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CHARACTERISATION OF THE UNDRAINED SHEAR STRENGTH OF EXPANSIVE CLAYS AT HIGH INITIAL WATER CONTENT USING INTRINSIC CONCEPT

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ABSTRACT: Twenty-four direct shear tests were conducted on remolded/reconstituted specimens to study the effect of initial water content on the undrained shear strength of expansive clays. The laboratory tests illustrate that the shear behavior of the studied clayey soil is dependent on both the confining pressure and the initial water content at which the specimen was prepared. In fact, the undrained shear strength decreases with increasing initial water content. Similarly to the compression behavior, the intrinsic concept can also be used to predict the undrained shear strength of the studied soil. Additionally, the relationship between the void index, which is a normalized invariant of void ratio, and the undrained shear strength can be defined uniquely by a straight line. The experimental results also show that the normalized undrained shear strength, which is defined as the ratio of the peak undrained shear strength to the normal stress, varies with the initial water content from 0.25 to 0.50. Moreover, a decreasing trend is found for the range of pre-consolidation stress between 50 and 400 kPa.

Keywords: Clay, Laboratory test, Reconstituted, Shear strength, Expansive

1. INTRODUCTION

The mechanical and volumetric characteristics of clays can be predicted by assessing the behavior of remolded and reconstituted samples. In fact, these samples can be used as a framework to evaluate the behavior of natural clays. Burland [1] proposed an intrinsic concept as a basic reference for studying the compression behavior of reconstituted clays. According to Burland [1], the void ratio of a reconstituted clay can be uniquely normalized by using the void index invariant. Additionally, the intrinsic parameters are understood to be related only to the properties of soil materials and are not affected by the initial state of natural soils [1]. Furthermore, Burland, Rampello, Georgiannou, and Calabresi [2] extended the intrinsic framework to predict the shear behaviour of reconstituted clays. Since then, this notable concept has been widely used by researchers to predict the compressibility and shear behaviour of remoulded/reconstituted and natural clays all over the world [3-9].

To the best of the authors’ knowledge, there is a lack of experimental data regarding the effect of initial water content on the shear behavior of reconstituted/ remolded clays. Similarly to the intrinsic compression line (ICL), a reference line may be used to correlate the void index and undrained shear strength of reconstituted clays. Although the intrinsic characteristics are supposed to be independent of the initial state of the studied soil, it is anticipated that the shear behavior of a reconstituted clay may be affected by additional factors such as effective consolidation pressure and initial moisture content. Consequently, the following questions were investigated in this study:

a) What is the impact of the high initial moisture content of the preparation stage on the undrained shear strength of remolded/reconstituted clays?
b) Is the proposed intrinsic framework for studying the compressibility of reconstituted clays applicable to predict the undrained shear strength of clayey soils?
c) What is the trend of the undrained shear strength of reconstituted/ remolded clays with normal stress when the initial water content of the preparation phase is high?
d) What is the relationship between the void index and the undrained shear strength for reconstituted/ remolded clays?

Based on these questions, the influence of the initial water content of the preparation stage is investigated in this study for highly expansive clays. To consider the effect of the initial water content on the results, six series of initial water content was considered in the experimental tests. Additionally, the compression behavior of the studied clay was investigated to confirm the compatibility of the compression curves of a remolded/reconstituted specimen in the pre-consolidation stage with that of an identical sample consolidated in a standard one-dimensional consolidation apparatus.

2. INTRINSIC FRAMEWORK

Burland [1] proposed a baseline reference by introducing the ICL to predict the compressibility of reconstituted clays. Equations (1) and (2) present the void index definition, and the relation between the void index as the normalized void ratio parameter and the effective consolidation pressure, respectively:

$$I_v = \frac{e - e^*_{100}}{(e^*_{100} - e^*_{1000})} \tag{1}$$

$$I_v = 2.45 - 1.285(\log \sigma'_v) + 0.015(\log \sigma'_v)^3 \tag{2}$$

where I_v is the void index; e^*_{100} and e^*_{1000} are the corresponding void ratios at the effective consolidation pressures of 100 and 1000 kPa, respectively; and σ'_v is the effective consolidation pressure.

