two displacement rates of 1.25 mm/min and 0.024 mm/min, the variation in the nature of failure with the increasing number of laminae, based on the stress-strain graph, is less clear. These observations are specific to samples prepared at OMC. For conciseness, the stress-strain curves of samples prepared at other moisture contents are not shown here, as the basic trend of the graphs remains the same. The only notable difference is that greater ductility is observed in the stress-strain curves for samples prepared at water content greater than OMC, with the peak compressive stress attained at slightly higher strain magnitudes for a sample loaded at given displacement rate. Conversely, samples prepared at lower moisture content than OMC become more brittle, achieving peak stress at lower strains.

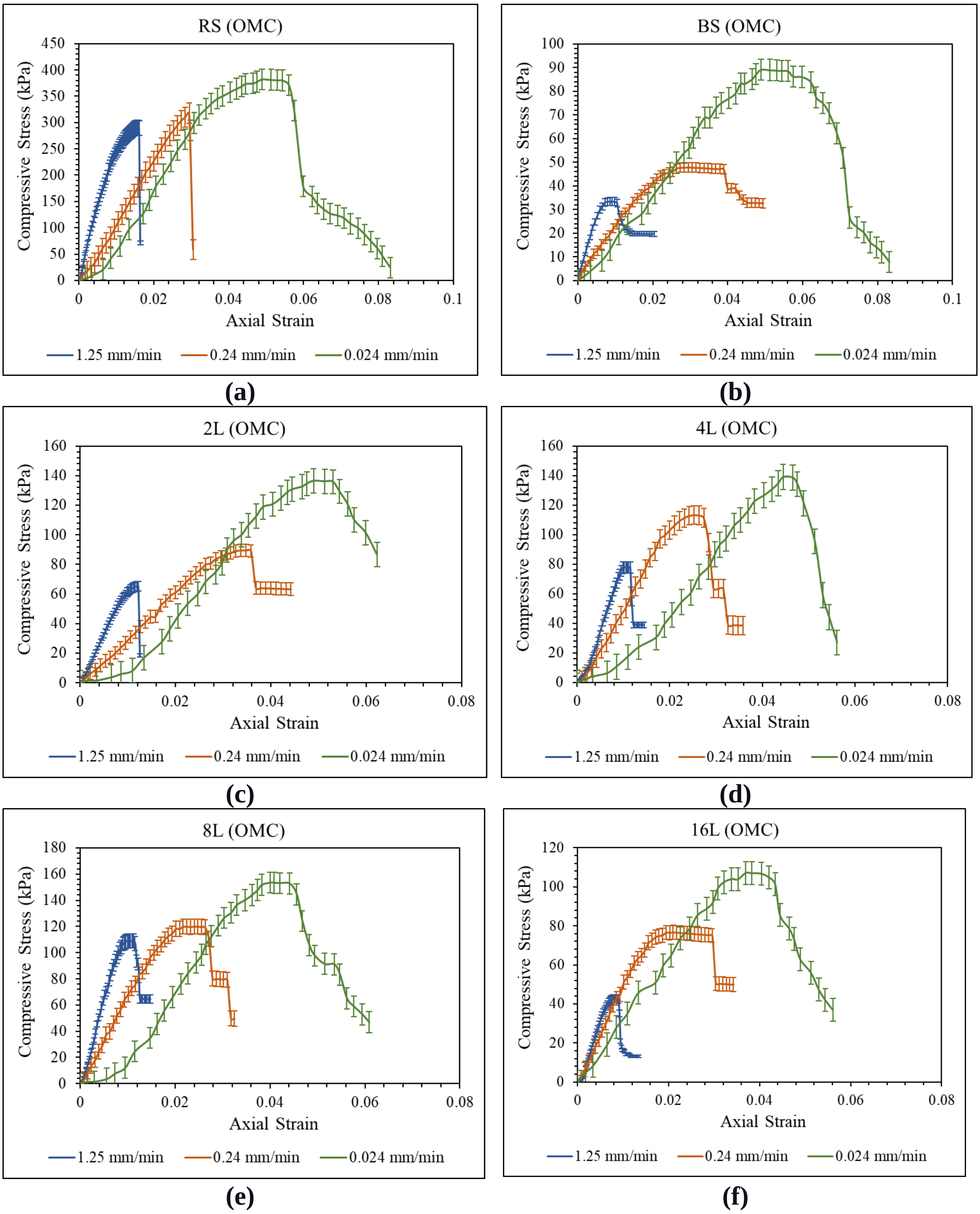


Figure 7. Stress-strain curves under UCS loading at different displacement rates for samples prepared at OMC for (a) homogeneous RS, (b) homogeneous BS, and reconstituted varved clay with (c) 2L, (d) 4L, (e) 8L, and (f) 16L

