British Journal of Applied Science & Technology
4(31): 4468-4479, 2014
ISSN: 2231-0843

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Strength and Deformation Characteristics of High Plasticity Offshore Clay

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Authors' contributions

This work was carried out in collaboration between both authors. Author CYL supervised the study. Author SYT managed the literature searches, design and analyses of the study and performed experimental process. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2014/12135
Editor(s):
(1) Verlicchi Paola, Department of Engineering, University of Ferrara, Via Saragat 1, Ferrara, Italy.
Reviewers:
(1) Anonymous, Petrobras Research Center, Brazil.
(2) Kigho Moses Oghenejoboh, Department of Chemical Engineering, Delta State University, Abraka, Oleh Campus, P. M. B. 22 Oleh, Nigeria.
Peer review History: http://www.sciencedomain.org/review-history.php?iid=635&id=5&aid=5978

Original Research Article

Received 19th June 2014
Accepted 22nd July 2014
Published 6th September 2014

ABSTRACT

The purpose of this study is to investigate the shear strength and stiffness characteristics of high plasticity offshore clay. A series of undrained monotonic triaxial compression and direct simple shear tests was conducted on reconstituted saturated offshore clay specimens. The clay specimens were tested under different confining pressures and overconsolidation ratios (OCR 1, 2, 4, 10 and 40) at constant dry density of about $1.25g/cm^3$. The offshore clay exhibits contractive behaviour. The test results show that an increase in OCR increases the normalized deviator stress and stiffness of the offshore clay. The normalized stiffness increases with increasing OCR but decreases with increasing axial strain. The normalized shear strength of high plasticity offshore clay increases with increasing strain rates.

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Keywords: High plasticity offshore clay; shear strength; overconsolidation ratio.

1. INTRODUCTION

For decades, the behaviour of offshore clay subjected to repeated loads are often analyzed by researchers due to the increased usage of offshore structures and concern for adequate seismic design [1-9]. On the other hand, there are also studies involving anisotropically consolidated undrained triaxial tests (CAU) and static direct simple shear tests (DSS) on offshore clay specimens [6,8-12].

However, there are limited studies considered on static strength of normally consolidated or overconsolidated high plasticity offshore clay specimens. More than a hundred offshore platforms are located in shallow and deep waters in between the East Coast of Peninsula Malaysia and West Coast of Sabah and Sarawak [13]. A better understanding of the fundamentals of shear strength and deformation characteristics of clay is essential to improve the accuracy of the solution of soil stability and settlement problem [14]. The objective of this paper is to investigate the static shear strength deformation behaviour of offshore clays with different OCRs (overconsolidation ratio) under isotropically consolidated undrained triaxial compression (CIU) and direct simple shear (DSS) tests.

2. MATERIALS AND METHODS

2.1 Soil Constituents

The clay specimens tested in this study represent the high plasticity offshore clay deposit located in Terengganu, Malaysia at the depths of 20m below the seabed. The typical geotechnical properties of the high plasticity offshore clay are given in Table 1.

Table 1. Geotechnical properties of high plasticity offshore clay

Geotechnical properties	Values
Liquid limit	54%
Plastic limit	27%
Plasticity index	27%
Clay fraction (d<0.002mm)	43%
Specific gravity	2.58

2.2 Testing Programs

Clay specimens used in the present study were reconstituted soil samples. The offshore clay was first oven-dried and crushed to powder form before water was added to form saturated soil with moisture content of 40%. The reconstituted clay was used for both triaxial and simple shear tests.

Undrained static triaxial compression (CIU) tests were conducted on isotropically consolidated offshore clay specimens with different OCRs and confining pressures at initial dry density of about 1.25g/cm^3. The soil specimens were 50mm in diameter and 100mm in height, and were fully saturated before being tested. The average Skempton *B*-value of the specimens after back pressure saturation was always higher than 0.98. Each clay specimen was consolidated for 12 hours before shearing took place. The triaxial testing apparatus was computer-controlled, and the stress-strain data were recorded automatically. The CIU tests were performed at axial strain rate of 3%/hr and the tests were discontinued when axial strain reached 15%. In order to investigate the effect of varying strain rates on shear behaviour of high plasticity offshore clay, CIU triaxial tests were performed with additional strain rates of 0.3 and 0.03%/hr.