Cerato and Lutenegger [8] undertook a series of sensitivity experimental tests to investigate the effect of initial water content on the ICL. Their findings indicated that the initial water content has an impact on the ICL line at both low and high vertical consolidation pressures.

Hong, Yin, and Cui [4] modified a one-dimensional consolidation device to include the effect of very low-stress levels of consolidation pressures on the ICL. The consolidation tests were performed on three different clays with initial water content (w_0) varied between 0.7w_L and 2.0w_L; w_L is the liquid limit of the studied clay. Finally, Hong, Yin and Cui [4] revised the ICL equation, based on the results of these tests, to consider the effect of the low stress level as follows:

$$I_v = 3.0 - 1.87(\log \sigma'_v) + 0.179(\log \sigma'_v)^2 \tag{3}$$

Habibbeygi, Nikraz and Chegenizadeh [5] performed eight series of one-dimensional consolidometer tests on expansive clays from Western Australia at different initial water content levels. Based on their results, the intrinsic compression behavior of expansive clays can be explained well by the ICL. However, the initial water content has a significant influence on the void index for stresses below the remolded yield stress. Furthermore, the intrinsic compression parameters are also dependent on the clay mineralogy, which must be considered in the ICL relationship.

Habibbeygi, Nikraz and Verheyde [6] reviewed nineteen one-dimensional consolidation test results of seven clays from all over the world, of which the liquid and plastic limits varied from 42% to 200% and 23% to 108%, respectively; the soil particle density varied from 2.60 to 2.83. Their findings showed that the void ratio can be normalized well by the void index. Consequently, a linear relationship can be used with a reasonable accuracy to estimate the relationship between the void index and the effective consolidation pressure within the range of 50 to 2000 kPa:

$$I_v = 2.142 - 1.055(\log \sigma'_v) \tag{4}$$

Chandler [3] employed the intrinsic concept to explain the shear behavior of reconstituted clays by introducing an intrinsic strength line (ISuL). Chandler [3] reviewed the shear strengths of various clayey soils with plasticity and void indexes ranging from 12 to 60, and -1 to approximately zero, respectively. It was concluded that the normalized shear strength of the reconstituted clays (R^*_{su}), which is defined as the ratio of undrained shear strength to the effective confining stress, is independent of the plasticity index of the studied soil, and is equal to 0.34.

3. MATERIALS AND TEST PROCEDURES

3.1 Geotechnical Properties

Twenty-four series of direct shear tests on reconstituted / remolded samples were performed to study the undrained shear strength of clays at high initial water content. Six different initial water content ratio values (i.e. w_0/w_L =0.6, 0.7, 0.8, 0.9, 1.0, and 1.1) were adopted to investigate the effect of initial water content on the undrained shear strength.

Disturbed samples were collected in bulk from an underdeveloped suburb, named Baldivis, south of the capital city of Western Australia. The studied clay is referred as ‘Black clay’ herein owing to the dark grey to black color of the clayey soil. The main clay mineral of the studied soil is assessed as smectite based on the results of X-ray diffractometry tests [5]. The high level of smectite in clay minerals explains the high potential of swelling and expansion of the studied soil with the change in water content. The Atterberg limits (w_L and w_P) were measured in accordance with ASTM D4318 [10] and assessed to be 82% and 35%, respectively. A hydro pycnometer was used to measure the soil particle density (G_s) of the studied clay in accordance with ASTM D854 (G_s = 2.6). According to the wet-sieve test results, the clayey soil comprised 20% sand, 12% silt, and 68% clay. Finally, direct shear tests were performed for various normal stresses of 50, 100, 200, and 400 kPa (ASTM D3080) [10].

