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Impact of Strain Rate on the Shear Strength and Pore Water Pressure Generation of Saturated and Unsaturated Compacted Clay

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ABSTRACT: A series of consolidated-undrained (constant water content) triaxial compression tests were performed on compacted low plasticity clay under saturated and unsaturated conditions. The purpose of the test series was to evaluate the impact of strain rate and initial suction on the undrained shear strength of the clay. Consistent with trends in the literature, the shear strength of saturated clay increased at approximately 13% per log cycle of decreasing time to 15% axial strain. The excess pore water pressure at failure measured at the bottom boundary of the specimen was found to decrease with increasing strain rates for saturated specimens but increase for unsaturated specimens. The rate of increase in the shear strength of unsaturated clays having suction values up to 140 kPa (degrees of saturation greater than 85%) was found to be greater than that of the clay under saturated conditions.

INTRODUCTION

The impact of high axial compression rates on the shear strength of soils is important to understand when simulating dynamic loading of soils in events such as explosions and earthquakes, as well as in rapid construction. Although a number of studies investigating the effect of strain rate on saturated clays have been performed over the last 60 years (Casagrande and Shannon 1948; Richardson and Whitman 1963; Olson and Parola 1967; Lefebvre and LeBoeuf 1987), there has not been a thorough investigation of the role of unsaturated conditions on the shear behavior or generation of excess pore water pressure in compacted clays subject to high strain rates. This study focuses on the results from a series of undrained triaxial compression tests on saturated and unsaturated specimens of compacted, low-plasticity clay performed under different strain rates.

REVIEW OF PREVIOUS STUDIES

It has been well established in several classic studies that the shear strength of remolded saturated clays is dependent upon the axial strain rate during axisymmetric triaxial compression testing (Casagrande and Shannon 1948, Richardson and Whitman 1963; Olson and Parola 1967; Lefebvre and LeBoeuf 1987). These studies found that the shear strength of clay increases with increasing strain rate with an average rate of 10% per log cycle of the time to failure for normally consolidated soils, where failure was defined as an axial strain of 15%. Zhu and Yin (2000) investigated the effects of strain rate for different over consolidation ratios. It was observed for all OCR tested the undrained shear strength increased with increasing strain rate. More importantly, the rate at which the shear strength increased per log cycle increase in strain rate increased with increasing OCR. Olson and Parola (1967) were one of the only researchers who investigated the behavior of compacted clay soils in unsaturated conditions. However, they only considered the effect of strain rate on shear strength by varying the initial compaction water contents which were not related to specific suction values. Thus, the role of unsaturated conditions could not be distinguished from the soil structure induced by compaction, and they did not monitor the generation of excess pore water pressure during shearing.

TESTING MATERIAL

A clay soil obtained from a soil stockpile at a construction site on the University of Colorado Boulder campus, referred to as Boulder clay, is evaluated in this study. The clay was processed after collection to remove all particles greater than the #10 sieve, which provided a more homogeneous and consistent material for experimental testing. Soil classification tests were performed on Boulder clay to measure the relevant geotechnical properties (ASTM D422, ASTM D4318, ASTM D854, ASTM D698, ASTM D2435). These soil properties are listed in Table 1. The degrees of saturation after application of different suction values to triaxial specimens and after equilibrium using the vapor equilibrium technique were used to define points on the soil water retention curve (SWRC) for Boulder clay, shown in Figure 1. The van Genuchten (1980) SWRC model was fitted to the points, and the parameters α_{vG} and n_{vG} are shown in the figure. The air entry value for this soil was estimated to be 111 kPa.

Table 1: Properties of Boulder Clay

Property	Value	Units	Property	Value	Units
D_{10}	< 1.7×10^{-4}	mm	Classification (USCS)	CL	-
D_{30}	< 0.001	mm	LL	43	-
D_{50}	0.001	mm	PI	22	-
% Fines	100	%	γ_{d_max}	17.5	kN/m^3
G_s	2.70	-	w_{opt}	16.5	%

