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THE INFLUENCE OF THE COARSE FRACTION ON THE PLASTIC PROPERTIES OF CLAY SOILS

by

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ABSTRACT

The importance of the nature of the clay fraction in determining the plastic properties of soils is well known; this paper shows that the characteristics of the coarser fraction can also have an appreciable effect, and that therefore the plasticity of soils cannot be fully understood unless this effect is taken into account.

Mixtures of montmorillonite and kaolinite with coarser material were examined. It was found that when the coarse fraction consisted of glass spheres the liquid and plastic limits of the mixtures were proportional to the percentage of clay present. However, when the coarse fraction consisted of angular glass or quartz particles, higher liquid and plastic limits were generally observed. Mica, with platy particles, produced even greater increases. Small particles of coarse material produced greater effects than larger particles, but broadly graded particles gave results similar to those of comparable single-sized material. The effects were generally greater with montmorillonite mixtures than with kaolinite mixtures.

In supplementary experiments it was found that the liquid and plastic limits of a mixture of two clays are not necessarily the means of the values for the component materials.

1. INTRODUCTION

Plasticity is the most characteristic property of clay soils, and measurements of the plasticity of a soil usually give a good general indication of its other engineering properties. Because of this plasticity, along with grading, is used as the basis for the classification of soils by the method originally developed by Casagrande,[1] and the liquid and plastic limits of soils are generally measured by routine tests before they are used in road construction. A knowledge of the factors which govern the values obtained in the plasticity tests should therefore lead to a better interpretation of the test data, and so to a better understanding of the engineering behaviour of soils on site.

Although the clay mineral component of a soil is of great importance in determining its plasticity, there are other factors which may be of comparable importance in some materials. Some of these have been discussed elsewhere.[2] The various factors act simultaneously in natural soils, making it difficult to isolate their individual effects, and in addition natural soils usually contain several minerals in variable proportions. These difficulties may be overcome by examining the properties of artificially prepared mixtures.

TABLE 1

Origin, composition and specific gravity of the materials

Material	Origin	Composition*	Specific gravity‡
Kaolinite "Supreme Kaolin"	English Clays, Lovering Pochin and Co. Ltd., St. Austell, Cornwall	95 per cent well ordered kaolinite. 96 per cent finer than 2 microns	2.60
Montmorillonite "Surrey Finest"	The Fullers' Earth Union Ltd., Redhill, Surrey	95 per cent natural calcium montmorillonite. 78 per cent finer than 2 microns	2.74
Silty-sand sized crushed glass A	Produced by crushing 4 mm diameter clear lead glass Ballotini to pass B.S. No. 36 sieve	Sharply angular particles	3.00
Silty-sand sized glass spheres B	Produced by mixing together single-sized grades of clear lead glass Ballotini to make up the same grading as the crushed glass	Spheres	2.81
Natural quartz sand C	Old Sulehay Pit, Nr. Wansford, Huntingdonshire	Subangular† particles, stained with iron-oxide	2.65
Crushed quartz silty sand D	Produced by crushing sand from Leighton Buzzard, Bedfordshire, to pass B.S. No. 36 sieve and adjusting the grading to have almost equal parts of sand and silt	Angular particles, except for some of the largest which are subrounded†	2.65
Mica silt E	The fraction passing B.S. No. 200 sieve of powdered Indian muscovite	Flakes	2.80

* Details of the shape of the particles in materials A to E were determined by microscopical examination

† The shape of particles intermediate in the series angular to rounded is described as either subangular or subrounded depending on the degree to which angularity has been modified

‡ Determined by the B.S. method[3]

TABLE 2

Grading, shape and size of particles used for coarse fraction

Grading	Shape and size (mm)				
	Spheres (Glass)	Angular (Glass)	Angular (Quartz)	Natural (Quartz)	Flaky (Mica)
Broad grading	B 0.04-0.4 (30% <0.076)	A <0.42 (28% <0.076)	D <0.42 (44% <0.076	C 0.053-0.2 (10% < 0.076)	
Restricted grading: Large			F 0.076-0.42		
Small		M <0.053	G <0.076		E <0.076
Single sized: Large	H 0.3-0.4	K 0.3-0.42			
Intermediate	I 0.11				
Small	J 0.04	L 0.053-0.076			

Notes on Table 2:

For origin and composition of materials A to E see Table 1
F is the fraction of D retained on B.S. No. 200 sieve, G the fraction passing
H, I and J are single-sized grades of clear lead glass Ballotini
K, L and M are fractions separated from A by the appropriate B.S. sieves

This paper reports experiments carried out to examine the effect on soil plasticity of the characteristics of the sand and silt sized particles which comprise the coarse fraction of the soil. Tests were made on artificially prepared mixtures of pure clay minerals with sand and silt of known characteristics. The results allowed a clear idea to be obtained of the relation between the plasticity of the material and the quantity and type of clay present, and also enabled the effects of the composition and nature of the coarse fraction to be examined. In addition, the effect on their plasticity of mixing two clay materials together was briefly examined.

2. CHARACTERISTICS OF THE COARSE FRACTION

The materials and size ranges of the clays and coarse fractions used to study the various factors involved are shown in Tables 1 and 2. The effect of each coarse fraction was assessed by testing mixtures of it with two clays which were almost pure kaolinite and montmorillonite. Grading curves of the materials are shown in Fig. 1.

Particle shape may vary from spherical to sharply angular, and may also show flattening or flakiness. A study of the effect of spherical particles was made possible by using glass spheres, particles of different diameters ranging from 0.04 mm to 0.4 mm being mixed to give a suitable grading. The results were compared with those for sharply angular particles by using crushed glass with a similar grading. The most common mineral of the sand and silt ranges of natural materials is quartz. Therefore, a natural quartz sand having subangular particles (see Table 1) was examined, and compared with a crushed quartz silty sand representing the most angular form which quartz particles are likely to take. To examine the effect of flakiness, mixtures containing silt-sized muscovite mica were examined. Muscovite mica particles show an extreme degree of flattening, and sometimes occur as a major constituent of soils, often in the silt size-fraction.