Undrained direct simple shear (DSS) tests were also performed on high plasticity offshore clay to investigate the stress-strain relationships shearing along a horizontal plane after K_o consolidation. A modified computer-controlled simple shear testing apparatus incorporated with a data logging system was used. However, due to the limitation of the apparatus in the laboratory, the pore pressure of the soil specimens could not be measured during undrained shearing. Hence, only the horizontal shear strength of the soil specimens were measured. Shear strain rate of 3.8%/hr was applied on offshore clay specimens measuring 70mm in diameter and 25mm in height, with initial dry density of about 1.25g/cm^3. During consolidation, lateral strain was prevented by a consolidation clamp that was fitted to the outside of the metal washers. The clamp was then removed before shearing. The summary of CIU and DSS test conditions undertaken in this study is listed in Table 2.

Table 2. Summary of test conditions

Tests	Water content (%)	Confining pressure, σ_{vc}' (kPa)	OCR
CIU	40	100, 200, 300, 400	1, 2, 4, 10, 40
DSS	40	100, 200, 400	1, 2, 4, 10

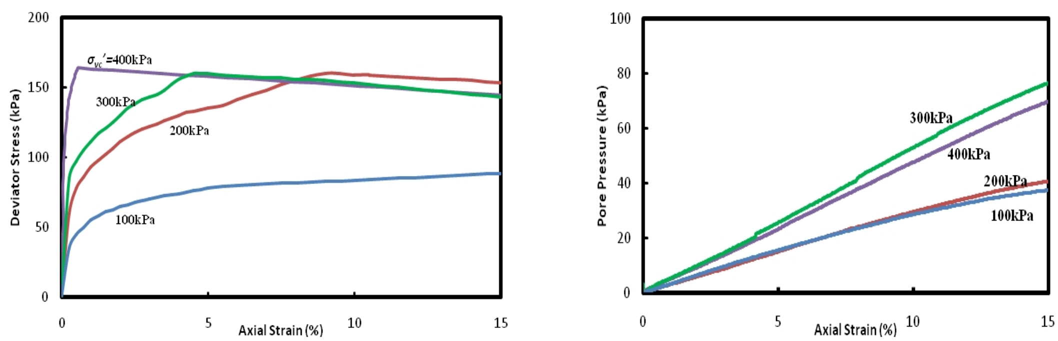
3. RESULTS AND DISCUSSION

3.1 Shear Strength Behaviour of Offshore Clay

The typical stress-strain and pore pressure response for high plasticity offshore clay under CIU and DSS tests are illustrated in Figs. 1 and 2, respectively. The undrained strength of clay specimens increases with increasing confining pressures. The clay specimens exhibit contractive tendency resulting in positive excess pore pressure with increasing confining pressures. During undrained shearing, the pore pressure increases with the increase in deviator stress [15].

The peak strength of clay specimen is reached at lower axial strain as confining pressure increases under triaxial compression. It can be observed that the peak strength for offshore clay is almost similar when confining pressure exceeds 200kPa. On the contrary, the DSS results presented in Fig. 2 shows that the peak strength is significantly larger at higher confining pressure when confining pressure is increased beyond 200kPa. The difference between the CIU and DSS test results can be attributed to the different shearing mechanism and rates of strain that are imposed to the clay specimens.

