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Relationship Between Undrained Shear Strength with Atterberg Limits of Kaolinite/Bentonite – Quartz Mixtures

Kil Zeminlerin Drenajsız Kayma Dayanımı ile Atterberg Limitleri Arasındaki İlişki

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Öz

Bu çalışmanın temel amacı, kum kil karışımlarının drenajsız kayma dayanımı ile Atterberg limitleri arasındaki ilişkinin, hem düşen koni deneyi hem de Casagrande yöntemi kullanılarak incelenmesiydi. Casagrande yöntemiyle elde edilen değere yakın likit limiti belirleyen düşen koninin penetrasyon derinliği, kil içeriği ile değiştirilmiştir. Aynı kil tipinin, daha yüksek bir kum içeriğine sahip karışımlarda daha az drenajsız kayma dayanımı değerleri elde edildiğini gösterilmiştir. Drenajsız kayma dayanımı küçük miktarlardaki kum değerleri için düşükken; kil miktarı arttıkça, drenajsız kayma dayanımı artmıştır. Sonuç olarak, kum kil karışımlarının Atterberg limitini belirlemek için kullanılan düşen koni deneyi için bir denklem, drenajsız kayma dayanımı ve başlangıç su içeriğine bağlı olarak önerilmiştir.

Anahtar Kelimeler

“Kaolin, bentonit, kuvars, drenajsız kayma dayanımı, Atterberg limit,”

Abstract

The main purpose of this study was to investigate the relationship between the undrained shear strength and the Atterberg limits of quartz clay mixtures using the falling cone test and the Casagrande method. As a result, the penetration depth obtained from fall cone test, which determines the liquid limit close to the value obtained by the Casagrande method, was changed by the presence or absence of fine grained soils. It was shown that same clay type with a much higher quartz content concluded smaller undrained shear strength values. The undrained shear strength value with a small amount of quartz was the lowest; increasing with the increase in fines content. The relationship between the undrained shear strength and the Atterberg limits for all the samples depend on three parameters: (1) quartz / clay (kaolinite or bentonite) mixtures ratio, (2) type of clay (plasticity; high - low plasticity), and (3) plastic limit value. Finally, an equation for the fall cone test used to determine the Atterberg limit of quartz clay mixtures, was proposed based on the undrained shear strength and initial water content.

Key Words

“Kaolinite, Bentonite, Quartz, Undrained Shear Strength, Atterberg Limits”

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1. INTRODUCTION

The fall cone test firstly was developed as a method for estimating the strength of remoulded cohesive soils. Then, it was widely used as a standard method for determining the liquid limit of clays in many countries. In the past, several empirical estimates have been made of the strength at the liquid limit.

The liquid and plastic limits, as called Atterberg limits (liquid limit, w_L; plastic limit, w_P), which represent the consistency characteristics of soils, are the important indices among the physical properties of soils. All over the world, the Casagrande cup and thread rolling methods have been used to determine the liquid limit and plastic limit of clay soils. On the other hand, the fall cone method has been used to find the liquid limit of clay soils in many countries. Also, the fall cone method is also used to calculate the undrained shear strength (S_u) of soils. Recently, in 2004, fall cone method was provided as the ISO/TS Standards for determining the liquid limit and the undrained shear strength of soils. In general, the shear strength of a soil can be considered to have three components qualitatively: cohesion, friction, and dilatancy (Lambe, 1960). Cohesion, in general, is considered as a part of the shear strength that can be mobilized due to forces arising at the particle level and is independent of the effective stress (Lambe, 1960), and hence is regarded as a physico-chemical component of the shear strength. Yong and Warkentin (1966) feel that cohesion of clays is so dependent on the interaction characteristics of the clay–water system that a definitive description as to what constitutes cohesion becomes virtually impossible. The main objective of this paper is to show experimental verification of the relationship of these limits in terms of undrained shear strength by means of a fall cone method. This paper describes the reappraisal of the fall cone method and Casagrande cup for determining simultaneously both liquid and plastic limits of quartz-kaolinite/bentonite mixture soils. The fall cone tests for determining the liquid limit of soils are mainly standardized. The cone type with mass and apex angle is 30°, 80 g cone. The former is always called 'BS cone' implying the British Standard type.

The fall cone apparatus includes a specimen cup, 55 mm in diameter and 40 mm in height. In BS 1377, test 2(A), the test procedure for determination of the liquid limit includes the following: "The re-mixed soil shall be pushed into the cup with a palette knife, taking care not to trap air." This implies that the process of placing the soil in the specimen cup is influenced by individual judgment and is probably the most difficult step in the fall cone test.

A total of 112 soil samples including 52 kaolinite-quartz and 60 bentonite–quartz mixtures, were tested during this investigation. The bentonite and kaolin samples were prepared by thoroughly mixing the powder with distilled water and curing the mixture for at least 24 hours before testing. 52 kaolinite-quartz and 60 bentonite–quartz mixtures were tested using both the fall cone apparatus and the Casagrande percussion device to determine their liquid limits. The samples of 52 kaolinite-quartz and 60 bentonite–quartz mixtures were tested to determine their liquid limits and plastic limits from their linear log d – log w relationships. For this purpose, the number of fall cone tests was increased to obtain more data points with depths of penetration falling between 3 and 39 mm to better define the relationship for each soil.