In addition to particle shape, the effect of particle size and grading must be considered. The influence of particle size was examined by comparing the effect of different single-sized materials. The effect of grading was examined by comparing broadly graded materials with the other extreme of grading—the single-sized materials.

3. TEST PROCEDURE

In the standard test procedure[3] the liquid and plastic limit tests are carried out on that fraction of the soil passing the B.S. No. 36 sieve, which has a mesh aperture of 0.42 mm, so that this was the largest size of particle considered in this investigation. For each type of coarse material, mixtures were prepared containing the various required percentages by weight of "Supreme Kaolin" or "Surrey Finest" clay, (see Table 1). All components were in the air-dry condition when mixed together, due allowance being made for their air-dry moisture contents. The various components used in the mixtures had specific gravities ranging from 2.60 to 3.00 (Table 1), so that although all the mixtures were prepared with the same range of clay contents on a weight basis, some had slightly different ranges of clay contents on a volume basis. Calculations showed that the conclusions were not likely to be affected by the basis used for expressing the clay contents.

The liquid and plastic limits of the mixtures were measured by the British Standard method are are plotted against their percentage clay contents in Figs. 2-5. The curves are discussed by comparing them with the straight lines joining the origin and the values for 100 per cent clay, which are shown in the figures as broken lines, and which will be referred to in the discussion.

4. PARTICLE SHAPE AND THE LIQUID LIMIT

The effect of particle shape was studied using graded coarse fractions of glass, quartz and mica (materials A to E). In each case mixtures containing 25, 50 and 75 per cent of clay were examined, and also the pure clays.

4.1 Spherical and angular glass silty sand

The results using these almost identically graded materials (Fig. 2) showed the effect of the extremes of angularity on the influence which the coarse fraction had on the liquid limit of clay mixtures. The results for kaolin mixtures with both spherical and angular glass silty sand lay on a straight line through the origin. With montmorillonite mixtures, the glass spheres gave results close to a straight line through the origin, but for angular particles the results were considerably higher, particularly at low clay contents.

4.2 Natural and angular quartz

The natural quartz sand (Fig. 3) produced greater increases in the liquid limit of montmorillonite mixtures than the glass spheres; its effect was as large as that of the angular quartz silty sand (Fig. 4). This may be due not only to the subangular shape of the natural quartz particles, but also to roughness and other differences in their surface characteristics (see Table 1). The effect in kaolin mixtures produced by the angular crushed quartz, which was not shown by the angular crushed glass, may be accounted for by the presence of a greater proportion of material in the silt size-fraction (see Fig. 1); the effect of this will be discussed later.

4.3 Mica flakes of silt size

Mica provided a material having an extremely flattened particle shape. No plastic or liquid limits could be measured for the mica itself, but mixtures containing this mineral had extremely high liquid limits (Fig. 5). This effect was not accounted for by the silt-size grading of the mica, as can be seen by comparing the results with those for angular glass silt M and angular quartz silt G, which are shown in the same figure.

5. PARTICLE SIZE AND GRADING AND THE LIQUID LIMIT

The influence of particle size on the effect which the coarse fraction of the soil has on the liquid limit was studied by using glass and quartz particles of single sizes and of restricted gradings.

5.1 Spherical and angular single-sized glass particles

Mixtures of montmorillonite containing 75 per cent of single-sized glass particles (materials H to L) showed that as the particle size of the glass was reduced the liquid limit of the mixture increased (Fig. 6). This was true for both spherical and angular particles. The effect was not so apparent in kaolinite mixtures. The effect of angularity in increasing the liquid limit of mixtures is also shown. When the results for the mixtures containing 75 per cent of single-sized materials are compared with those for similar broadly graded materials (Fig. 2) it is seen that the values of the liquid limits and plastic limits for the broadly graded materials lie within or very close to the range of values given by the single-sized materials.

5.2 Angular quartz sand, and angular quartz silt

Mixtures of montmorillonite containing 50 per cent of angular quartz of restricted grading showed (Table 3) that silt-sized coarse material G gave mixtures of higher liquid limit than sand-sized coarse material F. These silt-sized and sand-sized materials were obtained by separating angular quartz silty sand D on a No. 200 B.S. sieve, and a mixture containing this silty sand had a liquid limit which lay between those obtained using the two fractions derived from it. This particle size effect was not seen with kaolinite mixtures.

6. PLASTIC LIMIT AND PLASTICITY INDEX

The effect of the characteristics of the coarse fraction on the plastic limit of the mixtures was generally similar to its effect on the liquid limit (see Figs. 2-5).

Figure 7 shows the plasticity index plotted against the clay content for mixtures of montmorillonite and kaolinite with various types and proportions of coarse fraction. For kaolinite mixtures the points fall fairly close to a line joining the origin to the point for 100 per cent kaolinite. In the case of montmorillonite mixtures the points were displaced from a similar line to somewhat higher values, but to a first approximation could still be represented by a linear relation passing through the origin. This shows that the results are generally consistent with the concept[4] that the activity (the ratio of the plasticity index to the percentage clay-sized material) is constant for any one soil type. The results also indicate that, in addition to the effect of clay mineral type, the character of the coarse fraction of a soil may produce small variations in activity especially in the case of montmorillonite mixtures. Mixtures containing mica were an exception, showing greater variation of activity with clay content.

7. THE PLASTICITY OF MIXTURES OF DIFFERENT CLAY MATERIALS

The discussion has so far been concerned with mixtures having a single clay mineral. However, the clay fractions of natural soils frequently contain more than one clay mineral, so that it is important to know the relation between the plastic properties of a mixture of clay minerals and those of the individual components.

