THE MECHANISM OF THE DEFORMATION OF CLAY

By

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ABSTRACT

Kaolinite-water mixtures, containing from 23 percent to 33 percent water, were subjected to compression plastometer tests and their plasticity was studied by means of the calculated strain-stress functions. X-ray diagrams taken of the compressed samples showed that an oriented texture developed during the compression, i.e., the basal planes of the flaky clay particles were arranged parallel to a plane normal to the direction of the applied stress. For the purpose of discussion the concept of the "plastic unit cell" is introduced. The "plastic unit cell" is a cubic volume element, the faces of which are perpendicular to the three principal stresses. The size of the "plastic unit cell" is very small as compared with the size of the macroscopic sample but large as compared with the size of one clay particle. It is the smallest unit for all considerations where macroscopic strain and stress distributions are involved. For all considerations involving the correlation between the characteristic strain-stress function of the material, the motions of the clay particles and water, and the forces present between the particles, the "plastic unit cell" is the largest unit.

The clay particle in itself is rigid and, therefore, it cannot undergo the same deformation as does the "plastic unit cell". All of the clay particles present in a "plastic unit cell" together can go through a series of motions (translations and rotations) which, in effect, simulate the deformation of the "plastic unit cell". In the case of the compression test, the translatory and rotatory movements of the clay particles lead to the development of the oriented texture.

INTRODUCTION

The problem of the plasticity of clay-water mixtures is of great practical and theoretical interest. Much information has been accumulated concerning the behavior of the clay-water system under many types of internal and external conditions. However, a general explanation which would account for all of the observed phenomena has not yet been proposed, and the problem of plasticity in terms of the structure of clay and water is still not solved. The present work has been undertaken in order to initiate and test a concept of the plastic behavior of clay-water mixtures; this concept is based mainly on the kinematics of the motions of the clay particles during deformation.

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The observations which can be made on plastic materials are usually connected with deformations and deformation rates produced by the application of external forces. The problem appears to be, therefore, to relate these macroscopic observations to the movements of the submicroscopic constituents and to the forces which act between them. This correlation must be done in two steps:

(1) The true stress-strain relations of the given material must be computed from the observed data. This means not only the elimination of all arbitrary constants from the measurements but also the avoidance of any kind of measuring device which can be evaluated only by the assumption of a certain type of stress-strain function. It seems obvious that the true stress-strain function cannot be determined if an arbitrary assumption about the character of this function must be made first. Plastic materials have an intermediate position between solids and liquids. Plastic materials closer to the solid state are usually treated according to an idealized stress-strain function of the type shown, for example, by Van Iterson (1947) and reproduced in Figure 1. Plastic materials closer to the liquid state are treated as "Bingham" liquids with a typical $D\mathcal{T}$-diagram shown, among others, by Houwink (1937) and reproduced in Figure 2.

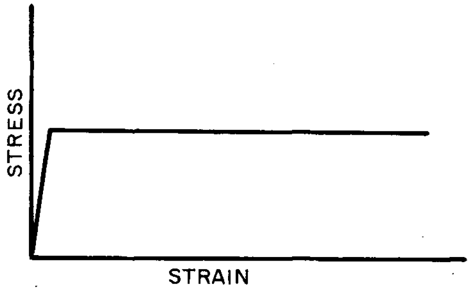

Figure 1. — Stress-strain function of a plastic material according to Van Iterson.

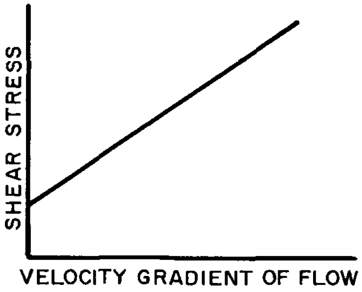

Figure 2. — $D\mathcal{T}$ — diagram according to Houwink.

Neither representation is satisfactory for clay-water mixtures in the workable state, for workable clay-water mixtures have no yield point (defined as a sharp inflection following the elastic part of the strain-stress curve).[1] This excludes the use of the idealized stress-strain function represented in Figure 1. Constant stresses in a wide stress range of practical importance do not produce permanent flow as implied from the Bingham function, which excludes the $D\mathcal{T}$-representation.

Because of these factors all measuring devices which produce heterogeneous strain distribution must be excluded. Evaluation of the measurements which were obtained from a sample containing hetero-

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[1] This statement applies only to clay-water mixtures in the workable state and does not concern clay-water mixtures of high water content.

geneous strain distribution would require integration of the different strains over the different parts of the body, but this cannot be done without prior knowledge of the stress-strain function. Only those devices can be used which produce homogeneous strain distribution in the sample; if the strain distribution is found to be homogeneous, the homogeneity of the stresses can safely be postulated.