2. RELATIONSHIP BETWEEN S_u with W_L & W_P of QUARTZ –KAOLINITE/BENTONITE MIXTURES

Hansbo (1957) proposed the relationship between cone penetration d and undrained shear strength (S_u) based on the fall cone and shear tests of soils as;

$$S_u = k\frac{mg}{d^2} \text{ (kPa)} \tag{1}$$

where m is a mass of cone (gram), k is a cone factor, g is a gravity acceleration (=9.8 m^2/s). k value, mainly depends on the apex angle of cone and in the BS cone is k=0.85 (Wood, 1985). In this paper, equation (1) is used to compute the S_u of 52 kaolinite-quartz mixtures and 60 bentonite-quartz mixtures soils. For the British cone (30°/0.785 N), the depth of penetration corresponding to the liquid limit is 20 mm (BS 1377). It may be noted that, using a penetration of 20 mm and k value of 1 (Wood, 1983) or 0.85 (Wood, 1985), the undrained shear strength computed from equation (1) is 1.96 or 1.67 kPa, respectively.

Equation (1) shows that the undrained shear strength is inversely proportional to the square of the depth of penetration. Data from Skempton and Northey (1953) show that the undrained shear strength at the plastic limit is about 100 times that at the liquid limit. Thus, it can be computed from equation (1) that the cone penetration at the plastic limit is 2 mm for the British cone. The British fall cone apparatus (BS 1377, British Standards Institution 1990), with a 30° cone and weighing 0.785 N, and the Casagrande percussion device were used during this investigation.

The linear log d – log w model is expressed as follows:

$$\log w = \log c + m * \log d \tag{2}$$

where w is the water content, c is the water content at d=1 mm, m is the slope of the flow curve, and d is the depth of cone penetration. For computing the cone liquid limit (w_{Lc}), equation (3) is rewritten as;

$$w_{LC} = c * (20)^m \tag{3}$$

The data points and the log d – log w relationships (flow curves) of quartz- kaolinite for 52 mixtures are shown in Figure 1. The data points and the log d – log w flow curves obtained from quartz- bentonite for 60 mixtures are shown in Figure 2. Both the *m* values and the *c* values of these flow curves are determined from linear regression analyses on the data points, and the corresponding values of the coefficient of determination (R^2) range from 0.932 to 1. For kaolinite-quartz mixtures, the c constant was ranging from 26.681 to 4. 856 and the average value of c is 14.765. These indicate a strong linearity of the log d – log w relationship. When the kaolinite content increases, the constant value of c decreases. Also, the slope of the flow curve, m, was calculated 0.366 as an average value (Figure 1).

The same result was shown for quartz- bentonite mixtures (Figure 2). For bentonite-quartz mixtures, the c constant was ranging from 50.22 to 6.20 and the average value of c is 26.629. When the kaolinite content increases, the constant value of c decreases. Also, the slope of the flow curve, m, was calculated 0.4011 as an average value. The results show that, bentonite- quartz mixtures have higher water content than kaolinite-quartz mixtures, because of the c constant and m slope of the flow curve is bigger.

Shimobe (1999; 2000) proposed the regression equation of d-Su relationship (R=0.964) based on a large number of his BS cone and shear test data of soils as;

$$S_u \text{ or } S_{ur} = \frac{224.468}{d^{1.576}} \quad (kPa) \tag{4}$$

where Su is undrained shear strength of the undisturbed soil or remoulded soil, respectively. Similarly, Federico (1983) also indicated this relationship of remoulded soils using the BS cone as;

$$S_{ur} = \frac{263.082}{d^{1.571}} \quad (kPa) \tag{5}$$

In this study, two different equations were obtained. The first equation was obtained by using Kaolinite quartz mixtures and the second equation was obtained bentonite quartz mixtures (Figure 3).

$$S_u = \frac{25.82}{d^{0.5}} \ (kPa) \tag{6}$$

Equation 6 was obtained by using kaolinite quartz mixtures. In equation (6), the slope of the flow curve is smaller than the bentonite quartz mixtures. Equation 7 was obtained by using bentonite quartz mixtures (Figure 3).

$$S_u = \frac{667.08}{d^2} \ (kPa) \tag{7}$$

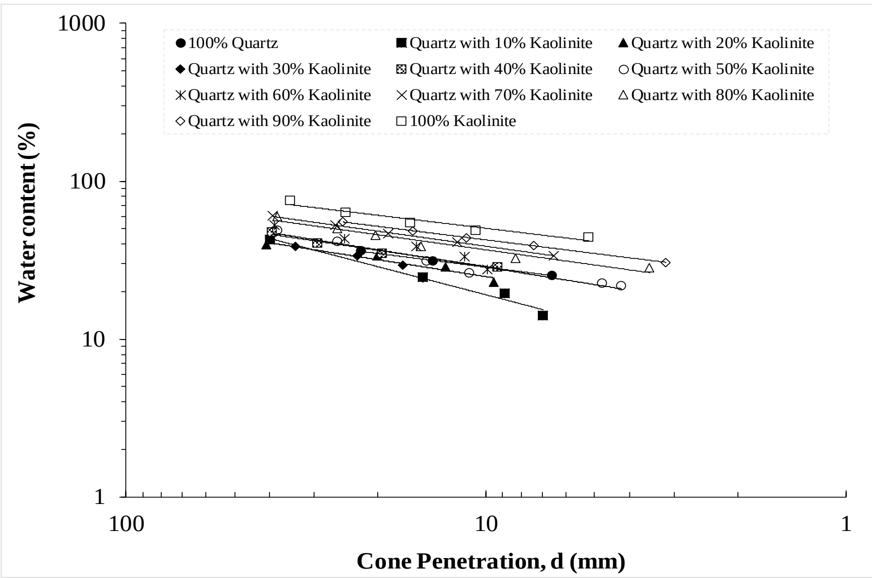

Figure 1: Logarithmic penetration depth versus logarithmic water content relationships for the kaolinite-quartz mixtures.

