An Inclusive Study on the Effect of Strain Rate on the Stress-Strain Behavior and the Undrained Shear Strength of Clay Soils in Kombolcha, Ethiopia

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Abstract-This research aims to study the effect of strain rate on the stress-strain association and shear strength of clay soils in Kombolcha, Ethiopia. Field and laboratory experimentations were conducted on 3 soil samples collected at 4.5m depth, considering the physical and engineering properties of the soil. Unconsolidated, undrained triaxial compression tests were performed under confining pressure on the specimens that were axially loaded at a rate of strain varying from 0.38mm/min to 1.14mm/min by taking 2 points above and below 1% of the specimen height. Stress-strain relations were developed under the stated different rates of strains to describe their effect. It was revealed that the strain rate effect was observed. By increasing the strain rate shifts the stress-strain curve upward, and the corresponding shear strength of the soil also increased under effective stress. Accordingly, the strain rate increased the shear parameters. The average angle of friction increased by 13.43%, 15.08%, 13.18%, and 14.33% when the rate of strain changed from 0.38 to 0.57mm/min, 0.57 to 0.76mm/min, 0.76 to 0.95mm/min, and 0.95 to 1.14mm/min respectively, while the average cohesion increased by 17.67%, 19.52%, 14.87%, and 16.48%. The failure at strain rate 1%/min of sample height (0.76mm/min) was uniformly distributed and there was uniform pore pressure distribution throughout the sample height. The effect is slightly more when the shear strength increased at the left side than at the right side. Average shear strength parameters such as cohesion and angle friction were recorded for strain rates from 0.57mm/min to 1.25mm/min specifically for the clay soils found in Kombolcha town, Ethiopia.

Keywords-inclusive study; rate; strain; shear; soil

I. INTRODUCTION

Investigation on the properties of soil is significant in designing and building structures with foundations secured by materials such as soils and/or rocks. Soils have a maximum shearing resistance that they can sustain to the applied shear stress, which is a function of the effective normal stress that can determine its magnitude [1]. Shearing resistance is developed by friction, interparticle forces, cementation, or bonding at particle contacts, therefore, if the effective normal stress is zero, then the shearing resistance must be zero (unless there is cementation between the particles). If at a point on any plane within a soil mass the shear stress becomes equal to the shear strength of the soil then failure will occur. One of the factors that affect the shear strength of the soil is the strain rate [2]. The strength of saturated clay, as observed in undrained shear tests increases with the increasing strain rate [3-5]. The peak shear resistance increases from slow to fast strain rate.

Small strains occur from increased strength in terms of effective stress, and large strains from decreased excess pore pressure [6, 7]. Increasing the strain rate applied to a saturated soil means larger effective stresses and consequently greater shear resistance [8]. At large strains, the relationship between void ratio and effective stress is strain-rate dependent. As the strain-rate is increased, larger effective stress is required to

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hold the soil at any given void ratio [9]. At faster strain rates, adjacent soil particles find it more difficult to move relatively, and, unless restrained by increased effective stress, will tend to ride up over one another. The measured pore water pressure is smaller at fast than at slow strain rate. The behavior of the pore pressure following a sudden increase in the strain rate proves that there is fundamentally an inverse relationship between the strain rate and the excess pore pressure [10-12]. The effect of strain rate on the stress-strain relationship and shear strength of clay by conducting a series of triaxial compression tests on remolded soil samples prepared with 38mm diameter and height of twice the diameter was studied in[13-15]. The type of triaxial test employed was Consolidated Undrained (CU) test with pore pressure measurement and by using different effective consolidation pressures. The specimens were axially loaded at a rate of strain varying from 0.001mm/min to 2mm/min. The results show that the strain rate affects both the stress-strain relationship and the strength of the soil. As the strain rate increases, the strength of the soil also increases, but the strain rate has a more pronounced effect on the cohesion and little effect on the angle of internal friction of the soil [16].