3.2 Sample Preparation and Test Procedure

Disturbed samples were initially oven dried at 105±5 °C for at least two days prior to preparation to achieve a constant weight. Then, the samples were ground manually by a rubber pestle and mortar to prepare a homogenous powder. A predefined amount of water was then added to the powder to prepare a specimen following Burland's procedure of reconstituted sample preparation [1]. Finally, all specimens were kept in multiple airtight bags for at least one day to be homogenized prior to testing. To mitigate the effect of friction between the specimen and the shear box, the inner faces of the box was covered by a small amount of silicone grease. The specimen size was measured to be 63.5 x 63.5 x 31 mm. Two porous stones were used at the top and bottom of the specimen, respectively, to allow free draining in both directions.

Prior to applying the shear displacement, the consolidation pressures were applied gradually to the specimens to be consolidated to the predefined normal stresses, in accordance with Table 1. For this purpose, the specimens were prepared at the predefined initial water content and carefully poured into the mold by controlling the total mass. The total mass of every specimen was calculated based on the completely saturated condition and the related water content. Then, the theoretical total mass of the specimens was compared with the measured total masses. An error of less than 3% was accepted in the overall mass measurement. Consolidation pressure increments were applied to each specimen in accordance with Table 1. The specimens were maintained at the consolidation pressure of each stage until the completion of the primary settlement of that stage of loading.

After the pre-consolidation stage, direct shear tests were performed on four series of specimens at normal stress (24 specimens in total) in accordance with ASTM D3080 [10] to investigate the effect of the initial water content and normal stress on the shear behavior.

4. DISCUSSION AND RESULTS

4.1 Pre-Consolidation Stage

In this study, the specimens were initially pre-consolidated to a predefined pressure in accordance with Table 1. Each consolidation stress increment remained on the specimen to complete the primary consolidation of the stage. Then, compression curves were plotted for four different normal stresses (i.e. 50, 100, 200, and 400 kPa), as shown in Fig. 1. The compression curves of the specimens for each stage were then compared to the corresponding compression curve of an identical specimen, which was consolidated in a one-dimensional oedometer. Fig. 1 shows the compression curves for the pre-consolidation stage and the one-dimensional consolidation for different initial water contents. As shown in this figure, the $e - \log \sigma_v'$ curves of the pre-consolidation stage are well-matched with the compression curves derived from the consolidometer test.

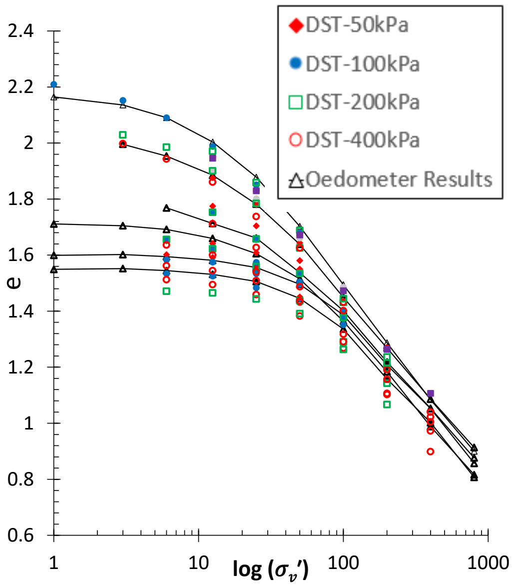

Fig. 1 Comparison of compression curves for the pre-consolidation stage and the one-dimensional consolidometer test

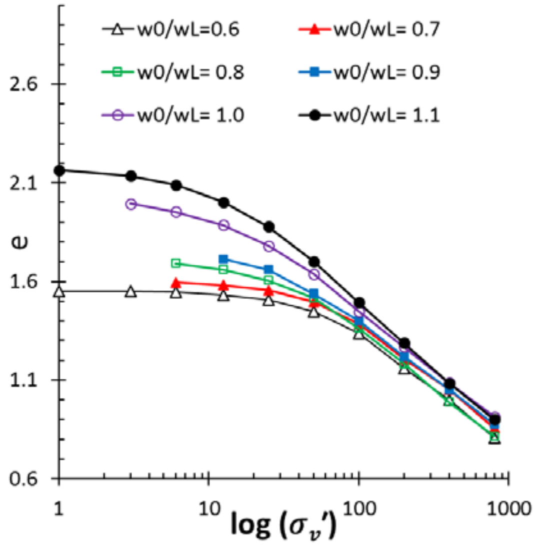

Fig. 2 Semi-logarithmic compression curves ($e - \log \sigma_v'$)