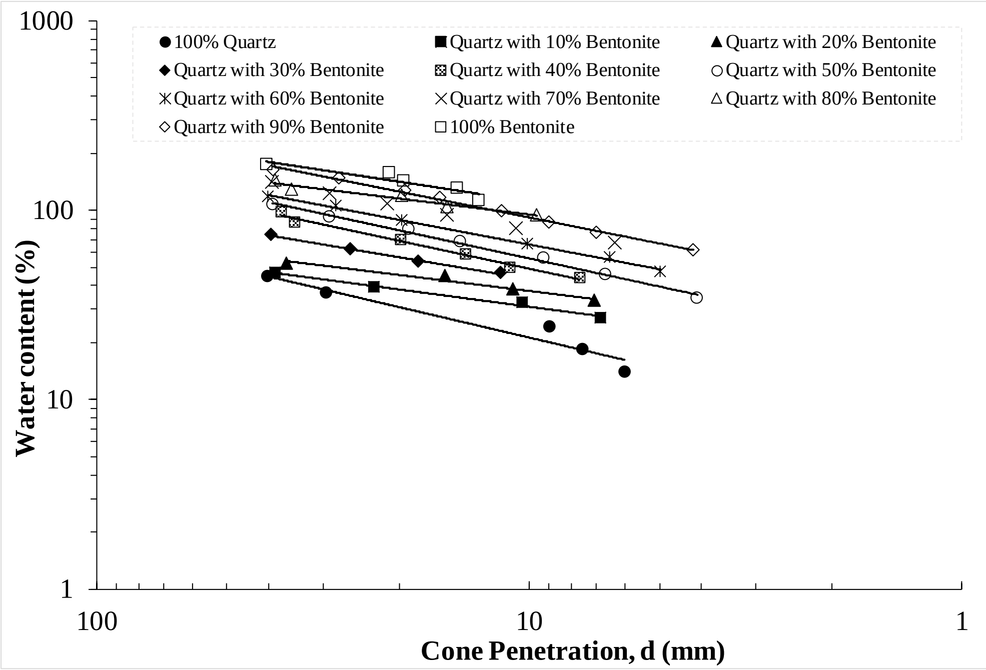

Figure 2: Logarithmic penetration depth versus logarithmic water content relationships for the Bentonite-quartz mixtures.

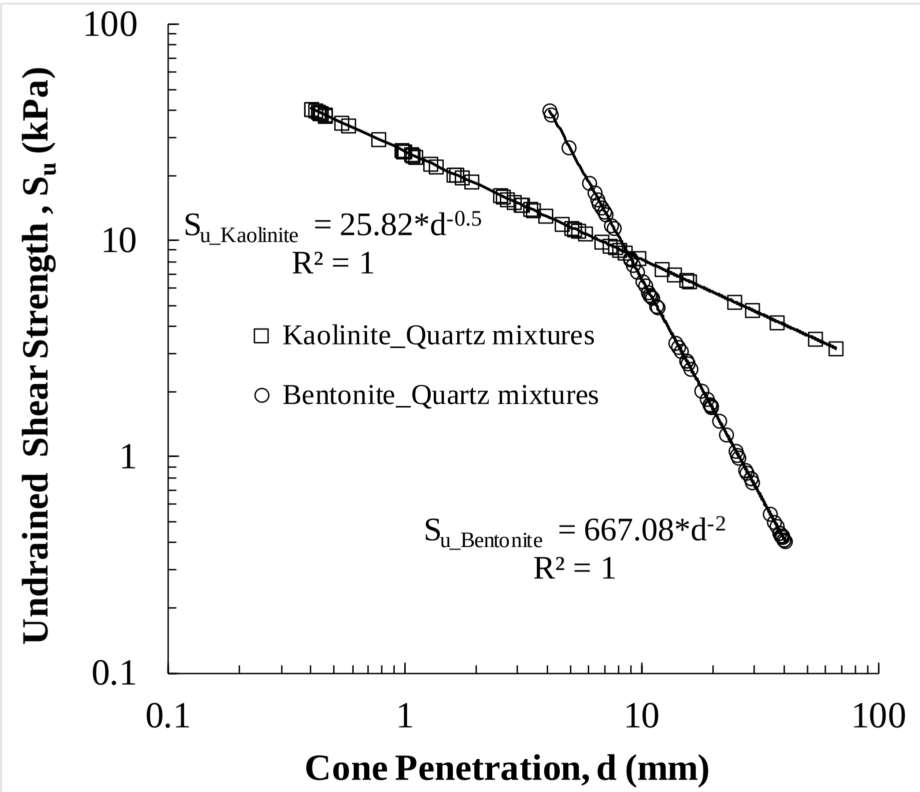

Figure 3: Relationship between undrained shear strength and cone penetration of Bentonite-quartz and Kaolinite-quartz mixtures.

