THE FABRIC OF MECHANICALLY COMPACTED KAOLIN

by

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ABSTRACT

AN electron microscope study was made to determine the effect of mechanical compaction method on the fabric produced in a compacted commercial kaolin. Direct platinum-shadowed carbon replicas were made from horizontal and vertical fracture surfaces within the middle third of cylindrical specimens compacted by static load, impact, and kneading compaction at optimum moisture content and at 3% above and below optimum. Replicas were studied in the electron microscope to arrive at a qualitative evaluation of fabric. No oriented fabric or edge-to-face random fabric of individual particles, as postulated by others, was found. Regardless of compaction method the fabric was found to consist of parallel and random arrangements of packets of kaolin flakes. Both impact and kneading compaction produced essentially the same fabric consisting of trajectories of parallel packets, probably the result of shearing deformation during compaction, within essentially randomly oriented zones of packets. Static load compaction produced a fabric in which some tendency of the packets to orient normal to the direction of loading was apparent. For all compaction methods some increase in parallel packet orientation was noted with increase in molding water content. The mode of parallel orientation differed between static load compacted specimens and those produced by either impact or kneading compaction. Results of the study indicate that some revision of concepts regarding particle orientation due to mechanical compaction should be made.

INTRODUCTION

IN soil mechanics it has long been recognized that the arrangement of particles in fine-grained soils has a profound effect upon the engineering properties of such soils. The earliest concept of clay soil fabric in civil engineer-literature appears in the writings of Terzaghi (1925). In this concept it was suggested that particles were small enough for molecular forces to cause them to adhere one to another and thus build up a "honeycomb" fabric. Very fine-grained clay soils were conceived to be honeycomb structures of second order in which the larger floccules were built up by adhesion of smaller floccules.

These early concepts of Terzaghi were expanded somewhat by A. Casagrande (1932) to include soils consisting of colloids and bulky silt-size particles in which the clay flocs were considered to link with larger clay particles and the silt grains to form a somewhat random flocculent structure.

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At about the same time as Terzaghi's early writings a geochemist, Goldschmidt (1926), concluded that clay properties were due to crystalline minerals surrounded by adsorbed water films and that the water molecules adhered to one another because of their polar character. He also expressed the opinion that certain sensitive clays derived their properties from the fact that the flaky minerals were arranged in an unstable "cardhouse" fabric.

Based on the surface chemical properties of the clay colloids, Lambe (1953) presented a view of inorganic clay soil fabric in which undisturbed marine clays were thought to have a cardhouse fabric similar to that postulated by Goldschmidt, whereas fresh-water clays were thought to have a somewhat less open and random arrangement of particles. Remolded clays were shown as having an essentially parallel (oriented) arrangement of particles.

Rosenqvist (1955) presented a very similar view of the fabric of clays to that previously described by Lambe. A three-dimensional picture of edge-to-face fabric in a clay was presented by Tan (1957). Electron microscopy was used by Rosenqvist (1959, 1962) to show the existence of such a fabric in a marine clay.

Mitchell (1956), using the petrographic microscope and specially prepared thin-sections of clays, substantiated many of the views of Lambe and others on the differences in fabric between marine and fresh water clays and, in addition, showed that remolding produced a higher degree of orientation in clays.

In two papers, Lambe (1958a, 1958b), based on indirect evidence from tests on engineering properties of mechanically compacted clays, concluded that clays compacted on the dry side of optimum owed their lower bulk density to the development of a random or cardhouse fabric and that compaction on the wet side of optimum moisture content produced a more oriented arrangement of particles as a result of more fully developed double-layer water films.

Seed and Chan (1959), in a study of the structure and strength of compacted clay, concluded that the views of Lambe were essentially correct. They also suggested that the shear strains developed during kneading and impact compaction could change the fabric from random or flocculated, at low moisture content where penetration of the rammer is small and shear strains small, to parallel or oriented, where rammer penetration and shear strains are large.

A subsequent study by Trollope and Chan (1960) on soil structure and the step–strain phenomena developed the concepts that "packets" of oriented clay particles could build up and that complete remolding to produce an oriented fabric could only occur in regions within the clay soil where large shear strains developed. A consequence of this latter concept is that remolded compacted soils would be only partially remolded or partially oriented.

