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PLASTICITY CHARACTERISTICS OF SOME CARBONIFEROUS CLAY SOILS IN NORTH CENTRAL IRELAND AND THEIR SIGNIFICANCE

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ABSTRACT

The relationship between plasticity index, liquid limit and clay size content of gleyed clay soils was examined. Straight line relationships were estimated for plasticity index and liquid limit and for plasticity index and percentage clay size material. The significance of these relationships is discussed in relation to mineralogy, soil series and mole drainage.

INTRODUCTION

Mechanical analysis alone does not indicate the varying properties of soils within the clay range. However, a close relationship often exists between the clay content of the same stratum of a soil and some chemical and physical properties of that soil. Thus, only the clay (less than 0.002 mm) content alone has to be analysed in most Ijsselmeer polder samples, and other characteristics such as organic matter and $CaCO_3$ contents can be deduced from known relationships with the clay content (1). For engineering purposes, plasticity measurements of soils are made to supplement mechanical analysis. In the Unified Classification System of engineering soils, a plasticity chart after Casagrande (2) is used to correlate the principal physical characteristics of clay soils. In this chart (Fig. 1) a line known as the A line is used to separate inorganic clays (above the line) from inorganic silts and organic silts and clays (below the line). The A line is defined by

$$I_p = 0.73\ (W_L - 20)$$

where I_p is the plasticity index and W_L is the liquid limit. At the same liquid limit, increasing plasticity index indicates an increase in toughness and dry strength but a decrease in permeability (3, 4). In this context toughness is the soil consistency near the plastic limit; the tougher a thread of soil near the plastic limit is, the higher the cohesion and the activity of the clay (4). Dry strength is the resistance of soil to crushing when dry and increases also with increasing activity of the clay (4). Experi-

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ence has shown that the results of plasticity tests on soil samples taken from the same stratum plotted on the plasticity chart follow a straight line roughly parallel to the A line. Kezdi (3) has provided a number of these lines for clays, silts and loess in Hungary.

Skempton (5) has shown that clays of different origin exhibit different relationships between clay content and plasticity index. He defined the activity of a clay as plasticity index/percentage clay size particles by weight. Skempton found values of 0.53, 0.95 and 1.33 for Weald, London and Shellhaven clays and quoted values of 1.5 and 1.6 for estuarine clays from the Shannon River and Belfast Lough respectively. Skempton's results indicate that the plasticity index depends on the mineralogical nature of the clay and on the nature of the exchangeable cations. Typical activity values for some soil minerals are: quartz—0, calcite—0.18, muscovite—0.23, kaolinite—0.46, illite—0.90, Ca-montmorillonite—1.5, and Na-montmorillonite—7.5 (3, 5).

It is apparent, therefore, that the plasticity of a clay soil reflects its texture and mineralogical composition. Since soil texture and mineralogy determine in large measure the physical and chemical behaviour of soil, plasticity characteristics may be used to derive qualitative ideas about soil properties. Plasticity characteristics are widely used along with other tests in assessing the suitability of a soil as a pavement foundation material for roads and airfields (6). Since plasticity characteristics are fairly easy and cheap to determine, they may have a value in agriculture. They could be used to extend the results of soil surveys where mechanical analyses are freely available to practical soil management. If relationships could be established between plasticity characteristics and such soil properties as permeability, cohesion, friction co-efficient and critical points on the moisture characteristic curve, e.g., field capacity, among others, it would greatly aid in extending the application of experimental results between and among Soil Series. This type of information would be of great importance to mole drainage in particular.

EXPERIMENTAL

During investigations into the effects of depth and spacing on water intake into and durability (structural stability) of mole drains, soil samples for plasticity measurements were taken in the 0.3 to 0.6 m stratum of soil on 30 sites. Most samples were taken between 0.35 and 0.45 m below the soil surface (moling depth) but in a few sites with unusual features more than one horizon was sampled.

All the soils sampled were boulder clays derived from Carboniferous limestones, shales and sandstones. Their varying textures could be ascribed to their relative abundance of the degraded and weathered parent rocks. All samples were subsoils with less than 1% organic matter and were structureless. Plastic and liquid limits were determined on the moist samples without predrying after all particles larger than

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1.6 mm were removed by hand (7). In addition, mechanical analyses were available for a few sites and for similar strata in six other sites totalling nine analyses. Mechanical analyses were not made on the remaining samples because of the expense and time involved. The activity of the clay derived may therefore be regarded as provisional although substantial change is not expected.