In addition to verifying the compression curves of the pre-consolidation stages, the effectiveness of the intrinsic framework in normalizing the void ratios of reconstituted/ remolded clays was investigated in this study. Fig. 2 illustrates the intrinsic compression curves ($e - \log \sigma_v'$) of the Black clay prepared at various initial water contents in a semi-logarithmic space of $e - \log \sigma_v'$. As expected, the comprsion curves are inverse S-shape curves with a slight upward concave. Similar S-shape compression curves were reported in the literature for clays with different predominant clay minerals and degrees of plasticity [4-7].

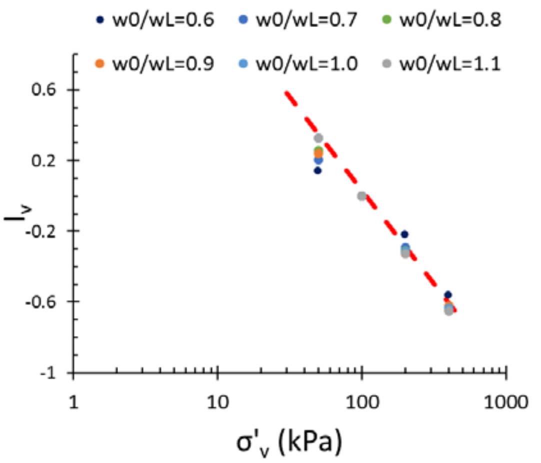

Fig. 3 Semi-logarithmic normalized compression curves ($I_v - \log \sigma'_v$)

The compressibility results of the pre-consolidation stages normalized using the intrinsic framework are replotted in Fig. 3. As shown, the relationship between the void index and the compression pressure can be correlated by a linear line in a semi-log plane. The ICL equation (Eq. 4) is also plotted in the figure for comparison. As shown, the ICL can predict reasonably well the compressibility of the studied soil. However, there is a disparity between the calculated values of I_v from the experimental tests and the estimated values from the linear line of the ICL for lower consolidation pressures. This indicates that the initial water content at which the specimen was prepared has a great impact on the void index of reconstituted/remoulded clays at low stress levels.

4.2 Undrained Shear Strength

After the pre-consolidation stage, direct shear tests were undertaken to assess the undrained shear behavior of the pre-consolidated specimens. Fig. 4 presents the relationship between the undrained shear strength and axial strain for four different normal stresses of 50, 100, 200, and 400 kPa. As seen in Fig. 4 (a), the maximum undrained shear strength and undrained residual shear strength are nearly equal for different initial water contents. However, the gap between the peak shear strength and residual shear strength increases with increasing normal stress (Refer to Fig. 4a to Fig. 4d). For instance, the peak undrained shear strength is greater than 1.5 times the residual shear strength at a normal stress of 400 kPa.

According to the direct shear test results, w_0 has a great effect on the shear behaviour of the studied soil. In fact, S_u^* decreases with increasing w_0 at the same normal stress. Furthermore, this gap increases significantly when the normal stress increases. The gap between the shear strength of the specimen prepared at different initial water contents is significant, especially for high normal stress values (i.e. 200 and 400 kPa; refer Fig. 4c and 4d).