Aylmore and Quirk (1962), working with electron microscopy of carbon surface replicas, showed the existence of domains of oriented clay platelets in a natural clay. Michaels (1959) has also discussed the formation and existence of packets of oriented clay particles.

Of necessity this review of what has been reported on the fabric of clay soils, and in particular on compacted clays, is brief and incomplete. For a more complete and thorough review the reader is referred to a paper by Meade (1964).

SCOPE

With the exceptions of the work done by Rosenqvist (1959, 1962), Mitchell (1956), and Aylmore and Quirk (1962), the fabric of clay soils and of mechanically compacted clays has been inferred from physico-chemical principles and indirect evidence from engineering properties tests. Mitchell's work, done with the light microscope, could not resolve individual clay particles; hence a sufficiently detailed direct view of the clay fabric could not be obtained. The work of Aylmore and Quirk was done with the electron microscope on undisturbed clays and did not include the effects of remolding. Rosenqvist's studies were likewise done with the electron microscope and did include some study of the fabric of remolded clay. Both of these last-named studies showed that electron microscopy could adequately resolve details of clay soil fabric.

The research reported in this paper was undertaken to determine the fabric of a compacted kaolinite clay and, further, to determine differences and changes in fabric as a function of mechanical compaction method and variation in molding water content by utilizing the direct method of electron microscopy.

INVESTIGATION

A well-crystallized, fine-grained, commercial Georgia kaolin (Hydrite UF, sold by the Georgia Kaolin Company) was selected for this study because previous electron microscopy of this material had shown that individual particles and particle-to-particle relationships could be readily resolved.

Cylindrical specimens were compacted in the Harvard Miniature Compaction Mold by kneading, impact, and static load compaction methods. Specimens were compacted at optimum mosture content and at 3% above and below optimum for all methods of compaction. Optimum moisture content and maximum dry density were determined for the kneading compaction method and compactive effort for the other two methods adjusted to yield the same dry density obtained by kneading compaction.

After molding, all specimens were air-dried and then vacuum-dried in a vacuum desiccator to constant weight. Shrinkage of the specimens during this process was very small and of insufficient magnitude to affect the character of the fabric.

When completely vacuum dried the middle third of each cylindrical specimen was cut out for preparation of the fabric specimens. The middle third specimens were then carefully fractured to produce surfaces both normal to and perpendicular to the cylindrical axis of the original specimen. Fracture surfaces were gently blown free of debris and trimmed to about 1 cm square.

Fracture surface specimens were replicated in a high vacuum thin-film evaporator. Areas to be replicated were masked with lead foil masks having an opening approximately 6 mm square. Fracture surfaces were shadow-cast with platinum using the carbon–platinum pellet technique developed by Bradley (1958) and then replicated by evaporated carbon (Bradley 1954).

Because of the relative roughness of the fracture surfaces it was found to be necessary to reinforce the platinum–carbon replicas prior to stripping. This was done by carefully moistening the replica with ethylene dichloride sprayed from an atomizer and immediately gently pressing a one-half mil thick piece of clear polystyrene foil onto the moistened replica.

Replicas were stripped from the compacted clay specimens by immersion in an ethanol–water solution. In general, the stripped reinforced replicas at this stage would have a considerable amount of embedded kaolinite particles still clinging to the platinum–carbon replica. These particles were removed by floating the replicas alternately on the surface of 48% hydrofluoric acid and 0.5 N sodium hydroxide solution with intermediate washings on the surface of clean triple-distilled water. When inspection of the replicas in a light microscope under 80× magnification revealed that the replicas were clean they were carefully cut into 2 mm squares using a very sharp razor blade.

In order to preserve orientation of the replica squares for viewing in the electron microscope the right-hand edge of horizontal specimen squares and the top edge of vertical specimen squares were dyed with a concentrated ethanol solution of rosaniline hydrochloride. Replica squares were then mounted on 300-mesh standard copper electron microscope grids. The polystyrene reinforcing foil was then dissolved from the mounted replicas using the Jaffe (1948) technique.