RESULTS

Fig. 1 shows the plasticity index plotted against the liquid limit for 34 samples. The line of best fit is

$$I_p = 0.88\,(W_L - 17.6);\ r = 0.990$$

Twenty-three of the samples are classed as inorganic clays of high plasticity ($W_L \geqslant 50$). The remaining 11 samples are classed as inorganic clays of medium plasticity. The estimated line of best fit is almost coincident with that given for Tortonian clay (Budapest) by Kezdi (3), and both lines cover the same range of plasticity. Fig. 1 also shows that the Irish clays referred to as Wexford, Lucan and Coalisland analysed by Kirwan and McGlynn (8) and Dublin (Swords) are very close to the estimated line.

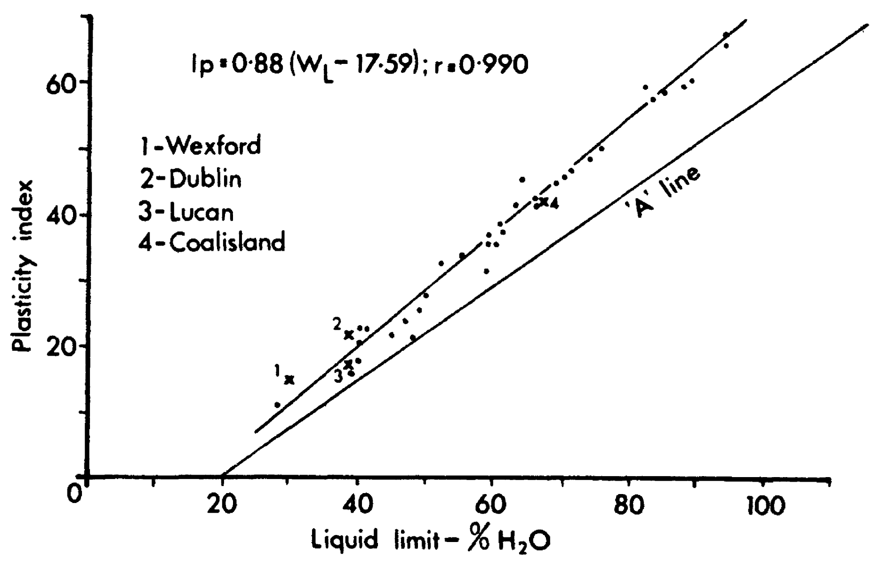

Fig. 1: Relationship of plasticity index to liquid limit of soils in North-central Ireland

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These clays were not included in the estimation of the line of best fit; however, Coalisland, Lucan and Swords clays are of carboniferous origin. Since all the samples were derived from glacial till and boulder clay, substantial variations in plasticity values between sites in any one area or Soil Series and between different horizons at the one site may be expected. These variations were confirmed (Table 1).

Variations shown in Table 1 may be ascribed to varying contents of clay-sized material in the samples. This was suggested in the field and all available mechanical analyses were used to confirm this.

TABLE 1: Variation in plasticity values in Ballinamore and Garvagh Soil Series (9)

Site	Horizon (m)	W_p (%H_2O)	W_L (%H_2O)	I_p	Soil Series
Cleendargan	0.35–0.45	28	89	61	Ballinamore
Jamestown	0.35–0.45	26	94	68	Ballinamore
Lislahy	0.35–0.45	24	70	46	Ballinamore
Carrigallen 1	0.36–0.41	23	39	16	Garvagh
Carrigallen 2	0.43–0.51	26	85	59	Garvagh
Leitrim 1	0.35–0.45	25	93	58	Garvagh
Leitrim 2	0.35–0.45	28	94	66	Garvagh

Fig. 2 shows the plasticity index plotted against the clay content. The slope of the estimated line is 1.32 and this is the estimated activity of the Carboniferous clays of North-central Ireland. The small value of the intercept may be neglected on the physical reasoning that the line passes through the origin and this only means the vertical translation of the line by 0.4 units of plasticity index. The activity derived for these clays is almost equal to the highest value derived by Skempton (5) for Shell-haven, but his data were derived from reconstituted samples. Plasticity tests on natural soils are best made on samples near the field moisture content (7). The activity of 1.32 is much greater than that reported for Hungarian clays which vary in activity from 0.96 for Oligocene clay, through 0.99 for Tortonian clay to as high as 1.23 for Sarmatian clay all from the Budapest region (3). Hungarian bentonite is reported to have an activity of 2.6 (3). Fig. 2 also shows the values for Wexford, Lucan and Coalisland clays (8). While the Lucan and Coalisland clays are reasonably close to the estimated time, the value for Wexford clay is well off.