The soils used in this investigation include mixtures of commercially available bentonite/kaolinite with quartz. The soils indicate that bentonite is dominantly composed of montmorillonite while kaolinite is composed of kaolinitic soils. The variation of undrained strength of soil with water content has been known in literature (Lee 2004; Trauner et al. 2005; Hong, et al. 2006). The various forms of relationship of undrained strength with ratio of water content to liquid limit (Lee 2004; Berilgen et al. 2007); undrained strength (either C_u or S_u) with liquidity index (Yilmaz 2000; Koumoto and Houlsby 2001; Berilgen et al. 2007); C_u with water content (Berilgen et al. 2007); C_u with consistency index (Berilgen et al. 2007) as reported by various researchers has been formulated.

Casagrande (1939) proposed an average shear strength of soil at the liquid limit as 2.65 kN/m^2. Norman (1958) reported that the shear strength at the liquid limit determined by using an apparatus conforming to the British standard ranged from 0.8 to 1.6 kN/m^2 whereas using an apparatus of ASTM standards, the strength ranged from 1.1 to 2.3 kN/m^2. Youssef et al. (1965) found that the values of shear strength of clay at the liquid limit of a large number of soils shows a mean value of 1.7 kN/m^2. According to Federico (1983), the shear strength at the liquid limit of soils, falls within limits of 1.7 and 2.8 kN/m^2. Wood (1985) showed a mean value of shear strength at the liquid limit as 1.7 kN/m^2. Wroth and Wood (1978) adopted a mean value of 1.7 kN/m^2 as the best estimate of undrained shear strength of a remolded soil at its liquid limit. In the present work, the liquid limit has been determined by the fall cone method. This study provides a mean value of 2.55 kN/m^2 as the shear strength at the liquid limit. This result is also consistent with the literature.

From the results of Skempton and Northey (1953), Wroth and Wood (1978) assumed that the shear strength at the plastic limit is one hundred times the shear strength at the liquid limit. From the same results, Nagaraj et al. (1994) and Belvisco et al. (1985) defined plasticity index as the range of water content producing a 100-fold variation in shear strength. This 100-fold variation of shear strength is based only on the results obtained by Skempton and Northey (1953). This finding is then used to derive a simple relationship between undrained shear strength and the liquid limit and the plastic limit of soil. Undrained shear strength of soil at the plastic limit is 170 kN/m^2.

Table 1 shows the A, β and R^2 values obtained from figure 1 for 52 quartz – kaolinite mixtures with using equation 1. The undrained shear strengths were determined for 22 clay (kaolinite/bentonite) – quartz soil samples by the fall cone test, the liquid limit of which varied from 24.69 to 60.79%. When water content was plotted against shear strength on a log-normal scale an exponential line for each soil sample was obtained. Figure 4 shows typical results for quartz – kaolinite mixtures the 52 samples tested. The relationship was obtained for water contents greater than the liquid limit to less than the plastic limit of the soil. Table 2 shows the A, β and R^2 values obtained from figure 5 for 60 quartz – bentonite mixtures with using equation 1. The exponential behavior between undrained shear strength and water content was also observed for data of quartz–bentonite mixtures. The result is shown in Figure 5 and Table 2.

The undrained shear strength-water content relationship has been found to be exponential in a log-normal plot. This relationship has been found to be valid for a range of water contents beginning from lower than the plastic limit to much greater than the liquid limit for a wide variety of soils with liquid limits ranging from 24 to 61%. This linearity in relationship has been used for formulation of an expression that gives the undrained shear strength of a quartz clay mixtures at any water content based solely on its plastic and liquid limits. Undrained shear strength results at different water contents obtained from fall cone tests are also incorporated in Figures 4 and 5. Figures 4 and 5 show good agreement of the S_u with those of water content. This example is typical of all such results obtained.

Table 1. Kaolinite quartz mixtures calculations

Test Sample	Kaolinite (%)	Quartz (%)	A	β	R^2
1	100	0	2E+12	-6.803	0.937
2	90	10	2E+12	-7.005	0.999
3	80	20	1E+10	-5.974	0.950
4	70	30	6E+10	-6.265	0.999
5	60	40	2E+7	-4.467	0.952
6	50	50	4E+8	-5.342	0.944
7	40	60	2E+9	-5.76	0.977
8	30	70	4.89E+5	-3.652	0.92
9	20	80	1E+8	-5.256	0.935
10	10	90	9.82E+4	-3.183	0.866
11	0	100	7E+10	-6.898	0.996

