

CHARACTERISATION OF ARIAKE AND OTHER MARINE CLAYS

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ABSTRACT: Characterisation of marine clays is an important aspect of understanding their behaviour. Investigation showed that there is a good linear relationship between percent clay and liquid limit and plastic limit. Sand and silt fraction has only diluted the magnitude of liquid limit and plastic limit. The ratio of plastic limit to liquid limit is almost a constant irrespective of percent sand fraction and is a function of clay mineral type or mixture of clay minerals, associated cations and ion concentration. Marine clays of Japan around Ariake bay (Hachirogata, Ariake – Ushiya, Meguri, Okishin and Yamaashi) have shown good correlation between plastic and liquid limits and this ratio ranged between 0.35 to 0.50 as against 0.07 (Limonmorillonite) to 0.88 (halloysite) of pure clay minerals. Cochin marine clay behaviour compares well with Ariake-Ushiya, although their geological history is entirely different. The revised plasticity chart with liquid limit and plastic limit as coordinates appears to be a better representation of fine grained soils.

INTRODUCTION

Marine clays forms one of the important groups of fine grained soils. Lots of civil construction activities take place in such marine clays throughout the world. Most of the marine clays are highly compressive and of low strength. Characterisation of marine clays is an important aspect of understanding their behaviour. Ariake clays of Japan are very widely studied to better understand their behaviour (e.g., Sridharan and Miura 2000, Sridharan et al., 2000 & Ohtsubo et al 1995 to name a few). Liquid limit, plastic limit and percent clay fraction characterize any fine grained soil to a great extent. The primary source of the level of liquid limit and plastic limit is the type and percent of clay size fraction. The associated type and magnitude of exchangeable cations, the cation concentration and the percent clay size fraction determines the liquid and plastic limit. Both the liquid limit and plastic limits are determined in the laboratory with well defined procedures which are altogether different and are well documented in the literature (e.g., Casagrande 1958). Since both these are primarily a function of type of clay minerals, associated cations and their characteristics, these two limits can as well characterize the soil to a great extent. In this paper the importance of these two water content limits are studied in characterizing the fine grained soils and in particular marine clays.

Atterberg limits

The consistency limits are used to define the different ranges of states in which a cohesive soil can exist from liquid to solid. Originally Atterberg setup five consistency limits to illustrate the range of consistency (Sridharan and Prakash 1998). With time, only three of the above limits, namely flow limit, the roll-out limit and the cohesion limit retain their recognition and are now referred to as the liquid, plastic and shrinkage limits respectively. Since the introduction of Atterberg limits in 1911 (Casagrande 1948) several papers have been published on the same. Sridharan and Rao (1975) have discussed the mechanisms controlling liquid limit of clays and Sridharan et al (1986, 1988) discussed the liquid limit of montmorillonite and kaolinitic soils. It has been brought out that the thickness of electrical diffuse double layer significantly contributing to the liquid limit of montmorillonitic clays. In other words factor affecting the thickness of diffuse double layer like dielectric constant of the fluid, the valency and concentration of exchangeable cation will have significant influence on the liquid limit behaviour of montmorillonitic soils (Sridharan et al 1986a) whereas the liquid limit of kaolinitic soils is not practically affected by the diffuse double layer thickness. However particle arrangement brought about by the interparticle forces significantly influences the liquid limit of kaolinitic soils (Sridharan et al 1988, Sridharan and Rao 1988). Although no specific conclusions have been drawn in the literature with regard to mechanisms controlling the plastic limits, the level of plastic limits is also influenced by parameters which influences the

liquid limits. According to Grim (1962) the range of moisture contents from that value just adequate for ground clay to form a coherent mass (plastic limit) to that value where an extremely small stress causes deformation (liquid limit) can be taken as the plasticity characteristics. In other words every fine grained soil possess this characteristic water content which characterise them to a great extent. In this paper the ratio of plastic limit to liquid limit water content as a dominating parameter characterising a fine grained soil is examined.