The effect of overconsolidation ratio on normalized peak strength (s_u/σ_{vc}', where s_u is the peak strength, and σ_{vc}' is the vertical normal stress) for both high plasticity and Drammen [16] offshore clay specimens is depicted in Fig. 3 for DSS and CIU tests. The DSS and CIU test conditions for high plasticity and Drammen offshore clay specimens are similar. It may be observed that normalized peak strength increases linearly as OCR increases from 1 to 40. The high plasticity offshore clay indicates a slightly higher normalized peak strength than that of Drammen clay for specimens tested under triaxial compression. However, the normalized peak strength for both offshore clay specimens are similar for the results obtained from DSS tests. Mayne [17] found that other offshore clays such as Bangkok clay, Atchafalaya clay, Maine clay and Boston Blue clay also display similar behavior.



(a) Deviator stress versus axial strain **(b) Pore pressure versus axial strain**

Fig. 1. CIU stress-strain results for high plasticity offshore clay

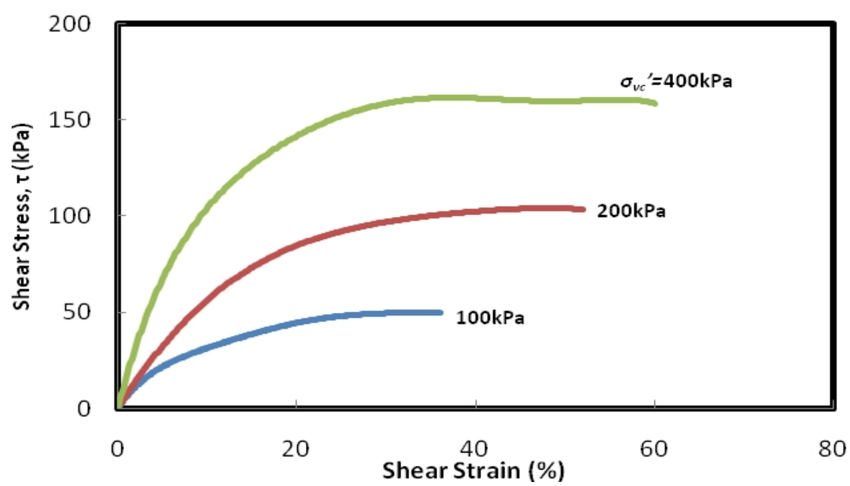


Fig. 2. DSS shear stress-strain results for high plasticity offshore clay

3.2 Soil Friction Angles

Table 3 indicates the friction angle and plasticity index of high plasticity offshore clay and various offshore clay specimens from other regions. The friction angle and plasticity index of both high plasticity and Drammen offshore clay are quite similar, perhaps due to the similar clay fraction in the soil. It can be observed that the friction angle decreases with increasing plasticity index of offshore clay. Several studies have been reported in the literature regarding the variation of friction angle with plasticity index for normally consolidated reconstituted or undisturbed natural clays [18-21]. Fig. 4 illustrates the plot of effective friction angle versus plasticity index, indicating that friction angle decreases with plasticity index of clay specimens. The friction angle of high plasticity offshore clay appears to be consistent with the typical friction angles range of other offshore clays.

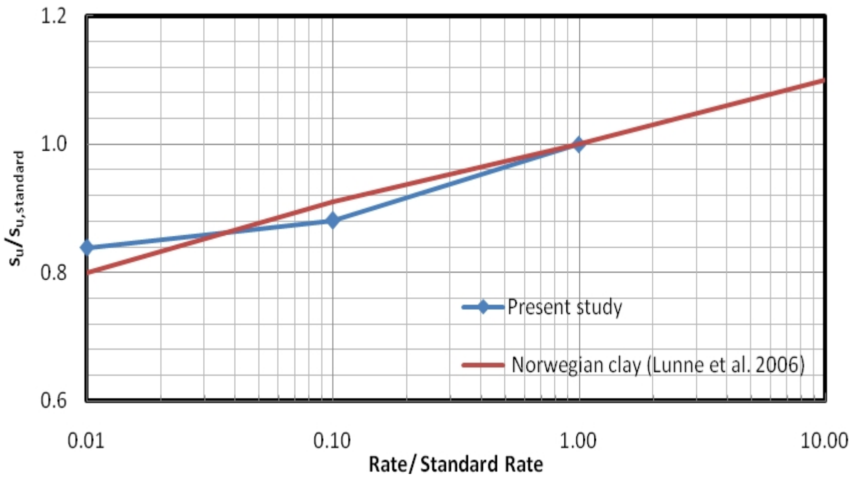


Fig. 3. Comparison of undrained direct simple shear and triaxial monotonic shear strength of Drammen and high plasticity offshore clay as function of OCR

