# A PLASTICITY CHART AS AN AID TO THE IDENTIFICATION AND ASSESSMENT OF INDUSTRIAL CLAYS

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ABSTRACT: The plastic properties of clays are sufficiently variable to offer a simple but practical aid to identification. This can be done by using their Atterberg 'plastic limit' and 'plasticity index' values as parameters for an identification chart. The advantages and disadvantages of the technique are discussed, and results for a wide variety of clay minerals, particularly industrial clay types, are illustrated. A brief summary is also given of the effect of non-clay impurities, and reference is made to the correlation of Atterberg limit values with other physical properties of clays.

## INTRODUCTION

An easily-interpreted plasticity chart is offered for using the Atterberg limits of clays as an aid in their identification and for studying their physical properties. As the apparatus required is simple and inexpensive, this determinative technique has obvious attractions for poorly-equipped laboratories and even for temporary field stations. The chart was compiled principally for geological staff working overseas in developing countries, where the main interest in clay minerals lies in their possible commercial exploitation, and the accent is placed on the recognition of industrial clay types.

Identification of monomineralic clays such as fuller's earth, bentonite, attapulgite or sepiolite, and the kaolins is possible. These are the most sought-after clay types. Identification of heterogeneous mixtures, and of the less commercially important species illite and chlorite, offers greater difficulties. These may occur in industrial clays as constituents of ceramic raw materials used in the production of heavy clay ware.

The chart can also be used as an aid in assessing the physical properties of a clay which are of importance for its commercial exploitation. It can also serve

as a guide to the changes taking place in these properties during processing. Some references to these uses of the chart will be made in the course of the discussion. An example is in the examination of a ceramic raw material consisting of a hetero-geneous mixture of clay minerals and iron oxides. The most important characteristic of such a body is its firing behaviour, little of which can be inferred from the mineralogical composition which will, in any case, be difficult to determine from Atterberg limits. Practical trials are required to evaluate its potential use. However, with these mixtures Atterberg limits are useful for the information they provide on the clay's plastic properties, and hence on its shaping and drying behaviour as a moist ceramic body, irrespective of its mineralogical composition. A more detailed discussion of the application of Atterberg limits to such appraisal techniques will have to be dealt with elsewhere.

Because of the relationships between plasticity and other physico-chemical properties of clays, Atterberg limit determinations are useful even when equipment for the more definitive techniques in clay mineral identification, such as X-ray diffraction, DTA, and infra-red analysis, are available. Although the measurement of Atterberg limits requires a larger sample (50–75 g dry weight) than these other methods, this presents no problem in commercial appraisal programmes where the collection of samples of at least this size is desirable.

## DEVELOPMENTS IN THE USE OF ATTERBERG LIMITS

Atterberg recognized five distinct stages in the development of a clay–water system from a maximum cohesive condition at low water content to a fluid slip at high water content (Bauer, 1960). Two of these, now called plastic limit and liquid limit, have long been accepted by civil engineers as important criteria for characterizing finely-divided cohesive soils, and standard procedures have been drawn up for their determination (British Standards Institution: B.S. 1377:1967).

The liquid limit is taken as the water content of the soil at which it will just begin to flow when jarred in a specific manner. The plastic limit is the minimum water content at which the soil can just be rolled by hand into threads 3 mm ($\frac{1}{8}''$) thick without crumbling. Both are expressed as a percentage by weight of the oven-dried soil. At moisture contents between the two limits the soil is in a plastic state, so that the arithmetical difference between the two values, known as the plasticity index, is a measure of the range of moisture content over which the soil behaves plastically.

The present mechanical method of measuring the liquid limit, using a cup of wet soil paste dropped for a specified distance onto a rubber base, was originally devised by Casagrande (1932). He also proposed a plasticity chart for interpreting Atterberg limit results in terms of soil engineering properties (Casagrande, 1948) which now forms part of most classification systems in soil mechanics. The essential details of this chart, which uses plasticity index and liquid limit as parameters, are shown in Fig. 1.
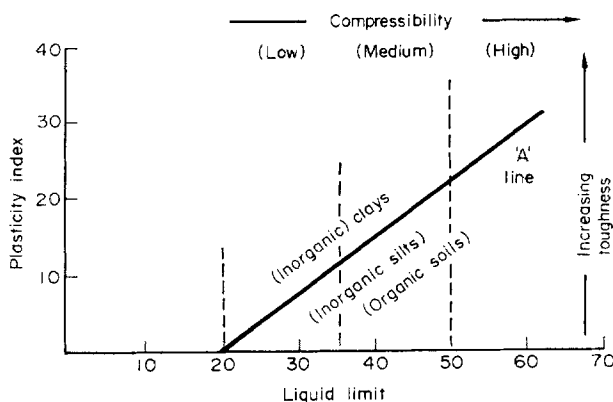
Fig. 1. Plasticity chart for classification of cohesive soils (after A. Casagrande).

An empirical boundary called the 'A' line, with a slope expressed by the equation plasticity index = 0·73 (liquid limit − 20), separates inorganic clays from inorganic silts and organic soils. Further vertical subdivisions of the chart are made to distinguish differences in engineering properties such as compressibility, permeability and toughness. Soils located within each area of the chart are assigned a definitive code in the classification and would be expected to behave similarly in con-structional engineering.