TEST RESULTS AND DISCUSSIONS

Clay Minerals

In this investigation the authors' results as well as published in the literature have been used for discussion. Fig. 1a, shows the relationship between clay percent and plastic limit and liquid limit of bentonite – sand mixtures. Bentonite – 1 is authors' results. Bentonite – 2 is that of Lupini et al (1981). The variations in plastic limit and liquid limits are brought out by varying the percentage of sand. It is seen that as long as the sand percent is not high, the relationship between plastic limit and percent bentonite or liquid limit and percent bentonite can be taken as linear passing through origin. Many similar results could be cited from the literature. Fig. 1b shows the relation between liquid limit and plastic limit for the results presented in Fig. 1a. The important conclusion obtained from the results shown in Fig. 1b is that as long as the clay mineral is same and the reduction in w_L and w_P is due to dilution by sand percentage, the slope of w_P vs w_L relationship remains same. Fig. 2 illustrates the relationship between w_P and w_L for various clay minerals collected from literature as well as from authors' file (Grim 1962, Polidori 2003). Same clay minerals possess different value of w_P and w_L depending upon their geological history. However, the ratio of w_P / w_L remains same for particular type of clay mineral. In other words the ratio of w_P / w_L remains constant irrespective of the level of liquid limit as long as the clay mineral type is same. Range of ratio of w_P / w_L for various clay minerals is given in Table 1. It can be seen that for bentonite the ratio of w_P / w_L could be as low as 0.07 and as high as 0.26. Depending on the geological history, location, its purity and particle size the ratio of w_P / w_L can vary to some extent for a particular clay mineral. Maximum ratio of w_P / w_L obtained is for halloysite and it is 0.88. It is well known that in the Casagrande's plasticity chart (Casagrande 1948), plasticity index (Y-axis) and the liquid limit (X-axis) are related and the A-line is defined as

$$I_p = 0.73[w_L - 20] \quad (1)$$

Eq. 1 can be written in terms of w_P and w_L as

$$w_P = 0.27[w_L + 54] \quad (2)$$

Thus the equation of A-line in terms of w_P and w_L is given in Eq.2. The A-line is also drawn in Fig.2. In Fig.2, since y-axis is w_P , CL and CH are grouped below the Aline and OL, ML and MH are grouped above the A-line. The letters in the boxes show the classification zones as given by Casagrande.

Table 1 Range of ratio of w_P / w_L for various clay minerals

Clay mineral	Ratio of w_P / w_L	References
Na-Bentonite	0.07 – 0.26	e.g., Lambe & Whitman
Illite	0.31 – 0.51	(1969), Sridharan et al
Kaolinite	0.36 – 0.70	(1986b), DiMaio & Fenelli
Attapulgitite	0.54	(1994), Lupini et al (1981),
Halloysite	0.88	Grim (1962), Seed et al
		(1964), Gibson (1953),
		Sridharan & Rao (1973),
		Park and Koumoto (2000),
		Olsen & Mesri (1970),
		Authors files

Fig. 3 shows the w_P vs w_L relationship obtained for three natural soils A, B and C. The changes in the liquid limit and plastic limits were brought by adding Ennore sand (Prakash and Sridharan 2004). The natural soils have the liquid limits of 77.2 % (A), 61.6% (B) and 88.7% (C) and their liquid limit got reduced to 47.3% (A), 38% (B) and 52.6% (C) on addition of 40% of sand. It is seen that the w_P vs w_L relationship is linear passing through origin. Thus one can conclude from Figs. 1, 2 & 3 that the relationship between w_P and w_L could be treated as linear as long as the type of clay mineral present does not change whereas its percentage magnitude can change. Fig. 4 shows the ratio of w_P / w_L for the mixtures of two different clay minerals. It is seen that ratio varies as it ought to be. In Fig.4 the results of bentonite – kaolinite mixtures of (i) Seed et al 1964 (ii) Sivapullaiah and Sridharan 1985 and (iii) DiMaio and Fenelli 1994, and bentonite – illite mixtures of Seed et al 1964 are plotted between w_P / w_L vs percent bentonite . The ratio of w_P / w_L for kaolinite alone varied as 0.77 (Seed et al 1964), 0.78 (Sivapullaiah and Sridharan 1985) and 0.66 (DiMaio and Fenelli 1985). The ratio of w_P / w_L of bentonite alone varied as 0.089 (Seed et al 1964), 0.093 (Sivapullaiah and Sridharan 1985) and 0.167 (DiMaio and Fenelli 1994). The ratio of w_P / w_L of illite alone is 0.51. The mixtures showed the ratio of w_P / w_L is primarily depended upon the type of clay mineral or mixtures of clay mineral type that consists of the clay.

