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FABRIC OF CONSOLIDATED KAOLINITE

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Abstract—Fabric refers to the spacial arrangement of clay particles in a sample relative to a reference plane. X-ray diffraction data yield an 'amount of orientation' (*AO*) that varies from zero for ideal random to 100 for ideally oriented fabric. The *AO* has been related to the average angle of inclination of clay particles to the reference plane.

Fabric data from 50 samples involving 2000 determinations are presented on the effects of: the method of sample preparation prior to one-dimensional consolidation; the magnitude of consolidation stress from 0·1 to over 1000 kg/cm^2; changes in direction of consolidation stress; isotropic consolidation; and disturbance during removal of samples from oedometer cells. The single most important variable was the method of sample preparation, as illustrated by the following data on samples consolidated one-dimensionally to 1·5 kg/cm^2:clay initially moist, $AO = 27$ per cent; air-dry clay, $AO = 44$ per cent; clay slurries, $AO = 76$–95 per cent. The change in fabric with increasing consolidation stress was most pronounced with samples at very low stresses, the changes in fabric were small for consolidation stress increments usually encountered in engineering practice.

Fabric data provide a very sensitive measure of sample disturbance. Extrusion causes significant disturbance at the center of a 24 cm dia. sample cylinder.

INTRODUCTION

Many aspects of the engineering behavior of cohesive soils have been explained by various authors (van Olphen, 1951; Lambe, 1960; Seed and Chan, 1961; Olsen, 1960; Mitchell, 1964; Olson and Mesri, 1970) in terms of the 'structure' of the clay phase. Structure is the combination of the geometrical arrangement of particles and the forces operating between them. The geometrical arrangement of particles and associated voids is called 'fabric' and is the component of structure that is most amenable to measurement. Since the structure concept has been invoked to explain so many features of clay behavior, a reliable quantitative method for determining the fabric of clay is extremely important.

Martin (1962) described a method for quantitative fabric measurement of wet clay samples. The technique is: (1) impregnate the wet clay with polyalcohol, (2) grind a flat surface and (3) examine the surface by X-ray diffraction with a diffractometer equipped with a Schulz pole figure device for measuring the amount, direction, and variability in particle orientation within the clay mass. The objective of the present discussion is to present some refinements concerning the validity of the method and its quantitative expression followed by observations on fabric change resulting from (1) variation in initial clay preparation, (2) sample disturbance and (3) one-dimensional consolidation.

The results reported herein entailed more than 50 engineering-sized samples upon which over 2000 individual fabric measurements were made.

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PROCEDURE

The complete method from impregnation through XRD data collection has been thoroughly treated previously (Martin, 1966) and is only briefly reviewed here. Specimens for XRD examination are prepared from Carbowax 6000 (Union Carbide Corp.) impregnated samples. $\beta = 0$ specimens have the surface to be examined by XRD cut normal to the direction of the first major stress application. Usually, a $\beta = 0$ specimen means XRD data from the horizontal plane. Peak ratio, *PR*, is defined as net peak amplitude of 002 kaolinite peak divided by net peak amplitude of 020 kaolinite peak both measured at a fixed tip angle, ϕ. The peak ratio, *PR*, is a measure of the amount of orientation. Figure 1 shows the pole figure device motions which permit accurate measurement of the angle of maximum orientation relative to the specimen surface. The angle of maximum orientation is obtained from a series of tip curves, ϕ, in which the specimen rotates around the XX'-axis with the detector set on the 2θ position of the 002 kaolinite peak. The curve generated, intensity vs tip angle ϕ gives the angular distribution of diffracted intensity about the z-axis for a selected azimuth angle, α. Another measure of the amount of orientation is defined by *W*, which is the width of the tip curve in degrees ϕ measured at one half the maximum amplitude of that particular tip curve.

Numerous tests were performed by Martin (1962, 1966) to confirm that the procedure for impregnating wet clay with Carbowax and grinding a flat surface does not disturb measurably the fabric of the original wet clay mass. The following test further confirms the validity of the method.

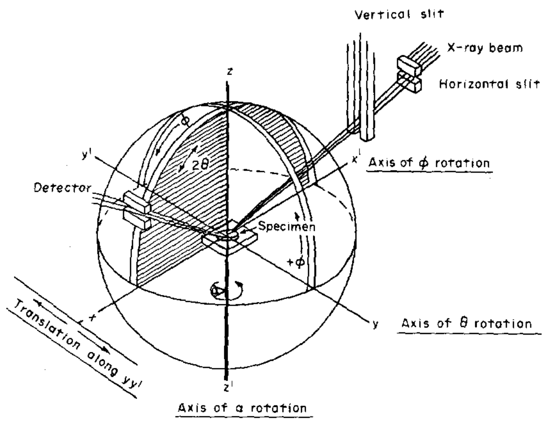

Fig. 1. Movements for pole figure diffractometer.