The location of specific clay types on this chart has been considered by a number of authors (Casagrande, 1948; Martin & Lambe, 1957; Grim, 1962; Dumbleton & West, 1966) usually in an attempt to define the contribution of a clay constituent to the engineering properties of the soil as a whole, but the application of the chart for clay mineral identification is limited and rather restrictive. The 'A' line has little diagnostic value in the interpretation of Atterberg limits in terms of clay minerals, as the latter tend to plot within a narrow band extending along the length of the 'A' line, and some mineral species may be found on either side of it. On the Casagrande chart the area above a line drawn at 45° through the origin is not used.

Fuller use of Atterberg limits is made if a chart is compiled with plastic limit and plasticity index as parameters, as in Fig. 2. The plastic limit is plotted on an arithmetic scale, but the plasticity index, to cope with the wide range in values met with among the clay minerals, is plotted on a logarithmic scale. The latter accentuates small differences in results at low plasticity index levels, where they reflect important changes in clay type, and places less emphasis on small differences at high plasticity index levels, where they are less meaningful.

A satisfactory spread of data is obtained and the clay minerals tend to fall into specific areas on the chart. The points in Fig. 2 refer to clay samples which are considered to be characteristic or of special interest, and will be considered in more detail later. They have been chosen from a large number of results on materials

received from a number of countries and from a variety of geological environments, and were obtained with close control of mineralogical composition, physical nature of the samples, and operator technique. All samples were brought to an air-dry state before testing.

The calculated position of the 'A' line on the clay identification chart is shown in Fig. 2, but no further reference is made to it. The choice of parameters for this
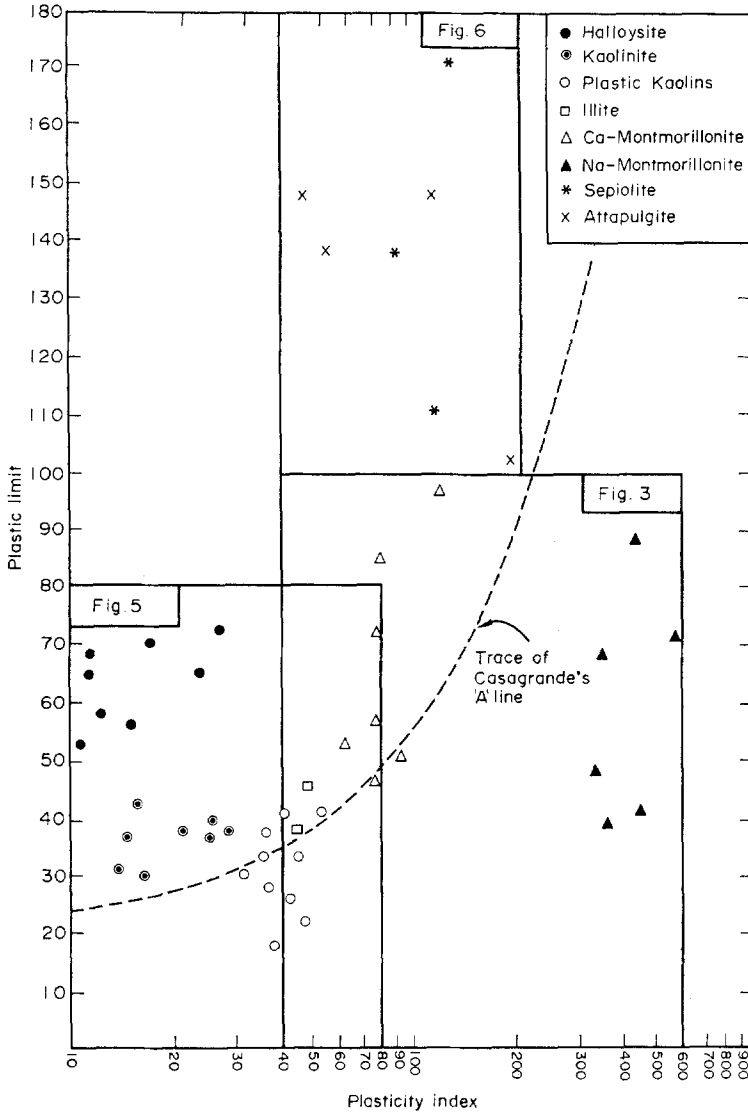


FIG. 2.   Clay identification chart using plastic limit and plasticity index as parameters; (synopsis of Figs 3, 5 and 6).

figure was also influenced by the fact that the plastic limit and plasticity index reflect important differences in the physical properties of clays of use in their commercial assessment. The plasticity index gives an indication of the 'degree' of plasticity shown by a clay body and may often be correlated with properties such as specific surface area, dry strength, and rheological behaviour. The plastic limit gives an estimate of the sorptive properties of clays (in this case for water) and may be correlated with other characteristics such as shrinkage on drying.

## TESTING OF CLAY-GRADE MATERIAL

The data in Fig. 2 refer to high-grade or esentially pure clay minerals. For the identification of impure clays, or the clay component of soils and sediments, Atterberg limits can be used only if the non-clay constituents are taken into account when interpreting the results or, alternatively, removed prior to testing.

As the influence of sand and silt impurities on the plasticity of clays is essentially one of dilution, their effect can often roughly be allowed for by a suitable calculation, assuming that the limits for the clay constituent are reduced proportionally to the amount of non-clay material present. However, not only does this require a measurement of $<2$ $\mu$m content of the soil, which is lengthy and tedious, but it assumes that the $<2$ $\mu$m constituents do not contribute to the plasticity of the soil.