3.4 Visual analysis of failed soil samples under UCS loading

Figures 8 to 13 display the failure patterns of UCS-tested homogeneous RS (Figure 8), BS (Figure 9), and reconstituted varved clay samples consisting of 2L (Figure 10), 4L (Figure 11), 8L (Figure 12), and 16L (Figure 13). To simplify understanding and representation, the failure mode is discussed by referring to the displacement rates as "high displacement rate" and "low displacement rate," and the water content is referred to as "dry side of OMC" and "wet side of OMC". The high displacement rate is 1.25 mm/min, and as there was no major visual difference in the failure patterns between soil samples tested at displacement rates of 0.24 mm/min and 0.024 mm/min, both are grouped under "low displacement rate". As the water content in the soil samples increases, the samples exhibit more ductile behavior. Differentiating the failure mode at intermediate moisture contents is challenging, so only the extreme moisture contents on both the dry and wet sides are chosen for visual analysis. Upon reviewing the images of failed soil samples, it becomes apparent that each soil profile fails uniquely, based on its composition, with reconstituted varved clays showing more complex failure patterns.

In Figure 8, the failure modes for RS samples are shown under varying moisture contents and displacement rates. For samples prepared at moisture content on the dry side of OMC and tested at a high displacement rate, a well-defined Y-shaped failure surface is observed (Figure 8a), which indicates brittle failure. This suggests that the soil cannot withstand significant deformation before fracturing abruptly, which is characteristic of brittle behavior under rapid loading with low moisture content. For a RS sample with similar moisture content but tested at a lower displacement rate, a single oblique failure plane forms (Figure 8b). Although this is still a brittle failure, the response is less sudden, and the failure planes are less sharp, as the lower displacement rate gives the soil more time to respond to the applied load. For samples prepared at moisture content on the wet side of OMC and subjected to high displacement rates, shear failure occurs with the failure plane forming in the upper half of the sample, accompanied by visible surface peeling (Figure 8c). Unlike the abrupt failure observed in RS samples prepared at moisture content on the dry side of OMC, Figure 8(c) suggests that higher moisture content allows for some plastic deformation before failure under the same loading rate. When tested at a lower displacement rate, the homogeneous RS sample prepared at moisture content on the wet side of OMC exhibits a single, less pronounced oblique failure surface, along with noticeable bulging and horizontal minor cracks (Figure 8d). This smoother shear surface with minor cracks indicates that higher moisture content combined with a slower displacement rate allows for more gradual deformation, leading to greater absorption of stresses and resulting in a more ductile failure behavior.

High displacement rate (Dry side of OMC)	Low displacement rate (Dry side of OMC)	High displacement rate (Wet side of OMC)	Low displacement rate (Wet side of OMC)
(a)	**(b)**	**(c)**	**(d)**

Figure 8. Failed homogenous RS samples after UCS test under varying displacement rates and moisture content

Figure 9 shows the failure patterns for homogeneous BS samples tested for UCS. For samples prepared on the dry side of OMC and tested at high displacement rates, a combination of multiple fracturing and axial splitting is observed (Figure 9a). This behavior is due to the substantial amount of clay in BS (Table 1), which acts as a brittle material under dry conditions. In contrast, when the same sample is loaded at lower displacement rates, multiple fractures are still visible but appear less sharp and are accompanied by minor vertical cracks (Figure 9b). The contrast in failure patterns of homogeneous BS samples prepared in the same way but tested at different displacement rates is attributed to the gradual soil grain adjustment at slower displacement rates. For the homogeneous BS sample prepared on the wet side of OMC and tested at a high displacement rate, a single oblique failure surface with a smooth inclined failure plane is observed, which is indicative of ductile-type failure behavior (Figure 9c). For the same sample tested at low displacement rates, bulging in the middle portion of the sample along with irregular cracks is observed, which indicates progressive failure (Figure 9d). Such observation in Figure 9(d) is attributed to the higher clay content in BS, followed by the sample being prepared at higher moisture content and subjected to gradual loading. The visual observations of failure modes in BS highlight its high sensitivity to moisture content compared to RS. This is evident from the significant transition in the patterns of failed samples of homogeneous BS, which shift from brittle behavior at high displacement rates in dry samples to ductile behavior at low displacement rates in wetter samples. These differences in the observed patterns of failed homogeneous samples of RS and BS emphasize the role of moisture content and displacement rate in determining the failure mechanisms in soils.