Thin sections across shear zones when viewed with polarized light show the same orientation bands whether the thin section is 50 or 10 μm thick. The *PR* on specimens with uniform fabric remains unchanged from a specimen thickness of 7 mm down to a specimen thickness of 20 μm (the absolute intensities progressively decrease when the thickness becomes less than 100 μm, but not the *PR*). The above X-ray data indicate that any surface smearing resulting from the preparation technique is insignificant for two prepared surfaces more than 20 μm apart. The microscope observations indicate that surface smearing is insignificant for two smeared surfaces 10 μm apart.

All tests were done with kaolinite clay (Peerless No. 2, R. T. Vanderbilt Co.). The grain size distribution of the clay was 90 per cent finer than 10, 60 per cent finer than 2 and 45 per cent finer than 1 μm. The Atterberg limits were: liquid limit = 58 per cent, plastic limit = 28 per cent, plasticity index = 30 per cent. The s.g. equalled 2·65. Unless otherwise specified the clay was used without any pretreatment. A generalized consolidation curve covering the stress range of interest is given in Fig. 4(B).

PHYSICAL MEANING OF PEAK RATIO

The peak ratio (*PR*) is a quantitative numerical measure of orientation for the tip angle ϕ at which the measurement is made. For one-dimensionally consolidated samples, the maximum observed *PR* consistently occurs at a tip angle very close to the direction in which the major stress was applied. An index for the amount of orientation (*AO*) is given in terms of the observed *PR* at the tip angle which gives the maximum 002 amplitude of the ϕ curve and the observed *PR* for a truly random sample:

$$AO = \left[\frac{PR_{\text{obs}} - PR_{\text{random}}}{PR_{\text{obs}}}\right]_{\phi\,\max} \times 100. \quad [1]$$

The *AO* is defined in such a way that the amount of orientation in a random sample is numerically zero and in an ideally oriented sample approaches 100 per cent.

It has been shown (Martin, 1966) that a $PR = 2{\cdot}0$ is truly ideal random for kaolinite and that this can be achieved experimentally; thus *PR* random in equation (1) equals 2·0. The maximum *PR* obtained experimentally has been 400, which corresponds to an $AO = 99{\cdot}5$ per cent.

Ideally, random fabric is usually visualized as the situation where the average orientation of the basal planes of one particle relative to its neighbors is at an angle of 45° which implies that all possible orientations are present in equal abundance. Ideal orientation, at the other extreme, is where the angle between the basal plane of one particle and its neighbors is zero. With the aid of the pole figure device, this distribution of particles about the pole of the maximum orientation direction is measurable experimentally. Martin (1966) defined a function *W* which is a measure of the distribution of particles about the pole of maximum orientation. This function *W* is the width of the tip curve in degrees measured at the one half maximum amplitude position. Experimentally, *W* varies from 105°–110° for random samples and from 21°–23° for the maximum orientation possible to achieve with Peerless No. 2 kaolinite. Based upon X-ray diffraction data obtained on single flakes of muscovite and chlorite (assumed to have 'ideal' orientation) Martin (1966) showed that the theoretical *W* for ideal orientation of kaolinite would be 20°.

With this information, it is now possible to set up an expression in terms of *W* that will give an average inclination angle of 45° for random and 0° for ideal orientation. The expression is:

$$\text{Average inclination angle} = \frac{W_{\text{obs}} - 20}{2}. \quad [2]$$

The 20 comes from the theoretical ideal orientation calculated for kaolinite employing experimental data for ideal oriented single flakes of muscovite and chlorite. Since the experimental width of tip curve W_{obs} includes both plus and minus ϕ angles, the expression is divided by 2 to give the average inclination angle. The upper limit of experimental W_{obs} for random kaolinite is 110°, which upon substitution in equation (2) gives an angle of 45° for random. The minimum value of *W* experimentally obtained on the best oriented samples was 21° ϕ, yielding an average inclination angle of only 0·5°.

Figure 2 shows a plot of *AO* vs average inclination angle for 24 different kaolinite samples covering a wide range of consolidation pressures and preparation techniques. It would appear that a linear scale for *AO* from 0–100 per cent is a reasonable approximation for expressing orientation that is consistent with the physical concept of particle arrangement as described above.

EFFECT OF PREPARATION AND HANDLING

General

Before discussing fabric data for different amounts and types of consolidation, the sensitivity of fabric to changes in sample preparation and handling is examined. Two specific variables are considered: placement

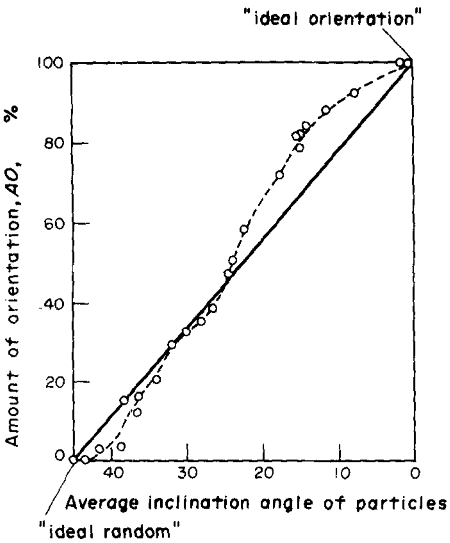

Fig. 2. Amount of orientation vs average angle of inclination between particles.

condition and amount of sample disturbance. The latter includes a discussion of sample heterogeneity.