With clays containing appreciable amounts of sand and silt it may well be equally, if not more, convenient to separate a clay fraction and determine the Atterberg limits on the clay material itself. A separation of this sort may be done as a routine part of the laboratory investigation of a raw clay in any case, particularly if its commercial application is being considered. The fraction can be prepared by decanting the fines from a suspension in water, but the use of a dispersing agent must be avoided in view of its possible effect on the physico-chemical, and hence the plastic, properties of the clay.

Suspensions that are prone to flocculation can more conveniently be fractionated with the aid of a hydrocyclone. The type finding most use in the author's laboratory is a small glass model which treats clay slurries at a rate of 1–2 gal/min and provides a separation at a particle size within the range 5–10 $\mu$m. For empirical and comparative work this may be accepted as roughly equivalent to a 'clay' product. The strong shearing forces that are set up by the centrifugal motion of the slurry as it passes through the cyclone temporarily break up clay floccules and thereby provide a quick and effective size separation. In the absence of a chemical peptizing agent the separated clay fraction usually settles quickly, but in many cases it was found more convenient to de-water the suspension with a small filter press, which produces a thick clay cake quickly and easily air-dried.

## MONTMORILLONITE CLAYS

One important aspect of the Atterberg limit tests arises from the considerable differences in plastic properties brought about by variations in the type of ex-
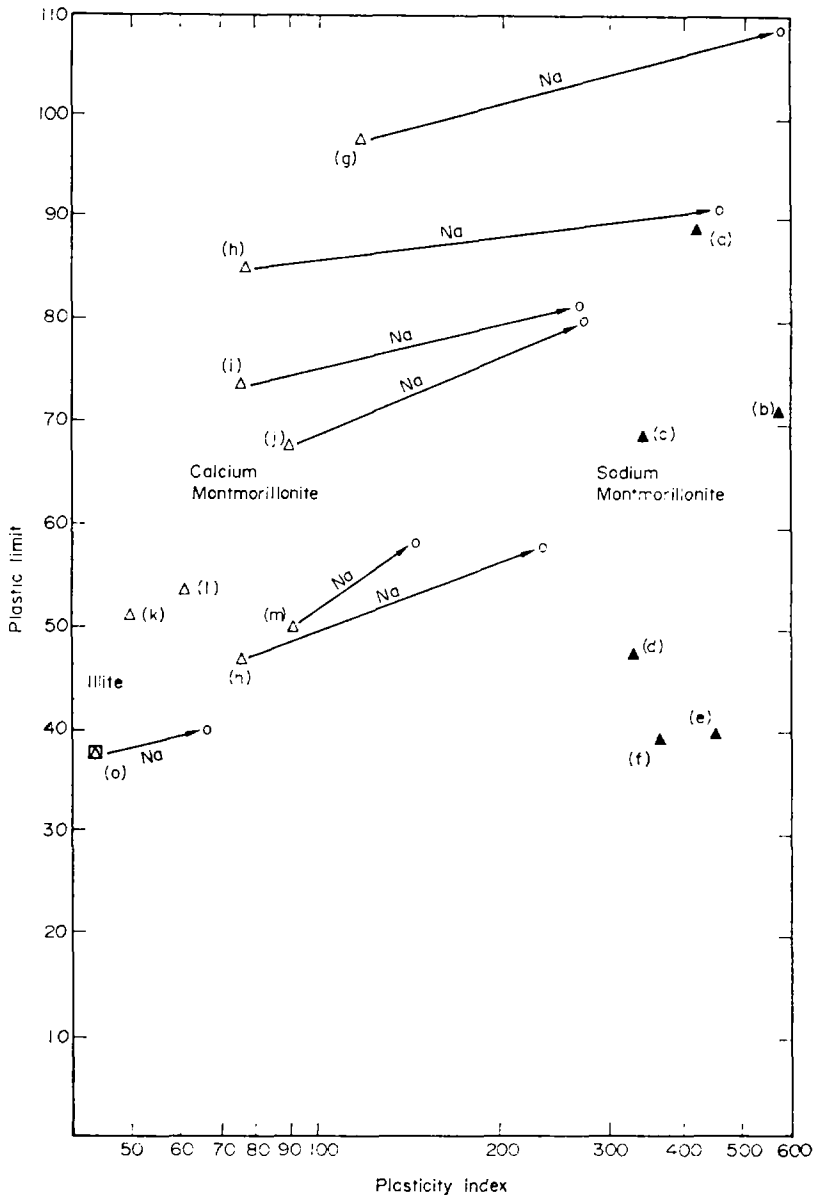
FIG. 3. Location of montmorillonite-group clays on the identification chart. (a) Buff-coloured Wyoming bentonite (drilling mud 'Magcogel'). (b) Grey Wyoming bentonite. (c) 'Hectorite' (saponite), Lake Natron, Tanzania. (d) Algerian bentonite. (e) North African bentonite, commercial grade. (f) Wyoming bentonite, commercial grade. (g) Montmorillonite, Baulking, Berkshire. (h) 'Woburn Clay' (fuller's earth) Berkshire. (i) Clay fraction from red montmorillonitic soil, Nevis Island. (j) 'Surrey Powder', Fuller's Earth Union. (k) Raw fuller's earth, Nutfield, Surrey. (l) Hungarian fuller's earth, commercial grade. (m) Clay fráction from ferruginous basaltic soil, Mauritius. (n) Gypsiferous montmorillonite, Botswana. (o) London Clay (illite plus montmorillonite).

changeable cation adsorbed by montmorillonite clays. This enables a distinction to be made between naturally occurring calcium montmorillonite (fuller's earth) and sodium montmorillonite (bentonite) and can provide a measure of the effectiveness of sodium exchange procedures for processing fuller's earth. These factors have considerable industrial importance.

