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ORIGINAL PAPER

Water Content Ratio: An Effective Substitute for Liquidity Index for Prediction of Shear Strength of Clays

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Abstract Undrained shear strength of saturated clays is a very important property in geo-technical engineering practice. Since the collection of undisturbed samples and testing the same is difficult task and time consuming process, any attempt to obtain correlations between shear strength and consistency limits would be highly desirable. Several attempts have been made in the past to correlate shear strength with Liquidity index. The computation of Liquidity index involves the value of plastic limit determined by Casagrande thread rolling method; but the determination of the same is relatively a difficult task in geotechnical engineering practice especially so in less plastic soils. It has been shown that a good linear correlation exists between log of shear strength and water content ratio (ratio of water content to liquid limit). With the help of numerous experimental results, it could be established that water content ratio could replace the well-known parameter liquidity index to predict shear strength. This enables to eliminate the determination of the plastic limit. The relation between water content ratio and liquidity index depends on the liquid limit to plastic limit ratio, irrespective of the geological origin of the soil.

Keywords Liquidity index · Undrained shear strength · Liquid limit · Natural · Water content

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1 Introduction

Undrained shear strength is an important parameter in geotechnical engineering practice and it is essential to get good assessment of the same. Since shear strength determination is a careful and time consuming process, the need for a faster and easier technique for rapid estimation of shear strength of saturated clays is necessary. But collection of undisturbed samples of extremely soft clays is a difficult task, as the sampling tubes cannot hold the samples due to its poor adhesive strength. At the same time, it is found far easier to collect representative samples, though disturbed, with the help of mechanical means such as augers. The authors who had taken up a comprehensive study on Cochin marine clays (Jose et al. 1987, 1988), tried to develop correlations between the index properties of clayey soils and shear strength. This paper presents the results of the investigation to predict shear strength of saturated clays based on the moisture content and liquid limit.

Attempts have been made by earlier workers to correlate shear strength with liquidity index (defined as the ratio of difference between natural water content and plastic limit to the difference between liquid limit and plastic limit) of clays. Wroth and Wood (1978), Yilmaz (2000) to name a few, proposed relationship between shear strength and liquidity index. Leroueil et al. (1983) related undrained cohesion with liquidity index in non-linear form. Schofield and Wroth (1968), upon examination of vane shear test data from Skempton and Northey (1952) made the observation that the liquid limit and plastic limit do correspond approximately to fixed strengths which are in the proposed ratio of 1:100. Based on this observation, Wroth and Wood (1978) proposed an equation;

$$c_u = 170\ e^{-4.6 I_L} kP_a \qquad (1)$$

where c_u–Undrained shear strength, I_L–Liquidity Index.

The liquidity index determination involves determination of Casagrande's thread rolling plastic limit which requires careful attention especially in the case of less plastic soils. Haigh et al. (2013) discuss in detail the plastic limit test, one of the standard tests of soil mechanics. This paper reviews the original definitions and bring out the necessity of carrying out this carefully. Any attempt to introduce a different parameter without the determination of plastic limit, will be desirable and useful. The shear strength of a soil is dependent on its water content and its plasticity characteristics. Any increase in water content is necessarily accompanied by a reduction in shear strength. But at the same water content, different soils have different strengths, as shown in Table 1. This is primarily due to their respective plasticity characteristics.

It may be mentioned here that the soils have been collected from in and around the Greater Cochin area (Kerala, India) with the distance between them varying from 10 to 30 km. The shear strength of these soil samples were obtained from laboratory vane shear tests on hand remoulded saturated samples. A minimum of two tests were carried out on each sample and the average value was taken. Care was taken to ensure full saturation by keeping the sample in a desiccator and effecting vacuum saturation. As it can be seen from Table 1, if the moisture content alone is taken as the basis, the shear strength behaviour does not show a regular trend.

Even though a comparison between moisture content and shear strength does not indicate any possibility for a correlation between the two, incorporation of the liquid limit values into the analysis shows some definite trends. Table 1 also shows the liquid limit values for the soils tested. It could be clearly seen that for the same water content, the shear strength is directly proportional to the liquid limit values. Thus it is evident that shear strength values can show a definite trend if it is correlated to moisture content along with their respective liquid limits. A new parameter called 'water content ratio' (WCR) defined as the ratio of moisture content to liquid limit is introduced herein to normalize the type of soil in order that correlations could be attempted. Obviously shear strength is inversely proportional to WCR.