In this research, Unconsolidated Undrained (UU) triaxial test was used to measure the undrained shear strength of clay soil from Kombolcha. The soil in the town is dominantly fine-grained, belonging in the clay group. The aim of this research is to set quick and convenient UU shear tests for the clay soils found in the study area and to determine the best strain rate for the elastic and shear strength behaviors of soils [17]. Kombolcha is an industrial and grooming town that has seen increase in its infrastructures. The town is found in the Eastern part of the Amhara region, Ethiopia, and is located about 375km north of the state capital, Addis Ababa, along the road to Mekelle and 23km southeast of Dessie city. It is situated on the western margin of the Main Ethiopian Rift valley and covers an area of about 120km^2. Soils found in this town belong mostly to the fine-grained clay class [18].

II. RESEARCH METHODOLOGY

To achieve the study goals, 8 soil samples were collected from Kombolcha at a depth of 4.50m from the ground surface. From the samples, 3 were nominated to represent the other 5 samples according to their physical properties. The remolded clay specimens were prepared and used in the laboratory [19]. The selected samples' locations are presented in Table I.

Moisture content and field densities of the 3 pits were determined in the field and the samples were transported to the laboratory while they were kept in a plastic bag to prevent moisture loss. The measured amount of the wet soil was put in a conventional oven of 105℃ and kept for 24 hours and was examined to determine its weight loss in order to the determine moisture and density of the collected soils [20].

TABLE I. TEST PIT LOCATION AND COORDINATES OF THE STUDY AREA

Pit No.	Location	Latitude (DMS)	Longitude (DMS)
Pt-1	Kurangoye	11° 5' 27.59"	39° 43' 11.64"
Pt-2	Elkbeye	11° 4' 48.36"	39° 42' 50.76"
Pt-3	Sheshaber	11° 5' 27.59"	39° 42' 35.64"

A. Soil Grain and Consistency Limit Test

Sieve analysis was performed to determine the distribution of the course, larger-sized particles, and hydrometer test was conducted for 24 hours to determine the distribution of finer particles (less than 0.075mm). Two jars with 1000ml capacity were used. A control jar with distilled water and 5g of sodium hexametaphosphate was used as a dispersing agent and the other was a soil sample with distilled water and 5g of dispersing agent. A mechanical stirrer was also used for mixing the soil samples with distilled water and the dispersing agent. Soils passing through a 0.425 mm sieve were used to determine the plastic and liquid limits of fine-grained soil. The specimens were soaked for 30 minutes and mixed for 5 minutes [21-23].

B. Specific Gravity and Free Swell Determination Tests

The specific gravity of the samples was determined with the help of a pycnometer using a soil sample that passed through the 2mm sieve. The sample was connected to the hydrometer and was oven-dried at 105℃. A minimum soil sample of 20g was used [24]. Free swell index is the increase in the volume of soil, without any external constraints, on submergence in water. Representative oven-dried soil samples having mass of 10g passing through 0.425 mm sieve were put in 100ml of water in a jar for 24hours. Swelling was examined as a percentage of the volume change to the original volume [25 ,26].

C. Compaction Test

Laboratory compaction procedures were used to determine the relationship between water content and the dry unit weight of soils. The soil samples were compacted in 3 layers with a 24.4N rammer dropped from a height of 305mm producing a compactive effort of 600 kN-m/m^3. 8% of 3000g of the test sample were added in mm as the initial water content and 4% water content increments were used to obtain a well-defined maximum dry unit weight. After obtaining the density and moisture of each compacted soil sample, Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were determined from the compaction curve [27,28].