*Sodium montmorillonite (bentonite)*

The naturally occurring sodium montmorillonites or bentonites are characterized by exceedingly high plasticity indices, and produce figures up to three or four times greater than any other clay type. Typical results are shown in Fig. 3. The best quality swelling bentonites (Wyoming type) show plasticity index values up to 550–600. Lower figures are obtained from other bentonites, with values down to 100 for the so-called potassium bentonites or sub-bentonites. The latter have generally developed from montmorillonites bearing potassium as an exchangeable cation, but which has become 'fixed' in interlayer positions and inhibited swelling. They are, therefore, essentially mixed-layer illite-montmorillonite clays with partial swelling properties.

For montmorillonites proper some variation in plasticity indices is to be expected with crystal lattice substitutions, but this is usually overshadowed by differences in clay mineral content. The commercial processing of raw clay to provide better-quality marketing grades usually enhances plasticity index values, by increasing the clay content or by yielding a more finely-divided product. Determination of liquid limits can, therefore, be a useful control in the beneficiating process.

The liquid limit measurement for the sodium montmorillonites is surprisingly reproducible for the high water contents involved, although a standard procedure must be rigidly followed. The notable thixotropic properties of these clays cause changes in the clay–water relationship with time, and inflated liquid limit (and corresponding plasticity index) values may be obtained if the clay paste is allowed to 'age' unnecessarily prior to testing. On the other hand, this feature may be turned to advantage as a means of checking whether or not the clay has pronounced thixotropic properties.

The plastic limit values of the sodium montmorillonites have shown considerable variations, and some results much lower than those for the calcium montmorillonites have been recorded. This appears to be due partly to the fact that the plastic limit consistency in the thread-rolling procedure is more difficult to judge with sodium clays than with other cation-based clays (White, 1958), and partly due to the different drying characteristics of bentonites when brought to the air-dry state prior to re-wetting for the Atterberg limit tests.

*Calcium montmorillonite (fuller's earth)*

Calcium montmorillonites occupy an intermediate position on the chart, with plasticity indices between the plastic kaolins and bentonites. Typical values lie between 50 and 100 (Fig. 3).

Despite their high specific surface area, the water sorption properties of calcium montmorillonites do not quite reach the level of sepiolite and attapulgite, and the highest plastic limit recorded is about 100. The lower end of the plastic limit range is about 50. The higher values are generally obtained from the richer grades of fuller's earth but some variation occurs with compositional differences in clay type, nontronite in particular giving lower limits, even at high purity.

In the identification chart some overlap occurs between the calcium montmorillonites and other clays, especially at lower plastic limits and plasticity indices. A useful check can be made, however, with an additional preparation technique utilizing the high cation exchange capacity of the montmorillonite. Replacing the exchangeable calcium by sodium converts the clay to its sodium form, which then yields higher Atterberg limits. The plastic limit shows only a small increase, but there is a large increase in the plasticity index to a value more characteristic of a swelling bentonite.

The laboratory procedures usually employed for the preparation of sodium-exchanged clays are too lengthy and tedious for routine clay identification purposes. This can be overcome simply by the addition of a soluble salt of sodium, in powdered form, to the dry clay prior to testing. The addition of water to induce plasticity brings the salt into solution and initiates the exchange reaction. The reaction, however, is reversible and may not go to completion unless the sodium occurs in a high concentration relative to that of the displaced calcium. This is resolved in turn by using an acid radicle which forms a water-soluble salt with sodium and an insoluble one with calcium. The calcium expelled from the lattice exchange sites is precipitated as an insoluble compound, and thereby prevented from competing with the sodium still in solution.

Three reagents—sodium carbonate, sodium oxalate and sodium tungstate—have been tried, and the carbonate found to be the most effective. It not only produces higher liquid limits for the sodium-exchanged clay, but less is needed, it is cheapest, and is used in industry for this purpose. (In calculating the Atterberg limit results from the water contents of the plastic clay, the amount of reagent present in the oven-dried sample must be taken into account.)

The main disadvantage of this simple technique is that the cation exchange capacity of the clay is not known in advance, so that the appropriate sodium carbonate requirement cannot be assessed. The presence of excess salt in solution reduces the liquid limit, and hence the plasticity index. This is shown in Fig. 4 for a montmorillonite from Woburn, Bedfordshire, to which 1–7% of sodium carbonate was added. The cation exchange capacity (75 meq/100 g) was satisfied by the addition of 4–5% sodium carbonate, and thereafter the plasticity index decreased. The plastic limit at this fully exchanged point is rather difficult to determine satisfactorily and any deviation that occurs at high electrolyte concentration, as in Fig. 4, may be spurious.