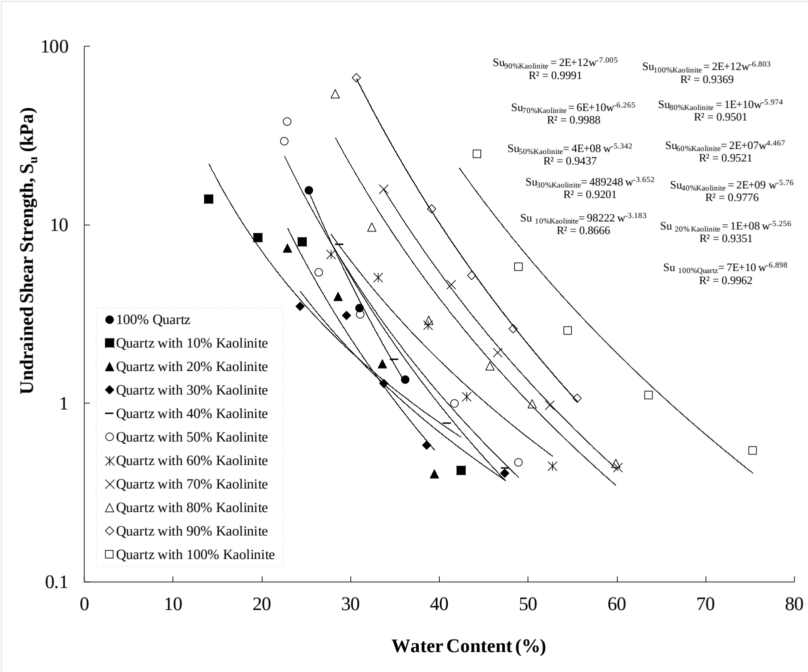

Figure 4: Relationship between undrained shear strength results as obtained from fall cone test and water content for quartz - kaolinite mixtures

Table 2. Bentonite quartz mixtures calculations

Test Sample	Bentonite (%)	Quartz (%)	A	β	R^2
1	100	0	9E+12	-5.921	0.967
2	90	10	2E+9	-4.37	0.995
3	80	20	1E+13	-6.177	0.977
4	70	30	9E+9	-4.821	0.996
5	60	40	2E+9	-4.599	0.995
6	50	50	7E+7	-4.029	0.994
7	40	60	4E+7	-4.032	0.987
8	30	70	2E+9	-5.194	0.993
9	20	80	4E+11	-6.831	0.962
10	10	90	3E+10	-6.49	0.985
11	0	100	283395	3.499	0.936

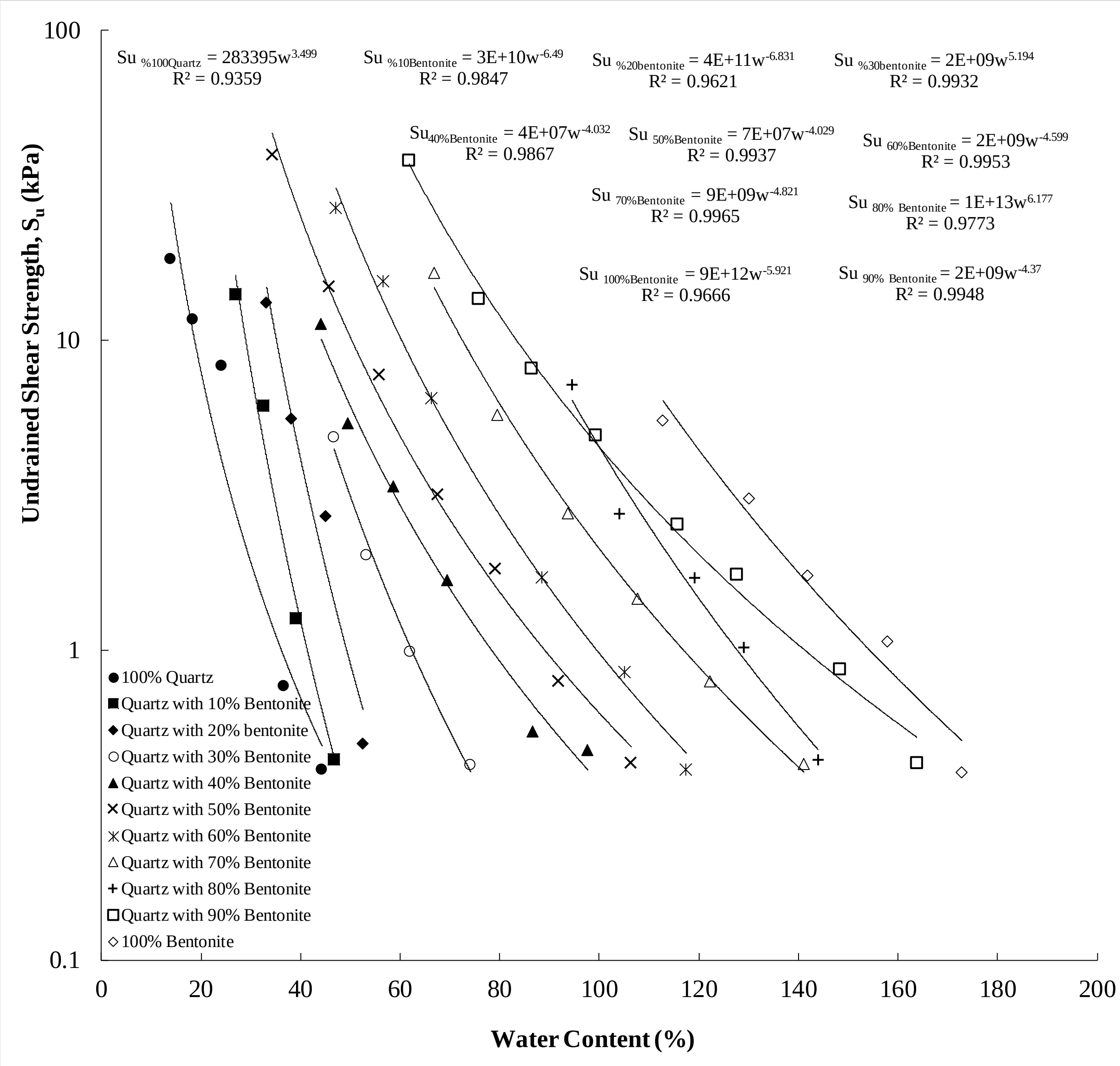

Figure 5: Relationship between undrained shear strength results as obtained from fall cone test and water content for quartz - bentonite mixtures