DISCUSSION

Fig. 1 indicates that the plasticity index of soils derived from Carboniferous parent materials may be obtained from the liquid limit by using the relationship shown.

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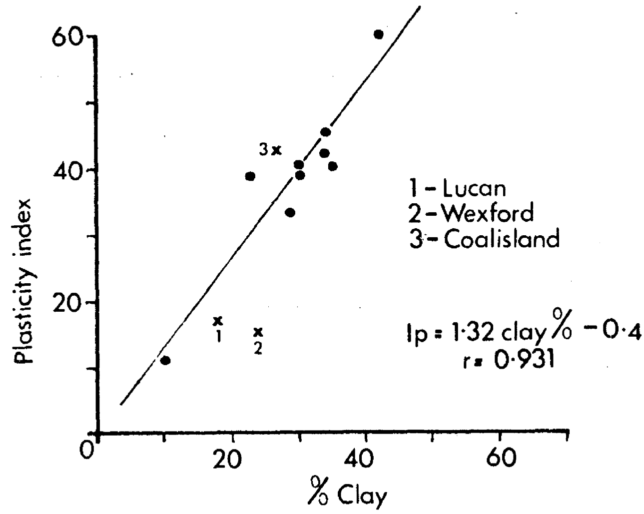

Fig. 2: Relationship of plasticity index to the percentage of clay size fraction (<0.002 mm) of some soils in North-central Ireland

Once the liquid limit and plasticity index are known, the plastic limit ($W_L - I_p$) may be obtained. Fig. 2 indicates that the plasticity index may also be derived from the content of clay size material. Since mechanical analyses results are widely available in Soil Survey Bulletins, additional useful information may be obtained by applying the relationships derived. Alternatively, the clay content of a soil may be predicted from plasticity measurements. For example, the clay content of Brown London clay near Harlow, Essex, is estimated as 52% from a plasticity index of 55 given by Skempton and Henkel (10). Results shown by Skempton (5) and Kezdi (3) indicate that the relationships may differ for clays of different origin.

The relationships between clay content, plasticity index and liquid limit shown in Figs. 1 and 2 are not surprising in view of the soil mineralogy. Kiely (11) has studied the mineralogy of two sites, one (Cleendargan) in the Ballinamore Soil Series (9) and one (Garadice) in the Garvagh Soil Series (9). He has shown that the mineralogy of both sites is somewhat similar for a given particle size fraction but there is twice as much clay in the Cleendargan (36.8%) as in the Garadice site (Table 2). According to the provisional relationship in Fig. 2 the estimated plasticity indices of Kiely's subsoils are 49 and 24 for the Cleendargan and Garadice sites respectively. The organic matter content was 0.8% for Cleendargan and 0.9% for Garadice (11) and was similar to that in the soils analysed in this paper. The soils only differ significantly in the content of expanding clay minerals (montmorillonite group) and of intergrades.

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TABLE 2: Content and mineralogy of the fine soil fractions in Soils of Ballinamore (B) and Garvagh (G) Soil Series [from Kiely (11)]

Soil fraction	Size (μ)	% of soil B	% of soil G	% quartz B	% quartz G	% expand. clay mineral B	% expand. clay mineral G	% illite B	% illite G	% kaolin B	% kaolin G
Fine silt	5–2	17.0	16.7	85	80	2	2	5	5	0	0
Coarse clay	2–0.2	20.8	12.8	58	74	4	8	8	9	4	4
Medium clay	0.2–0.08	10.5	4.5	0	0	57	45	26	35	7	9
Fine clay	<0.08	5.5	1.0	0	0	60	45	30	41	0	0