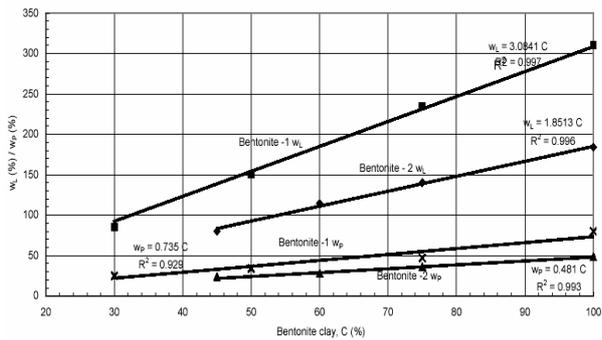


Figure 1a Relationship between percent bentonite clay, C and liquid limit, w_L .

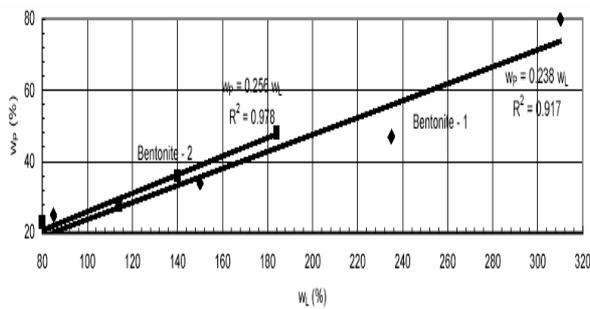


Figure 1b Relationship between liquid limit, w_L and plastic limit, w_P

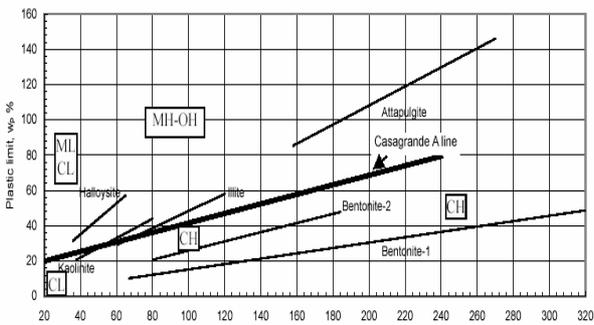


Figure 2 Relationship between liquid limit, w_L and plastic limit, w_P for pure clay minerals

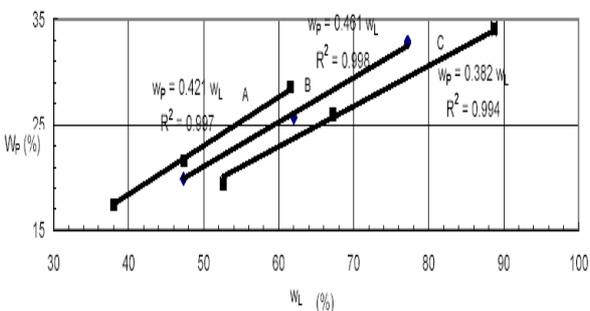


Figure 3 Relationship between liquid limit, w_L and plastic limit, w_P for natural soils