2 Determination of Physical Properties of Clays

All the soils were tested for their Atterberg limits and grain size distribution characteristics. The liquid limit was determined by Casagrande apparatus with percussion method as specified by IS: 2720 (Part 5)- 1985 and ASTM D4318. The plastic limit was determined by rolling out a thread of the fine portion of a soil on a flat, non-porous surface. The procedure is defined in IS 2720 part 5 and by ASTM D4318. For determining the shear strength of the clays, laboratory vane shear test as per IS: 2720 (part 30) -1980 and ASTM D4648 were used.

3 Experimental Investigations

The water content ratio introduced herein has been extensively used in different forms to study the liquid limit behavior of clayey soils (Nagaraj and Jayadeva 1981) and the compressibility characteristics (Nagaraj and Srinivasa Murthy 1983, 1986). Griffiths and Joshi (1988) further elucidate the compression behavior as affected by cementation bonds using non-dimensional parameter e/e_L (void ratio/void ratio at liquid limit), which is nothing other than water content ratio. Relationships between vane shear strength and water content for ultra soft clay grounds showing water

Table 1 Physical properties and Shear Strength of Cochin Marine clays from four locations

Sl. no.	Soil	Water content w (%)	Shear strength (kN/m^2)	Liquid limit w_L (%)	Plastic limit (%)	Plasticity index (%)	Water content ratio, w/w_L
1	Cochin marine clay (Parur)	105.6	2.10	108	43	65	0.97
2	Cochin marine clay (Maradu)	105.0	1.75	105	45	60	1.00
3	Cochin marine clay (Elamkulam)	105.8	2.36	119	47	72	0.89
4	Cochin marine clay (Kumbalam)	98.0	1.90	98	39	59	1.00

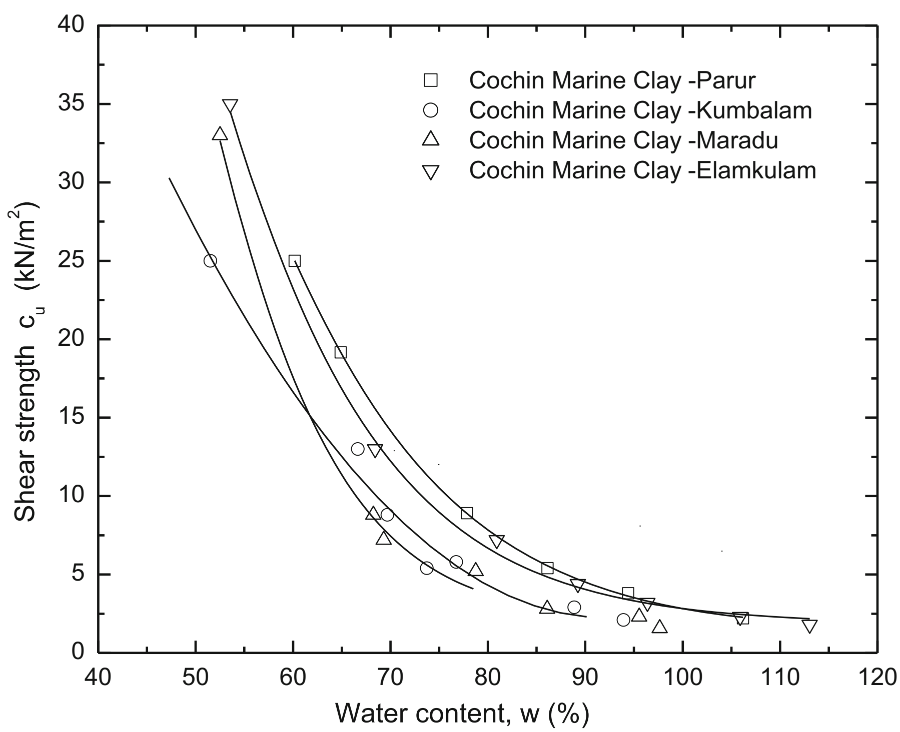
content decrease with depth was established by Yosuke et al. (2004).