Table 3. Comparison of friction angle for various offshore clays

Clay	PI (%)	Friction angle, φ'(°)	Clay fraction (%)	Reference
Present study	27	26	42	-
Drammen clay	27	30.7	45 – 55	[8]
Weald clay	24	26	-	[22]
Boston blue clay	15	30	26.5	[23]
London clay	49	21	50	[24]
Bombay marine clay	70	24	48	[25]

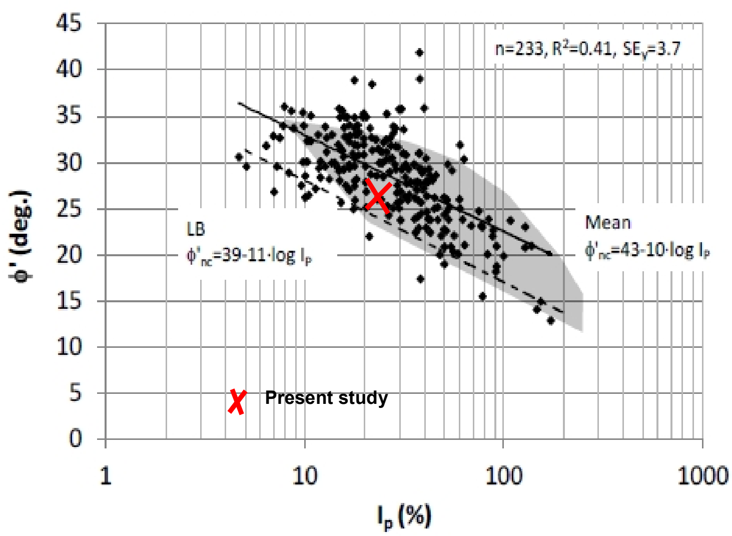


Fig. 4. Effective friction angle vs. plasticity index for normally consolidated reconstituted and undisturbed clays (after Ladd et al. [20])

3.3 Soil Stiffness-OCR Relationships

The normalized undrained secant stiffness (E_u/σ_{vc}') determined at different strain levels are plotted against strains (on logarithmic scale) as shown in Fig. 5. It is apparent that the normalized secant stiffness of both normally and overconsolidated offshore clay specimens decreases rapidly with increasing strain levels. As the soil yields, the normalized stiffness begins to decrease as the soil experiences plastic deformation [26]. Similar behaviour was reported in the literature [15,27-30] for normally consolidated London clay, Bangkok clay, Boston Blue Clay III, natural Bothkennar clay and Magnus clay, respectively. It is also noted that the normalized stiffness of high plasticity offshore clay increases with OCR, which is also in agreement with the findings of Seah and Lai [27] and Sangatana [28] on Bangkok clay and Boston Blue Clay, respectively. The stiffness of normally consolidated offshore clay degrades faster at lower strains than that of overconsolidated offshore clay and thus, E_u/σ_{vc}' is lower at higher strains. Abdulhadi [31] also reported the same finding on normally consolidated and overconsolidated reconstituted Boston Blue Clay tested under anisotropically triaxial compression test.