This step-wise addition of sodium carbonate is obviously too lengthy a process for routine clay identification purposes. As a confirmatory test for calcium mont-
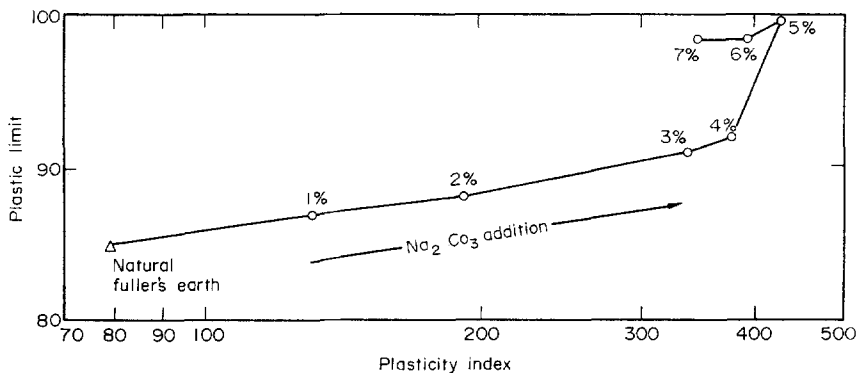
FIG. 4. Change in Atterberg limit values for increasing additions of sodium carbonate to a calcium montmorillonite from Woburn, Bedfordshire.

morillonite a single addition of 4% sodium carbonate is usually sufficient to produce Atterberg limit figures near to those of the sodium-exchanged clay.

With these clays the plasticity index (or liquid limit) values provide a useful indication of the ease with which a sodium montmorillonite can be obtained from a raw fuller's earth, and the quality of the bentonite produced. If the test values of the fully-exchanged form of a fuller's earth are required they can be obtained by ensuring that any free sodium carbonate is removed from the clay paste. In preparing the clay sample excess carbonate is added to a slurry of the fuller's earth, which is then filtered to remove the reagent unused in the exchange reaction. The small filter press mentioned earlier has proved excellent for this purpose. The very small amount of sodium carbonate left in the damp filter cake afterwards has little effect on the liquid limit. Results for the fully-exchanged sodium forms of some of the fuller's earths in Fig. 3 are indicated by arrows marked with the symbol Na and pointing towards a small circle representing the new limit and index values. The highest grade of fuller's earth tested was a sample from a borehole at Baulking, Berkshire, which, on sodium exchange, produced plasticity indices as high as the best quality Wyoming bentonite.

Other clays have much lower cation exchange capacities and the addition of sodium carbonate prior to testing has less or little effect on the Atterberg limits. In fact the plasticity index usually decreases. Thus the presence of montmorillonite in a mixed clay assemblage can be checked in this way, and a comparison of the Atterberg limits obtained from an untreated clay and its sodium-exchanged counterpart may give an indication of the likely montmorillonite content. Results for a typical London Clay sample, composed of illite with subsidiary montmorillonite and quartz, were as follows:

| | Plastic limit | Plasticity index | Liquid limit |
|---|---|---|---|
| Untreated clay | 38 | 43 | 81 |
| 1% sodium carbonate added | 39 | 56 | 95 |
| 2% „ „ „ | 40 | 65 | 105 |
| 3% „ „ „ | 41 | 57 | 98 |

As before, the results illustrate the manner in which the liquid limit (and plasticity index) decreases again once the optimum addition of sodium carbonate has been exceeded. For routine testing, a standard addition of 2% sodium carbonate (half the full amount) is made for clays in which less than half is expected to be montmorillonite.

The interpretation of such results may be complicated by the presence of exchangeable cations other than calcium, if these have different powers of replacement. A few clays of fuller's earth type, which also contained magnesium as an exchangeable cation, have given liquid limits after the addition of sodium carbonate, that were rather lower than expected. Further work is being done to clarify some of these factors, although the discovery that a fuller's earth will not fully react to the addition of sodium carbonate is, in itself, an important commercial consideration.

## KAOLIN GROUP CLAYS

### Kaolinite

Although some kaolinites are virtually non-plastic and give plasticity indices less than 10 (off the chart in Fig. 2), most do show some plastic behaviour, with plasticity indices that vary according to grain size. Typical examples are illustrated in Fig. 5.

The lowest plasticity indices are generally obtained from hydrothermal kaolin deposits where the clay is both coarse and well crystallized. The raw china clays from Swaziland, Cornwall and Nigeria (i, j and m in Fig. 5) are examples. Processing of these clays, to remove mica and provide more finely-divided products for industrial uses, such as paper filling and coating, produces kaolinites of higher plasticity. The three Cornish china clays in Fig. 5 (samples j, k and l) have 35, 50 and 75% respectively of $<2$ $\mu$m particles. The Georgia kaolins (samples p, q, r and s) have average grain sizes of 4·5, 1·5, 0·8 and 0·5 $\mu$m respectively. The finest of these are almost as plastic as the ball clays.

'Secondary' kaolin clays, formed by weathering and eventually carried into sedimentary deposits, are generally finer grained and less well crystallized, both features producing higher plasticity indices. Such alluvial kaolinites are grouped for convenience under 'plastic kaolins', the most characteristic of which are the ball clays.