4 Significance of Water Content Ratio

The utility and versatility of the proposed parameter, water content ratio is brought out by Figs. 1 and 2. The shear strength at different water contents obtained from laboratory vane shear tests on remolded representative saturated samples of Cochin marine clays collected from the four sites are given in Fig. 1. Even though the four sites are within Greater Cochin, the sampling locations are separated by about 10–30 km. But the clays are of the same geological origin. The samples give four separate curves as shown in Fig. 1 without showing any unique relationship.

The liquid limit value of any clay is dependent on the type of clay mineral with associated cations and the clay content of the sample (Mitchell 1976). As the clay content increases, liquid limit also increases. Similarly, percent clay remaining same, clays containing montomorillonite clay mineral will have higher liquid limit than kaolinite clay.(Sridharan 1991). Both these have significant influence on the shear strength of clayey soils. But the influence of both is conveniently incorporated by normalizing the water content by expressing it as a ratio of liquid limit.

Fig. 1 Water content versus shear strength



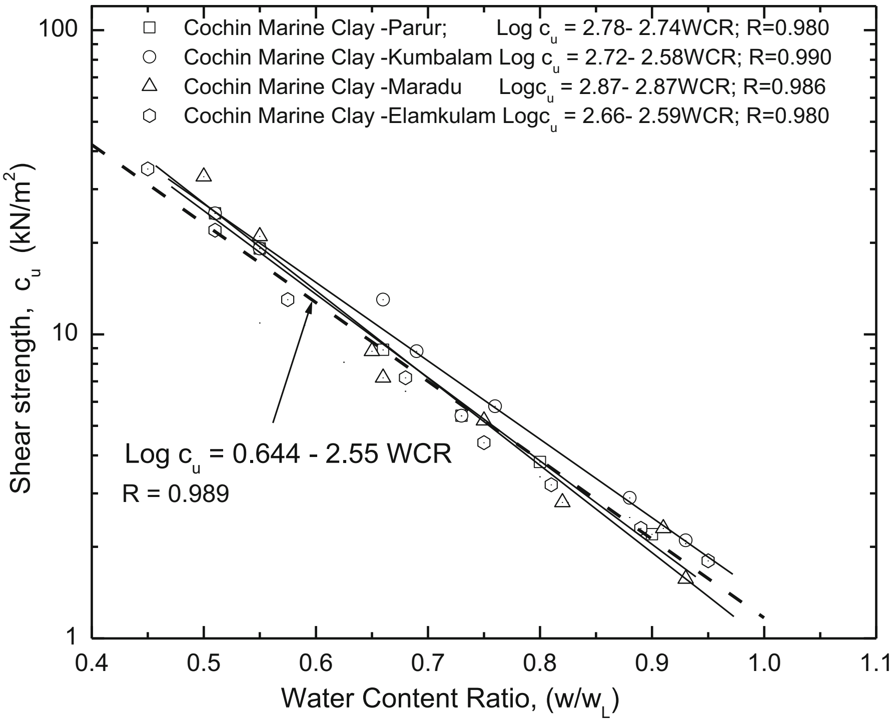


Fig. 2 WCR versus log shear strength

Figure 2 gives a plot between WCR and shear strength (on log scale) for the same four clays. Good linear relationships have been obtained for the four soils. These clays have almost the same slope. It may be mentioned here that their liquid limits varied from 98 to 119%. A combined plot for all the four soil samples together is also given in the figure. It can be seen from the plot that a unique linear correlation could be obtained between water content ratio and log of shear strength, though the liquid limit values of the individual samples are different (Table 1).

A statistical fit to the experimental data gives the following relationship with a high correlation coefficient of 0.989,

$$\mathrm{Log}\ c_u = 0.644 - 2.55\ \mathrm{WCR} \tag{2}$$

where c_u = undrained shear strength in kPa.