D. Consolidation and Permeability Test

This test was performed to determine the magnitude and rate of volume decrease a laterally confined soil specimen undergoes when subjected to different vertical pressures. From the measured data, the consolidation curve (pressure-void ratio relationship) can be plotted. These data are useful in determining the compression index and the recompression index of the soil. Besides, the obtained data can also be used to determine the coefficient of consolidation and the coefficient of secondary compression of the soil. Tests were carried on the undisturbed samples by pushing the consolidation ring into the ground at a depth of 4.50m during the sample collection. The samples were transported to the laboratory while they were kept in a plastic bag. Soil samples with diameter of 63mm and height of 20mm were loaded with pressures from 7kPa to 1600kPa. For each loading the compression was recorded from the dial gauge at intervals of 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 1440 minutes for 24 hours. Unloading to examine unloading behavior was also done in steps. A total of 3 consolidation tests were run on undisturbed samples and different results were obtained. From the test results of the consolidation curve (pressure-void ratio relationship), compression index (Cc) and expansion index (Ce) were determined [29]. The purpose of the permeability test is to determine the permeability (hydraulic conductivity) of the soil by the falling head test method. A representative soil sample that passed through the 4.75mm sieve was collected and compacted at optimum moisture content to achieve maximum dry density in a mold having 10cm diameter and 12.73cm length. After the soil sample was saturated, its permeability was examined by allowing the water to come through it falling from the initial head. The head change and the time taken to the water to come through the sample were recorded until the water begun to flow out of the water bath [30].

E. Unconsolidated Undrained Triaxial Compression Test

In this paper, remolded cylindrical specimens passed through the 2.36mm sieve and having a diameter of 38mm and a length twice the diameter (76mm) were used. All the test samples were compacted within 6 layers in a manner that can represent the site condition of the soil. Axial load was applied to produce axial strain at a rate of approximately 1%/min of the specimen height, which is used as a reference rate in this study. The confining pressure was calculated from the unit weight of the soil, the depth where the samples were collected, and by assuming a coefficient of earth pressure at rest to represent the site that was conveniently used as per Kombolcha town soils behavior. Hence, 5 different strain rates were used, the conventional strain rate of 0.76mm/min and 2 strain rates below and 2 above it. Trials were done during the triaxial test for each selected pit sample. The trials were conducted with increasing strain rate of 0.5% (0.38mm/min), 0.75% (0.57mm/min), 1% (0.76mm/min), 1.25% (0.95mm/min) and 1.5% (1.14mm/min) of specimen height with confining pressure of 50kPa, 100kPa, and 150kPa in order to assess the better strain rate for Kombolcha clay soils. A failure envelope was used to determine the shear strength parameters of the test samples [31-33].

III. RESULTS AND DISCUSSION

A. Soil Index and Density Results

As described in Table II, the average moisture content was 31.60%, which lies between stiff and soft clays.

TABLE II. MOISTURE CONTENT, BLUK AND DRY DENSITY, SPECIFIC GRAVITY, AND ATTERBERG'S LIMIT RESULTS

Pit No.	Location	Moisture content, %	Bulk Density, g/cc	Dry density, g/cc	Liquid limit, (%)	Plasticity Index (PI %)	Soil class	Specific gravity, at 20^0C
Pt-1	Kurangoye	30.12	1.75	1.34	63.68	33.11	CH	2.75
Pt-2	Elkbeye	29.71	1.85	1.43	56.47	31.50	CH	2.72
Pt-3	Sheshaber	34.84	1.77	1.31	78.32	44.04	CH	2.76

The ranges for bulk density and dry density are 1.75 to 1.85 and 1.31 to 1.43g/cc respectively, which are within the range of silt or clay. The soil grain size analysis ranges results of the obtained samples are 5.82 to 10.14% sand particles, 25.44 to 32.14% silt, and 57.43 to 67.25% the clay fraction. These results show that clay soil is dominantly found, which was also indicated by the results of Atterberg limit results. The liquid limit for these clay soils was found above 50% and a plasticity index of more than 30% was obtained. Hence, soils are classified as highly plastic clay (CH) as presented in Table II with an average specific gravity of 2.75.

B. Compaction and Free Swell Results

Optimum Moisture Content (OMC, %) and Maximum Dry Density (MDD, g/cc) of the test pits are listed in Table II. They vary from 22.50% to 29.80% and from 1.39g/cc to 1.55g/cc respectively. Maximum dry density of the soil for all pits is greater than the in-place dry density of the soil, which shows that it needs densification to attain maximum density and optimum moisture.