Figure 4 shows the liquid limits of mixtures containing equal parts of montmorillonite and kaolinite, together with various proportions of crushed quartz silty sand. The liquid limit results related closely to a straight line through the origin, but lay closer to the results for pure kaolinite than to those for pure montmorillonite, showing that the two clays when mixed together did not behave by simple addition. Except at the lowest clay content, the plastic limits for the mixtures (which are also shown in Fig. 4) did not lie between those for the pure clays, but were below the values for kaolinite, again showing that the two clays when mixed together did not act by simple addition.

To investigate this effect more fully, mixtures of montmorillonite and kaolinite in different proportions were examined without the addition of coarse material. Figure 8 shows that the liquid and plastic limits of the mixtures fell below the straight line relation that would be expected if each clay acted independently of the other.

8. DISCUSSION

If the coarse fraction played no part in determining the liquid limit of clay mixtures other than as a diluent of the clay fraction, so that the liquid limit of the mixture was reached when just enough water was present to bring the clay fraction to its liquid limit, then the relation between liquid limit and clay content would be a straight line through the origin and the value for 100 per cent clay. This relation and that for the plastic limit are shown in Figs. 2-5 by the broken lines. Properties of the coarse fraction which impart a resistance to deformation will tend to produce an increase in the liquid limit above the values shown by the broken lines, as was shown in the experiments. Some of the factors which would be expected to affect the liquid limit of a mixture containing a particular ratio of clay to coarser non-clay material are as follows:

(a) Resistance of the clay-water phase to deformation.

Decreases as moisture content increases.

Decreases (for a particular moisture content) as liquid limit of clay decreases.

(b) Resistance of the coarse phase to deformation.

(i) due to sliding resistance of points of contact between particles.

Decreases as closeness of packing matrix decreases, i.e. as moisture content increases.

(ii) due to difficulty of geometrical re-arrangement of particles during deformation, arising from the resistance both of neighbouring particles and of the clay-water matrix.

Decreases as closeness of packing decreases, i.e. as moisture content increases.

Decreases as stiffness of clay-water matrix decreases, i.e. as moisture content increases.

Decreases in series: platy-angular-spherical.

TABLE 3

The effect on liquid and plastic limits of the particle size of crushed quartz in 1 : 1 mixtures with clay minerals

Composition of the coarse fraction	Composition of the clay fraction			
	Montmorillonite		Kaolinite	
	Liquid limit per cent	Plastic limit per cent	Liquid limit per cent	Plastic limit per cent
Crushed quartz sand F	78	28	44	22
Crushed quartz silty sand D	82	28	44	22
Crushed quartz silt G	90	26	45	23

These factors are consistent with the following experimental observations on mixtures of clay with coarser materials, and account for many of them.

(1) Glass spheres added to montmorillonite produced very little increase in the extra water required to bring the mixture to its liquid or plastic limit, while angular glass and natural and angular quartz particles produced considerable increases.

The liquid and plastic limit results for mixtures of glass spheres with montmorillonite lie on or close to the broken lines through the origin (Fig. 2), suggesting that the glass spheres are playing little part in determining the liquid limit of the mixtures. When the coarse fraction was composed of angular particles of crushed quartz (Fig. 4) relatively higher liquid limit values were obtained; i.e. when enough water has been added to the mixture to bring the clay component to the liquid limit the material does not flow, and more water has to be added to overcome the rigidity imposed on the mixture by the coarse fraction. Results of a similar magnitude were obtained with mixtures of crushed glass and montmorillonite (Fig. 2), and also with natural quartz sand (Fig. 3), in which the particles were not so sharply angular as in the crushed quartz, but may have had rougher surfaces, which could be expected to contribute to the effect.

(2) The amount of extra water required to bring mixtures to the liquid or plastic limit generally increased proportionally with the percentage of coarse fraction present.

(3) Similar but smaller effects were obtained with mixtures of coarse material with kaolinite.

This shows that the composition of the clay fraction also influences the amount of extra water required.

(4) Mica, with platy particles, produced very great increases in the liquid and plastic limits.

The very large amount of extra water required by the mixtures of mica and clay to bring them to their liquid or plastic limits (Fig. 5) can be thought of as being due to the flaky particles of the mica forming an interlocking structure which has to be separated and lubricated with clay and water before the mixture can be made plastic. The surface properties of the mica particles and their interaction with the fine clay minerals may play a part in the formation of this structure.

(5) The activity of kaolinite mixtures was more or less independent of the mixture proportions, but with montmorillonite mixtures the coarse fraction produced small increases in the activity. Mica was exceptional in producing larger effects (Fig. 7).

(6) Small particles produced greater increases in the liquid and plastic limits than large particles.

Additions both of glass spheres and of crushed glass or quartz had more effect on the liquid limit of montmorillonite when they were of finer grading (Fig. 6, Table 3). Any adsorption of water on the surface of the glass or quartz particles will reduce the effective moisture content of the clay fraction, and will therefore tend to increase the liquid limit. Small particles will tend to have a greater effect than large ones, due to their higher specific surface area. However, the calculated specific surface areas for glass or quartz spheres of diameter 0.04 mm and 0.002 mm are approximately 0.05 m^2/g and 1 m^2/g, and the smallness of these areas compared with the range of total surface areas reported for montmorillonite (210-595 m^2/g)[5] shows that this mechanism cannot account for the observed effects.

(7) Broadly graded particles gave results similar to those of comparable single-sized particles.

(8) In the case studied, the liquid and plastic limits of mixtures of two clays were not in simple proportion to the values for the two components.

This observation was made on mixtures of montmorillonite and kaolinite with and without the addition of a coarser fraction (Figs. 4 and 8).