The placement condition is determined by the combination of the water content, w, of the clay and the method of placement of the clay in the consolidation cylinder. A 'slurry' is a mixture of saturated clay at any water content, above the liquid limit, which has been mechanically mixed. Slurries with a wide range of water contents were placed by pouring into the consolidation cylinder. The slurry water content at which a demarcation line forms between sediment volume and supernatant liquid depended upon the water content of the slurry and also the mechanical mixing energy and any chemical pretreatment.

At the other extreme, 'air dry' clay was carefully placed in successive 1 in. layers until the cylinder contained the desired weight of clay. Air dried kaolinite had a water content of about 0·7 per cent. An intermediate condition, designated 'wet-up', was obtained in the following manner. A air dry preparation, as just described, was allowed to imbibe water very gradually through the bottom porous stone until the entire clay mass appeared moist. At this time the water level was very slowly raised (5 mm/hr) until free water appeared over the top of the clay. This wet-up procedure gave an initial water content between 100 and 120 per cent.

The oedometer cylinders for slurry and wet-up samples had diam. of 7·62 and 24·1 cm with sample heights, after initial consolidation, of $3{\cdot}8 \pm 0{\cdot}5$ cm and $12{\cdot}7 \pm 1$ cm respectively. Air dry samples were prepared in the small oedometer.

Preparation condition

The major influence of preparation procedure on fabric was the initial water content. Figure 3 shows a wide range in the peak ratio or amount of orientation for different water contents at the time of preparation. The decrease in void ratio, e, for each condition was produced by increasing the consolidation stress.

The $w = 5600$ per cent slurry curve of Fig. 3 contains differences in consolidation stress and in chemical treatment. All the $w = 5600$ per cent slurries were strongly flocculated slurries produced by washing the clay with acidified NaCl and then removing the free salt. The slurry which gave $e = 5{\cdot}6$ had a polyelectrolyte aggregate added to increase further the flocculation while the slurries which gave $e = 1{\cdot}0$ and $1{\cdot}55$ had a sodium chloride solution (0·5 N) added to reduce flocculation slightly.

In Fig. 3, for a constant amount of orientation, AO of 73 per cent ($PR = 7{\cdot}4$) the void ratio range is 0·18 to 5·6. For a constant void ratio 1·2, the AO range is from 50–95 per cent ($PR = 4$–44). Obviously, there is no unique relation between the amount of orientation and void ratio. Although the angle of orientation was not measured in every case, it should be noted that all measurements were on $\beta = 0$ surfaces at $\phi = 0$, which is for all practical purposes identical to the angle of maximum orientation for one-dimensionally consolidated samples.

Table 1 shows fabric variations for different initial conditions where all samples were consolidated one dimensionally to $1{\cdot}5\ \mathrm{kg/cm^2}$. The most significant point shown by the data in Table 1 is that the water content at the time of initial placement is very important. This is evident by comparing the fabric of the wet-up and air-dried samples which had the same water content as initially placed and that adding water (wet-up sample) had no effect on AO upon subsequent consolidation to $1{\cdot}5\ \mathrm{kg/cm^2}$. Also, for slurries, the water content of the slurry influences AO to a larger degree than the chemical treatment used.

Sample heterogeneity and disturbance

Sample heterogenity represents scatter in the data above the variation due to the total experimental error

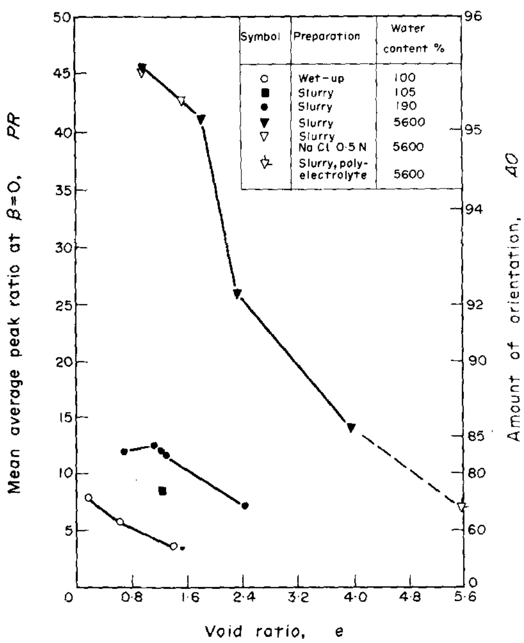

Fig. 3. Peak ratio and amount of orientation for different kaolinite samples consolidated to different void ratios.