According to figure 4 and 5, the relationship between water content w (abscissa) and undrained shear strength S_u (ordinate) is given in terms of a power trend line function transformed to w-log (S_u) graph plot as;

$$S_u = A * \omega^{\beta} \tag{8}$$

where A is the constant and β is the slope of the best fit exponential line to the data points, respectively. The A constant value ranging from 28.3395 with 2E+12 and β value ranging from -3.183 with -7.005. Regression analysis of the results comparing undrained shear strength and water content is shown in figure 4 and 5. As seen in Table 1 and 2; a good correlation is indicated (R^2>0.94).

The undrained shear strengths at both liquid and plastic limits in Casagrande and fall cone methods are shown in figure 6. Furthermore, these values indicated by the previous researchers also are presented together in this figure. As a result, the undrained shear strength at liquid limit $(S_u)_{WL}$ is approximately 2.55 kPa irrespective of the difference of test methods and liquid limit values (Figure 6). However, though the undrained shear strength at plastic limit $(S_u)_{PL}$ has a wide range in comparison with liquid limit [$(S_u)_{PL}$=71-460 kPa], as its recommended value, $(S_u)_{PL}$ =170.52 kPa proposed by researchers seems to explain the measured values on average. While figure 6 indicates a general trend which clearly will be useful for some workers where the Atterberg limits are available, the liquid and plastic limits are a physical property while the undrained shear strength is a mechanical property of the soils and hence empirical methods to obtain the shear strength should always be treated with caution.

It can be observed that the undrained shear strength values at liquid limit water content is quite variable and are both test dependent and on the soil type. The variation of the shear strength with soil type being important from as low as 0.8 kPa to as high as 10 kPa. Many of the researchers (Wroth and Wood, (1978), Stone and Phan (1995)) developed an instrumented cone penetrometer to establish the moisture content of soil with strength 100 times that of the liquid limit which could be defined as the plastic limit. But the method has not got universal acceptance. In this study, we found that undrained shear strength ratio at plastic limit to liquid limit is nearly 80.

In this study, plot of ratio of undrained shear strength at plastic limit to liquid limit versus liquid limit by both Casagrande's method and Fallcone method are presented in Figure 7. From this figure, it can be seen that the undrained shear strength ratio at plastic limit to that of liquid limit is quite variable, being as low as 13 to as high as 360. It can also be observed that the strength ratio has an increasing trend with the liquid limit.

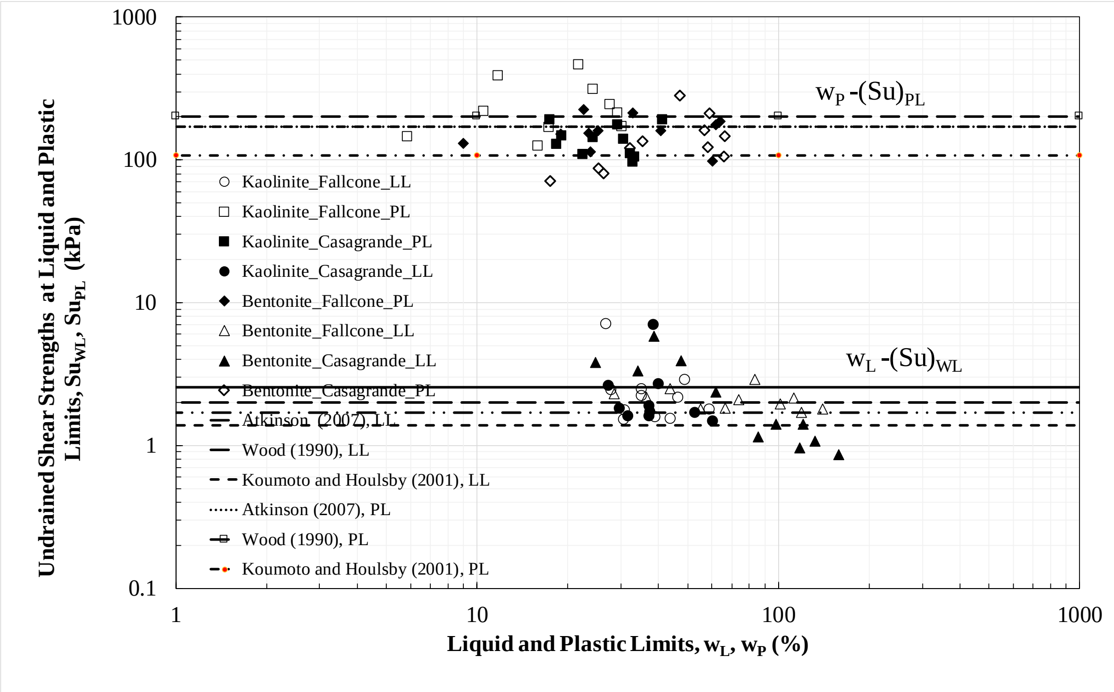

Figure 6: Undrained shear strengths at liquid and plastic limits in Casagrande and Fall cone methods results as obtained for quartz – (kaolinite /bentonite) mixtures