It may be concluded that the plastic properties of clay soils cannot be fully understood unless the influence of the characteristics of the coarse fraction is taken into account. However the magnitude of this influence is of practical significance only when the coarse fraction either comprises the major part of the soil, or is of very fine particle size, or consists of mica.

9. REFERENCES

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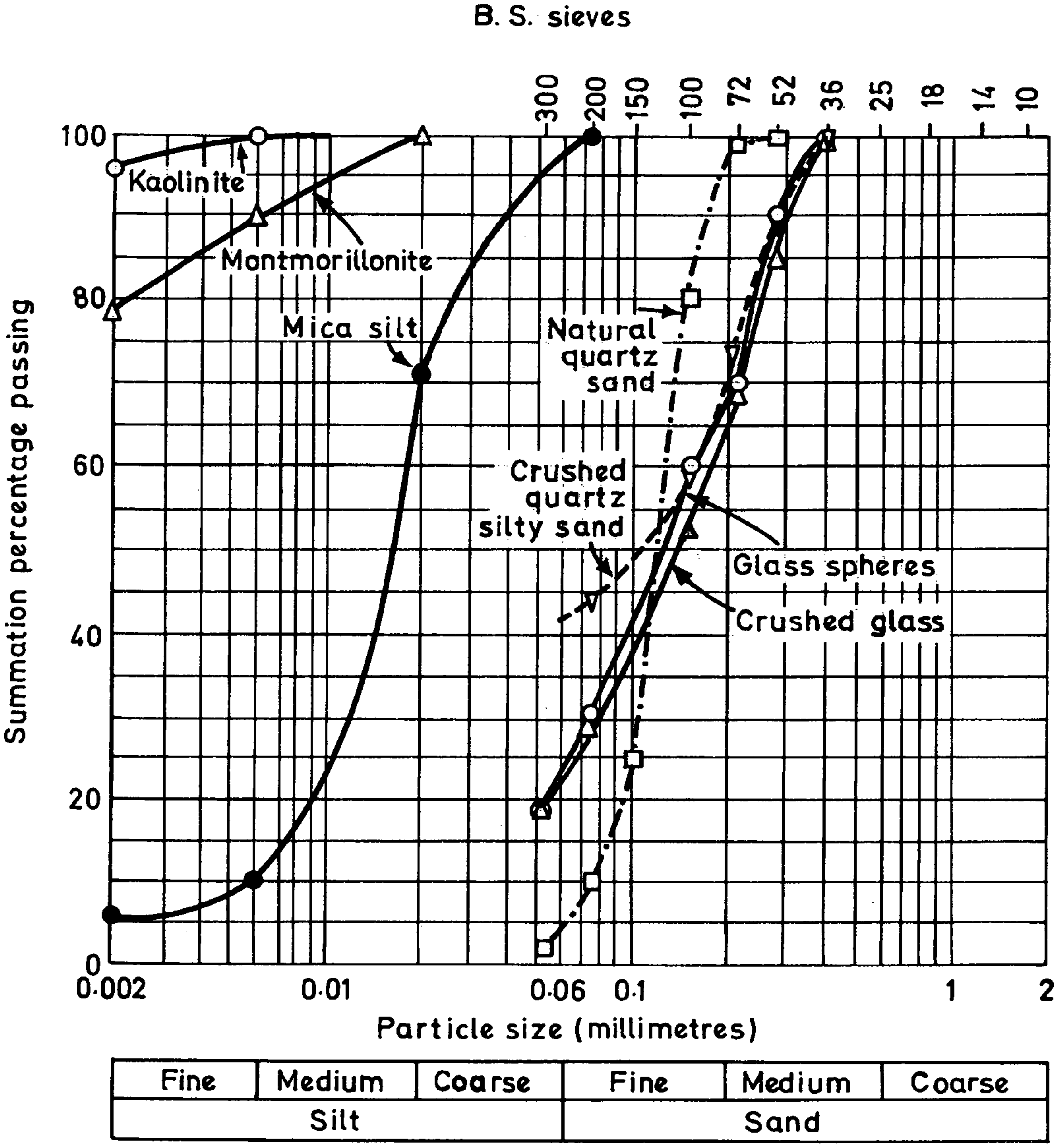