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Table 1. Initial water content and fabric after consolidation to 1·5 kg/cm^2

Preparation*	Water content (%) before consolidation	Void ratio e	$\overline{PR}$ on $\beta = 0$	AO %†
Slurry	400	—	14·6	86
Slurry	190	1·38	11·6	83
Slurry‡	105	1·25	8·5	76
Wet-up	120	—	3·5	43
Wet-up	100	1·43	3·6	44
Air-dry	0·7	—	3·6	44

* See text for details.
† Amount of orientation as defined by equation (1).
‡ Slurry dispersed by adding Na_2CO_3 solution to give an equilibrium pH of 7·3 to the slurry.

in data reproducibility. The reproducibility of data is influenced by instrument factors and sample preparation procedures. A check on the instrument, including alignment of an impregnated clay specimen, was established from data on PR variations measured on identical surfaces of four different specimens over a period of one year. The results showed that the coefficient of variation (100SD/$\overline{PR}$) never exceeded 10 per cent. Therefore coefficients of variation exceeding 10 per cent are a measure of sample heterogeneity.

Initial studies showed that the vertical variation in PR through the 3·8 cm height of a 7·6 cm dia. sample consolidated one-dimensionally to 1 kg/cm^2 was extremely variable. The top section of Table 2 contains data for samples that were all prepared from slurries with w = 190 per cent and consolidated to 1 kg/cm^2. Following consolidation, the bottom platen was removed and the clay sample extruded by forcing the consolidation piston through the cylinder. The $\overline{PR}$ value for each sample given in Table 2 represents 12–50 separate surfaces taken at different vertical locations along the vertical centerline of the cylinder. The coefficient of variation is so large that there is a two-fold change in the mean value of PR, $\overline{PR}$, between samples. Even the samples with the least percent variation show a heterogeneity that is statistically significant at better than the 95 per cent confidence level. Martin (1966) suggested that the variation arose, in part at least, from sample disturbance during extrusion from the 7·6 cm dia. cylinder. The remainder of Table 2 provides data for examining the effects of sample disturbance.

All samples extruded from the 24 cm dia. cylinder (I, II, IV, and VI) are heterogeneous, showing coefficients of variation from 14–26 per cent. It is to be noted that there is no statistical difference in coefficient of variation between the slurry and wet-up preparations. Therefore, all other things being equal, one would not expect any difference in heterogeneity between slurry and wet-up preparations in a 7·6 cm dia. cylinder. By contrast with sample VI, which is very definitely heterogeneous at the level of measurement, sample V, which was carefully cut from the 24 cm dia. cylinder, has a very homogeneous fabric at the level of measure-

Table 2. Effect of removal method on fabric

No.	Preparation	Cylinder dia.	Removal method*	$\bar{\sigma}_c$ (kg/cm^2)	$\overline{PR}$† on $\beta = 0$	Amount of orientation (AO)	Coefficient of variation‡
1	Slurry, w = 190%	7·6	E	1·0	8·6	76·7	22
3	Slurry, w = 190%	7·6	E	1·0	23	91·3	23
4	Slurry, w = 190%	7·6	E	1·0	19	89·5	73
5	Slurry, w = 190%	7·6	E	1·0	10·1	80·2	50
6	Slurry, w = 190%	7·6	E	1·0	13	84·6	85
7	Slurry, w = 190%	7·6	E	1·0	9·2	78·3	22
8	Slurry, w = 190%	7·6	E	1·0	11·1	82·0	34
20	Slurry, w = 190%	7·6	C	0·06	7·0	71·4	12
I	Slurry, w = 190%	24	E	1·5	11·5	82·6	15
II	Slurry, w = 190%	24	E	1·5	11·8	83·0	17
IV	Wet-up	24	E	1·5	3·11	35·7	26
VI	Wet-up	24	E	1·0	3·38	40·8	14
V	Wet-up	24	C	1·0	3·64	45·0	4·8
25	Wet-up, under vac.	7·6	C	1·0	4·17	52·0	5·0
26	Wet-up, under vac.	7·6	C	1·0	4·00	50·0	9·1
27	Wet-up, air	7·6	C	1·0	3·53	43·3	5·4
28	Wet-up, air	7·6	C	1·0	3·51	43·0	8·3

* E = extruded, C = cut from cylinder. See text for details.
† $\overline{PR}$ on $\beta = 0$ surfaces at vertical centerline of cylinders.
‡ Coefficient of variation = 100 SD/$\overline{PR}$.

ment. Samples cut from the 7·6 cm dia. cylinder (Nos. 25–28) are also homogeneous within the level of measurement.