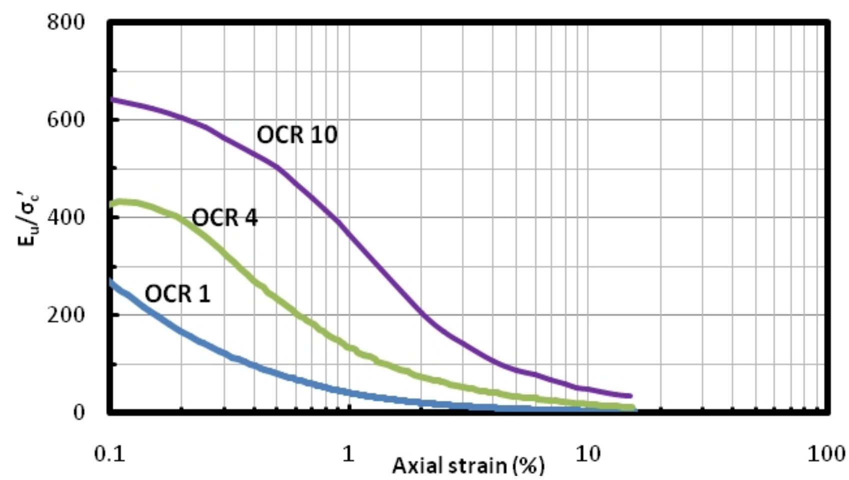


Fig. 5. Normalized soil stiffness–axial strain relationship in triaxial compression test for high plasticity offshore clay

3.4 Rate Effects

Fig. 6 indicates the effect of varying strain rates on normalized shear strength of Norwegian clay [10] and high plasticity offshore clay (present study). The standard strain rates used for both Norwegian clay and high plasticity offshore clay are 3%/hr and 0.55-0.75%/hr, respectively. The relationship of normalized shear strength and strain rates for Norwegian clay is determined from both DSS and anisotropically consolidated undrained (CAU) triaxial tests [10]. On the other hand, isotropically consolidated undrained (CIU) triaxial tests were carried out in present study to establish the relationship of normalized shear strength and strain rates for high plasticity offshore clay.

As shown in Fig. 6, the normalized shear strength ($s_u/s_{u,\ standard}$, where s_u is the peak strength of soil sample, and $s_{u,\ standard}$ is the peak strength of soil sample at standard strain rate) of high plasticity offshore clay and Norwegian clay increases with increasing strain rates (rate/standard rate). The finding is consistent with those reported by Lefebve and LeBoeuf [32], Sheahan [33]; Zhu and Yin [34] and Sorensen [35]. Undrained shear strength of clay is associated closely to the pore water pressure development induced by shearing. Fig. 7 depicts the pore water pressure response of high plasticity offshore clay at various strain rates. The pore water pressure generated in the specimen during shearing is higher at a lower strain rate than at a higher strain rate, as identified in several studies such as Richardson and Whitman [36], Sheahan [33] and Zhu and Yin [34]. Richardson and Whitman [36] and Sheahan [33] reported that the decrease of pore pressure is the primary mechanism of strength increase with increasing strain rate.

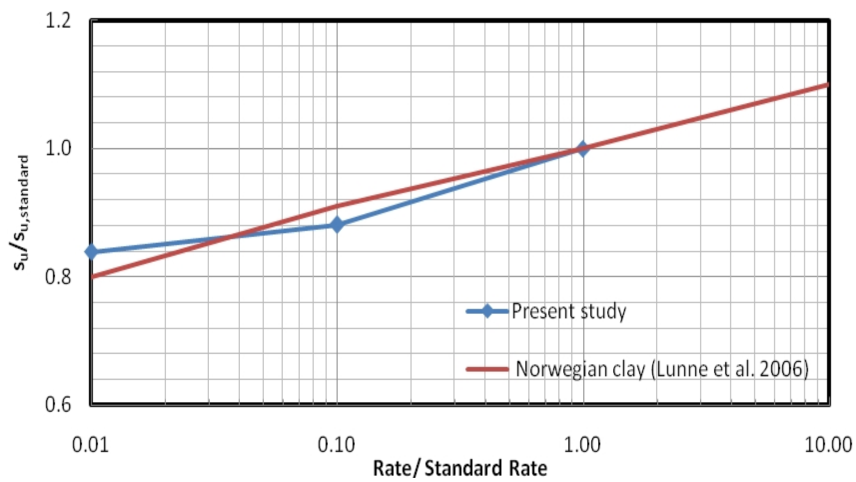


Fig. 6. Comparison of normalized shear strength for both Norwegian clay and high plasticity offshore clay