Replicas were scanned at magnifications ranging from 5000× to 10,000× in an Hitachi HS-7 electron microscope. Micrographs were taken at a magnification of 10,000× and enlarged to 22,700× for study. It should be noted that the apparent area covered by a replica 2 mm square is so large that it is impractical to attempt to take micrographs of the entire area at this magnification. Therefore, only micrographs of typical areas and certain specific features of other areas were taken in this study.

RESULTS

Results of the investigation are given in Plates 1 through 4 in the form of typical electron micrographs. Plates 1 and 2 show the changes in fabric for the kaolin compacted by kneading compaction. The upper micrographs are of fracture surfaces normal to the cylindrical axis of the compacted specimen; the lower micrographs are the corresponding fracture surfaces parallel to the axis. In Plate 1 micrographs (a) and (b) are for a molding water content of 3% below optimum, and micrographs (c) and (d) are for a molding water content at optimum. Plate 2 shows micrographs for a molding water content at 3% above optimum.

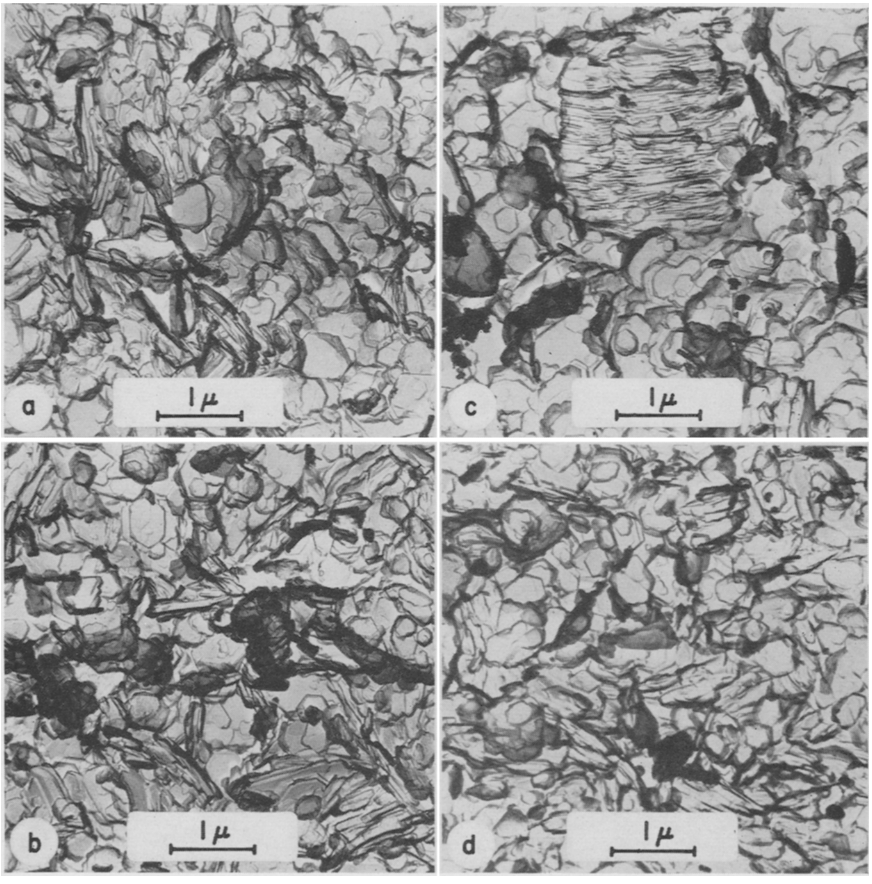

PLATE 1.—Kaolin clay compacted by kneading compaction. Micrographs (a) and (b), compacted at 3% below optimum moisture content. Micrographs (c) and (d), compacted at optimum moisture content. Micrographs (a) and (c) are sections normal to the direction of compaction; micrographs (b) and (c) are sections parallel to the direction of compaction.