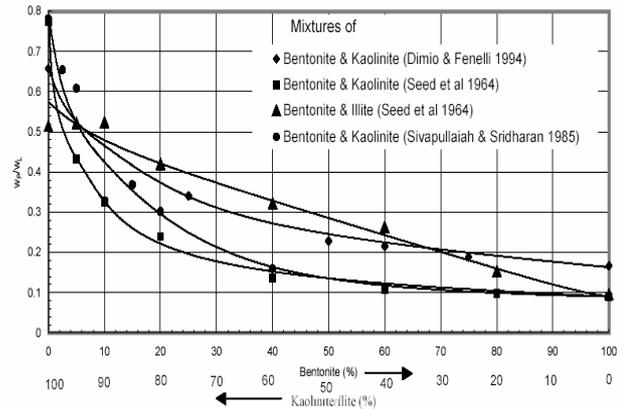


Figure 4 Relationship between w_P / w_L ratio and percent bentonite

Another important parameter that influences the ratio w_P / w_L is the type of exchangeable cations present (Sridharan et al 1986b). This influence is maximum for bentonite. Table 2 shows the variation in the ratio of w_P of homoionic clays which depends upon the type of cations present. Similar w_P / w_L ratio could be obtained from published literature (e.g., Lambe and Whitman 1969).

It is seen from Table 2 that the ratio of w_P / w_L increases as the valency of exchangeable ions increases and as the hydrated ionic radii increases, valency being same. The results of Anson and Hawkins (2002) show that ratio of w_P / w_L to vary from 0.06 (concentration of Ca = 0) to 0.224 (concentration of Ca ions to be 400 mg/l).

Table 2 Influence of valency and size of the adsorbed cations on the index properties of bentonites

Bentonite homoionised	w_L , %	w_P , %	w_P / w_L	Hydrated ionic radius Angstrom
Li^+ , Lithium	675	49.1	0.073	7.3 – 10.3
Na^+ , Sodium	495	19.2	0.099	5.6 – 7.0
NH_4^+ , Ammonium	223	55.8	0.250	5.37
K^+ , Potassium	233	57.8	0.248	3.8 – 5.32
Mg^{++} , Magnesium	129	49.9	0.387	10.8
Ca^{++} , Calcium	125	40.6	0.325	9.6
Ba^{++} , Barium	108	45.8	0.424	8.8
Al^{+++} , Aluminium	108	60.5	0.560	--
Fe^{+++} , Iron	120	63.5	0.524	--

Thus the primary parameters that influences the w_P / w_L ratio is mixture of clay minerals and the type of exchangeable ions and concentrations of ions.

Marine Soils

It has been brought out in the previous sections that w_P / w_L ratio depends upon the type of clay minerals or mixtures of clay minerals and associated cations and its concentrations. For montmorillonite/ bentonite the diffuse double layer primarily

contributes to the water holding capacity (Sridharan and Rao 1975). Factors affecting the diffuse double layer thickness viz., the valance of the exchangeable cations and cation concentration influences the liquid and plastic limits. Thus marine soils from the same region can be expected to have same ratios of w_p / w_L since they possibly have same type of clay mineral mixtures and same type of exchangeable ions and ion concentration. The percentage of non clay size fraction will dilute the values of w_p and w_L values and possibly w_p / w_L ratio may remain same. Fig. 5 presents the relationship between w_p and w_L for Ariake clay, the results of which got collected from published literature. Table 3 lists w_L , w_p , % < 2 μ m and w_p / w_L ratio and also corresponding references from where the results got collected. In spite of the different locations the relationship between w_p and w_L is reasonably a straight line passing through origin. The correlation coefficient $R = 0.87$ ($R^2 = 0.7607$) is quite acceptable. Fig. 5 also shows the w_p vs w_L relationship of Hachirogata marine clay (Ohtsubo et al 2000a). The correlation between w_p and w_L is quite good and Hachirogata clay has almost the same correlation of Ariake clay in general. In Fig.6 the relationship between w_p and w_L is shown for Cochin marine clay (Sridhran et al 2002, Jose et al 1999 and Rao et al 1992) and Ushiya – Ariake clay (Ohtsubo et al 2000a & 2000b). It is seen that the correlation is quite good. In spite of altogether different origins and different parts of the world the relationship is almost same. In Fig. 7, the relationship between w_p and w_L for various marine clays of Ariake bay have been shown for comparison. Cochin marine clay has also been shown. For clarity the experimental points are not shown. As have been noticed in Figs 5 and 6, the correlations between plastic limit and liquid limit have been found to be good for Meguri (Ohtsubo et al 1996), Okishin (Ohtsubo et al 1983) and Yamaashi (Ohtsubo et al 1996) also. Casagrande A line is also shown. It is seen that all the marine clays cut across the A-line. At higher liquid limits they group under MH/OH category. The slope of w_p vs w_L is 0.35 for Hachirogata; 0.362 for Ariake (Table 2); 0.382 for Ushiya; 0.43 for Meguri; 0.449 for Okishin; 0.499 for Yamaashi and 0.376 for Cochin.