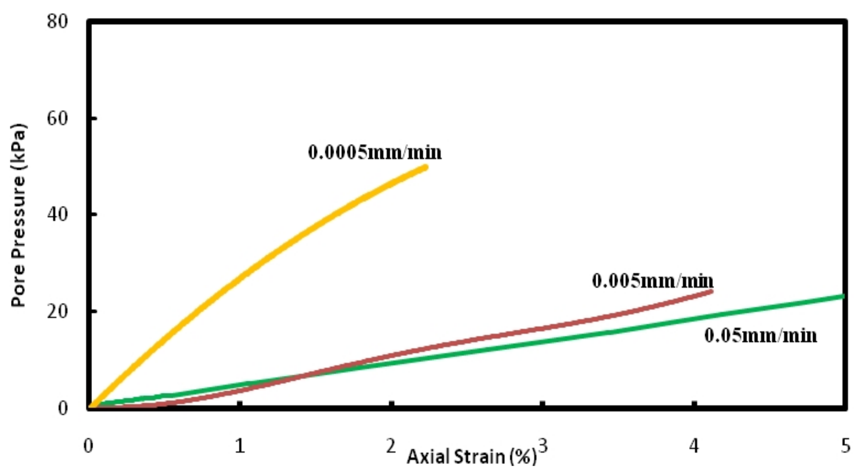


Fig. 7. Pore water pressure development for high plasticity offshore clay subjected to 400kPa confining pressure with various strain rates

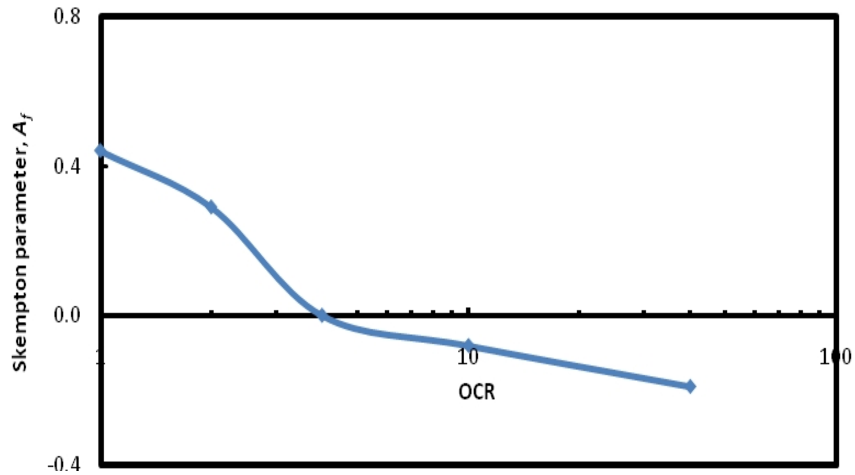


Fig. 8. Relationship of Skempton parameter at failure, A_f, with OCR for high plasticity clay