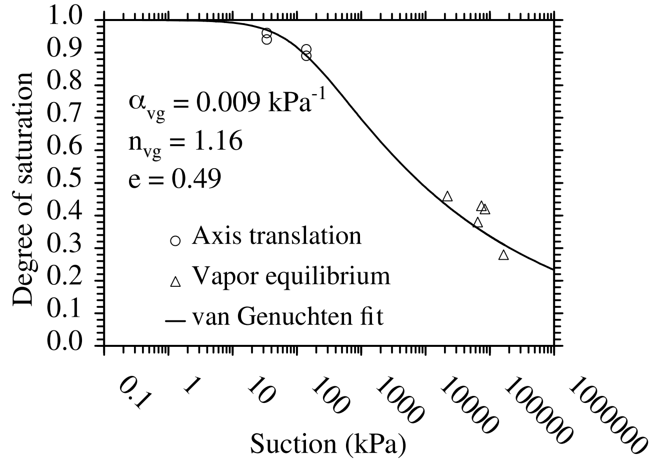
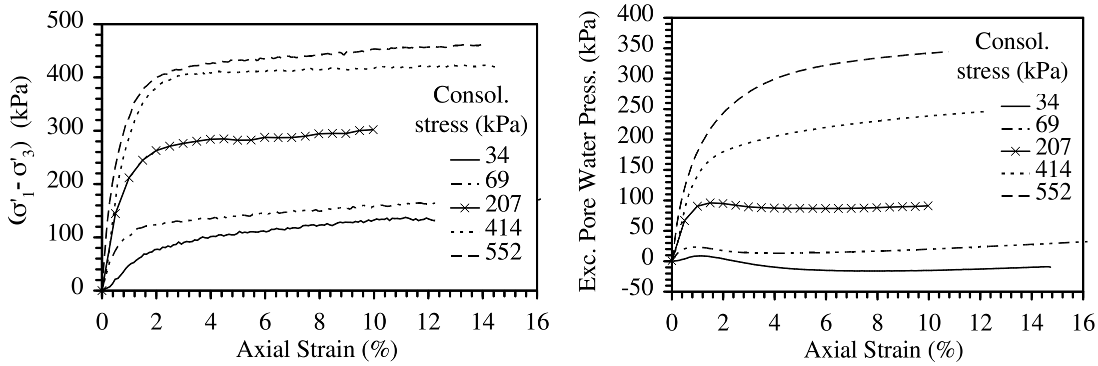


FIG. 1: SWRC for Boulder clay

CONVENTIONAL TRIAXIAL TESTING

Five consolidated-undrained (CU) triaxial tests were conducted in accordance to ASTM D4764 to determine the effective shear strength parameters of Boulder clay. These shear strength parameters were then used to compare to saturated and unsaturated CU tests performed at higher strain rates. Each clay specimen was compacted using a mechanical press in a cylindrical mold having a height of 71.1 mm and a diameter of 35.6 mm. To ensure uniformity throughout the specimen, each specimen was compacted using five lifts of equal mass. The target dry unit weight and water content for each specimen were 17.4 kN/m^3 and 17.5% respectively. These values correspond to 98% of the maximum standard Proctor dry density and 6% dry of the standard Proctor optimum water content, respectively. These testing conditions were chosen to so that small changes to the compaction water content would not result in large changes to the initial void ratio (dry density).

After the cell was assembled, the specimen was placed under a vacuum of 80 kPa, the cell was filled with water, and a seating cell pressure of 20 kPa was applied. Next, de-aired water was flushed through the specimen from the bottom while vacuum was maintained on the top. After water was observed to exit from the top of the specimen, the water vapor was flushed from the top platen and the specimen was placed under backpressure. The cell pressure and the pore water pressure were increased in stages until the measured value of Skempton's B parameter was 0.9, or when the B parameter remained constant with additional increases in backpressure. In most tests, a cell pressure of 483 kPa and a backpressure of 276 kPa were applied at the end of saturation. After saturation of each specimen, a specific effective stress was applied and consolidation was permitted to occur until the volume change inferred from the cell water level and backpressure water levels reached equilibrium. Upon completion of consolidation, the specimens of Boulder clay were sheared to an axial strain of 15% in 150 minutes (an axial shearing rate of 0.0686 mm/min). The time to failure (and corresponding shearing rates) were defined using the value of t_{50} for the soil specimens calculated from the consolidation data (ASTM D2435). During shearing, the variables measured include the pore water pressure at the bottom of the specimen, the axial load, and the axial displacement. The principal stress difference is shown in Figure 2(a) and the excess pore water pressure is shown in Figure 2(b).



