CORRELATIONS BETWEEN PLASTICITY ANGLE AND ENGINEERING PROPERTIES OF VOLCANIC ASH SOILS

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ABSTRACT

The presence of allophane and halloysite minerals impart special properties to volcanic ash soils including the absence of any correlation between the engineering properties and index properties for these soils. The plasticity angle has been suggested as a measure of the allophane content of volcanic ash soils by soil scientists and (plasticity angle) is defined by the angle, relative to the A-line intercept, where the Atterberg limits of the volcanic ash soils occur on the Casagrande plasticity chart.

This technical note examines the correlations between plasticity angle and engineering properties of volcanic ash soils. The Atterberg limits and engineering property data for volcanic ash soils were taken from literature. The results of the study suggest that the plasticity angle is a good indicator of the shear strength (represented by ϕ'_{peak} and ϕ'_{residual} values) and compressibility (represented by $C_c/(1+e_o)$) properties of allophanic and halloysitic soils from quite different geographical regions. The strong relationships between plasticity angle and engineering properties is attributed to the dependence of the plasticity angle as well as that of the engineering properties on the allophane content of the volcanic ash soils.

Key words: Atterberg limits, compressibility, mineralogy, residual soils, shear strength, statistical analysis (IGC: D1/D5/D6)

INTRODUCTION

Empirical relations based on natural water content and Atterberg limit considered applicable to sedimentary clays have not been used as indicators of engineering properties for volcanic ash soils containing allophane and halloysite minerals (Wesley, 1977; Lupini et al., 1981; Boyce, 1985; Vaughan, 1988). Volcanic ash soils often have index properties which usually fall well below the A-line on the Casagrande plasticity chart (Wesley, 1973a; Vaughan, 1988). Warkentin and Maeda (1974) and McNabb (1979) have suggested that this feature may be used to evaluate the intensity of allophanic character of volcanic ash soils. McNaab (1979) identifies the intensity of the allophanic character of a volcanic ash soil from the plasticity angle (α) formed by the location of the Atterberg limit values of the soil on the Casagrande plasticity chart relative to the A-line intercept (example point a in Fig. 1). The plasticity angle is defined as:

$$\text{Plasticity angle } (\alpha) = \tan^{-1} \frac{\text{plasticity index}}{\text{liquid limit} - 20} \quad (1)$$

It is implicit that volcanic ash soils with a strong allophanic character have a low plasticity angle and vice versa.

It is the intention of this note, to call attention to the possible correlations between plasticity angle (α) and shear strength and compressibility properties for volcanic ash soils. The Atterberg limits and engineering properties of volcanic ash soils were obtained from published literature.

DISCUSSION OF PUBLISHED RESULTS

Atterberg Limit Behavior of Volcanic Ash Soils

Figure 1 plots the Atterberg limits data (tested at field moist condition) of volcanic ash soils from Kenya (Newill, 1961), Indonesia (Wesley, 1973a, 1977; Moore and Styles, 1988), Papua New Guinea (Wallace, 1973), West Indies and Japan (Warkentin and Maeda, 1974; Rouse et al., 1986) and New Zealand (Jacquet, 1990). The points for the allophanic soils (i.e., soils containing allophane as the dominant mineral) are plotted at varying distances below the A-line. Halloysitic soils (i.e., volcanic ash soils containing halloysite as the dominant mineral) are also observed to generally possess high liquid and plastic limit values that causes most of their data points to plot below the A-line along with the allophanic soils (Fig. 1). Figure 1 also illustrates that pure, hydrated

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Fig. 1. Atterberg limit behavior for volcanic ash soils

halloysite clay specimens have a much lower range of liquid limits and plasticity indices than most of the halloysitic soils (data for halloysite specimens from Grim, 1962). Halloysitic soils are known to be associated with amorphous allophane mineral (Fieldes and Furkert, 1966; Wesley, 1973a, Wallace, 1973; Tuncer et al., 1977, Allbrook, 1983, Jacquet, 1990). The presence of allophane in halloysitic soils helps explain the higher range of consistency limits exhibited by the natural soils in comparison to the pure clay specimens.