Table 1 Consolidation stress increments at the pre-consolidation stage and normal stress for direct shear test

Sample	Initial Water Content Ratio (w_0/w_L)	Normal stress (kPa)	Vertical Consolidation Pressure Increments (kPa)
1 – 4	0.6	50, 100, 200 and 400	3, 6, 12.5, 25, 50, 100, 200, 400
5 – 8	0.7	50, 100, 200 and 400	3, 6, 12.5, 25, 50, 100, 200, 400
9 – 12	0.8	50, 100, 200 and 400	6, 12.5, 25, 50, 100, 200, 400
13 – 16	0.9	50, 100, 200 and 400	1, 3, 6, 12.5, 25, 50, 100, 200, 400
17 – 20	1.0	50, 100, 200 and 400	1, 3, 6, 12.5, 25, 50, 100, 200, 400
21 – 24	1.1	50, 100, 200 and 400	1, 3, 6, 12.5, 25, 50, 100, 200, 400

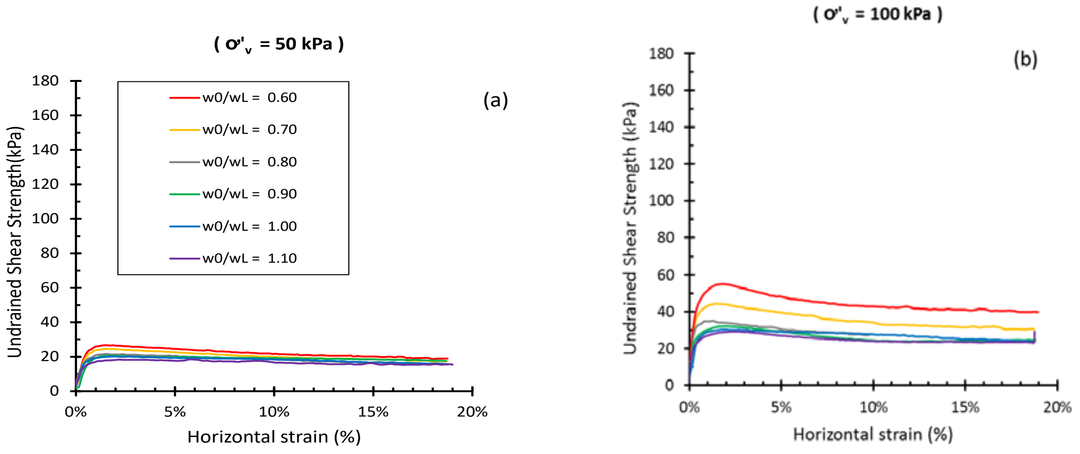

Fig. 4 Relationship between undrained shear strength (S_u^*) and axial strain (a) for 50kPa and (b) for 100kPa

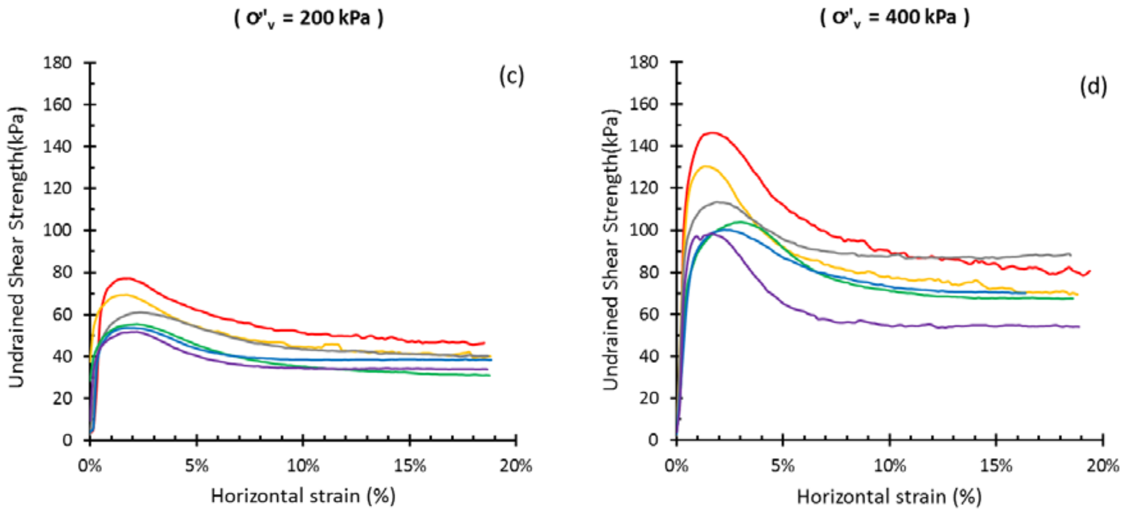

Fig. 4 Relationship between undrained shear strength (S_u^*) and axial strain (c) for 200kPa and (d) for 400kPa