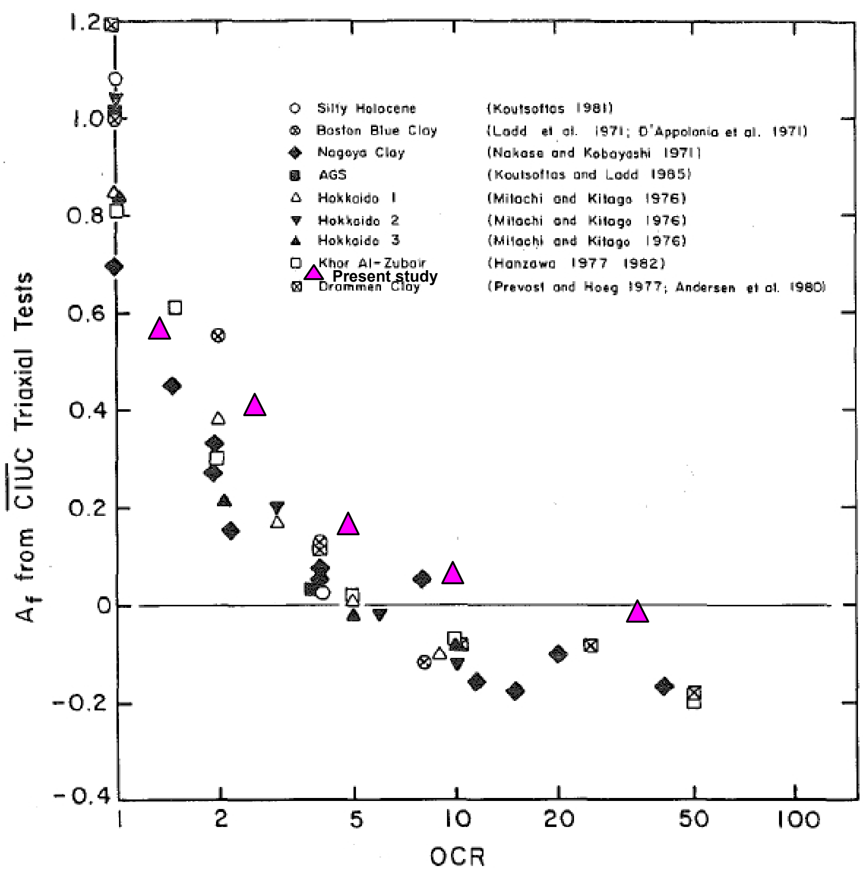


Fig. 9. Observed trend between A_f values and OCR for isotropically consolidated clays in triaxial compression

3.5 Pore-pressure Failure Parameter, A_f Parameter

Fig. 8 above indicates the variation of Skempton pore-water pressure parameter at failure, A_f, with increasing OCR for isotropically overconsolidated marine clay specimens. The value of A_f decreases with increasing OCR, and it tends to become negative when OCR is greater than 4. It is in agreement with CIU test results on many types of clays reported in the literature [37-43]. The test results presented by Bishop and Henkel [44] and Duncan and Seed [45, 46] also indicate that A_f becomes zero at OCR 4 and the values become negative at greater OCRs. The Oslo clay, Weald clay and London clay also yield approximately zero A_f values at an overconsolidation value of about 3 or 4 [47]. The magnitude of A_f may be negative for highly overconsolidated clay soils [48]. It is interesting to note that the variation of A_f with OCR is considerably small at higher OCR ranges as compared to the low OCR values.

Nakase and Kobayashi [49] found that A_f values from isotropically consolidated specimens became negative at lower OCR, while A_f values from K_o-consolidated specimens remained positive at OCRs greater than 10. This is because isotropic consolidation gives lower values of A_f than anisotropic consolidation at high OCRs [50]. The trend of A_f values for 9 different clays [8,37-40,51-53] subjected to a series of CIU triaxial tests are shown in Fig. 9 above.

4. CONCLUSION

High plasticity offshore clay displays different shear behaviour when it is sheared under CIU and DSS test conditions due to the different shearing mechanisms. However, the results obtained from both types of tests are comparable to those of Drammen clay under the same test conditions. The offshore clay exhibits contractive behaviour as indicated by the generation of positive excess pore pressure in CIU tests. The undrained secant stiffness of normally consolidated high plasticity offshore clay degrades more rapidly at lower strain levels that that of overconsolidated offshore clay, and hence, the soil stiffness of normally consolidated clay is lower at higher strain levels. The pore water pressure generated in offshore clay specimen during shearing is higher at lower strain rate than that at higher strain rate, thus it results in strength increase with increasing strain rates.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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