Figure 1 also plots the Atterberg limit data for platey kaolinite and meta-halloysite (dehydrated halloysite) specimens as these and other crystalline clay minerals (example, smectite, smectite-chlorite intergrades) are frequently encountered in the weathered deposits of volcanic ash soils (Hirashima, 1948; Birrell, 1952; Wesley, 1973a; Warkentin and Maeda, 1974; McNabb, 1979). The meta-halloysite specimens exhibit higher plasticity index values than the hydrated halloysite specimens (data from Grim, 1962), while the kaolinite specimens (data from Grim, 1962) exhibit higher plasticity index values than the allophanic and halloysitic soils with comparable liquid limit values (Fig. 1). The tendency of the halloysitic soil samples from Kenya (Kabete samples; Newill, 1961) and West Indies (data from Rouse et al., 1986) to plot closer to the A-line than other halloysitic soils (in Fig. 1) is hence possibly related to the presence of meta-halloysite (Kabete samples) and kaolinite and montmorillonite clay minerals (samples from West Indies) in them.

Correlations of Atterberg Limits and Plasticity Angle Values with Allophane Contents

The liquid limit values for both allophanic and halloysitic soils from New Zealand (data from Allbrook 1983; Jacquet, 1990), West Indies and Japan (data from Warkentin and Maeda, 1974) are correlated significantly with their amorphous allophane contents using a linear regression

equation

$$w_L = 2.0A + 48.1 \quad (2)$$

(where A refers to the percent allophane content on a dry soil weight basis for the volcanic ash soil, correlation coefficient r of the linear equation = 0.90, Eq. (2), Table 1). The plastic limits of these volcanic ash soils also increase linearly with their percent allophane content and a significant correlation ($r=0.85$, Eq. (3), Table 1) exists between the two parameters.

An examination was made of the particle size distribution for the volcanic ash soils whose Atterberg limits and percent allophane contents were used for obtaining the linear regression Eqs. (2) and (3) (see Table 1). This examination revealed that the volcanic ash soils from the West Indies and Japan (Warkentin and Maeda, 1974) and New Zealand (Allbrook, 1983; Jacquet, 1990) contained only low to moderate clay fractions. The allophanic soils from New Zealand tested by Allbrook (1983) for example contained clay fractions varying from 21% to 42%, silt fractions varying from 52% to 76% and sand fractions varying from zero to 30%. By comparison, the New Zealand volcanic ash soils tested by Jacquet (1990) contained clay fractions ranging from 10% to 15%, silt fractions ranging from 31% to 45% and sand fractions ranging from 21% to 40%. The allophane soils from the West Indies and Japan tested by Warkentin and Maeda (1974) contained clay fractions varying from 17% to 19%, silt fractions ranging from 23% to 51% and sand fractions varying from 25% to 59%. It must, however, be stated that the workers whose Atterberg limits and percent allophane content values were used for developing the linear regression Eqs. (2) and (3) (Table 1) have themselves observed (for example, see Warkentin and Maeda 1974, Jacquet, 1990) that volcanic ash soils with high allophane contents may not permit meaningful particle size analysis to be made; the reason being that,

Table 1. Statistical data for various relationships for volcanic ash soils

Eqn. No.	Relation	Number of data points (n)	Degrees of freedom (n-2)	Correlation coefficient (r)	Percentage of results explained ($r^2 \times 100$)	Critical levels of r^* at 5% and 1% levels of significance		Intercept	Slope	Linear regression equation
						$r_{0.05}$	$r_{0.01}$			
2	w_L versus A^{**}	17	15	0.90	81	0.48	0.61	48.1	2.04	$w_L = 2.0A + 48.1$
3	w_p versus A	17	15	0.85	72	0.48	0.61	27.5	1.76	$w_p = 1.76A + 27.5$
4	ϕ'_{peak} versus plasticity angle (α)	21	19	-0.72	52	0.43	0.55	44.9	-0.36	$\phi'_{\text{peak}} = 44.9 - 0.36\alpha$
5	ϕ'_{residual} versus plasticity angle (α)	18	16	-0.74	55	0.47	0.59	45.5	-0.42	$\phi'_{\text{residual}} = 45.5 - 0.42\alpha$
6	ϕ'_{peak} versus plasticity index (PI)	18	16	-0.20	4	0.47	0.59	37.2	-0.035	$\phi'_{\text{peak}} = 37.2 - 0.035PI$
7	$\frac{C_c}{1+e_o}$ versus α	14	12	0.73	53	0.53	0.66	-0.091	0.016	$\frac{C_c}{1+e_o} = 0.016\alpha - 0.091$