Sample No. 20 cut from a 7·6 cm dia. cylinder after consolidation to only 0·06 kg/cm^2 shows about half as much variation in *PR* as the least heterogeneous sample consolidated to a much higher consolidation stress, but extruded from the 7·6 cm dia. cylinder. In fact, sample No. 20 shows less variation in *PR* than slurry samples extruded from a 24 cm dia. cylinder. This is particularly significant when one realizes that all fabric data from the 24 cm dia. samples given in Table 2 were taken from the axial center of the sample.

In summary, all the evidence strongly suggests that kaolinite consolidated to as much as 1·5 kg/cm^2 is severely disturbed throughout the clay mass during extrusion from a cylinder as large as 24 cm in dia.

EFFECT OF CONSOLIDATION

The effect of one-dimensional consolidation on fabric was implied by the data already presented in Fig. 3. In the present section, the effect of one-dimensional compression where there is no change in direction of major stress application throughout the sample history will first be presented. Then the effect on fabric of a change in direction of consolidation will be discussed. Finally, the fabric produced by anisotropic stresses due to one-dimensional compression will be compared to that produced by an isotropic state of stress.

One-dimensional consolidation with no change in direction of major stress application ($\bar{\sigma}_c$ perpendicular to $\beta = 0$ surface) corresponds to a normally consolidated sediment prior to any tilting or folding of the sediment formation. Under these conditions, consolidation would be expected to produce orientation because of the highly anisotropic shape of clay particles. Figure 4(A) shows the increase in amount of orientation (*AO*) as a function of consolidation stress, $\bar{\sigma}_c$, for various preparation conditions. Every point in Fig. 4(A) represents the mean *PR* for between 8 and 40 different surfaces all normal to $\bar{\sigma}_c$; i.e. $\beta = 0$ surfaces, on the particular sample under investigation. The data in Fig. 4(A) again point out the great importance of sample preparation on fabric. The plotted void ratio points in Fig. 4(B) are for the identical samples on which the fabric data of Fig. 4(A) were obtained. Unfortunately, void ratio data for many of the fabric samples are not available.

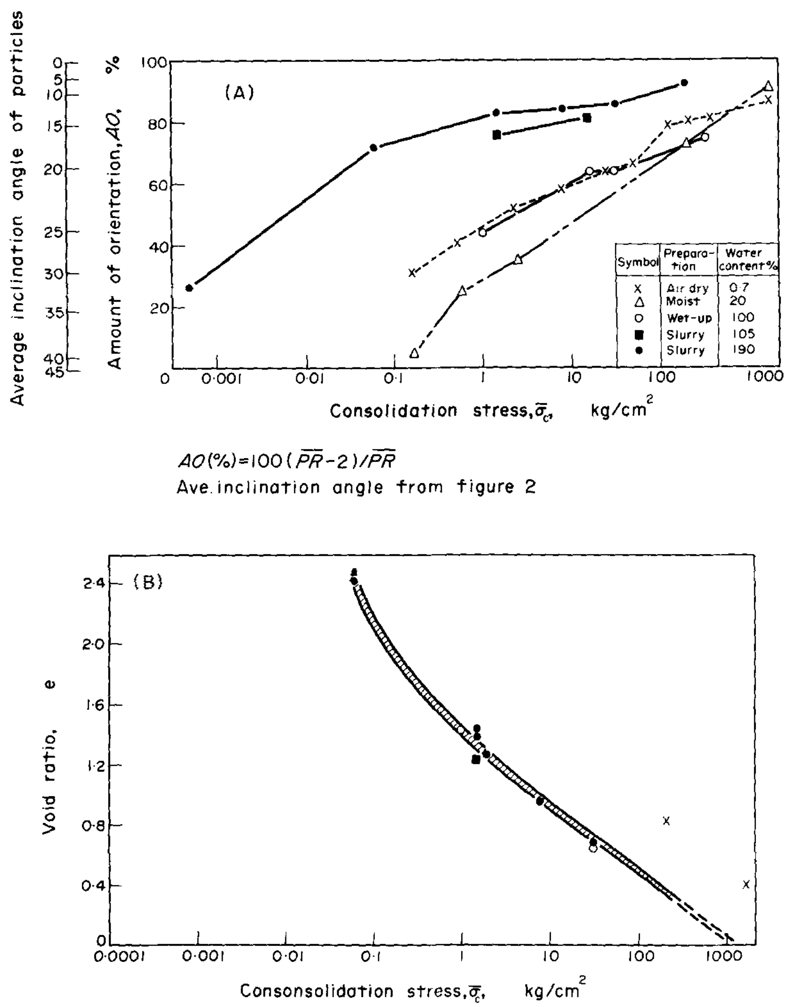

Fig. 4. Effect of one-dimensional consolidation of kaolinite on: (A) Fabric; (B) Void ratio.