5 Liquidity Index and Shear Strength

As mentioned earlier, attempts have been made by several workers to correlate shear strength with liquidity index of clays (Skempton and Northey 1952; Yilmaz 2000). Wroth and Wood (1978) proposed a relationship between these two parameters Leroueil et al. (1983) related undrained cohesion with liquidity index in non-linear form.

$$(C_u)_r = 1/(I_L - 0.21)^2$$

The above two relations are presented in Fig. 5 along with the results of Cochin marine clays. It may be seen that the strength values of Leroueil et al. (1983) ranged from 1 to 5 kN/m^2, the author's values ranged from 1.5 to 30 kN/m^2, Wroth and Wood (1978) suggested that strength ranges from about 0.7 to 2.6 kN/m^2 based on vane data. The results presented in Fig. 3 indicate that the correlation coefficient obtained (0.982) is marginally less than the one (0.989) obtained using liquid limit water content as the normalizing parameter in Fig. 2.

6 Test Results for Other Soils

Figure 4 shows the plot between water content ratio and shear strength for five different soils viz., bentonite, kaolinite, black cotton soil, red earth and another marine clay from Kuttanad (located at a distance of approx. 100 km from Cochin), along with the combined plot for the Cochin marine clay.

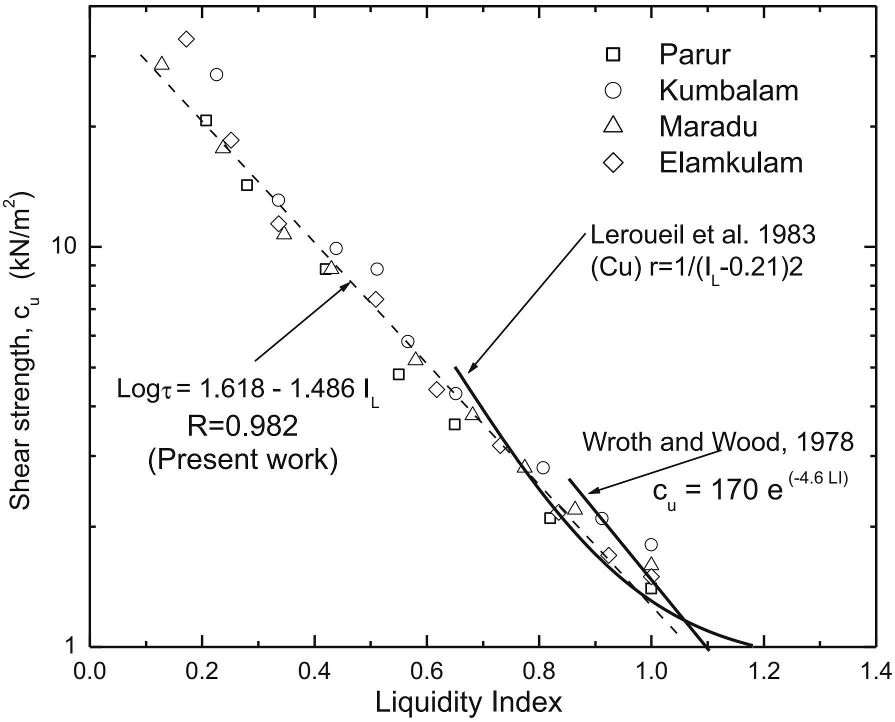


Fig. 3 Liquidity index versus log shear strength

It is seen that a good linear relationship is obtained between log of shear strength and water content ratio. However the slopes of the linear relationships are different as seen from Fig. 6 and Table 2. While kaolinite clay/red earth has the least slope, bentonite shows the maximum slope, other soils falling in between. Both red earth and kaolinite have almost the same slope (0.31 and 0. 29 respectively).Their liquid limits are also in the same range, however their clay size percent are vastly different (Table 2).

Figure 5 presents the relationship between shear strength and liquidity index for the five soils discussed in Fig. 4. It can be seen that no unique and linear relationship is possible. Although red earth and kaolinite have liquid limit in the same range (51 and 47%), it is seen from Fig. 5 that the points do not merge into a single line. Similarly, although black cotton soil and bentonite have montmorillonite as principal clay mineral, no uniqueness is seen in the plots.

Preliminary studies presented above indicate the possibility of substituting liquidity index with the simpler parameter namely water content ratio, in predicting the shear strength of clayey soils. In order to confirm the alternative parameter namely Water content ratio over liquidity Index, further studies were made with the help of data collected from literature (Kayabali and Tufenkcl 2010) for 5 clays from Turkey. Figure 6a shows the liquidity index vs shear strength plot for Turkey clays and Fig. 6b shows WCR vs shear strength plot for the same clays. It can be observed from Fig. 6a, b that there exists a good correlation withWCR—shear strength plot as good as the Liquidity index–shear strength plot. The correlation coefficient of WCR—shear strength for Cochin marine clays, Kuttanad clays, Bentonite, Kaolinite etc. are more or less same as correlation coefficient for Liquidity index–Shear strength plots.