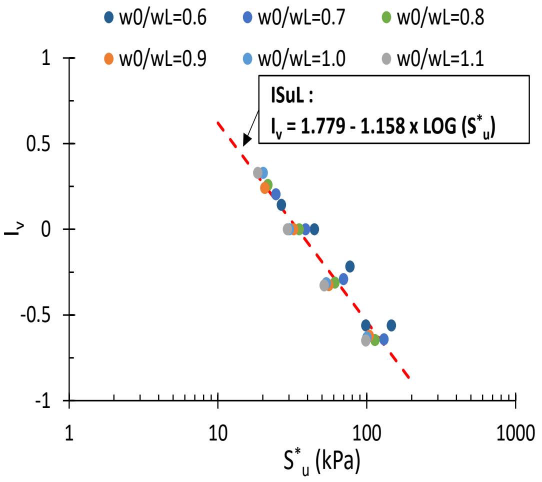

Fig. 5 Undrained shear strength (S_u^*) versus normal stress

Figure 5 illustrates the relationship between the peak undrained shear strength (S_u^*) and the normal stress applied to the specimen prior to applying the shear displacement. S_u^* is defined as the maximum undrained shear strength that can be applied to the clayey soil before it decreases and the axial strain increases rapidly. As shown, S_u^* has a linear relationship with the normal stress for different initial water contents (Fig. 5). As expected, the undrained shear strength of a specimen prepared at a higher initial water content is less than that of a specimen prepared at a lower initial water content. S_u^* increases with increasing normal stress, and the difference between S_u^* at different initial water contents increases with increasing normal stress The values of S_u^* at 50 kPa normal stress are similar for various initial water contents. However, S_u^* is greater at low initial water contents than the related values at high values of w_0.

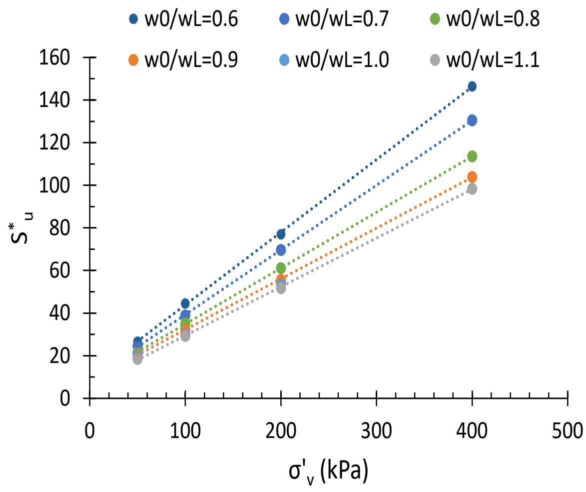

Fig. 6 Void index versus undrained shear strength (S_u^*)

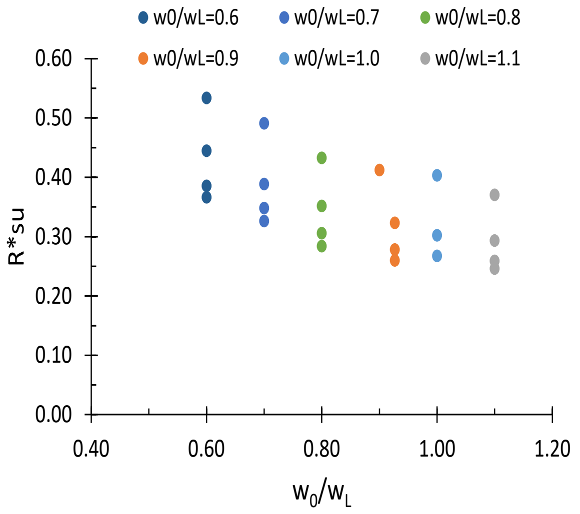

Fig. 7 Normalised undrained shear strength (R_{su}^*) versus normalised initial water content