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Table 3. Mean peak ratio for wet-up kaolinite consolidated normal and parallel to the original stress direction

Sample	Stress direction relative to $\beta = 0$ surfaces	Consolidation stress, $\bar{\sigma}_c$ (kg/cm^2)	Fabric on surfaces normal to direction of final consolidation stress†		
			$\overline{PR}$	SD	CV
1. Initial	Normal	—*	3·64	0·17	4·7
2. Oedometer	Normal	32	5·58	0·59	10·6
3. Oedometer	Normal	512	7·81	0·30	3·8
4. Initial	Parallel	—*	1·86	0·16	8·6
5. Oedometer	Parallel	32	3·16	0·19	6·0
6. Oedometer	Parallel	512	5·12	0·29	5·7

* Batch $\bar{\sigma}_c = 1$ kg/cm^2.
† $\overline{PR}$ = mean peak ratio, SD = standard deviation, CV = coefficient of variation (%).

The effect of changing the direction of major stress application was investigated by preparing two oedometer samples from the same uniform batch of clay consolidated one-dimensionally to 1 kg/cm^2. One sample was prepared so that additional consolidation would be parallel to the $\beta = 0$ surface; i.e. a 90° shift in direction of the major stress application. A comparison of the mean peak ratios, $\overline{PR}$, for these samples consolidated normal and parallel to the $\beta = 0$ surface given in Table 3 show that a very large consolidation stress is required to change the direction of preferred orientation.

That the preferred orientation direction has been completely reversed is clearly evident from a comparison of the pole figures in Fig. 5 for samples 3 and 6 of Table 3. The pole figure represents the stereographic projection of amplitude contours obtained from 002 kaolinite diffraction peak data on a series of ϕ curves at many α angles. The pole figure gives the statistical distribution of kaolinite particle orientation with respect to the major pole of orientation, ϕ_{max}, marked by X in the pole figures. The asymmetry about the zenith is just as large in Figure 5(B) where both initial and final consolidation stresses were normal to the plane of the figure, as in Fig. 5(A), where only the final consolidation stress was normal to the plane of the figure. Only half of each pole figure is shown because the other half of each pole figure shows the same asymmetry. The fact that ϕ_{max} for consolidation normal and parallel to the $\beta = 0$ surface is the same provides further confirmation that the direction of preferred orientation on sample 6 (Fig. 5B) has been changed completely so that the preferred orientation on both samples (3 and 6) is normal to the final $\bar{\sigma}_c$, although sample 6 initially had its preferred orientation parallel to the final $\bar{\sigma}_c$.

The effect of additional consolidation at 90° to the original consolidation direction also was examined for a more oriented original clay fabric. Since it has been shown that initial preparation frequently dominates the final observed fabric, great care was taken in these tests. Two identical samples were trimmed from a 24 cm dia. slurry batch with axes perpendicular to the original consolidation pressure, placed in standard oedometers, and prepared for loading. Sample B was loaded to 2 kg/cm^2 and the load doubled every day until a final load of 32 kg/cm^2 was applied. The final load was left on 3 days, at which time the sample was carefully cut from the cell and impregnated. Sample A was not loaded but was carefully cut from the oedometer cell and impregnated. Therefore, samples A and B have had identical treatment except that sample A only had the initial consolidation, $\bar{\sigma}_i$, of 1 kg/cm^2 applied normal to the $\beta = 0$ surface while sample B had a final consolidation, $\bar{\sigma}_f$, of 32 kg/cm^2 applied parallel to the $\beta = 0$ surface. Remember that the $\beta = 0$ surface is by definition taken as normal to the initially applied major stress.

Table 4 summarizes the results of fabric measurements. Additional consolidation parallel to the $\beta = 0$ surface definitely changed the fabric of this moderately oriented kaolinite and increased the fabric heterogeneity as shown by the large percent increase in the coefficient of variation on both $\beta = 0$ and $\beta = 90$ surfaces. However, Table 4 shows that 32 kg/cm^2 is not adequate to reverse the direction of the initial orientation.

A graphical picture of the fabric change is revealed in the pole figures of Fig. 6, where the fabric detail of samples A and B can be directly compared. Complete

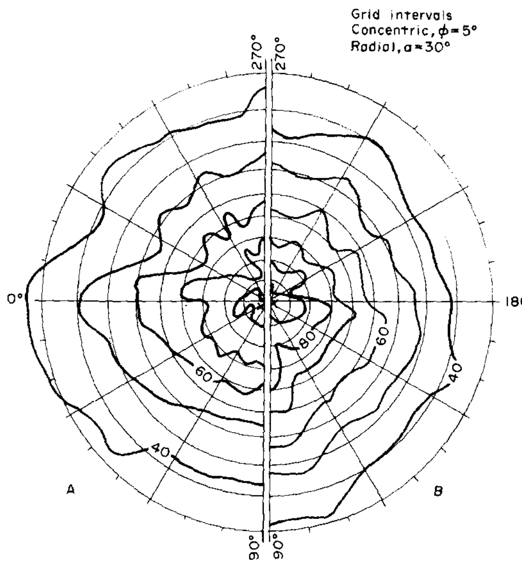

Fig. 5. (002) Pole figures for kaolinite surfaces normal to final consolidation of 512 kg/cm^2: (A) Sample no. 6, $\bar{\sigma}_f$ direction at 90° to $\bar{\sigma}_c$ direction; AO = 67·2 at $\phi_{max} = -1$. (B) Sample no. 3, $\bar{\sigma}_f$ direction = to $\bar{\sigma}_c$ direction; AO = 77·3 at $\phi_{max} = -1$.