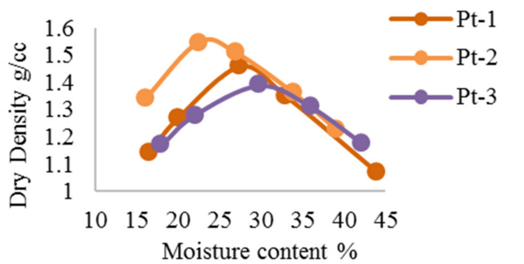


Fig. 1. Standard proctor compaction test results for pit one.

C. Soil Free Swell, Consolidation, and Permeability Results

The results of the free swelling of the study area lie within the range from 49.21 to 60.25%, which describes the medium swelling potential (Table III). The magnitude of the compression index varies between 0.25 and 0.29 whereas the swelling index of the clay soils ranges between 0.0169 and 0.0280. The soils fall within the permeability range of 6.78×10^{-5} to 8.09×10^{-6} cm/s at 20^0C, which indicates that the area is accumulated by fine soils with low permeability.

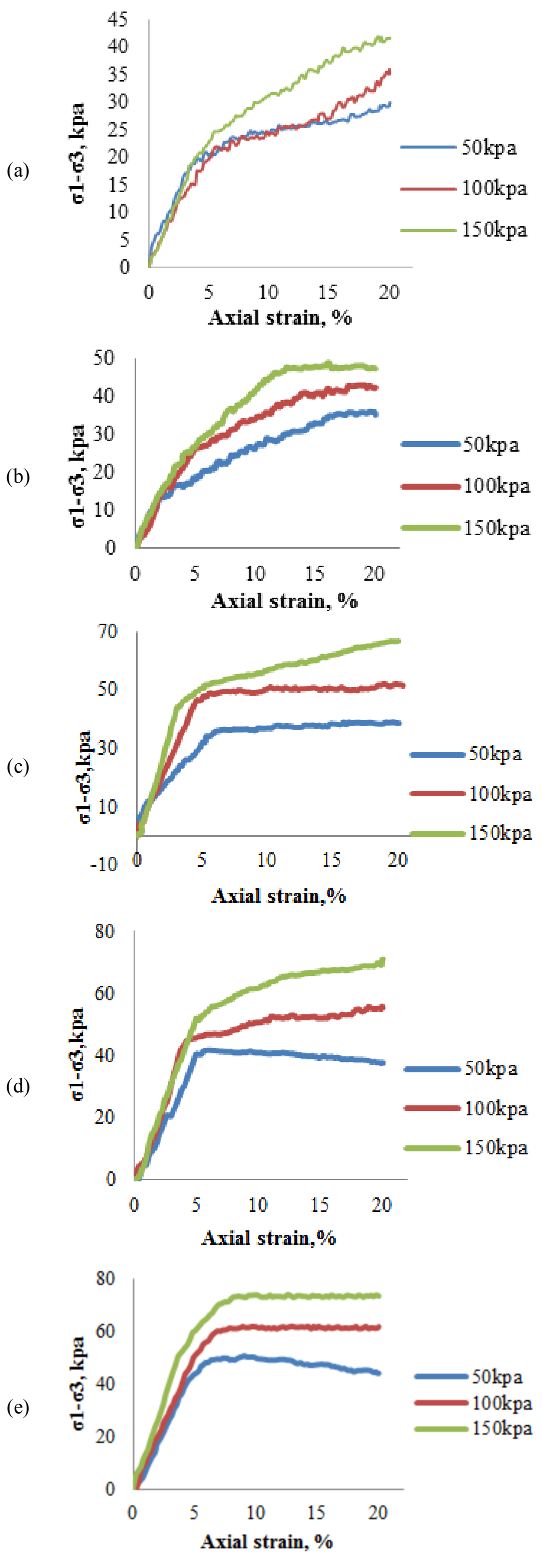
TABLE III. COMPACTION PROPERIES, COEFFICIENT OF COMPRESSION AND SWELLING INDECES, AND PERMEABILITY RESULTS