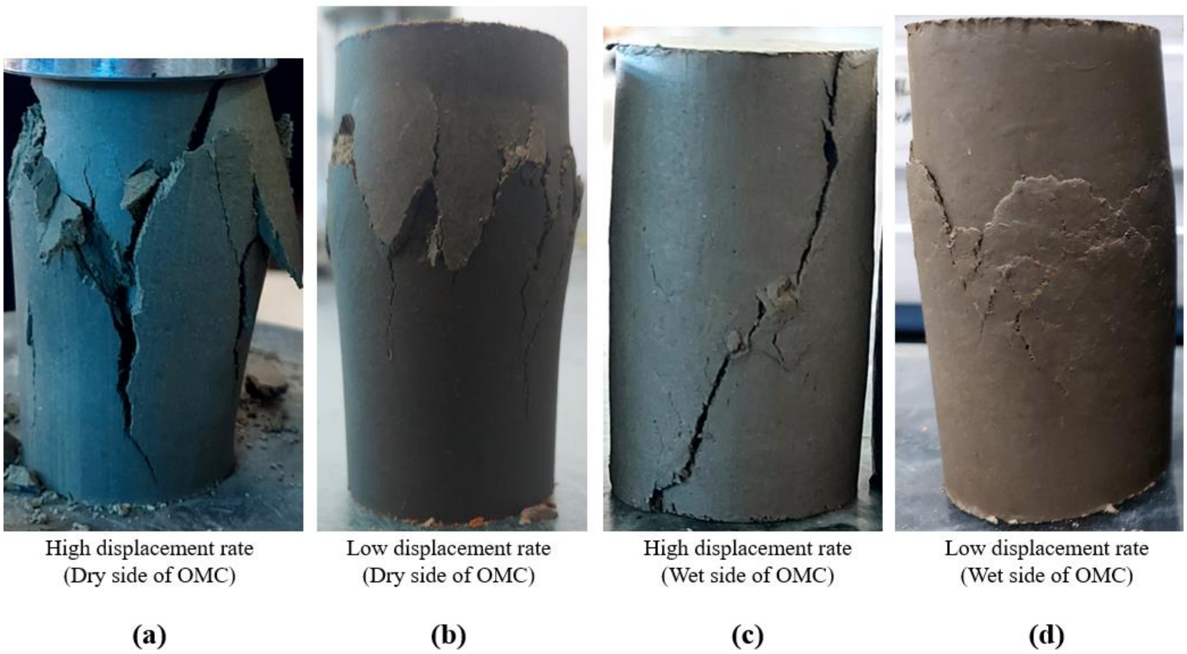


Figure 9. Failed homogenous BS samples after UCS test under varying displacement rates and moisture content

For the 2L reconstituted varved clay samples (Figure 10), the failed samples show that damage under UCS loading is primarily observed in the BS lamina, with the RS lamina hardly being affected. For the 2L sample prepared at a moisture content below OMC and tested at a high displacement rate, a sharp fracture is observed in the BS lamina, with the fracture being parallel to the direction of load application (Figure 10a). The fracture in this case is abrupt and brittle, causing the failed portion of BS to break off instantly, followed by pulling away some of the surficial soil from the RS lamina. Additionally, a rough and tortuous shear plane is also observed to form within the BS lamina. When the 2L sample prepared at the same water content is subjected to loading at a lower displacement rate, multiple vertical slips form within the BS lamina (Figure 10b). Also, shear generation in this failed sample is evident at the interface between the layers, where the RS and BS laminae show separation along the interface plane, with some surface layers of RS peeling off. There is also slight bulging in the BS lamina in both Figures 10(a) and 10(b), with the RS lamina remaining mostly intact in both cases. In the 2L samples prepared at a moisture content on the wet side of OMC and tested at a high displacement rate, a wedge-shaped failure mass develops in the BS lamina, which results in the development of an axial splitting plane in the RS lamina (Figure 10c). This means that the formed wedge in the BS lamina generates tensile forces in the RS lamina. For the same sample tested under low displacement conditions, ductile deformation with visible bulging in the BS lamina, followed by development of diagonal cracks is observed (Figure 10d). In this case, the RS lamina also shows development of smooth cracks.