Table 4. Fabric of moderately oriented kaolinite resulting from additional consolidation normal to the initial consolidation

Sample	Fabric $\beta = 0$ Surfaces $\overline{PR}$*	CV†	$\beta = 90$ Surfaces $\overline{PR}$	CV
A. Reference, initial consolidation of 1 kg/cm^2 perpendicular to the $\beta = 0$ surface.	8·19	5·7	1·24	7·2
B. Additional consolidation of 32 kg/cm^2 parallel to the $\beta = 0$ surface.	3·78	10·8	2·02	16·3

* $\overline{PR}$ = mean value of average peak ratios determined on ten surfaces in direction stated.

† CV = Coefficient of Variation, 100 SD/$\overline{PR}$.

pole figure data were obtained on four separate surfaces at 1 mm vertical intervals from Sample B with essentially the same result. Also, the entire experiment was repeated with the same results. The sketch in the lower left to Fig. 6 shows the relation of the surface from which the pole figure data were obtained. The effect of additional consolidation parallel to the $\beta = 0$ surface produced a definite shift in preferred orientation direction because Fig. 6 shows a 45°–60° spin (α rotation) and a 25° tip (ϕ rotation). The sketch in the lower right of Fig. 6 is an idealized presentation of the preferred orientation as interpreted from the pole figures. The orientation of clay particles relative to the rectangular block is shown by dots for particle faces and by dashes for clay particle edges; therefore,

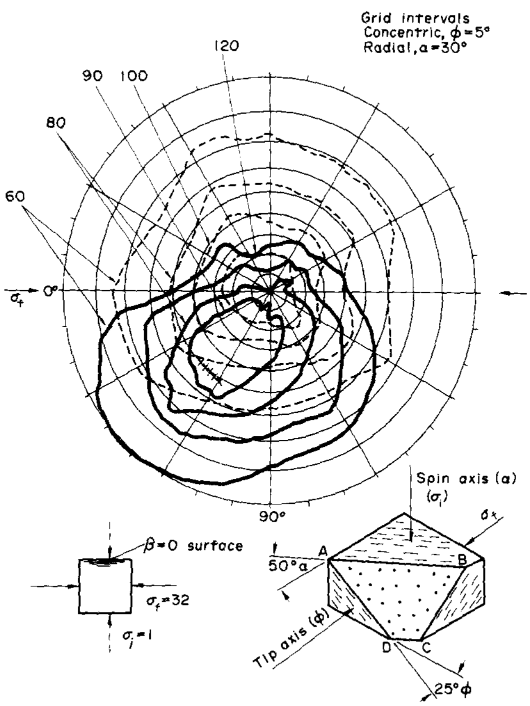

Fig. 6. (002) Pole figures for $\beta = 0$ surfaces of kaolinite: —— (A) Surface normal to σ_i = 1 kg/cm^2; AO = 75·9 at ϕ_{max} = −1; ---- (B) Surface parallel to σ_f = 32 kg/cm^2 AO = 70·1 at ϕ_{max} = −25.

preferred orientation is approximately parallel to the plahe ABCD.

Four measurements of small area peak ratio on the $\beta = 0$ surface of sample B at $\phi = 25°$ and for α between 45° and 60° gave a mean of 6·7 (AO = 70·1) with a maximum deviation from the mean of 0·2; however a 5° change in either ϕ or α outside this range reduced the spot peak ratio to 5·3 or less. Clearly changing the direction of applied stress from normal to parallel to the direction of preferred orientation primarily rotates the direction of preferred orientation toward being normal to the applied stress. A very large increase in applied stress would be required to completely shift the direction of preferred orientation when the clay has been moderately oriented initially.

It has been previously shown by Martin (1966) that isotropic stress up to 1 kg/cm^2 produced no measurable change in fabric. Kaolinite slurry at w = 190 per cent under a very small stress (a slurry 3 cm deep in a beaker) gave a $\overline{PR}$ = 2·7. This is the same $\overline{PR}$ obtained on kaolinite slurry at w = 190 per cent consolidated isotropically to 1 kg/cm^2. In contrast, one-dimensional consolidation of a w = 190 per cent slurry to 1 kg/cm^2 produces a $\overline{PR}$ of about 9 (see Fig. 4A). Consequently, the anisotropic stresses in one-dimensional consolidation are the cause of the orientation rather than the average consolidation stress per se. For normally consolidated kaolinite, the horizontal stress is about one-half of the vertical stress since the coefficient of earth pressure at rest K_o is about one-half.