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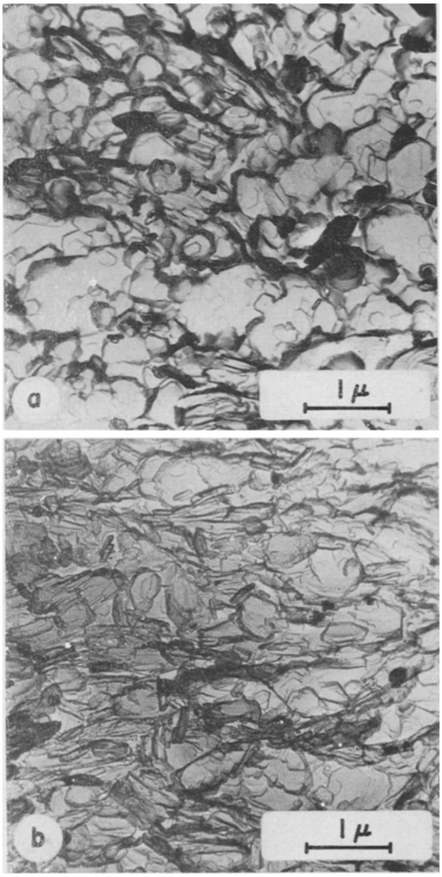

PLATE 2.—Kaolin clay compacted by kneading compaction. Clay compacted at 3% above optimum moisture content. Micrograph (a) is a section normal to the compaction direction; micrograph (b) is a section parallel to the compaction direction.

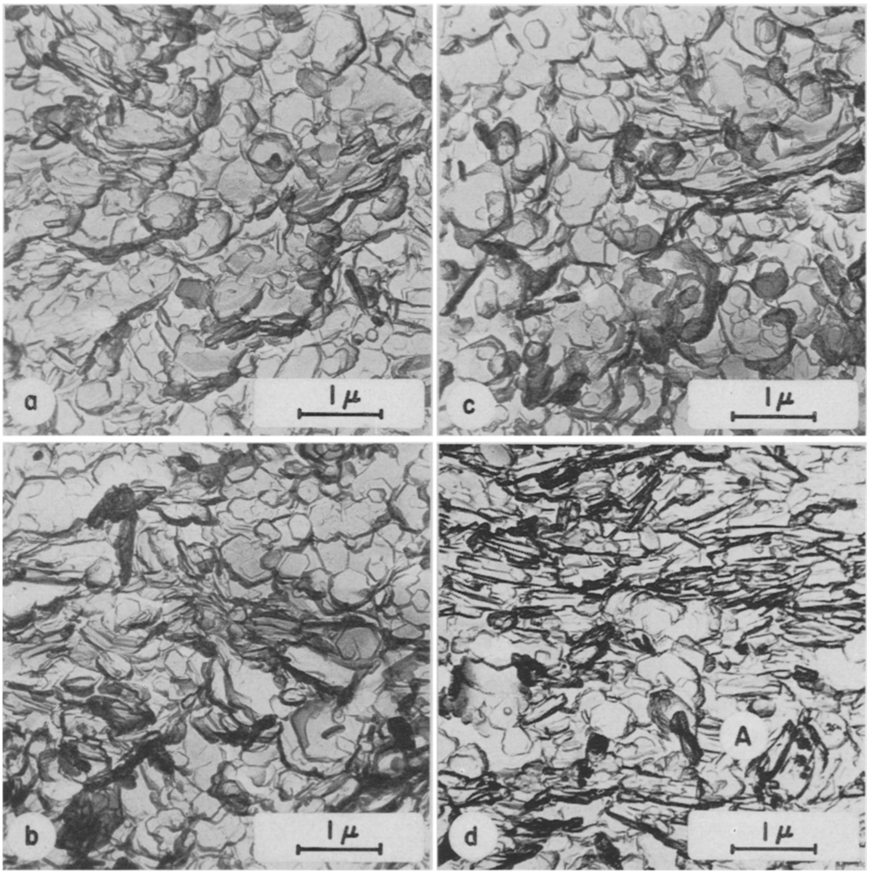

PLATE 3.—Kaolin clay compacted by impact compaction. Micrographs (a) and (b), compacted at 3% below optimum moisture content. Micrographs (c) and (d), compacted at 3% above optimum moisture content. Micrographs (a) and (c) are sections normal to the compaction direction; micrographs (b) and (d) are sections parallel to the compaction direction.