Fig. 1. GRADING CURVES FOR THE MATERIALS

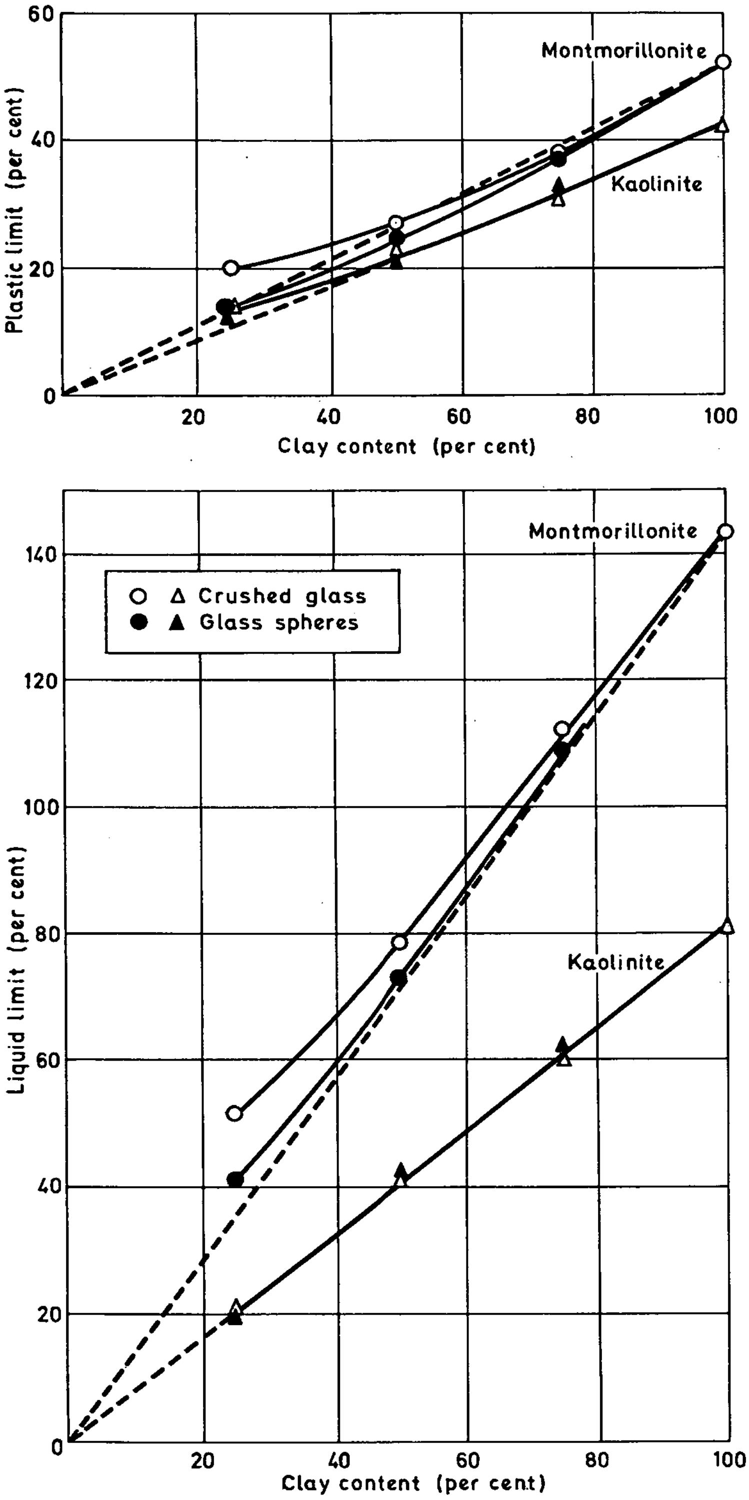

Fig. 2 RELATION BETWEEN CLAY CONTENT AND PLASTIC AND LIQUID LIMITS FOR MIXTURES OF CLAY MINERALS WITH SILTY-SAND SIZED GLASS OF DIFFERENT PARTICLE SHAPES

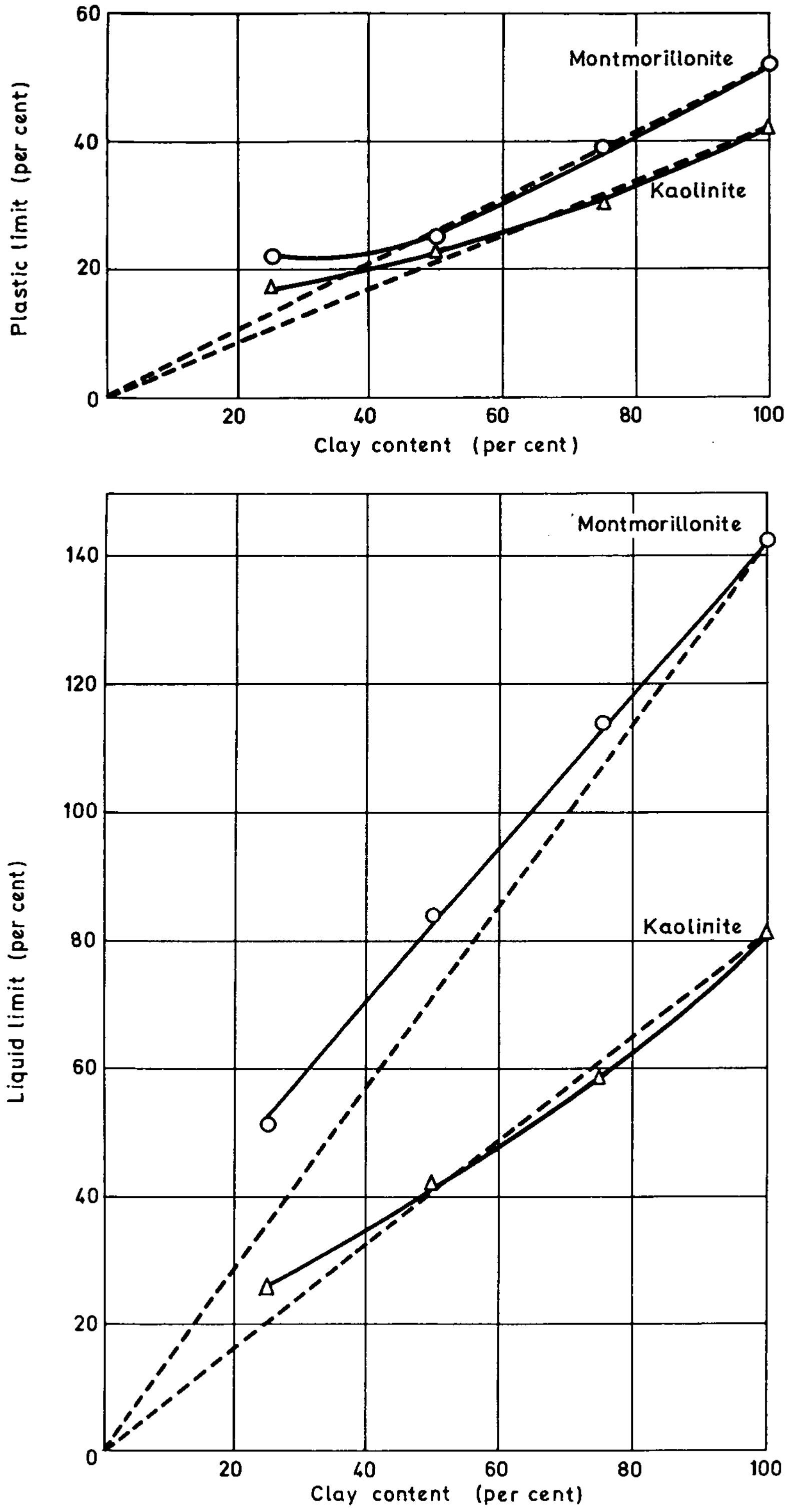

Fig. 3. RELATION BETWEEN CLAY CONTENT AND PLASTIC AND LIQUID LIMITS FOR MIXTURES OF CLAY MINERALS WITH NATURAL QUARTZ SAND