* data from Zuwaylif, 1970.

** A = percent allophane content on dry soil weight basis. Fig. 2. Variation of calculated plasticity angle values (α) with percent allophane content (A) for volcanic ash soils

despite chemical deflocculation and mechanical stirring of the allophane soil suspensions, the allophane mineral particles tend to flocculate after dispersion and resting leading to an underestimation of the clay fraction present.

Using the linear regression Eqs. (2) and (3), (from Table 1), liquid and plastic limit values were calculated respectively for various allophane contents (0% to 100%) of the volcanic ash soils. Plasticity angles pertaining to the calculated Atterberg limit values were obtained at

each allophane content and are plotted as a function of the allophane contents in Fig. 2. The figure shows the calculated plasticity angle values to decrease exponentially with an increase in allophane content for the volcanic ash soils.

Combining the results as shown in Figs. 1 and 2, it becomes evident that the low plasticity angle of a volcanic ash soil is essentially a consequence of its high allophane content (or strong allophanic character). The plasticity angle of $\approx 36^\circ$ at zero percent allophane content in Fig. 2 is very close to the (plasticity) angle of 37° reported for platey clay minerals (Allbrook, 1983). Additionally, knowing the plasticity angle, Fig. 2 can be used to obtain approximate allophane contents of volcanic ash soils that are relatively free from organic matter and platey clay minerals.

Relationships between Plasticity Angle and Engineering Properties of Volcanic Ash Soils

Figure 3(a) shows a plot of the variations of ϕ'_{peak} (effective stress-strength parameter for peak condition) versus plasticity angle (α) for the allophanic and halloysitic soils from Panama (Townsend et al., 1971), Indonesia (data from Terzaghi, 1958; Wesley, 1973b, 1974a, b, 1977, 1990), Papua New Guinea (Wallace, 1973), Tanzania (Bucher and Kyulule, 1980) and West Indies (Rouse et al., 1986). For the allophanic soils from Papua New Guinea (Wallace, 1973) and the West Indies (Rouse et al., 1986), only the effective stress-strength parameter data pertaining to residual condition (i.e., ϕ'_{residual}) are available. Since the peak and residual strengths are only slightly different in case of the allophanic soils (Wesley, 1977; Vaughan, 1988), the ϕ'_{residual} values of the allophanic soils from Papua New Guinea and West Indies were also approximated to represent their ϕ'_{peak} values for this study.

Fig. 3. Variations of (a) ϕ'_{peak} with plasticity angle values and (b) $C_c / (1 + e_0)$ with plasticity angle values, for allophanic and halloysitic soils

Figure 3(a) shows an inverse linear relationship between ϕ'_{peak} and plasticity angle values. Since a low plasticity angle reflects a high allophane content (Fig. 2), the trend of the results presented in Fig. 3(a) imply that an increase in allophane content also increases the ϕ'_{peak} values of the volcanic ash soils.