(a) **(b)**

FIG. 2. Data from conventional triaxial compression tests on Boulder clay: (a) Principal stress difference; (b) Excess pore water pressure

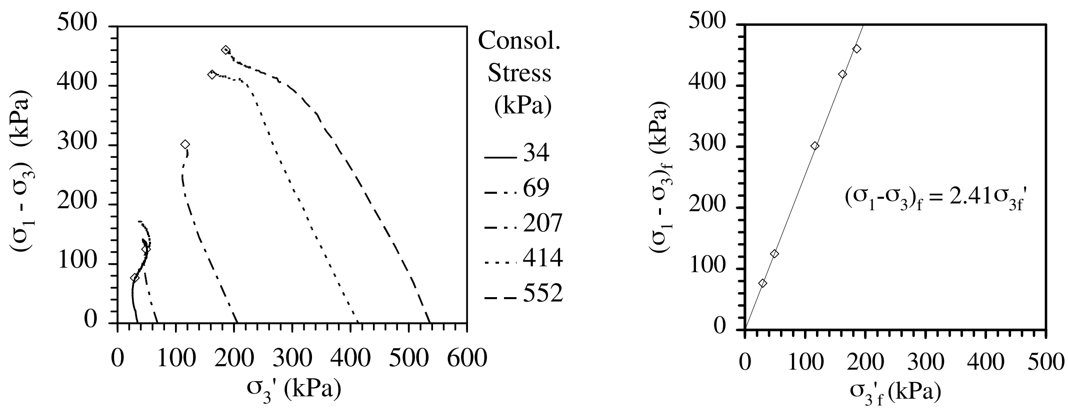
In each of the tests, shear failure of the specimen was defined as the point where the maximum value of internal friction is mobilized, which is referred to as the stress path tangency (SPT) failure criterion. In a consolidated undrained triaxial compression test, the point where the maximum friction is mobilized occurs at the maximum value of the principal stress ratio, σ_1'/σ_3'. Examination of a Mohr circle at failure indicates that the principal stress ratio is directly proportional to the friction angle [$\sigma_1'/\sigma_3' = \tan^2(45+\phi'/2)$]. The points of failure defined using the stress path tangency criterion in modified Mohr-Coulomb stress space (effective confining stress versus principal stress difference) for Boulder clay specimens consolidated to different initial consolidation stresses are shown in Figure 3(a). The failure envelope in triaxial stress space was defined by fitting a line through the five failure points and the origin. The angle of inclination of this line corresponded to the transformed friction angle, α as shown in Figure 3(b). The following equation was used to convert α to the effective friction angle, ϕ', as follows:

$$\phi' = \sin^{-1}\left(\frac{\tan(\alpha)}{2+\tan(\alpha)}\right) \quad (1)$$

The value of α calculated from the data in from Figure 3 and the calculated value of ϕ' from Equation 1 are presented in Table 2.

Table 2. Failure Envelope Parameters for Boulder Clay

Parameter	Value	Units
α	68.5	o
ϕ'	34.0	o



(a) **(b)**

FIG. 3. Results for Boulder clay: (a) Effective stress paths; (b) Effective failure envelope defined using the stress path tangency failure criterion

RATE EFFECTS ON SATURATED CLAY

To investigate the effects of strain rate on the shear strength of saturated Boulder clay, additional CU triaxial tests were preformed at increased loading rates. Tests were performed at three different axial strain rates: 0.1, 1.5, and 14.5 %/minute.

Each specimen was prepared and saturated using the same procedures discussed in the previous section for conventional CU triaxial tests. All specimens were sheared until reaching an axial strain of 15%, so the shearing rates correspond to times to failure of 150, 10, 1 min. Similar to the standard tests, the variables measured during shearing include the excess pore water pressure at the bottom of the specimen, axial load, and axial displacement. The variation of shear strength (in terms of the principal stress difference), principal stress ratio and excess pore water pressure with axial strain for Boulder clay are shown in Figures 4(a), 4(b), and 4(c), respectively. The shear strength at failure was defined using stress path tangency criterion, and the points of failure are indicated in Figures 4(a) through 4(c) with hollow squares.