The superiority of Water content ratio over Liquidity Index is underlined in the Fig. 6a, b. Thus the above results and discussions confirm that water content ratio can replace the parameter viz; the liquidity index. This indicates that one need not determine the plastic limit of the soils, for the purpose of predicting the shear strength.

7 Relation Between Water Content Ratio and Liquidity Index

The discussions in the earlier sections clearly brought out the superiority of the parameter Water

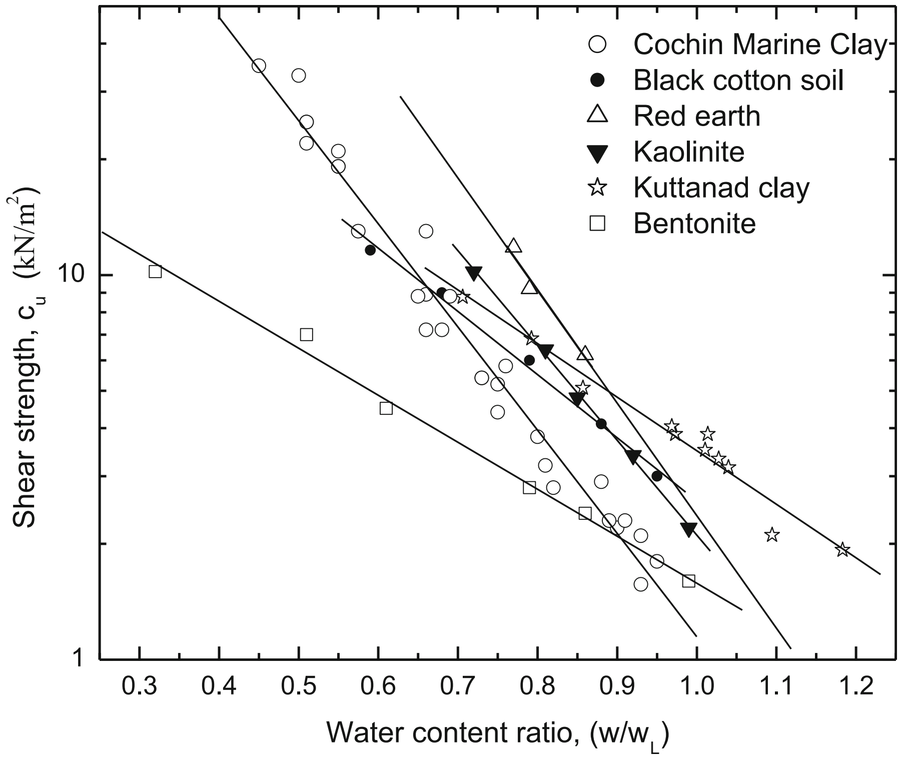


Fig. 4 WCR versus log shear strength for different soils

Table 2 Physical properties of the soils used in the study

Sl. no.	Soil type	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Clay (%)	Slope of WCR − log c_u
1	Bentonite	429	42	387	76	0.75
2	Kuttanad clay	170	86	84	70	0.72
3	Cochin marine clays (Table 1)	98–119	39–43	59–65	37–50	0.43
4	Black cotton soil	100	39	61	55	0.37
5	Red earth	51	35	16	44	0.31
6	Kaolinite	47	35	12	16	0.29

Content Ratio over the Liquidity Index in predicting the shear strength of soils. But literature review (Bjerrum 1954) reveals that there exists definite relationship between Liquidity Index and Sensitivity of clayey soils. In order to explore the possibility of substituting WCR withI_L (wherever relations exist with other geotechnical parameters), attempts were made whether definite relationship can be established between WCR and I_L.

Figure 7 shows the plots between WCR and I_L for Cochin marine clays from the four locations mentioned earlier (viz: Parur, Kumbalam, Maradu and Elamkulam), Kuttanad clay, Red earth, Bentonite and Turkey clay. It can be seen from this figure that even though excellent relationship between I_L and WCR exist for individual soils, the plots do not merge to a single straight line for the different soils.