The ϕ'_{peak} versus α relationship (number of paired observations = 21, Eq. (4), Table 1) provides a moderate correlation coefficient of -0.72 and 52% ($r^2 = 0.52$, Eq. (4), Table 1) of the variations in ϕ'_{peak} values are explained by the corresponding variations in the plasticity angle (α) values (Zuwaylif, 1970). With 19 degrees of freedom, the sample correlation coefficient (r) exceeds the critical levels of r at 5% and 1% levels of significance (Table 1). A reasonable correlation ($r = -0.74$, Eq. (5), Table 1) also exists between $\phi'_{residual}$ and plasticity angle values for allophanic and halloysitic soils from Papua New Guinea (Wallace, 1973), Indonesia (Wesley, 1974a, b, 1977, 1990), Tanzania (Bucher and Kyulule, 1980) and West Indies (Rouse et al., 1986). A very weak correlation ($r^2 = 0.04$, Eq. (6), Table 1) comparatively is obtained for the ϕ'_{peak} versus plasticity index relationship and this result is in agreement with the observation of previous workers (example, Wesley, 1977; Boyce, 1985).

The ϕ'_{peak} and $\phi'_{residual}$ values of the volcanic ash soils

from various geographical locations cited in this study were obtained mostly for remolded samples. In the case of the ϕ'_{peak} versus plasticity angle relationship (see Eq. (4), Table 1), seventeen of the twenty one ϕ'_{peak} values belong to remolded soil samples, while, for the $\phi'_{residual}$ versus plasticity angle relationship (see Eq. (5), Table 1), fourteen of the eighteen $\phi'_{residual}$ values belong to remolded samples. The ϕ'_{peak} and $\phi'_{residual}$ values of the volcanic ash soils from Indonesia (Wesley, 1973b, 1974a, b, 1977, 1990), Tanzania (Bucher and Kyulule, 1980) and Dominica, West Indies (Rouse et al., 1986) were obtained mainly for remolded samples that were prepared by compacting a soil sample to its in-situ density at its natural water content (Wesley, 1977) or by normally consolidating a remolded sample at near liquid limit water content to a given vertical stress value (Bucher and Kyulule, 1980). Townsend et al. (1971) and Wesley (1977) have observed, however, that remolding does not have more than a marginal effect on the shear strength parameters of the allophanic soils from Panama and Indonesia respectively.

Figure 3(b) plots the variation of $C_c / (1 + e_0)$ (termed relative compressibility or modified compression index, Holtz and Kovacs, 1981) with plasticity angle values for allophanic and halloysitic soils from Papua New Guinea (Wallace, 1973), Indonesia (Wesley, 1974a, b, 1990) and New Zealand (Jacquet, 1990). The C_c values (in the term $C_c / (1 + e_0)$) refer to the slopes of the void ratio-log pressure curves at pressures exceeding the critical/apparent preconsolidation pressures. The C_c values used in this study mostly (12 of the 14 data points refer to undisturbed samples) mostly were determined from tests on undisturbed samples. The two data points corresponding to remolded samples were obtained from Wesley (1974b); these remolded samples were prepared by Wesley (1974b) by compacting the soils at their natural water content. The increase in modified compression index with increase in plasticity angle ($r = 0.73$, Eq. (7), Table 1) implies that a reduction in allophanic content promotes increased compressibility of the volcanic ash soil. A lower allophane content was previously inferred to be associated with a lower ϕ' value; a lower ϕ' value implies a decrease in shearing resistance at particle contacts, explaining the higher compressibilities of volcanic ash soils with higher plasticity angle values (Fig. 3(b)).

CONCLUSIONS

The dependence of the plasticity angle and of the engineering properties of allophanic and halloysitic soils on their allophane content lead to the existence of correlations between plasticity angle (α) and engineering properties for the volcanic ash soils. The plasticity angle is inversely related, while, the effective stress-strength parameters (ϕ'_{peak} , $\phi'_{residual}$) are directly related to the allophane content of the volcanic ash soils. Consequently, a reasonably linear inverse relationship (correlation coefficient $r = -0.72$ to -0.74) exists between plasticity angle and $\phi'_{peak} / \phi'_{residual}$ values of the volcanic ash soils. Since a decrease in allophane decreases the shearing

resistance at particle contacts and promotes increased compressibility, a direct relationship ($r=0.73$) exists between $C_c/(1+e_0)$ and plasticity angle values for the volcanic ash soils.

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