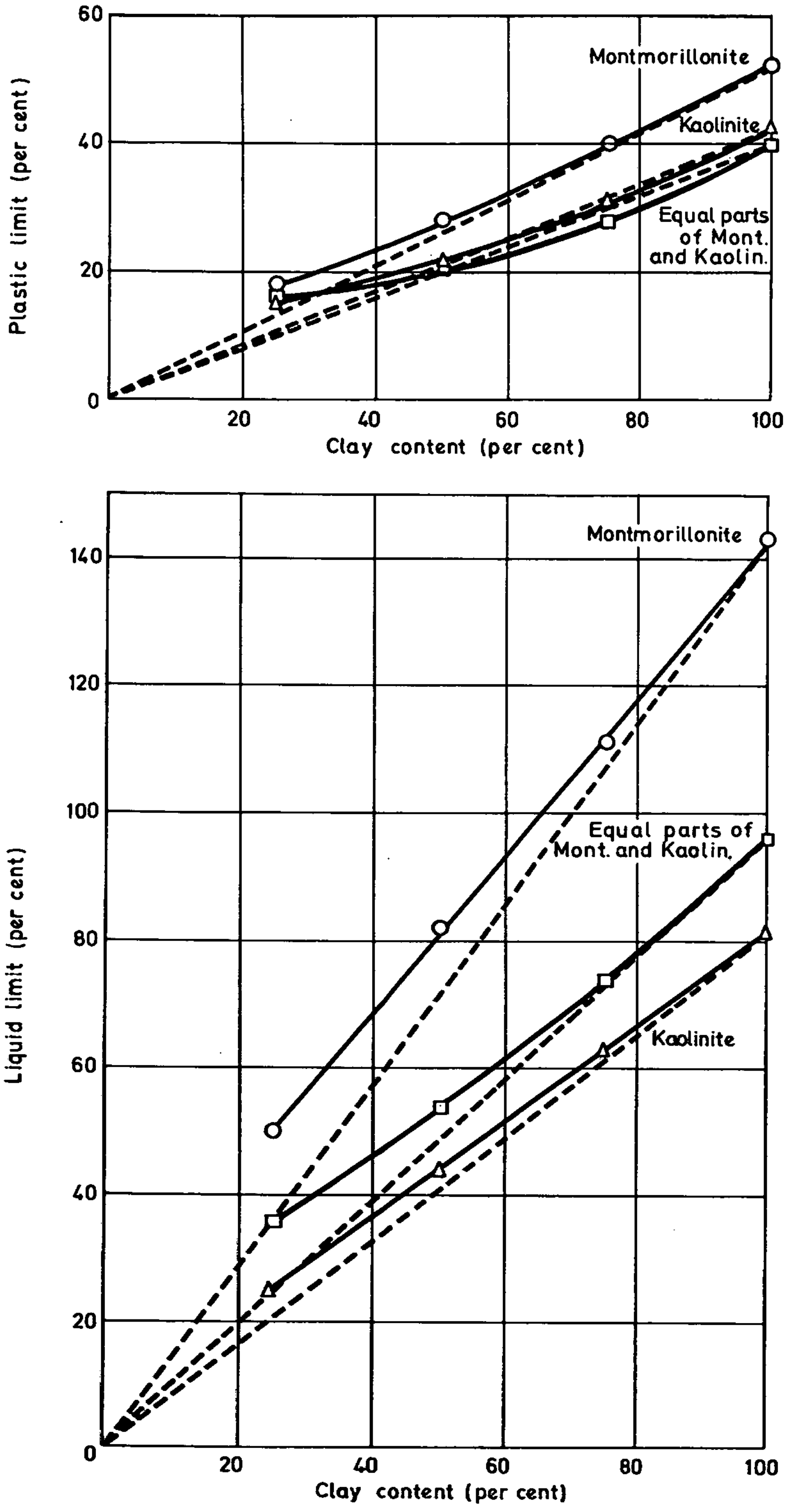

Fig. 4. RELATION BETWEEN CLAY CONTENT AND PLASTIC AND LIQUID LIMITS FOR MIXTURES OF CLAY MINERALS WITH CRUSHED QUARTZ SILTY SAND