High displacement rate (Dry side of OMC) | Low displacement rate (Dry side of OMC) | High displacement rate (Wet side of OMC) | Low displacement rate (Wet side of OMC)

(a) **(b)** **(c)** **(d)**

Figure 10. Failed 2L reconstituted varved clay samples after UCS test under varying displacement rates and moisture content

From the failure patterns of the 4L varved clay samples, it is observed that the lowermost lamina, consisting of RS, remains the least affected, while the failure plane clearly passes through the remaining three laminae (Figure 11). Compared to the 2L varved samples (Figure 10), where failure primarily occurs in the BS lamina, in the case of the 4L varved samples subjected to UCS loading, although the lowermost lamina consisting of RS remains the least affected, the other RS lamina is affected during sample failure due to being sandwiched between low-strength BS laminae at both ends.

For the 4L reconstituted varved samples prepared at a moisture content below OMC and tested at a high displacement rate, a double shear failure resembling an X-shaped failure surface is observed (Figure 11a). For the same sample tested at a low displacement rate, an axial split originates from the central lower portion of the sample in the BS lamina and extends upward into the RS laminae (Figure 11b). For the same sample prepared at a moisture content on the wet side of OMC and tested at a high displacement rate, the formation of a smooth, gently inclined, tortuous shear plane along a single surface is observed, accompanied by slight bulging (Figure 11c). When the same sample is tested at a low displacement rate, a smooth shear failure plane initiates from the uppermost BS-RS interface, which is indicated by significant horizontal cracking at this interface (Figure 11d). The failure surface is vertical (perpendicular to the direction of layering) in the BS lamina and gently inclined in the sandwiched RS lamina. Slightly more bulging is observed in this case, particularly around the RS-BS interface in the middle portion of the sample. The gentle angle of failure plane (< 45°) in Figure 11(c) and 11(d) can be attributed the lamination in the soil profile.

High displacement rate (Dry side of OMC) | Low displacement rate (Dry side of OMC) | High displacement rate (Wet side of OMC) | Low displacement rate (Wet side of OMC)

(a) (b) (c) (d)

Figure 11. Failed 4L reconstituted varved clay samples after UCS test under varying displacement rates and moisture content

In the failed 8L varved clay samples (Figure 12), the failure patterns are observed to be more complex compared to the 2L and 4L varved samples. It is evident from the figure that the lowermost RS lamina remains relatively unaffected and intact, while the RS laminae sandwiched between BS laminae undergo shearing, similar to the 4L varve case. For the sample prepared on the dry side of OMC and loaded at a high displacement rate, a tortuous "lambda"-shaped failure pattern is observed (Figure 12a). The sharp and abrupt failure surfaces reflect the brittle nature of the failure. When the same sample is subjected to a lower displacement rate, the sample splits axially, and material breaks off from the middle portion, with vertical cracks forming around the failed sample (Figure 12b). The upper portion appears plastically deformed, which indicates ductile nature of failure. For the sample prepared on the wet side of OMC and tested at a high displacement rate, multiple shearing planes develop with predominantly diagonal cracks and slight bulging (Figure 12c). When the same sample is loaded at a lower displacement rate, vertical cracks with occasional diagonal cracks develop throughout the sample (Figure 12d). The slight bulging, along with the gradual development of smooth cracks, indicates a greater degree of ductile deformation under slower loading conditions compared to the previous failed 8L varve sample in Figure 11(c).