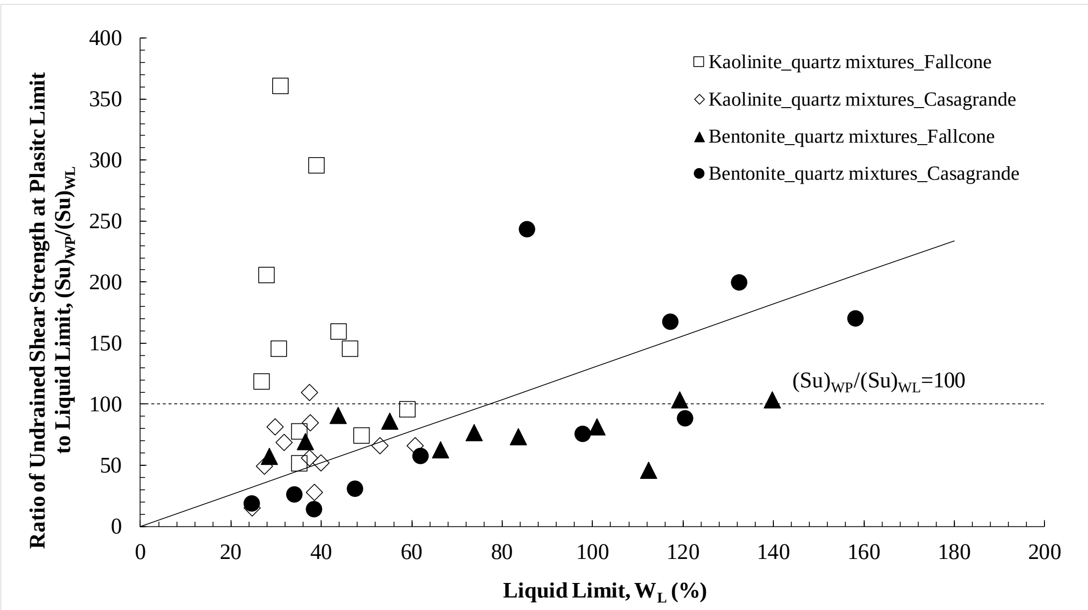

Figure 7: Undrained shear strengths ratio at plastic limit to liquid limit versus liquid limit Casagrande and Fall cone methods results as obtained for quartz – (kaolinite /bentonite) mixtures

Figure 8 is a plot of the same strength ratio versus plastic limit, which is observed to have a decreasing trend with the plastic limit. From Figures. 7 and 8, it is further evident that undrained strength is having a functional dependency of water content. To further verify this fact, the strength ratio is plotted versus the ratio of liquid limit to plastic limit, as shown in Figure 9. From these figure the strength ratio is found to increase with the ratio of liquid limit to plastic limit. The correlation of strength ratio is better with the ratio of liquid limit to plastic limit. With the above discussion, it can be understood that shear strength is not unique both at liquid limit and plastic limit. It was seen that though the value of undrained shear strength at the liquid limit water content is less, the variation was observed to be nearly sixty-seven times and that at plastic limit to be as high as eighteen times. The ratio of undrained strength at plastic limit to liquid limit could vary significantly.

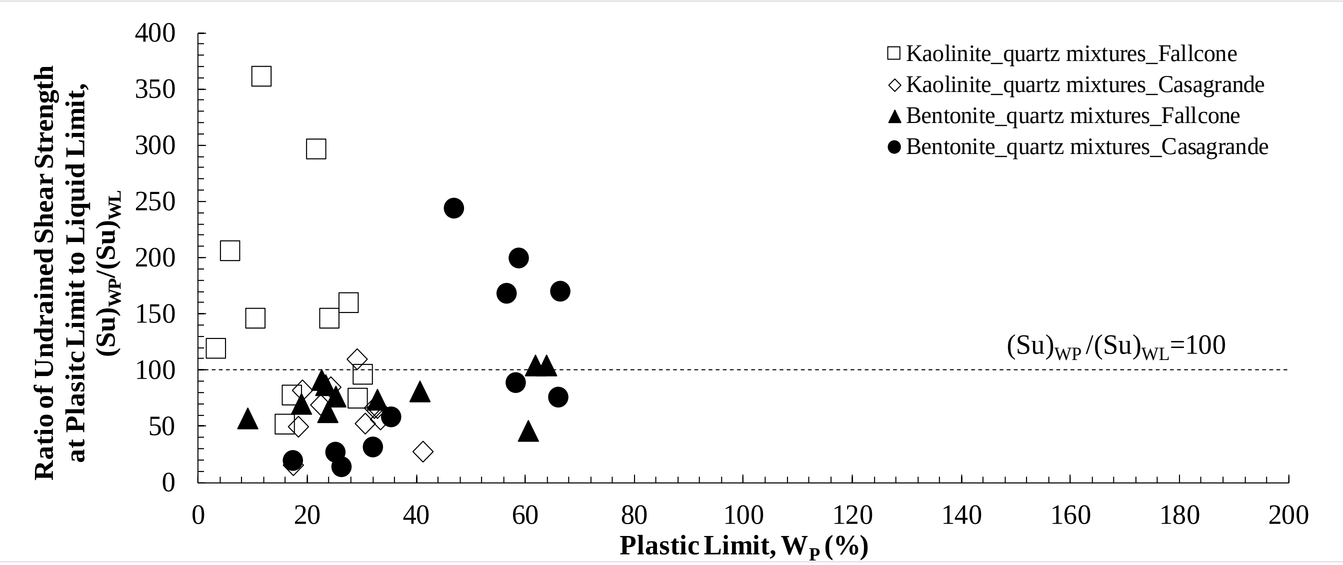

Figure 8: Undrained shear strengths ratio at plastic limit to liquid limit versus plastic limit Casagrande and Fall cone methods results as obtained for quartz – (kaolinite /bentonite) mixtures