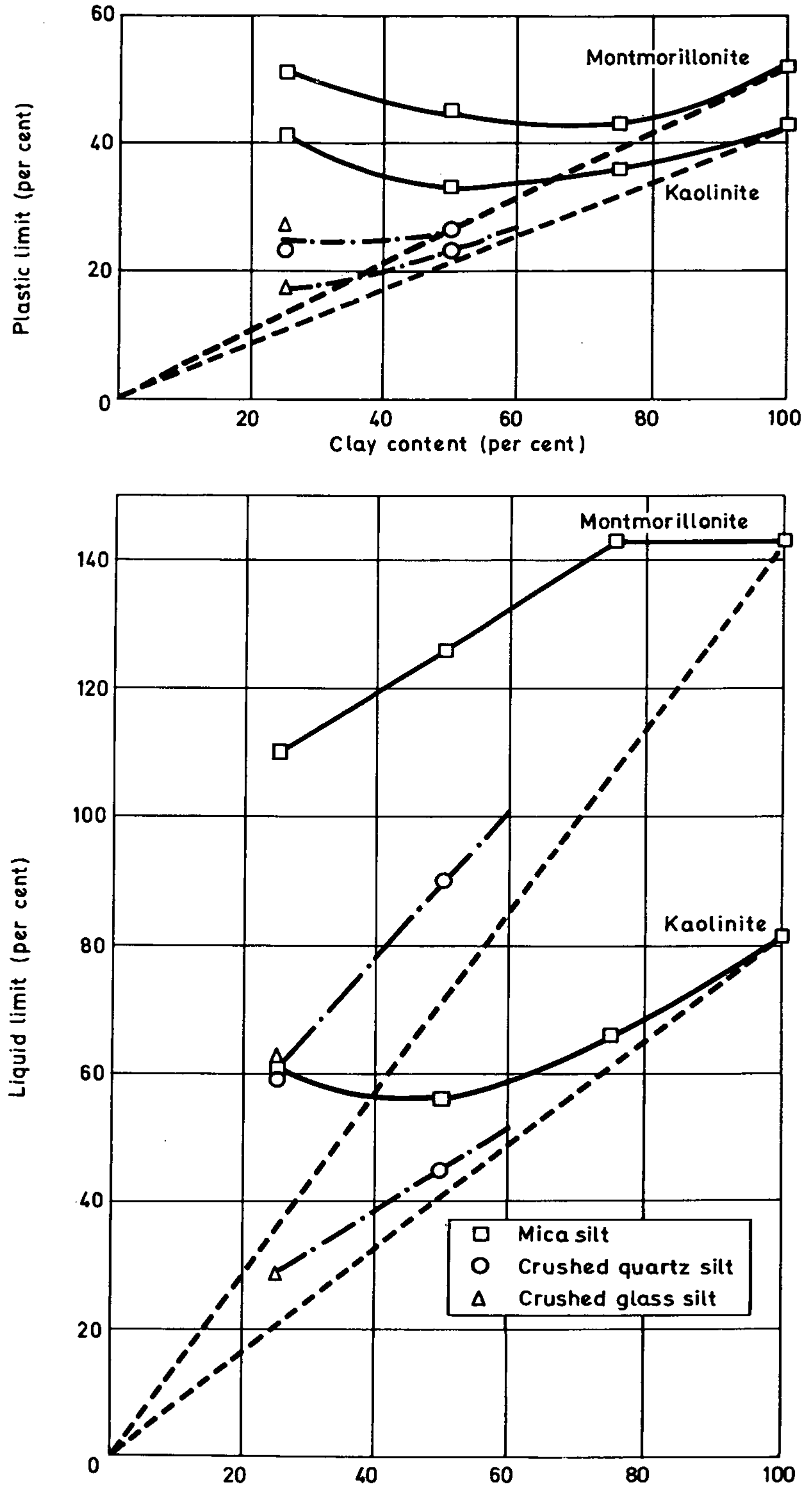

Fig. 5. RELATION BETWEEN CLAY CONTENT AND PLASTIC AND LIQUID LIMITS FOR MIXTURES OF CLAY MINERALS WITH MICA SILT (AND OTHER SILTS SHOWN FOR COMPARISON)