Consolidation and partial cementation of sedimentary kaolins, particularly on deep burial, may reverse the effect of weathering on these clays and cause a reduction in plasticity indices when they are brought in contact with water again
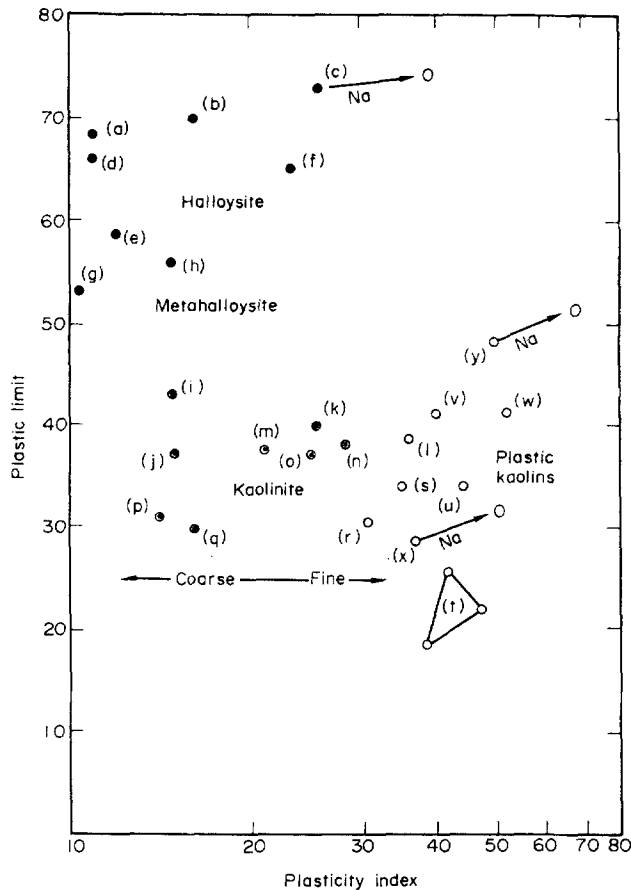
FIG. 5.   Location of kaolin-group clays on the identification chart. (a–c) Halloysite clays, New Hebrides. (d) Halloysite, Sabah. (e–f) Halloysite clays, Fiji. (g) Metahalloysite, Trinidad. (h) Ferruginous metahalloysite, Grenada. (i) Kaolinite, Mahlangatsha, Swaziland. (j–l) China clays, Cornwall. (m) Raw china clay, Jos, Nigeria. (n) Processed china clay, Jos, Nigeria. (o) Processed china clay, Swat, Pakistan. (p–s) Differing grades of kaolin, Georgia, USA. (t) Alluvial kaolins, Gambia. (u) Ball clay, South Devon. (v) Ball clay, Hong Kong. (w) Ball clay, Dorset. (x) 'Swamp' clay, Uganda. (y) < 10 μm fraction from plastic kaolin, St Vincent.

and kneaded to a paste for the Atterberg limit tests. Relatively low plasticity indices have been obtained from pisolitic kaolins. One such sample, a Cretaceous sedimentary clay from Nigeria, yielded a plasticity index of 9, which was of the same order as plasticity index values obtained from non-plastic, pisolitic (gibbsitic) bauxites of similar visual appearance. The latter may be distinguished by their much higher weight losses on ignition (up to 34%) compared to that for kaolinite (up to 14%).

The plastic limits of kaolinites are seldom greater than 40, which serves to distinguish them from the halloysites, described later.

The addition of sodium carbonate to these clays lowers their Atterberg limits. Some typical results are shown in Table 1.

TABLE 1. Atterberg limits of some kaolinite clays (values in brackets are results obtained after the addition of 2% sodium carbonate)

|  | Plastic limit | Plasticity index | Liquid limit |
|---|---|---|---|
| *Kaolinite only* | | | |
| China clay, Cornwall | 37 (36) | 15 (11) | 52 (47) |
| Processed china clay, Cornwall | 40 (41) | 25 (20) | 65 (61) |
| Alluvial kaolin, Devon | 41 (40) | 23 (20) | 64 (60) |
| Kaolinitic river clay, British Honduras | 38 (30) | 41 (25) | 79 (55) |
| Ball clay, Devon | 32 (32) | 44 (35) | 76 (67) |
| *Kaolinite with minor montmorillonite* | | | |
| Swamp clay, Uganda | 29 (32) | 37 (48) | 66 (80) |
| Plastic kaolin, St Vincent ($<10\mu$m fraction) | 48 (51) | 49 (64) | 97 (115) |

*Plastic kaolins*

The plastic nature of alluvial kaolins is an important factor in their assessment as ceramic clays, particularly as it depends on physical properties that also give rise to other useful characteristics such as high dry strength. The principal feature is the ability of poorly crystallized kaolinite to divide into very thin units and provide a higher surface area. This improves the plasticity and produces plasticity indices of 40–50 for the better quality ball clays, although the English ball clays often contain carbonaceous matter and micaceous material that contribute to their plasticity. The Dorset ball clays tend to be rather more plastic than the South Devon ball clays, two typical results being shown in Fig. 5 (w, u).

Illitic clays of similar plasticity usually contain minor to substantial amounts of iron in the clay structure and on calcining yield red to brown fired clay bodies. As ball clays used in ceramics are generally required to fire white or cream (black organic matter colouring impurities burn off on heating) this serves as a rough distinguishing test. There are also marked differences in fusion temperatures.

Other plastic kaolins illustrated in Fig. 5 are three alluvial clays from Gambia (t) which gave unusually low plastic limits, a ball clay from Hong Kong (v) which had been recognized as such from its Atterberg limits, and 'swamp' clays from Uganda (x) and St Vincent (y). The latter were kaolinitic in composition but derived some of their plasticity from a montmorillonitic constituent (identified from X-ray diffraction evidence). This was confirmed by the sodium carbonate test (see Table 1 and Fig. 5).

*Halloysite*

The structural formula for halloysite differs from that for kaolinite in containing an additional two molecules of water. This is only loosely held and is driven off on oven drying, the resulting water loss being equivalent to 14% by weight of the dried clay. As the Atterberg limit tests employ an oven-drying procedure to measure the moisture content of wet plastic clay, this low-temperature water will be removed as well as the water of plasticity and recorded as part of it. The plastic limit should, therefore, be enhanced by 14%. As the liquid limit would similarly be increased, the plasticity index, by difference, will not be affected.