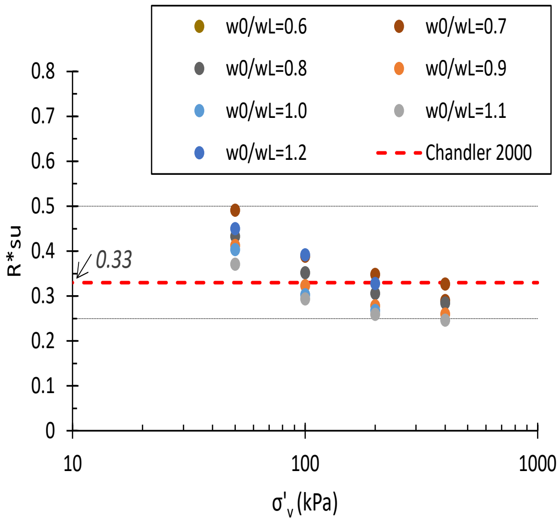

Fig. 8. Normalised undrained shear strength (R^*_{su}) versus normal stress

To investigate the advantage of using the intrinsic frame of reference, the void index is plotted against S^*_u in Fig. 6. Similarly to the ICL for compressibility of reconstituted samples, a line can be drawn on the results to correlate the undrained shear strength of such samples. This line is called the intrinsic strength line (IS_uL) in accordance with Burland 1996, and can be defined by a straight line with an acceptable correlation coefficient (R^2=0.94) as follows:

$$I_v = 1.779 - 1.158(\log S^*_u) \qquad (5)$$

To study the effect of w_0 and the normal stress on the related undrained shear strength, R^*_{su} is defined as the ratio of undrained shear strength to the effective normal stress in accordance with Chandler [3]. Fig. 7 displays the relationship between R^*_{su} and w_0/w_L for the studied clayey soil. As shown, R^*_{su} has a decreasing trend with increasing of w_0/w_L. This can be explained by the fact that specimens with greater w_0 values have higher void ratios in comparison to identical specimens at lower initial water contents.

Fig. 8 indicates the relationship between R^*_{su} and the normal stress in a semi-log plane. As shown, R^*_{su} has a decreasing trend with increasing normal stress, and varies between 0.25 and 0.50 for the range of normal stresses of 50 to 400 kPa. However, the graph almost becomes level at higher normal stresses and reaches approximately 0.25 to 0.30 for the normal stress of 400 kPa. Accordingly, R^*_{su} is not constant for the studied clayey soil; this is in opposition to the constant value of 0.33 proposed by Chandler [3]. For comparison, the constant line of R^*_{su}=0.33 is also plotted in this figure. As shown, R^*_{su} is greater than 0.33 for lower normal stresses, and decreases to below 0.33 for normal stresses as high as 400 kPa.

5. CONCLUSIONS

Twenty-four series of direct shear tests were undertaken on remolded/reconstituted specimens with different initial water contents to study the impact of the moisture content of the preparation stage and the normal stress on the undrained shear strength of clayey soils. The following conclusions are drawn based on employing the intrinsic framework to interpret the results:

Shear behavior of a reconstituted clay depends on the initial water content of the pre-consolidation stage. In fact, the shear strength of the reconstituted sample decreases with increasing initial water content. The difference between the undrained shear strength of samples pre-consolidated at different initial water contents increases with increasing initial water content.

There is a significant difference between the peak undrained shear strength and the residual shear strength when the normal stress increases.

Similar to the ICL for compression behavior, the relationship between the undrained shear strength and the normal stress of reconstituted/ remolded clays can be expressed with a reasonable accuracy by a straight line (ISuL).

The normalized undrained shear strength (R^*_{su}) depends on the normal stress, and has a decreasing tendency with increasing initial water content.

The normalized undrained shear strength (R^*_{su}) varies between 0.25 and 0.5 with the normal stress. Moreover, R^*_{su} decreases with increasing normal stress and is almost constant at approximately 0.30 for normal stresses higher than 200 kPa.

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