Pit No.	Free swell, %	OMC, %	MDD (g/cc)	Compression index, Cc	Swelling index, Ce	Coefficient of permeability at 20^0C, K(cm/s)
Pt-1	51.53	27.50	1.46	0.27	0.0178	8.09E-06
Pt-2	49.21	22.50	1.55	0.25	0.0169	6.78E-06
Pt-3	60.25	29.80	1.39	0.29	0.0280	7.19E-06

D. Unconsolidated Undrained Triaxial Compression Results

The plots of deviatoric stress to axial strain relationship for the same strain rates under different confining pressure for the 3 test pit samples are shown in Figure 2.

In a similar manner, the stress-strain curves for the not listed strain rates were performed. From these graphs, it was observed that an increase in confining pressure shifts the stress-strain curve upward with different patterns, which illustrate the increase in shear strength up to the failure point. Maximum deviatoric stresses at failure for each strain rate were obtained to determine the shear strength parameters called angle of friction and cohesion.



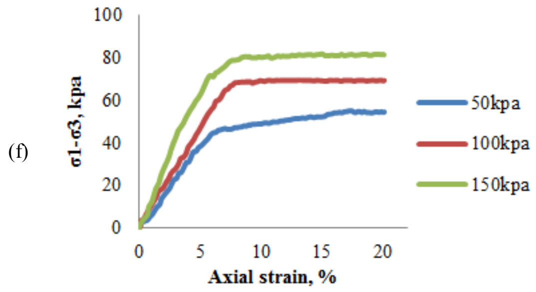


Fig. 2. Deviatoric stress-strain curves for Pt-1 at (a) 0.38, (b) 0.57, Pt-2 at (c) 0.57 and (d) 0.76, and Pt-3 at (e) 0.95 and (f) 1.14mm/min strain rates under 50, 100, and 150kPa confining pressure.

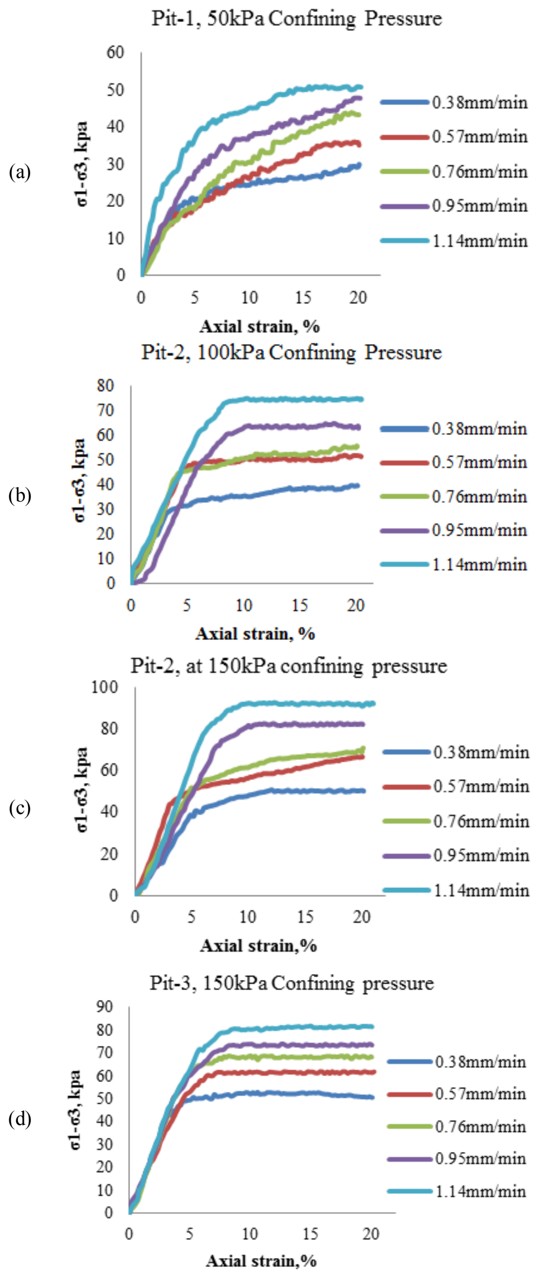


Fig. 3. Stress strain behavior of the three pits under various strain rates.