RATE EFFECTS ON UNSATURATED CLAY

To understand the effects of shearing rate on Boulder clay in unsaturated conditions, CU triaxial tests were performed on specimens subjected to values of matric suction equal to 34 and 140 kPa. Each specimen was sheared until reaching an axial strain of 15% in either 150 minutes or 1 minute (axial strain rates of 0.1 and 14.5 %/min, respectively) under constant net stress conditions. Each specimen was compacted, saturated, and consolidated using identical procedures to the saturated tests. To control suction in the soil specimen, the axis translation technique was used to independently control the pore air and pore water pressure in the specimen. A known air pressure was applied to the top of the specimen and a known water pressure to the bottom of the specimen. The difference between the applied air and water pressure is equal to the desired matric suction ($\psi = u_a - u_w$). To apply this technique, the top air pressure was applied through a coarse porous stone while the bottom water pressure was applied through a high-air entry (HAE) ceramic disk with a diameter of 76 mm (greater than that of the specimen). The air entry value of the disks used was 100kPa for the test at a suction of 34 kPa, and was 300kPa for the test at a suction of 140 kPa. The specimen was assumed to have uniform matric suction throughout when outflow from the specimen into a graduated burette remained constant for 24 hours. The process of saturation and suction equilibration required at least 3 to 4 weeks per test.

The principal stress difference versus axial strain for the saturated and unsaturated tests run at times to an axial strain of 15% in 150 minutes and 1 minute are shown in Figure 5(a). Similarly, the principal stress ratio versus axial strain for saturated and unsaturated tests is plotted in Figure 5(b). The excess pore water pressure versus axial strain for the saturated and unsaturated tests is shown in Figure 5(c).

ANALYSIS

The undrained shear strength (principal stress difference) defined by the stress path tangency failure criterion for saturated and unsaturated Boulder clay is plotted versus logarithm of strain rate in Figure 6(a). The shear strength for this soil in both saturated and unsaturated conditions increases log-linearly with increasing strain rate. The percent increase in shear strength for the saturated Boulder clay is approximately 13% per log cycle increase in strain rate. The log-linear slope of shear strength with strain rate is 16.1.