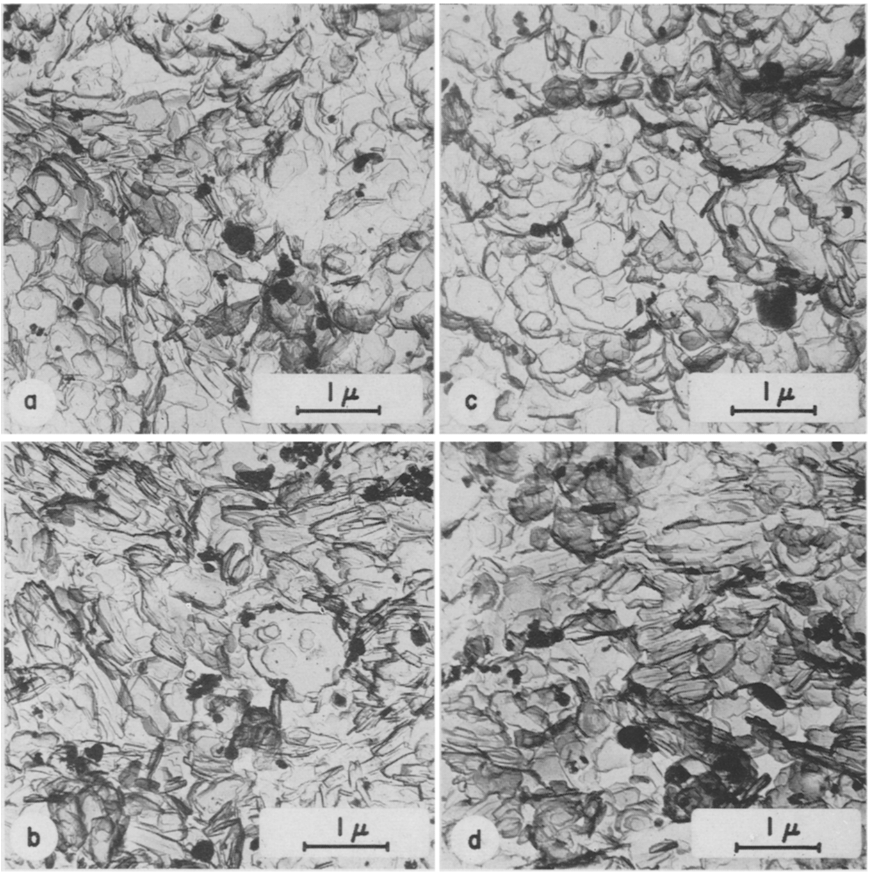

PLATE 4.—Kaolin clay compacted by static load compaction. Micrographs (a) and (b), compacted at 3% below optimum moisture content. Micrographs (c) and (d), compacted at 3% above optimum moisture content. Micrographs (a) and (c) are sections normal to the compaction direction; micrographs (b) and (d) are sections parallel to the compaction direction.

Inspection of these micrographs reveals, first of all, that there are few, if any, individual particle-to-particle contacts. Instead the major portion of the particles appear as oriented aggregates of particles or packets. At the lower molding water content the packets are arranged in an essentially random fabric in both horizontal and vertical sections. At optimum moisture content a more oriented fabric appears in the horizontal section and the angular relations between packets in the vertical section seem to have flattened out a bit. Both of these indicate a more oriented fabric than the almost wholly random one evident in the micrographs for the lower molding water content. At a molding water content 3% above optimum the horizontal section shows a high degree of orientation perpendicular to the cylindrical specimen axis and the vertical section shows considerably more packets (viewed edge on) oriented horizontally than can be seen in the micrographs for the optimum molding water content.

Plate 3 shows the changes in fabric for the kaolin compacted by impact compaction. Only micrographs for specimens compacted at a molding water content of 3% below optimum [micrographs (a) and (b)] and at 3% above optimum [micrographs (c) and (d)] are shown. As in the kneading compaction series, micrographs (a) and (b) show a rather high degree of randomness in the fabric formed by the kaolin packets. There is an indication that the fabric is perhaps a bit more oriented perpendicular to the cylindrical specimen axis than the corresponding kneading compaction fabric. Micrographs (c) and (d) show a rather high degree of orientation. This is particularly evident in the vertical section where many edge-on packets are lined up in nearly horizontal lines. A few packets at rather steep angles with the horizontal can be seen, as at A.