From the above discussions, it can be inferred that, even though an excellent relationship exists between I_L and WCR for soils of same geological origin, but a unique relationship between these two

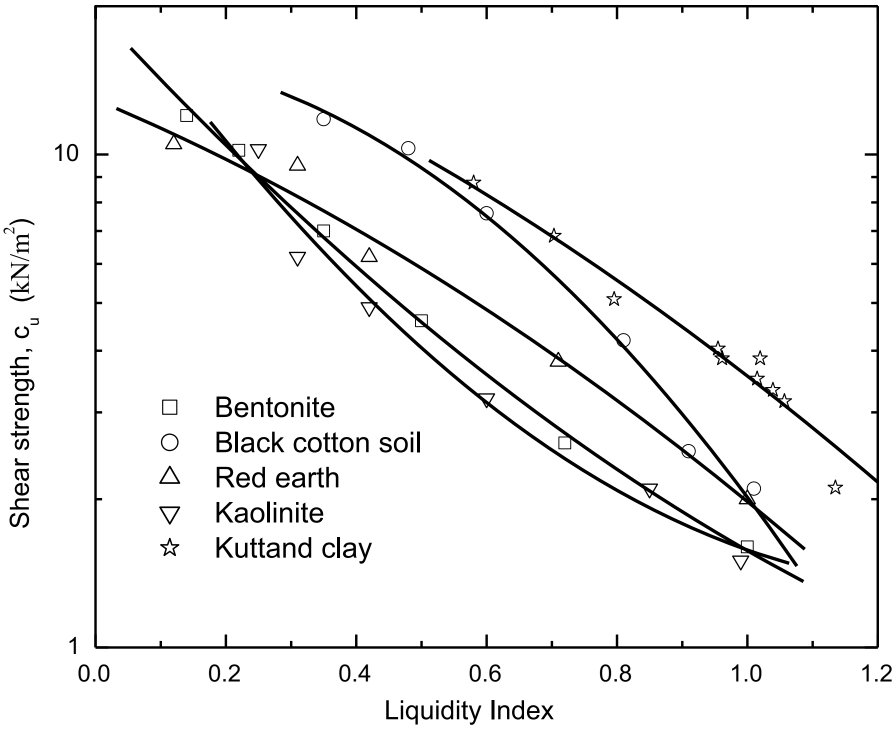


Fig. 5 Liquidity index versus Log shear strength for different Soils

parameters are not yielding. Hence further studies were made, by obtaining the relationships between I_L and WCR for different w_L/w_P ratios (ranging from 1.5 to 7.0) by arbitrarily assuming the liquid limit values (ranging from 50 to 400). The results along with the value of slopes obtained from Fig. 7 are given in Fig. 8. It can be seen from the plot that the slope of the linear relationship between I_L and WCR changes with w_L/w_P ratio. The figure also underscores the influence of w_L/w_P ratio on the slope of the WCR-I_L plots that irrespective of the geological origin and irrespective of the assumed value of ratio of liquid limit to plastic limit, the variation of the slope of the WCR-I_L plots follows a definite trend with the w_L/w_P ratio.

It can thus be seen from the above discussions that the proposed parameter namely Water Content Ratio could replace the well known parameter namely Liquidity Index with equal performance if not better. Further, the slope of water content ratio–liquidity index plot bears a very good correlation with w_L/w_P ratio but not with geological origin. In other words, fine grained soils could be from same geological origin but with different w_L/w_P ratio can behave very differently.

8 Conclusions

- Based on the experimental results on different types of saturated clays, a correlation could be established between undrained shear strength, c_u and water content ratio, WCR which is of the form.

  $$\text{Log } c_u = a - b\,(\text{WCR})$$

  where a and b are coefficients dependent on the soil type.
- The relationship between the Water Content Ratio and the shear strength for Cochin marine clays yielded an equation.

  $$\text{Log } c_u = 0.644 - 2.55\ \text{WCR}$$

  with a very high correlation coefficient of 0.989.
- The recommended parameter, WCR is simple (does not involve the determination of plastic limit) and can replace the liquidity index.
- Excellent linear relationship exists between Liquidity Index and Water Content Ratio.
- The slope of the plot between Liquidity Index and Water content Ratio follows a definite behaviour with the ratio of liquid limit plastic limit, w_L/w_P ratio, irrespective of the geological origin of the clay.