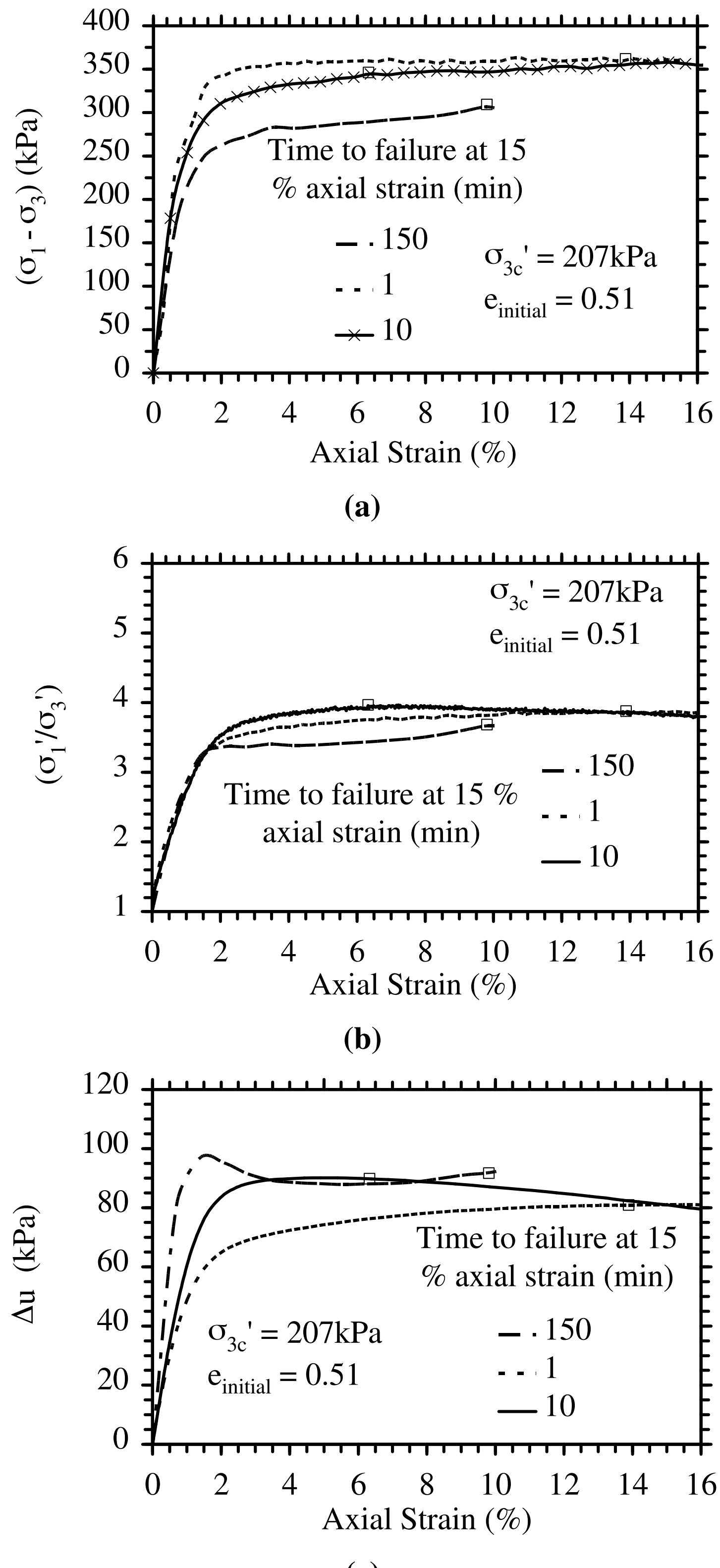


FIG. 4. Results from triaxial compression tests on saturated Boulder clay for different times to 15% axial strain: (a) Principal stress difference; (b) Principal stress ratio; (c) Excess pore water pressure