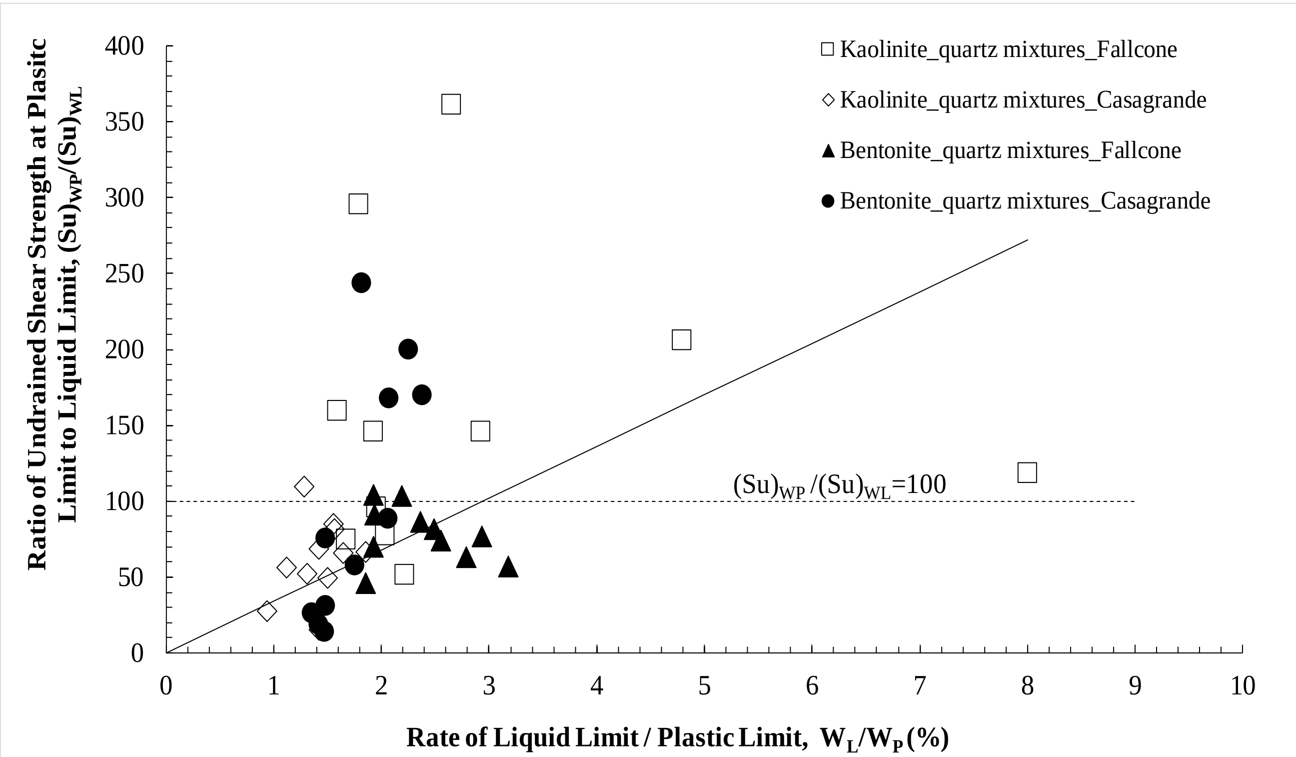

Figure 9: Undrained shear strengths ratio at plastic limit to liquid limit versus ratio of liquid limit to plastic limit Casagrande and Fall cone methods results as obtained for quartz – (kaolinite/bentonite) mixtures

3. CONCLUSIONS

The fall cone method can be used for determination of the liquid limit of the sand clay mixtures. It would be useful if the plastic limit could also be determined using the fall cone apparatus. The log d–log w relationships of 22 sand clay mixtures, with penetration depths ranging from 3 to 39 mm and percussion liquid limits ranging from 26 to 180%, are nearly linear, as determined from regression analysis. It is concluded that the fall cone method provides an alternative for a simple approach to determine both the liquid limit and the plastic limit. In addition, the fall cone test can also be used to determine the undrained shear strength of soils in terms of the cone penetration.

From the analysis of literature, undrained shear strength at the liquid limit has been found to have an average value of around 2.55 kN/m^2. The assumption Wroth and Wood (1978) that shear strength at the plastic limit can be taken as 100 times that at the liquid limit (170.5 kN/m^2) has not been experimentally verified and found to be valid. In this study shear strength at the plastic limit can be taken as nearly 80 times that at the liquid limit. The undrained shear strength-water content relationship has been found to be linear in a log-log plot. This relationship has been found to be valid for a range of water contents beginning from lower than the plastic limit to much greater than the liquid limit for a wide variety of quartz clay mixtures with liquid limits ranging from 24 to 61%. This exponential relationship has been used for formulation of an expression that gives the undrained shear strength of a quartz clay mixtures at any water content based solely on its plastic and liquid limits. It is concluded that that soils cannot have a unique value of strength at different values of water contents.

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