DISCUSSION

The ease with which clay particles are oriented by an anisotropic stress depends upon the bond strength between particles and upon stearic hindrances. In other words, the ease of changing soil fabric is determined by soil structure which includes the initial fabric and the forces operating between and within the fabric units. Fabric changes observed as a result of stress changes are then the net effect produced by the stress increment applied to the original soil structure. Hence, it is very unlikely that one would observe a unique relation between particle orientation and either void ratio or applied anisotropic stress. This statement is borne out by the data presented in Figs. 3 and 4.

All of the data show that the initial placement condition determines the general level of orientation that can be achieved by one-dimensional consolidation. This importance of the initial condition on the fabric developed has been repeatedly observed (Martin, 1962; Quigley, 1962; O'Brien, 1964; Thiem, 1967; Morgenstern and Tchalenko, 1967).

The importance of initial condition and the changes in fabric with one-dimensional consolidation are summarized in Fig. 4(A). Several points are worth emphasizing. The slurry samples start out with a much more oriented fabric than air-dry, moist, and wet-up samples. They also undergo much smaller changes in fabric as a result of one-dimensional consolidation at stresses above 0·1 kg/cm^2. In contrast, the anisotropic stress of one-dimensional consolidation changed the fabric of air-dry and moist kaolinite from essentially random to an amount of orientation (*AO*) of about 90 per cent. However, extremely large stresses were required to produce this change.

The maximum observed *AO* of 92 per cent with consolidated slurry samples is below the 99·5 per cent achieved by slow sedimentation and drying of a thoroughly dispersed $w = 750$ per cent slurry. The *AO* of 92 per cent corresponds to an average angle of inclination among particles of 8°. While this is indeed a high degree of orientation, it is still a long way from the 0·5° obtained with the $AO = 99·5$ per cent samples.

Increased orientation with increased one-dimensional consolidation is not limited to kaolinite. It has been observed on illitic clays (Quigley, 1962; O'Brien, 1964; Quigley and Thompson, 1966) and on montmorillonite (Englehardt and Gaida, 1963; Theim, 1967). Morgenstern and Tchalenko (1967) state that 'for flocculated kaolin prepared by sedimentation the development of intense orientation in this test is virtually complete at a stress level of 0·1 ton/ft.^{2}, (0·0976 k cm^2). Their own data on slurried kaolin are qualitatively very similar to the data given in Fig. 4(A). O'Brien (1964) observed analogous behavior for Pennsylvanian age underclays in Illinois.

Reviewing the literature for natural soils, Meade (1966) could find no unequivocal evidence for increase in orientation with depth of burial. Data presented herein suggest several possibilities for the lack of correlation between orientation and depth. These include the following: (1) the changes in fabric with increasing consolidation stress can be very small if the degree of orientation is high to start with (2), changes in fabric with consolidation appear to be related to the logarithm of stress, thus very large stress increments produce slight changes in fabric when the stress level is high, (3) sample disturbance may completely mask fabric changes with depth, especially since the amount of disturbance might increase with depth. In addition, varying depositional environments and/or natural cementation as observed by Quigley and Ogunbadejo (1972) might produce fabrics that would not necessarily be related to depth of burial. However, it is difficult to explain the essentially random fabric found by Meade (1966) for burial depths up to 600 m by this mechanism. An isotropic *in situ* stress condition during consolidation could, in theory, explain such a random fabric with depth. But abundant laboratory data (e.g. Brooker and Ireland, 1965) and some field measurements (e.g. Kenney, 1967) show that the *in situ* stresses are anisotropic during virgin compression since K_o for normally consolidated clays typically equals $0·6 \pm 0·1$.

The greater the preferred orientation the more important it is to know that the measurement is at the angle of maximum orientation. For this reason, every specimen for which *PR* data are given in Tables 1 and 2 and Figs. 2–4 was checked using the universal stage diffractometer to verify that the *PR* measurements were being made at the angle of maximum orientation. The very small fabric change observed by Morgenstern and Tchalenko (1967) when the direction of consolidation stress was shifted 90° may be due to a lack of knowledge regarding the direction of maximum orientation. In the present investigation the precise angle of maximum orientation, as well as the statistical distribution of particles about the axis of maximum orientation, was determined with the universal stage diffractometer. Thiem (1967) with X-ray diffraction and Lafeber (1967) with light microscopy also have employed the universal stage for locating the angle of maximum orientation.

Changing the direction of the one-dimensional consolidation stress by 90° appears to change the fabric by a fairly uniform rotation of the original fabric toward alignment normal to the new applied stress direction. The stress increment required to completely rotate the original fabric into alignment normal to the new stress direction again depends upon the initial soil structure, as shown by the data in Tables 3 and 4 and in Figs. 5 and 6.

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