The following is a summary of Kiely's data (11) for Cleendargan and Garadice subsoils respectively: % illite—6.9, 4.0; % chlorite—0.2, 0.3; % expanding clay minerals—10.6, 3.8; % intergrade minerals—4.7, 0.3; % kaolin minerals—1.6, 0.9; and % amorphous minerals—2.2, 1.2. Inert quartz constitutes the matrix of both soils. Illite and kaolin minerals contribute 6.9 and 4.0 units of plasticity index leaving 42 and 20 units to be accounted for mainly by expanding clay minerals. The intergrade minerals are mainly vermiculite partly interlayered and are likely to have an activity of about 1. Amorphous minerals contain appreciable quantities of very finely divided montmorillonite and are therefore grouped with the expanding clay minerals. However, the expanding clay minerals group contain 20 to 30% vermiculite. Expanding and amorphous clay minerals are 12.8% of Cleendargan soil and contribute 37.4 units of plasticity. The estimated activity of these is 2.9. Allowing for 25% vermiculite, the estimated activity of the expanding montmorillonite is 3.5. Similarly the estimated activity of the Garadice montmorillonite is 4.8. These preliminary calculations for the montmorillonite group of clay minerals are in line with those measured at Cornell University for montmorillonite with Ca and Mg in the exchange complex (12). The Cornell data are 3.5 for Mg-montmorillonite and 4.3 for Ca-montmorillonite. Little of the activity is likely to be due to Na ions which contribute about 0.33 milliequivalent/100 g (80 ppm) out of a cation exchange capacity of about 18 meq/100 g at the Cleendargan site. The bulk of the expanding clay minerals is finer than 0.2 μ (11).

The relationships derived here are unlikely to hold for some other clay soils derived from Carboniferous parent materials. For example, Kilrush and Abbeyfeale Soil Series both derived from Upper Carboniferous parent materials are practically devoid of montmorillonite but have abundance (20 to 50% of the particles $\leqslant$ 1.4 μ) of both mica and vermiculite (13).

Soils with high plasticity indices are associated with shallow A1 horizons; the A1 horizon of the Ballinamore Series is commonly 0.05 to 0.10 m deep. Below about 0.25 m the soil is structureless and not significantly influenced by weathering. Soil with low plasticity indices, and in which the sand grains are not cemented, generally tend

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to have deep Al horizons up to 0.36 m. Soils with high plasticity indices also tend to have very low permeability. The permeability of the Ballinamore subsoil is only 1×10^{-6} m/hr measured in a falling head apparatus. Plasticity results have no practical value in predicting permeability since all the soils measured are effectively impervious. If mole drains are drawn when highly plastic soil is wet or are drawn too deep, e.g., at 0.6 m or greater, they may fail to dry the ground since the soil around the mole fails in plastic flow rather than through brittle and plastic failure. Also, disturbed, highly plastic clay is very subject to compression by surface loading. In this way the loosening effects of mole drainage may be undone by using tractors with too wide a track gauge and track shoe. This effect has been observed in practice along with deformation of mole drains when a swamp dozer was used to draw a single mole plough at 1.5 m centres without off-setting.

Plasticity index appears to be related to the structural stability of mole drains. In the survey of mole drains, the moles were definitely unstable in soils with a plasticity index less than 30. This corresponds with a clay content less than 23%. Mole drains were moderately stable in sites with a plasticity index of 30 to 40 corresponding to clay contents of 23 to 30%. Mole drains were stable in sites with a plasticity index greater than 40. This corresponds reasonably well with English and New Zealand experience where soils considered suitable for moling have clay contents in excess of about 35% and 27% respectively. The coarser soil fractions (sand and gravel) and the occurrence of sand lenses and boulders also play a decisive role in the stability of mole drains. All the stable soils examined have less than 40% sand and usually have 20 to 30% sand fairly evenly divided between the coarse and fine fractions.

Plasticity index data may also have value in classifying soils according to physical behaviour. Croney and Coleman (14) have shown that a continuously disturbed soil (as used in making plasticity measurements) has a moisture content/suction relationship unique for each soil irrespective of whether it is wetting or drying. On disturbance at a given moisture content the suction of the moisture increases or decreases depending on initial conditions, such as field soil in the natural state or the same field soil which had been thoroughly slurried (14). The moisture/suction relationship of a field soil in the natural state thus represents that due to disturbance by the agencies of nature and man. Recently, too, plasticity values have begun to be assimilated into the theory of Critical State Soil Mechanics which is still in a state of development (15). The significance of plasticity data may be further appreciated as data from other soil series become available in conjunction with measurements of such properties as shear strength, soil moisture characteristics and force measurements on tillage and subsoiling tools.

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