The fully hydrated form of halloysite may exist only in the wet field condition. It is said to revert to meta-halloysite on drying between 60–100°C (Terzaghi, 1958) so that the full 14% low-temperature water may not be present in the air-dry clay prior to Atterberg limit testing. With a number of air-dried halloysites used for this test the loss in weight when oven-dried at 105°C provided figures varying between 2·2% and 8·5%.

In practice, the difference in plastic limits between halloysite and kaolinite is much greater than the above figures would suggest. Halloysite typically produces plastic limits of 60–70, compared with those of kaolinite which are generally below 40 (Fig. 5). Metahalloysite gives intermediate plastic limits between 40 and 60.

This suggests that the special tubular and trough-like form of the clay mineral is the main cause of the water retention properties of halloysite. As with attapulgite and sepiolite, described later, water is adsorbed on internal surfaces which play no part in the development of plastic flow, and is supplementary to the water of plasticity.

Halloysites are essentially non-plastic with plasticity indices of about 10–15, or less. Accordingly they display a marked lack of cohesion when moulded in the wet plastic state, and accurate plastic limit values may be difficult to determine by the usual thread-rolling procedure. For identification purposes, however, a roughly estimated end-point normally produces acceptable results.

As illustrated in Fig. 5 some halloysites give plasticity indices higher than 10–15, usually attributable to a montmorillonitic constituent. These have formed from volcanic tuffs, and the clay minerals are often so poorly ordered that identification by X-ray diffraction may be difficult or misleading. Little help is obtained from measurements of cation exchange capacity as an indication of the presence of montmorillonite, because of high values contributed by amorphous or allophanic constituents, and identifications may have to be confirmed by, or based on, information supplied by differential thermal analysis and chemical analysis or dissolution. Plasticity index values can, therefore, provide very welcome evidence of bulk mineral composition, as demonstrated by specimens a, b and c in Fig. 5. These are halloysites containing increasing amounts of montmorillonite. The effect of a 2% sodium carbonate addition to specimen c is also illustrated. Of the two Fiji halloysites (specimens e and f in Fig. 5), only the latter contains montmorillonite (from X-ray diffraction evidence).
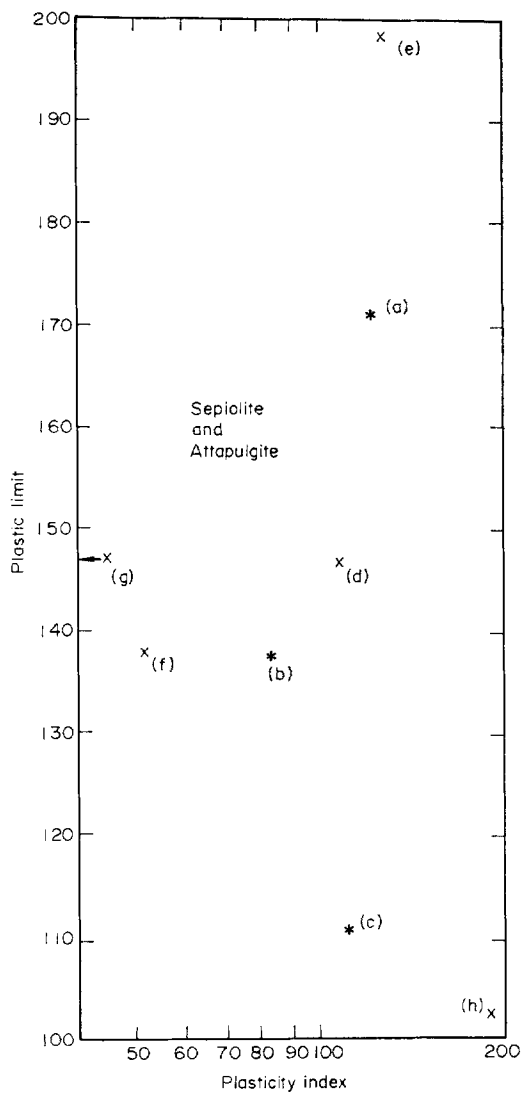
FIG. 6. Location of sepiolite and attapulgite on the identification chart. (a) Sepiolite, Somalia. (b) Sepiolite, Vallecas, Spain. (c) Sepiolite, Lake Amboseli, Tanzania. (d) Raw attapulgite, Torrejon el Rubio, Spain. (e) Clay fraction from (d). (f) Ground and classified attapulgite, South Africa. (g) Attapulgite shale, Somalia. (h) Ground and classified attapulgite, Attapulgus, USA.

## SEPIOLITE AND ATTAPULGITE

The crystal structures of sepiolite and attapulgite are built up of amphibole-like chains joined at the corners. These form long lath-shaped units with interior channels

running the length of the crystals. The channels are easily accessible to water molecules and when the clay is wet, contain moisture that takes no part in the development of plasticity at the surface of the clay particles. On drying, this non-essential water is driven off with the water of plasticity and greatly enhances the plastic limit values.

Plastic limits in excess of 100 are obtained. Examples are shown in Fig. 6. The highest value recorded, about 200, was obtained from a clay fraction (specimen e in Fig. 6) separated from a raw Spanish attapulgite (specimen d in Fig. 6). High water sorption figures are obtained even from less common forms of these minerals. A ground sample of mountain leather, for example, produced a plastic limit of 135.