Plots of the deviatoric stress versus axial strain with the different strain rate and same confining pressure is shown in Figure 3. Only 4 stress-strain graphs are presented (pit-1 for confining pressure of 50kPa, pit-2 for confining pressure of 100kPa and 150kPa, and pit-3 for confining pressure of 150kPa). By the same fashion, all 3 pit samples' stress-strain graphs were developed for confining pressures of 50kPa, 100kPa, and 150kPa under different strain rates. It was revealed that an increase in the strain rate shifts the stress-strain curve upward, which describes the faster strain rate induced increase in deviatoric stress and failure point of the soil under induced pressure. Figure 5 presents the shear strength parameters with the different strain rates for 3 test pit samples. The results were derived from Figures 2 and 3. From Figure 5, it is observed that the cohesion and the angle of internal friction increase when the strain rate increases. Shear parameters angle of friction (Ø^0) and cohesion (C in kPa) axes are determined for each stress path at failure strain rates. In a similar way the remaining three samples' determination is done and shear strength parameters are presented in Figure 6. The average angle of friction is equal to 6.81^0 and the average cohesion is 13.55kPa under the described strain rates. These results define clay soil behavior. The soils were weak to bear the imposed load from the buildings in Kombolcha.

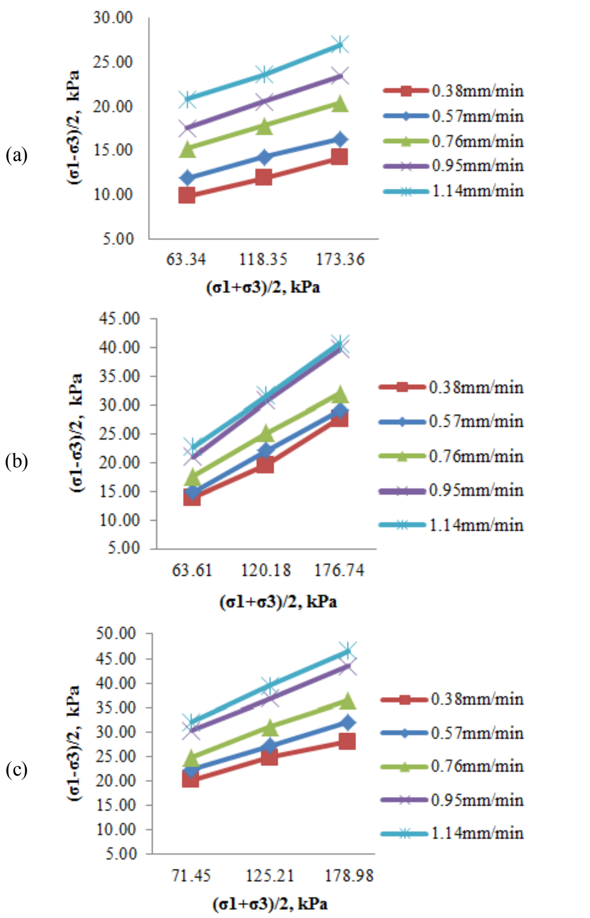


Fig. 4. Normal to shear stress chart at failure and different strain rates for (a) pit-1, (b) pit-2, and (c) pit-3.