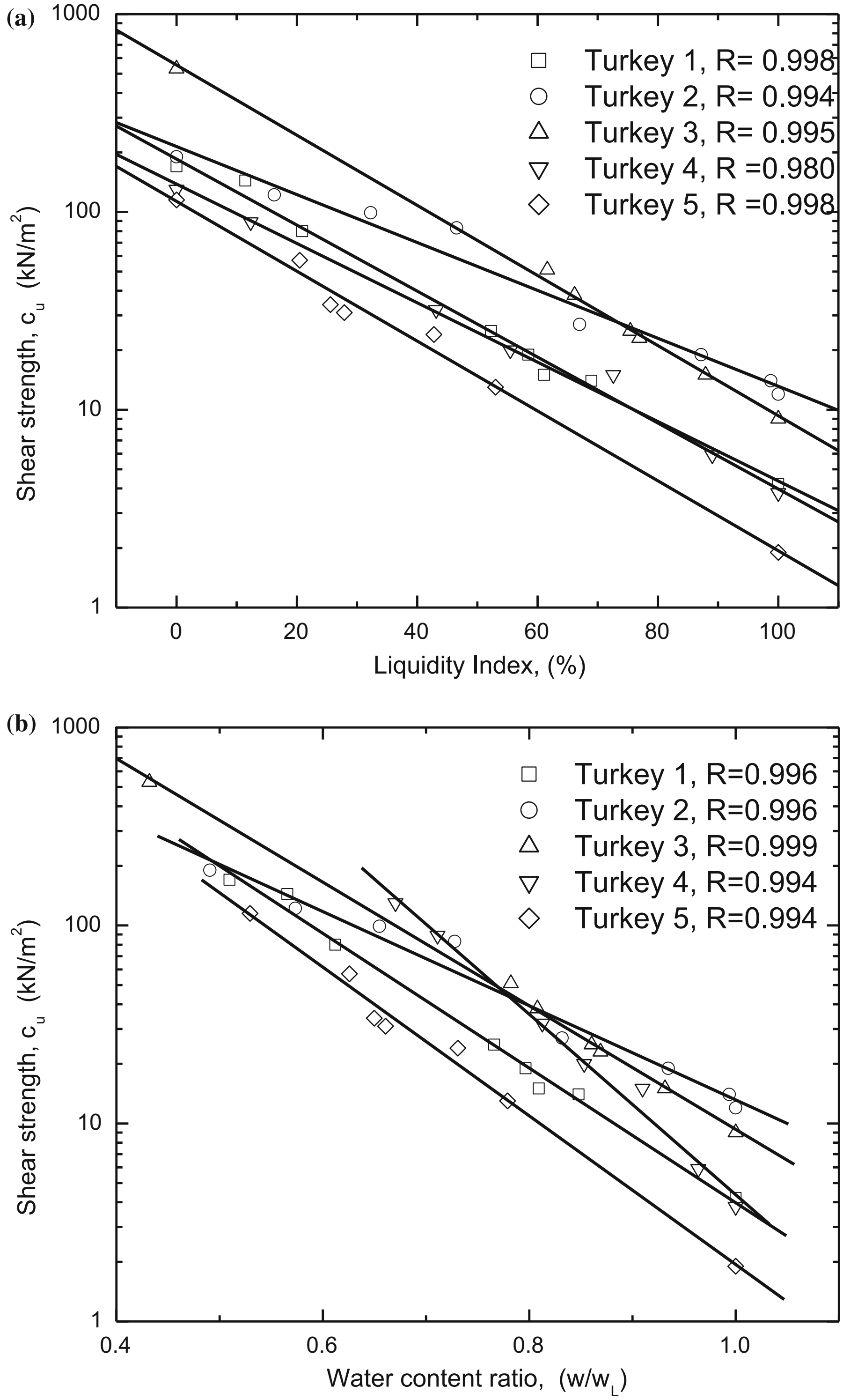
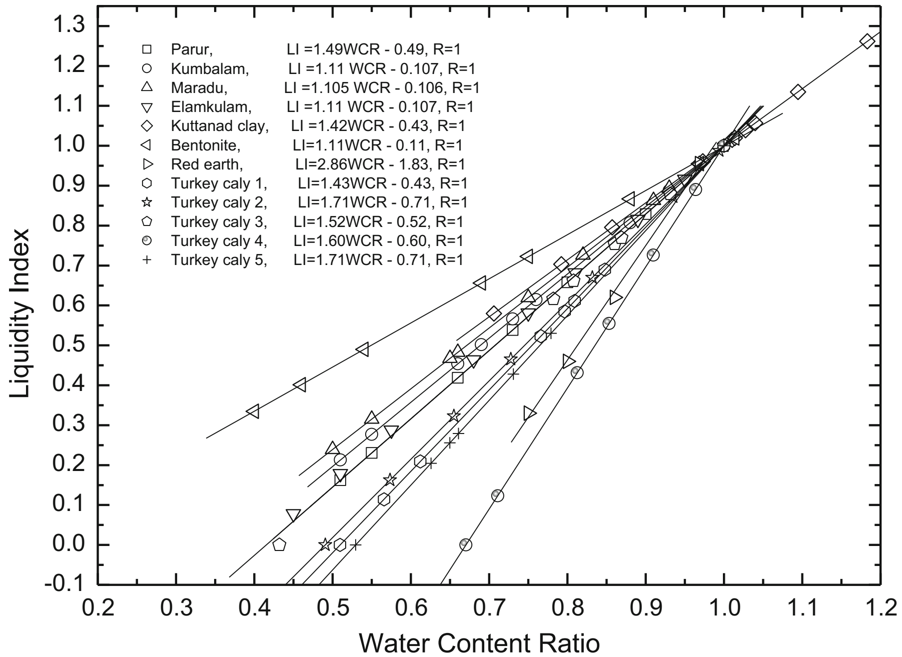