Sepiolite and attapulgite also yield high plasticity indices, ranging up to 200. The results depend on the physical state of the clay. The Somalia attapulgite (specimen g, Fig. 6) was submitted to the laboratories as a shale, and occurred as a compact fissile rock. Significantly, the crushed rock still yielded a plastic limit of 147, but because of its consolidated state, the attapulgite had lost most of its original plasticity and gave a plasticity index (difficult to measure accurately) of less than 40.

Most of the sepiolites examined so far have been the variety known as meers-chaum, which appears to have formed as an authigenic deposit from dissolved silica and magnesia in playa lake waters. The clay flocculates and settles as a spongy mass, which is soft when freshly dug from the deposit, but dries to an extremely tough and coherent material. Fine crushing is needed prior to the Atterberg limit tests to enable the clay to develop its full plasticity when re-mixed with water. Results for different crushing sizes of a Somalia sepiolite (specimen a, Fig. 6) were as follows:

|  | Plastic limit | Plasticity index | Liquid limit |
|---|---|---|---|
| Meerschaum, crushed to pass 36-mesh sieve* | 167 | 93 | 260 |
| „ „ „ „ 100-mesh sieve | 168 | 103 | 271 |
| „ „ „ „ 200-mesh sieve | 171 | 119 | 290 |

As will be seen from Fig. 6, there appears to be no way of distinguishing between sepiolite and attapulgite by Atterberg limits alone.

## ILLITE AND MIXED-LAYER CLAYS

Illite (and chlorite) clays are difficult to obtain in a sufficiently pure state for testing, and are not actively searched for as a specific industrial clay type. They are therefore considered only very briefly. They do find an extensive industrial use as a constituent of mixed assemblage clay deposits in the manufacture of bricks and other heavy clay ware products. A description of the use of Atterberg limits in providing technical data on the physical properties of ceramic clays, rather than mineralogical information, is outside the scope of this paper.

*This is the recommended maximum grain size for particulate material prepared for the standard Atterberg limit tests (B.S. 1377:1967).

A typical illite clay, and in particular a clay fraction prepared from an illitic soil with the removal of coarse micaceous constituents, would have plastic limit and plasticity index values both of the order of 40–50. Considerable variations are to be expected, however, both on account of varying composition of the clay mineral itself and the ill-defined boundary between illite and degraded mica. The latter may occur as a clastic constituent acting merely as a non-plastic diluent.

The addition of sodium carbonate reduces the Atterberg limits slightly, but not enough to off-set any increase caused by the presence of montmorillonite as a minor constituent. The results for a London Clay sample (also bearing quartz) have already been referred to. On the addition of 2% carbonate the plasticity index increased from 43 to 65.

The mixed layer illite-montmorillonite minerals are a special case, and further work is needed to clarify some of the apparent inconsistencies in their Atterberg limit values. Results so far have indicated that the montmorillonite component has less effect on the overall limits of these clays than in a mechanical mixture composed of the two minerals in the same ratio by weight. Thus, although a mixed layer illite-montmorillonite clay from Monmouthshire, of lower Devonian age, produced a fairly high plasticity index of 61, addition of 2% sodium carbonate increased this only fractionally to 63.

## NON-CLAY IMPURITIES

The effect of coarser particles on the plasticity of clays has already been mentioned. Other impurities affecting the Atterberg limit values of clays are those occurring in clay-size grades, especially secondary or free iron oxides and organic matter. On occasion other constituents showing high water sorption or release of water on oven drying may have to be taken into account. The presence of such materials tends to displace the clay's position vertically on the chart in Fig. 2. However, constituents such as porous altered feldspar, zeolites, hydrous carbonates, etc., are usually removed as silt and sand in fractionating the clay itself. An exception may be fine diatomaceous material which, both on account of its opaline nature and finely-porous, water-retentive texture, can give substantial water losses on oven drying.

Except for soils and other surface deposits, the presence of carbonaceous matter in substantial quantities is usually confined to clay deposits which have formed in an alluvial or shallow water environment. Ball clays may contain finely divided, almost colloidal, organic matter which is often said to increase their plasticity; its main effect appears to be more in the nature of a water adsorber which increases plastic and liquid limits but not plasticity index.

The presence of free iron oxides may produce unexpected results for clays, both in plasticity and for other properties such as dry strength. Although they may impart more plasticity to a soil their effect is mainly one of increased water sorption. However, the limonitic varieties found in lateritic soils and tropical red earths are very susceptible to changes in moisture. Their spongy nature in the wet field condition encourages water sorption, but drying tends to produce marked changes in their affinity for moisture and unless an air-dry ferruginous clay is given a soaking in

contact with water, and considerable manipulation prior to testing, the full Atterberg limit values may not be reached. Sherwood (1967) discusses the effect of cementation by hematitic iron oxides in African red clay soils.

Fortunately, the presence of such material in tropical soils can usually be inferred from their strong red to brown coloration. In Britain, similar results have been obtained from red glacial clays.

## CONCLUSIONS

A simple plasticity chart is proposed as an aid to the identification of clay minerals from their Atterberg limits, and has been of particular value for the recognition of industrial clay types. It is hoped that future work will extend its use, and that the development of new preparation techniques will enable identifications to be more definitive. Ancillary information arising from the Atterberg limit tests, although largely omitted from this paper, is also proving of considerable value in assessing the clay's commercial potential in terms of useful physical properties.

## ACKNOWLEDGMENTS

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