Clay mineral types in marine clays

In Table 1 it was brought out that depending upon the clay mineral type the slope of w_p vs w_L relationship gets varied. For Na bentonite it could be as low as 0.07 and for halloysite it could be as high as 0.88. Further it was shown in Table 2 that depending upon the exchangeable cation type the slope gets varied, 0.073 for Li^+ bentonite to 0.56 for Al^{+++} bentonite. Further, the hydrated size of the cations also alters the slope. Another parameter that influences the Atterberg limits is the ion concentration in the fluid. For montmorillonitic clays increase in the ion concentration decreased the double layer thickness and hence the liquid limit decreases (Rao et al 1992). For kaolinitic soils, increase of ion concentration makes the soil to flocculate and the liquid limit may increase (Sridharan et al 2000). Thus for the

marine clays both liquid limit and plastic limits are affected by the type and percent of different clay minerals present, type and

Table 3 Physical properties of Ariake clay from different sources

Location / Name	w_L , %	w_p , %	I_p , %	< 2mm, %	w_p / w_L	Reference
Kawazoe	116.0	46.0	70.0	58.1	0.397	Sridharan et al 2002
Kubota	68.0	25.0	43.0	51.0	0.368	Sridharan et al 2002
Isahaya	170.0	54.0	116.0	65.9	0.318	Sridharan et al 2002
Fukudomi	134.0	45.0	89.0	51.0	0.336	Sridharan et al 2002
Ariake clay, Kohoku Town	116.0	50.5	65.5	65.0	0.435	Du et al 2002
Ariake clay, Kohoku Town	122.0	43.3	78.7	85.0	0.355	Du et al 2002
Ariake clay, Kyushu Island	127.0	50.0	77.0	55.0	0.394	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	115.0	47.0	68.0		0.409	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	122.0	48.0	74.0		0.393	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	120.0	47.0	73.0		0.392	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	156.0	55.0	101.0		0.353	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	149.0	56.0	93.0		0.376	Hong and Tsuchida 1999
Ariake clay, Kyushu Island	116.0	46.0	70.0		0.397	Hong and Tsuchida 1999
Ariake clay, Kyushu E-17	127.0	49.0	78.0	54.2	0.386	Ohtsubo et al 1985
Ariake clay, Kyushu W-179-3	75.0	28.0	47.0	40.5	0.373	Ohtsubo et al 1985
Ariake	127.2	49.3	77.9	54.2	0.388	Ohtsubo et al 1997
Yokohama	89.5	43.0	46.5	34.2	0.480	Ohtsubo et al 1997
Sakai	71.7	26.4	45.3	39.5	0.368	Ohtsubo et al 1997
Kinkai	115.0	39.1	75.9	47.4	0.340	Ohtsubo et al 1997
Saga Paddy soil	75.3	28.2	47.1	40.5	0.375	Ohtsubo et al 1997
Nakaumi	149.9	49.4	100.5	54.5	0.330	Ohtsubo et al 1997
Kumamoto	63.0	27.0	36.0	58.9	0.429	Ohtsubo et al 1997
Isabuya bay clay	146.8	48.9	97.9	71.0	0.333	Kondo et al 1997
Ariake - Kantaku clay	133.2	46.6	86.6	70.0	0.350	Kondo et al 1997
Kumamoto Port	101.0	37.2	63.8	42.0	0.368	Kasama et al 2000
Kanazawa	118.1	35.8	82.3	41.8	0.303	Kasama et al 2000
Higashi - Ohgishima	113.7	33.5	80.2	50.5	0.295	Kasama et al 2000
Ariake	105.4	38.2	67.2	54.0	0.362	Kasama et al 2000
Ichikawa	83.8	32.1	51.7	39.0	0.383	Kasama et al 2000
Ariake clay	89.5	39.6	49.9	19.0	0.442	Hong 1998
Kubota reclamation area	68.0	25.0	43.0	51.0	0.368	Kaumoto et al 1998
Saga Agricultural Exp. Station	115.9	45.5	70.4	58.1	0.393	Kaumoto et al 1998
Isahaya marine mud	169.5	54.4	115.1	65.9	0.321	Kaumoto et al 1998