A feature, not shown in the micrographs for either the kneading or impact compaction series, which was fairly common in replicas of both series, was the appearance of long strings of oriented packets in the form of curved trajectories. This feature was least evident in the specimens compacted dry of optimum, most evident in those compacted at optimum, and somewhat less apparent in those compacted wet of optimum. Because both of these methods of compaction involve penetration of the rammer into the soil during compaction it is possible that these trajectories represent zones of large shear strain causing the packets to orient along the direction of greatest strain. At the higher molding water content, penetration would be greater with larger shear strains thus causing more of the trajectories; but at the same time double-layer moisture films are greater in thickness, allowing more mobility to the clay packets, so that as succeeding layers are compacted those below would show a tendency for the trajectories to flatten out.

Plate 4 shows the changes in fabric for the kaolin clay compacted by static load. Micrographs (a) and (b) show the fabric for a molding water content 3% below optimum and micrographs (c) and (d) show the fabric for a molding water content at 3% above optimum. Micrographs (a) and (b) reveal that there is a considerable degree of randomness in the fabric formed by the packets; however, the horizontal section does show more orientation perpendicular to the cylindrical specimen axis than in the corresponding cases for kneading and impact compaction. For the specimens molded on the wet side of optimum there is a very considerable degree of orientation as can be seen in both the horizontal and vertical sections [micrographs (c) and (d)]. (The chainlike feature along the top of micrograph (c) is, at least in part, an artifact consisting of a fold in the carbon replica.)

A notable difference in the character of the oriented fabric achieved by static load compaction wet of optimum from that of both the corresponding kneading and impact compaction specimens is most clearly shown in micrograph (d). While the edge-on packets show a high degree of orientation horizontally, the long chains of horizontal packets evident in the other forms of compacted clay are not present in any degree. Instead, each individual packet seems to have become oriented individually. In static load compaction shear strains are more uniform than in the other methods, therefore other mechanisms than large shear strain are probably responsible for the orientation. At the higher molding moisture content, double-layer water films would be thicker and more fully developed, electrolyte concentration would be reduced, and repulsive forces greater, thus creating a favorable situation for development of a parallel or oriented fabric.

CONCLUSIONS

1. Regardless of the method of compaction the fabric formed in the kaolin clay consisted of arrangements of packets of oriented clay particles. As pointed out by Michaels (1959) all surfaces of dry clay particles are capable of adhering to one another. In the dry state, before addition of molding water, it is probable that such adhesion does occur and that the packets are already formed. The addition of molding water in amounts less than that required to produce a slurry or viscous suspension would probably not disrupt the packets; hence persistence of the packets through the compaction process over the relatively limited moisture range in this study could be expected. The relative absence of individual particle edge-to-face relationships would seem to support this view.

2. In both impact and kneading compaction orientation of packets begins in zones of large shear strain close to the surfaces of the compaction rammer and appears in the fabric as long chains of oriented packets forming shallow trajectories in the compacted clay mass. This does not occur to any considerable extent on the dry side of optimum molding water content but does increase at optimum as thicker double-layer water films develop and shear strains become larger. Above optimum the trajectories flatten out due to the thicker water films and a greater opportunity for mobility.

3. The character of the oriented fabric observed in the kaolin clay compacted wet of optimum by static load compaction differs from that induced in the clay by either kneading or impact compaction. This is due to the absence of large non-uniform shear strains in this method of compaction

which generate long trajectories of oriented packets in the other compaction methods; hence the clay packets tend to act individually and to orient as moisture content increases by development of thicker double-layer water films and the dominance of dispersive over attractive forces.

4. At molding water contents below optimum all compaction methods produce an essentially random arrangement of packets. The slight amount of orientation observable in this clay at 3% below optimum moisture content showed an increase in the following order; kneading compaction, impact compaction, static load compaction.