Fig. 6 **a** Liquidity index versus log shear strength for Turkey clays, **b** WCR versus log shear strength for Turkey clays

Fig. 7 Water content ratio versus liquidity index



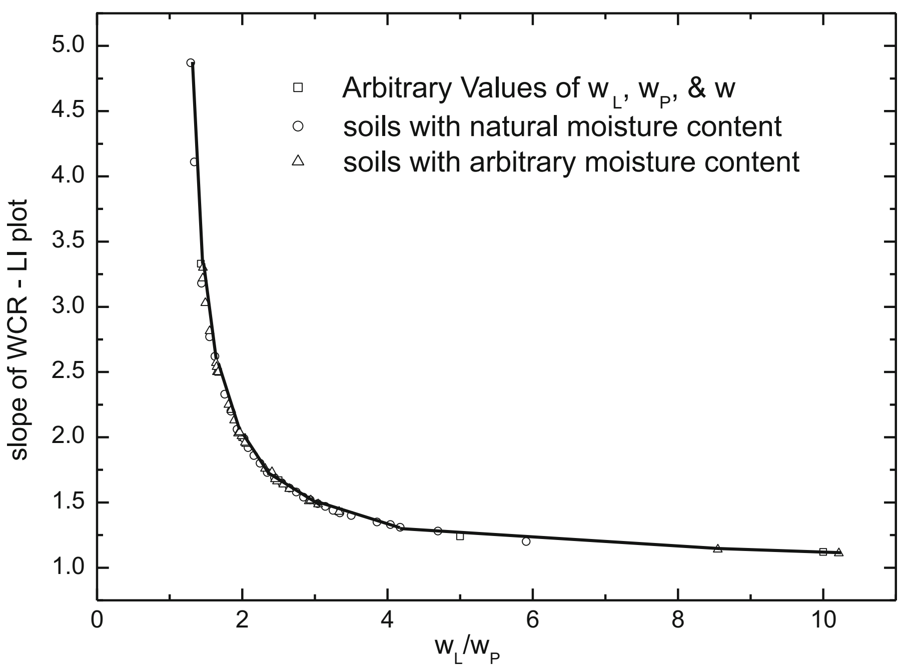


Fig. 8 Slope of WCR- I_L plot versus w_L/w_P ratio

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