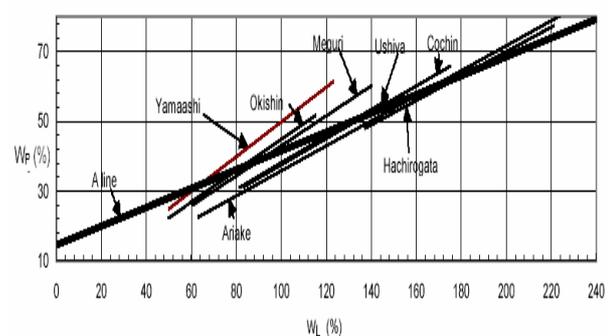


Figure 7 Comparison of w_p vs w_L relationship for different marine clays

amount of exchangeable cations and the ion concentration. It is clear from literature (Ohtsubo et al 2000) that the primary clay minerals present in Hachirogata clay is smectite. Other clay minerals viz., kaolinite, vermiculite, chlorite and mica are also present. In Meguri and Yamaashi (Ohtsubo et al 1990) smectite, mica and kaolinite are present more or less in the

same proportion. In the Cochin marine clay smectite (42%), kaolinite (38%) and illite (20%) are present (Rao et al 1992). Thus it is seen that in the natural marine clays from different regions, different clay minerals in different proportion exist, ion concentration can vary and different types of cations can be present resulting in a particular ratio of w_p / w_L . For any particular region, the w_p / w_L ratio vary marginally or remain same. The scatter of experimental points seen in the relationship (Fig. 5 & 6) is due to marginal variations in the influencing parameters. Overall it can be taken that for any region/location for the same soil profile it may be reasonable to consider that w_p / w_L ratio remains same.

CONCLUSIONS

Based on the investigations carried out the following conclusions are drawn. Both liquid limit and plastic limit are primarily a function of percent clay fraction, clay mineral type and associated cations present. Both silt and sand fraction act as a dilution factor. Whereas the ratio of plastic limit to liquid limit remains constant as long as the clay mineral type or mixture of clay minerals in the same proportion are same. Percent of silt and sand fraction does not affect the w_p / w_L ratio. However type of exchangeable cations and/or concentration of ions does influence the ratio of w_p / w_L . The w_p / w_L ratio could be as low as 0.07 for monovalent homoionic bentonites to as high as 0.88 for halloysite. Based on the extensive published data available on marine clays of Japan, and the results of authors it has been brought out that the w_p / w_L remains almost constant for a particular location. The ratio of w_p / w_L varies from 0.35 for Hachirogata clay to 0.499 for Yamaashi clay profile. For comparison, Cochin marine clay was studied. Interestingly the ratio of w_p / w_L is almost same for Cochin marine clays and that of Ariake – Ushiya clay although they are from different regions. Since different clay minerals, with different percentages and with different exchangeable cations and varying concentration of ions present in natural marine clays their w_p / w_L ratio varies, however within the range of pure clay minerals. Presentation of Casagrande's plasticity chart with plastic limit (in the y-axis instead of plasticity index) and liquid limit in the x-axis appears to be better since both w_p and w_L are independent parameter. The ratio of plastic limit to liquid limit appears to be a potential parameter for characterization of fine grained soils.

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