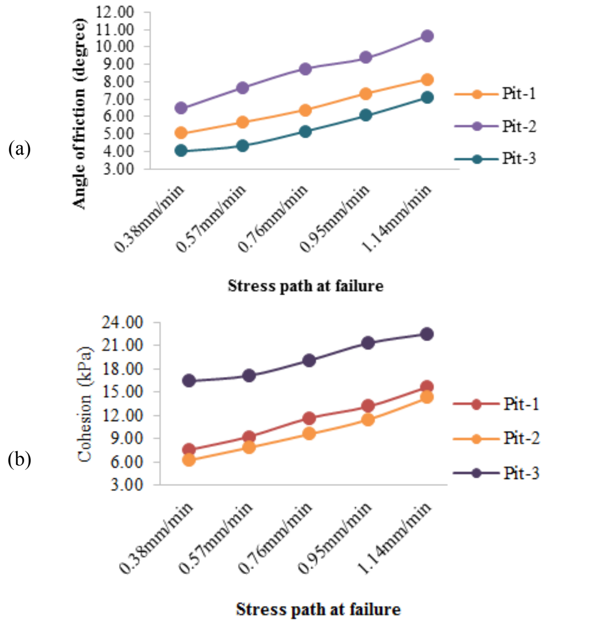


Fig. 5. Strain rate effect on: (a) angle of friction and (b) cohesion of soil.

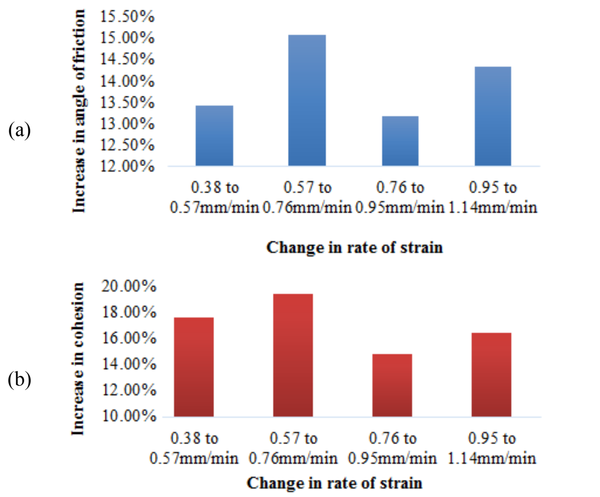


Fig. 6. Increase in soil shear parameters: (a) angle of friction and (b) cohesion.

Accordingly, at higher strain rates (0.75 to 1.25mm/min) produced in higher undrained shear strength for the clay soil samples, the results show that the failure at the strain rate of 1%/min (0.76mm/min) of sample height is uniformly distributed and there is uniform pore pressure distribution throughout the sample height. It was also shown that the angle of friction and the cohesion of soils are inversely related as indicated in Figure 5. As illustrated in Figure 6, the strain rate increased the clay soil shear parameters. These shear strength parameters actually indicate properties of clay soils with high plasticity. Hence, the average angle of friction increased by 13.43%, 15.08%, 13.18%, and 14.33% at strain rates of 0.38 to 0.57mm/min, 0.57 to 0.76mm/min, 0.76 to 0.95mm/min and 0.95 to 1.14mm/min respectively (Figure 6 a)), whereas, the average cohesion increased by 17.67%, 19.52%,14.87% and

16.48% respectively (Figure 6(b)). As indicated in the results of the angle of friction, the change in the strain rate is not significantly affected, but cohesion is slightly more increased with the early strain rates for these soils. The minimum average unconsolidated undrained shear test result for clay soils from Kombolcha occurs for the strain rate of 0.76mm/min to 0.95mm/min.

IV. CONCLUSIONS

The current study described the soils in Kombolcha town as dominantly clay soils. UU triaxial compression tests were performed on the soil at different strain rates. When the strain rate increased, the stress-strain curve moved up and the shear strength also increased. The failure at strain rate 1%/min of sample height is uniformly distributed and there was uniform pore pressure distribution throughout the sample height. The increase in undrained shear strength can be associated with the less excess pore water pressure during shearing at faster rates. Test were conducted on the clay soil of Komblocha using strain rates ranging from 0.75% (rate of 0.57mm/min) to 1.25% (rate of 0.95mm/min) of specimen height of the remolded samples and the average stress-strain and shear strength behaviors of these samples were studied.

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