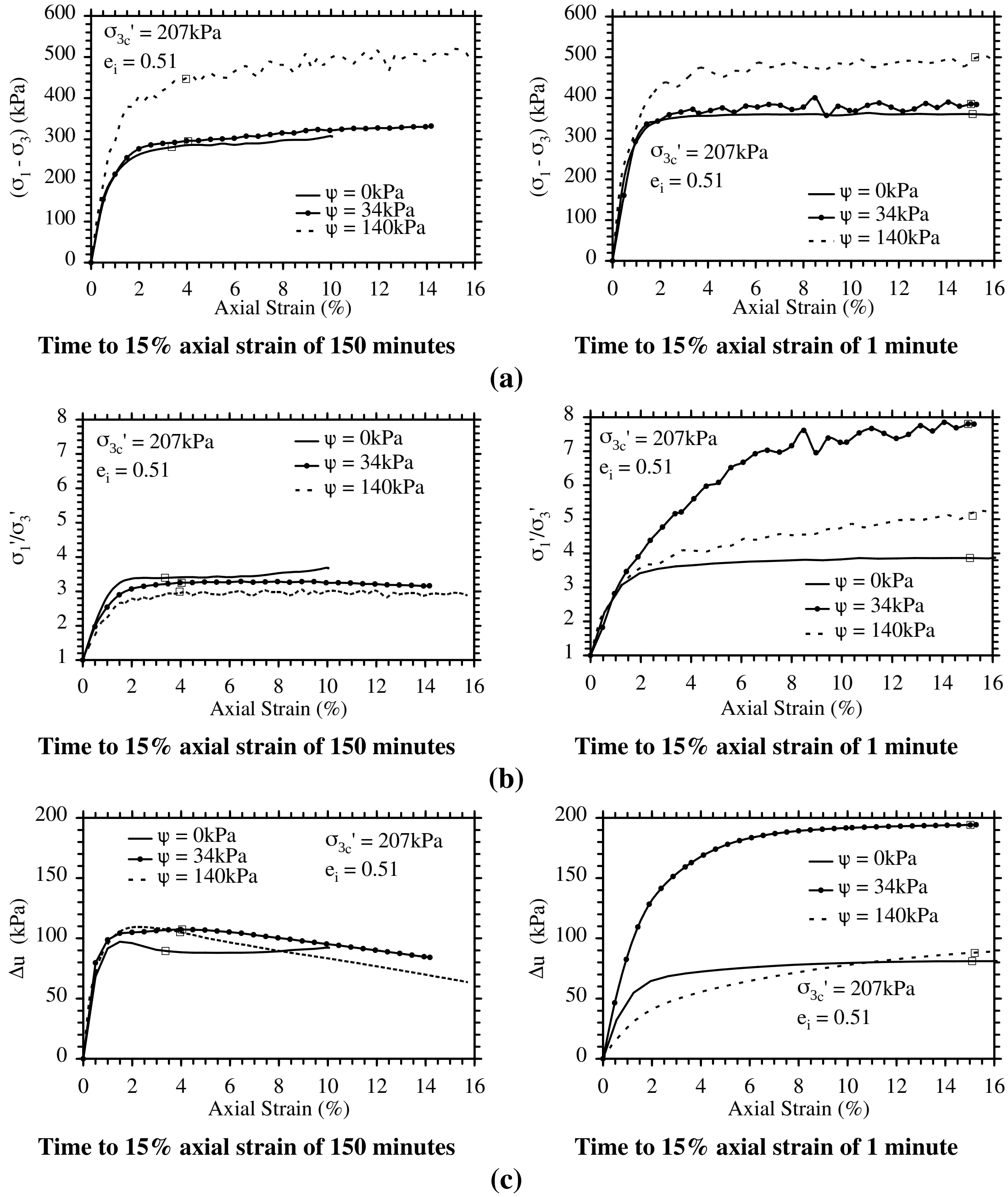


FIG. 5. Results from triaxial compression tests on unsaturated Boulder clay for different times to failure: (a) Principal stress difference; (b) Principal stress ratio; (c) Excess pore water pressure

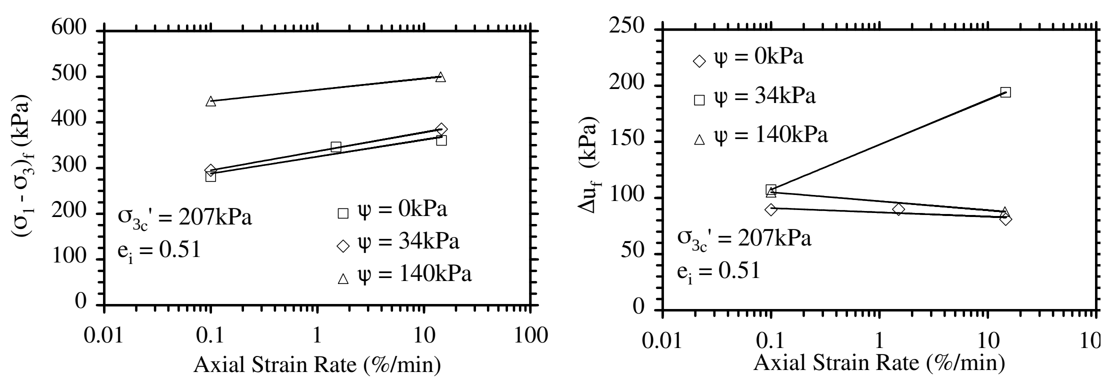
This average rate of increase in shear strength shown in Figure 6(a) is consistent with previous studies conducted on saturated, normally consolidated, remolded clays by Casagrande and Shannon (1948), Richardson and Whitman (1967) and Lefebvre and LeBoeuf (1987). The average rate of increase in shear strength per log cycle increase in strain rate is 15% for tests at a suction of 34 kPa corresponding to a log-linear slope of the shear strength with strain rate of 17.3. The average rate of increase in shear strength per log cycle increase in strain rate is 6% for tests at a suction of

140 kPa corresponding to a log-linear slope of the shear strength with strain rate of 11.3. These values are summarized in Table 3.

Table 3: Summary of shear strength increase with strain rate

Suction (kPa)	Slope	% increase in (σ_1- σ_3) per log cycle increase strain rate
0	16.1	14.1
34	17.3	15.2
140	11.3	6.4

Excess pore water pressures at the point of shear failure defined by the same failure criterion are shown in Figure 6(b). The excess pore water pressure at failure is positive for both saturated and unsaturated Boulder clay. A decrease in excess pore water pressure with increasing axial strain rate was observed for saturated clay, indicating that the compacted specimens have a dilative response during shear. This is consistent with observations of Richardson and Whitman (1967) and Lefebvre and Leboef (1987). Both studies found that for normally consolidated, remolded clay the undrained shear strength increased with increasing strain rate, accompanied by a decrease in pore water pressure. Accordingly, the increase in shear strength of compacted Boulder clay with increasing strain rate is due to an increase in effective stress caused by the decrease in pore water pressure. Also, as the saturated specimens are loaded at faster rates, there is a subsequent increase in the initial shear modulus (Figure 4(a)). This stiffening could inhibit the rearrangement of particles during shearing. Thus, rather than contracting during the load application, the soil at higher rates would dilate as the clay particles were forced to roll and climb over each other.