High displacement rate (Dry side of OMC) (a) | Low displacement rate (Dry side of OMC) (b) | High displacement rate (Wet side of OMC) (c) | Low displacement rate (Wet side of OMC) (d)

Figure 12. Failed 8L reconstituted varved clay samples after UCS test under varying displacement rates and moisture content

For the failed 16L varved clay samples prepared on the dry side of OMC and loaded at a high displacement rate, it is observed that the upper half of the sample forms a wedge, causing the lower portion to split axially (Figure 13a). This is again a typical characteristic of brittle failure. For the same sample tested at a low displacement rate, a distorted Y-shaped failure surface is observed (Figure 13b). The distortion is due to the presence of multiple laminae, while the smooth failure surface is attributed to the lower displacement rate. In the failed 16L varved samples prepared on the wet side of OMC and tested at high displacement rates, shear failure occurs along a single plane, passing through the entire height of the sample and affecting each lamina (Figure 13c). For the same sample tested at a low displacement rate, multiple smooth vertical cracks are observed to develop, particularly through the middle portion of the sample (Figure 13d). The crack development is smooth and progressive in nature.

High displacement rate (Dry side of OMC) (a) | Low displacement rate (Dry side of OMC) (b) | High displacement rate (Wet side of OMC) (c) | Low displacement rate (Wet side of OMC) (d)

Figure 13. Failed 16L reconstituted varved clay samples after UCS test under varying displacement rates and moisture content

Finally, it is observed that when samples are prepared on the wetter side of OMC, BS exhibits bulging under loading. Compared to the failure patterns of the laminated samples with 2L, 4L, and 8L varves, the least amount of bulging is observed in the 16L varved profiles. In fact, as the number of laminae increases, the bulging in the samples decreases. This suggests that as the number of layers increases and the thickness of the BS laminae decreases in the varved samples, the BS laminae, being sandwiched between RS laminae, experience restricted bulging.

4. Conclusions

The present study investigates the behavior of two types of soil samples under UCS loading, which includes homogeneous and reconstituted varved clay. The samples are tested for combinations of variations in displacement rate and moisture content, with additional consideration of different number of laminae in reconstituted varved clay. The results demonstrate that these variables significantly affect the undrained shear strength of the tested soil samples. The key findings are summarized as follows:

1. For all soil the profiles, the undrained shear strength consistently decreases with increasing displacement rate. This has been attributed to the limited internal stress redistribution when the soil is loaded at higher displacement rates, whereas at lower displacement rates, the soil structure has more time to mobilize internal strength which results in more more ductile behavior.
2. The stress-strain graphs indicate that soil exhibits brittle behavior in samples prepared at moisture content lower than OMC and subjected to higher displacement rates, gradually shifting towards a more ductile state in samples prepared at higher moisture content than OMC and subjected to lower displacement rates. This is further supported by visual analysis of the failed samples. For instance, in samples prepared at low moisture content, those loaded at high displacement rates exhibit brittle, abrupt failure with sharp failure planes, while those loaded at lower displacement rates show gradual brittle failure with smoother failure planes. In contrast, for samples prepared at high moisture content, the difference between failures at varying displacement rates is more pronounced, with samples loaded at lower rates displaying progressive failure surfaces and slightly more bulging compared to those loaded at higher rates. These observations suggest that both displacement rate and moisture content play key roles in determining the nature of failure in soils.
3. The number of laminae in the reconstituted varved clay samples significantly influences the undrained shear strength and failure pattern of the soil. Increasing the number of laminae from 2 to 4 and then to 8 enhances the undrained shear strength. This increase is attributed to the confining effect of the RS laminae on the BS laminae, which results in stronger interlayer bonding. However, when the number of laminae reaches 16, the undrained shear strength decreases drastically, as the numerous interfaces act as planes of weakness. This suggests that there is an optimal number of laminae that maximizes the undrained shear strength, beyond which additional laminae become detrimental.
4. Reducing the moisture content below the OMC in the soil samples leads to an increase in undrained shear strength, while increasing moisture content beyond OMC results in a sharp decline. This is due to the asymmetry in soil sensitivity to moisture variations, suggesting that soils are more sensitive to increases in moisture content than to decreases by the same amount, using OMC as the reference. This highlights the nonlinear relationship between soil strength and moisture content and demonstrates the critical role that moisture content plays in influencing the undrained shear strength of soils.

Overall, the findings of this study highlight the complex interplay between displacement rate, moisture content, and laminae in determining the strength and failure behavior of both homogeneous and varved clay soils under unconfined axial loading. This work underscores the need for more detailed study of multi-layered soils, such as varved clays, to accurately capture their strength and deformation behaviors.

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Declaration of Competing Interests

The authors declare there are no competing interests

Data Availability Statement

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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