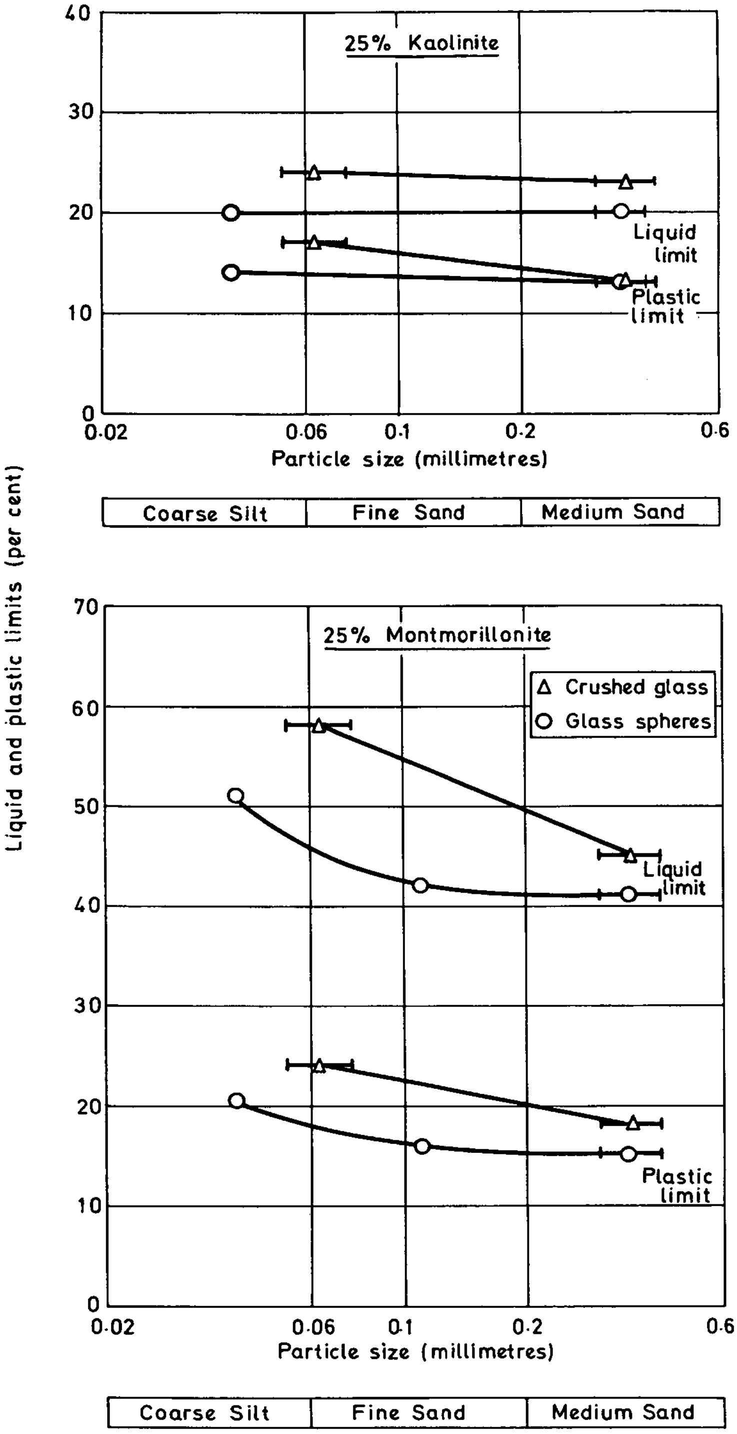

Fig. 6. THE EFFECT ON LIQUID AND PLASTIC LIMITS OF THE SIZE AND SHAPE OF GLASS PARTICLES IN MIXTURES WITH CLAY MINERALS

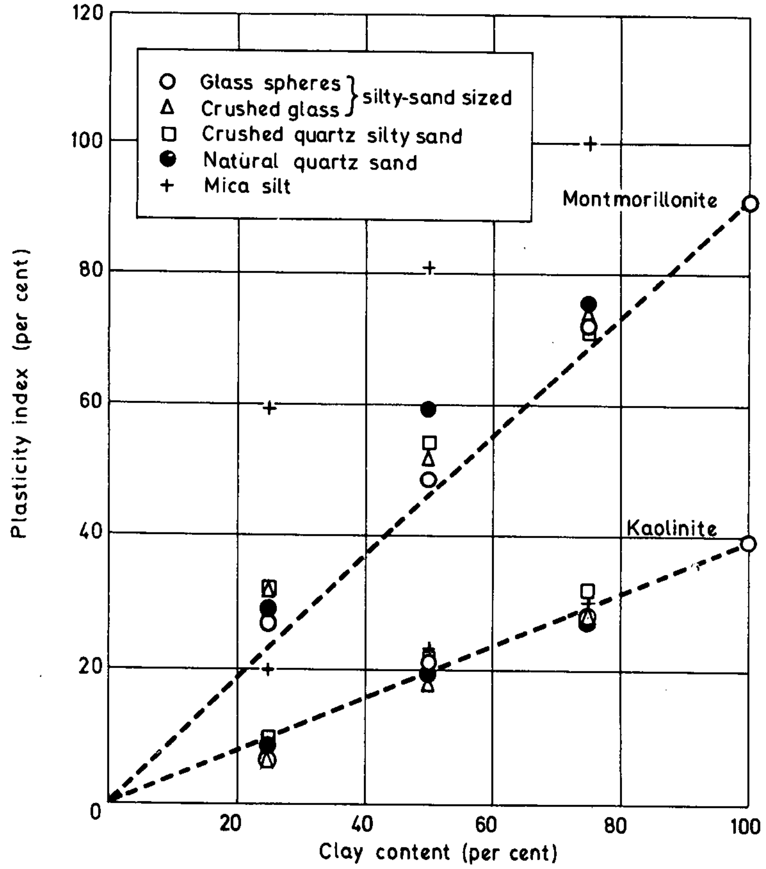

Fig. 7. RELATION BETWEEN PLASTICITY INDEX AND CLAY CONTENT FOR MIXTURES OF CLAY MINERALS WITH DIFFERENT COARSE FRACTIONS

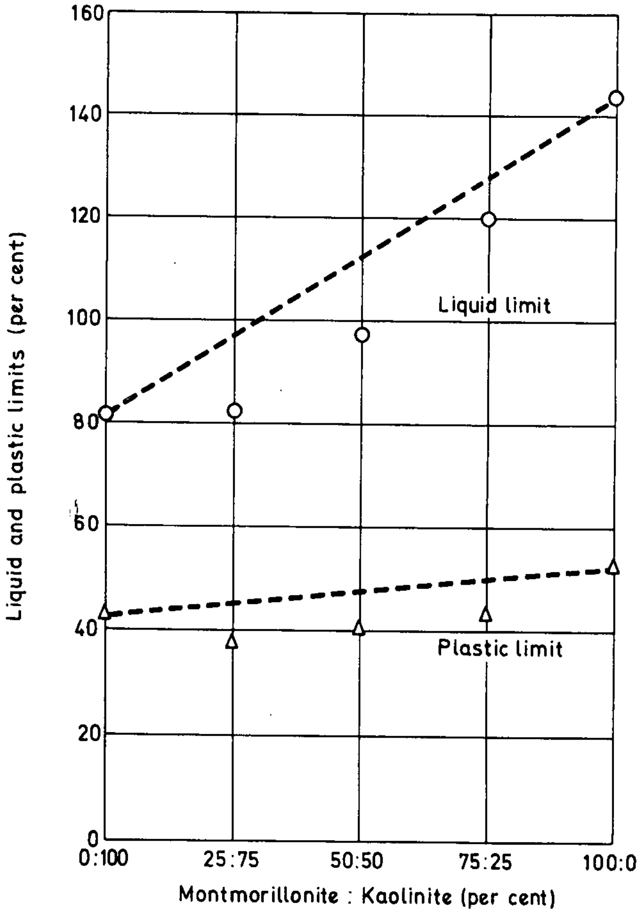

Fig. 8 RELATION BETWEEN CLAY COMPOSITION AND LIQUID AND PLASTIC LIMITS FOR MIXTURES OF MONTMORILLONITE AND KAOLINITE

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