(a) (b)

FIG. 6. Impact of strain rate on the response of saturated and unsaturated Boulder clay: (a) Undrained shear strength; and (b) Excess pore water pressure

Under the slowest loading rate of 0.1 %/min, the shear strength behavior of unsaturated Boulder clay under a suction of 34 kPa was similar to that of saturated Boulder clay, despite the effect of suction. It is possible that even the slowest shearing rate was not slow enough to permit the water to redistribute within the unsaturated specimen. It was only when the strain rate was increased to 14.5 %/min that the shear strength of the unsaturated specimen at a suction of 34 kPa was greater than that of the saturated specimen at the same axial strain rate. The reason for these observed trends was attributed to the role of excess pore water pressure during shear for the unsaturated specimens. The shear strength and excess pore water pressure at the point of stress path tangency for tests at an axial strain rate of 14.5 %/min are shown in Figure 7 as a function of matric suction. From this figure, it is clear that there is an increase in shear strength with increasing matric suction. This behavior is possibly due to both the role of the initial matric suction that serves to increase the initial effective confining pressure on the specimen, as well as the change in excess pore water pressure during shear, which increased with axial strain rate for the unsaturated specimens. This behavior was different from that of the saturated specimens.

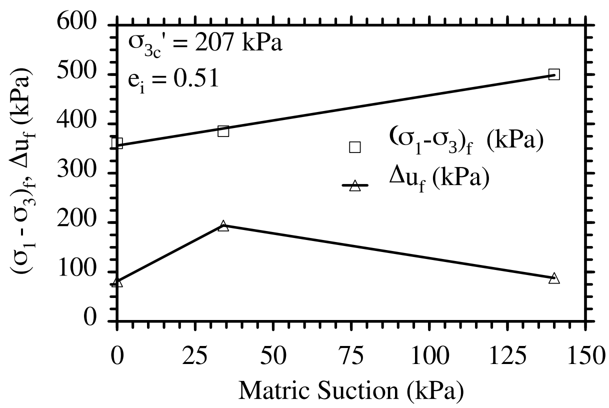


FIG. 7: Shear strength and excess pore water pressure at failure versus matric suction for tests at an axial strain rate of 14.5 %/min

One interesting observation is that the pore water pressure at failure for a suction of 34 kPa is greater than those for the tests with suction values of 0 and 140 kPa. This trend was confirmed with a second repeat test. An explanation for this behavior may be that the decrease in hydraulic conductivity with suction may affect the rate at which water can redistribute in the specimen due to the excess pore water pressure generated on the shear plane. Even in saturated specimens, the rate at which water redistributes spatially in the specimen in response to changes in excess pore water pressure on the shear plane will affect the magnitude of excess pore water pressure measured in the specimen (Gibson and Henkel 1954). The closer the specimen is to undrained conditions (i.e., the lower the hydraulic conductivity), the greater the potential for generating excess pore water pressures. At slower shearing rates, more time is available to allow for inter-pore redistribution of pore water throughout the specimen away from the shearing plane. However, at faster shearing rates, there may not be sufficient time available for this flow to occur. The reason that the specimens at suctions of 34 and 140 kPa had different magnitudes of excess pore water pressure is that the specimen with a suction of 34 kPa had a much higher degree of saturation. For low suctions where the degree of saturation is high, it is possible that relatively high excess pore water pressures have the potential to be generated. As the matric suction increases, rearrangement of the particles into predominantly air-filled pores spaces will not generate as high a magnitude of pore water pressures. Nonetheless, the specimen at a suction of 140 kPa still had a change in pore water pressure at the bottom of the specimen similar to that of the saturated specimen.

CONCLUSIONS

The results from this study confirm that saturated compacted clay experiences an increase in undrained shear strength with increasing strain rate. Furthermore, the increase in shear strength can be attributed to a decrease in pore water pressure and an increase in effective stress. The shear strength of unsaturated compacted clay increases with matric suction as expected, and also increases with increased strain rate. The pore water pressures at failure measured for unsaturated specimens at higher strain rates showed unexpected behavior, as they increased to a value greater than that for saturated conditions for low suction magnitudes, then decreased to a value similar to saturated conditions for higher suction magnitudes. This behavior was attributed to the change in hydraulic conductivity with increasing matric suction while the low suction specimen was still nearly saturated. Additional testing is underway to better delineate the role of excess pore water pressure generation in unsaturated soil over a wider range of suctions and loading rates.

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