5. The fact that very little individual particle fabric was observed in any of the specimens, either face-to-face or edge-to-face, but rather a packet or book fabric leads the authors to suggest that the following terminology would be more descriptive and appropriate for compacted kaolin clays. As an analog to the "cardhouse" fabric the authors propose the term "bookhouse". For the oriented fabric, "parallel packet" is proposed.

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REFERENCES

AYLMORE, L. A. G., and QUIRK, J. P. (1962) The structural status of clay systems, *Clays and Clay Minerals*, Proc. 9th Conf., Pergamon Press, New York, pp. 104–30.

BRADLEY, D. E. (1954) Evaporated carbon films for use in electron microscopy: *British Jour. Appl. Phys.* **5**, 65.

BRADLEY, D. E. (1958) Simultaneous evaporation of platinum and carbon for possible use in high resolution shadow-casting for the electron microscope: *Nature*, **181**, 875.

CASAGRANDE, A. (1932) The structure of clay and its importance in foundation engineering: *Jour. Boston Soc. Civ. Engrs.*, **19**, 168–209.

GOLDSCHMIDT, V. M. (1926) Undersokelser over lersedimenter: *Nordisk jordbrugsforskning*, nos. 4–7, pp. 434–45.

JAFFE, M. S. (1948) Auxiliary supporting nets for fragile electron microscopy preparations: *British Jour. Appl. Phys.* **19**, 1191.

LAMBE, T. W. (1953) The structure of inorganic soils: *Proc. Amer. Soc. Civ. Engrs.*, Separate No. 315, New York 49, pp.

LAMBE, T. W. (1958a) The structure of compacted clay: *Jour. Soil Mech. and Fdns. Div., Am. Soc. Civ. Engrs.* **84**, No. SM-2, 1654–1 through 1654–34.

LAMBE, T. W. (1958b) The engineering behavior of compacted clay: *Jour. Soil Mech. and Fdns. Div., Am. Soc. Civ. Engrs.* **84**, No. SM-2, pp. 1655–1 through 1655–35.

MEADE, R. H. (1964) Removal of water and rearrangement of particles during the compaction of clayey sediments—review: *U.S. Geol. Survey Prof. Paper* 497–B, 23 pp.

MICHAELS, A. S. (1959) Discussion to: physico-chemical properties of soils: soil-water systems: *Jour. Soil Mech. and Fdns. Div., Am. Soc. Civ. Engrs.* **85**, No. SM-2, part 1, pp. 91–102.

MITCHELL, J. K. (1956) The fabric of natural clays and its relation to engineering properties: *Proc. 35th Highway Research Board*, NAS-NRC **35**, 693–713.

ROSENQVIST, I. TH. (1955) Investigations in the clay-electrolyte water system: *Publ. Norwegian Geotechnical Inst.*, No. 9, Oslo, 125 pp.

ROSENQVIST, I. TH. (1959) Physico-chemical properties of soils: soil-water systems: *Jour. Soil Mech. and Fdns. Div., Am. Soc. Civ. Engrs.* **85**, No. SM-2, part 1, 31–53.

ROSENQVIST, I. TH. (1962) The influence of physico-chemical factors upon the mechanical properties of clays: *Clays and Clay Minerals*, Proc. 9th Conf., Pergamon Press, New York, pp. 12–27.

SEED, H. B., and CHAN, C. K. (1959) Structure and strength characteristics of compacted clay: *Jour. Soil Mech. and Fdns. Div., Am. Soc. Civ. Engrs.*, **85**, No. SM-5, 87–128.

TAN, T. K. (1957) Discussion on: soil properties and their measurement: in *Proc. 4th Int. Conf. on Soil Mech. and Fdn. Eng* III, London, pp. 87–89.

TERZAGHI, K. (1925) Modern conceptions concerning foundation engineering: *Jour. Boston Soc. of Civ. Engrs.* **12**, no. 10, 1–43.

TROLLOPE, D. H., and CHAN, C. K. (1960) Soil structure and the step-strain phenomenon: *Jour. Soil Mech. and Fdn. Div., Am. Soc. Civ. Engrs.* **86**, no. SM-2, Part I, 1–39.