The tests which fulfill this condition are the simple compression, tension, and shear tests conducted under certain safeguards for homogeneous strain. The frequently used torsion test using a solid cylinder is objectionable since the shear-strain is obviously not constant throughout the body.

(2) After the true stress-strain function of a test sample has been established, one may correlate the stresses with the forces which exist between the constituents of the clay-water mixture, namely, the clay particles and the water "matrix", and relate the strain to the movements which the constituents undergo during the test. In order to do so, it is convenient to proceed as follows: one may choose a small cube with its three axes parallel to the three principal stresses. If the size of this cube is very large as compared with the size of the clay particles, the stresses on its surface will equal exactly the stresses derived from the macroscopic (experimental) stress-strain function. However, if the size of this cube is comparable to the size of the clay particles, the stresses on its surfaces will deviate considerably from the values derived from the experimental stress-strain function and will fluctuate from one volume element to the other. Between these extremes a volume element can be defined which has such dimensions that its surface stresses do not fluctuate appreciably, but are constant from one volume element to another within, for example, one percent.

A volume element of such dimensions represents the borderline between the macroscopic and atomistic viewpoint. For all considerations where macroscopic stress and strain distributions are involved it is the *smallest unit;* it has all the phenomenological properties of the plastic body. For all considerations, however, where the correlation between the characteristic stress-strain functions and the clay particles and water is involved, this element is the *largest unit.* In such cases one can deal with the changes within this unit alone, taking the stresses which result from the macroscopic stress-strain function as external forces acting on the surface of this volume element. It seems convenient to have a special term for this volume element; therefore the term "plastic unit cell" is suggested.

The structure and the forces within the plastic unit cell and the kinematic and dynamic changes produced by the action of external forces on the surfaces of this cell comprise the problem which must be solved. This problem cannot be solved quantitatively; it is thought, however, that a semiquantitative treatment may be developed.

The properties of clay-water mixtures are believed to be caused by the following three factors:

(1) The anisodimensional shape of the clay particles (plates and laths).

(2) The strong surface forces of the clay particles caused by their very small extension in one direction (along the crystallographic *c* axis).

(3) The "rigidity" of the water adjacent to the clay-particle surfaces. The water close to these surfaces can be regarded as a solid.

Disregarding the last two factors, the effects of which will not be discussed in the present paper, the first factor alone leads to significant results. Investigation of the movement of the flaky clay particles in the plastic unit cell during deformation reveals that such movement is well suited to accomplish the basic process of plastic deformation. This basic process consists of a material transport from the shrinking direction to the expanding direction (Fig. 3).

It is obvious that rigid particles cannot undergo the same kind of volume changes as does the plastic unit cell as a whole. The integral volume change of the plastic unit cell must be brought about by differential translations and rotations of the rigid particles and by the flow of water around the rigid particles (or more likely around the rigid particles and some of the adherent rigid water films), to fill any voids and keep the volume constant. Spherical particles can make only translations (i.e., rotations are irrelevant in regard to the deformation). A sample consisting of spherical particles must have some of its spheres forced into other layers of spherical particles during deformation. If the concept of a "bond" between the particles is introduced, it is evident that many of these translations proceed in the bond directions, causing the eventual rupture of the bonds. (See Figure 3, bond 1-2, 3-4, 5-6, 6-7, 7-8, etc.).

The deformation process of a sample consisting of platelike particles takes place in an entirely different manner. In such a case the translations *and* rotations of the flakes are equally important during the process of integral volume change of the plastic unit cell. The movement of the flaky particles does not necessarily lead to the rupture of the bonds; they will glide along each other without losing their contact. This gliding process, connected with the rotation of the flakes, is *the characteristic feature* of the deformation of clay-water mixtures. Depending on the water content and on the cations present, the bond between two particles may be rigid, resulting in a finite strength of the clay-water mixture. However, only a small increase of the shear-stress might be needed to force one particle to glide over the surface of the other particle until a new equilibrium position is reached. Since on the average the angle between the two surfaces becomes smaller with the increasing rotation of two clay particles, it is understandable that the bond strength increases, along with increasing deformation.

There is a basic difference between the deformation of a body containing spherical particles and that of one containing flaky or fibrous particles.

Each step of deformation changes definitely and irreversibly the structure of the plastic unit cell of a body containing flaky or fibrous particles. The plastic unit cell of a body composed of spherical particles will be changed

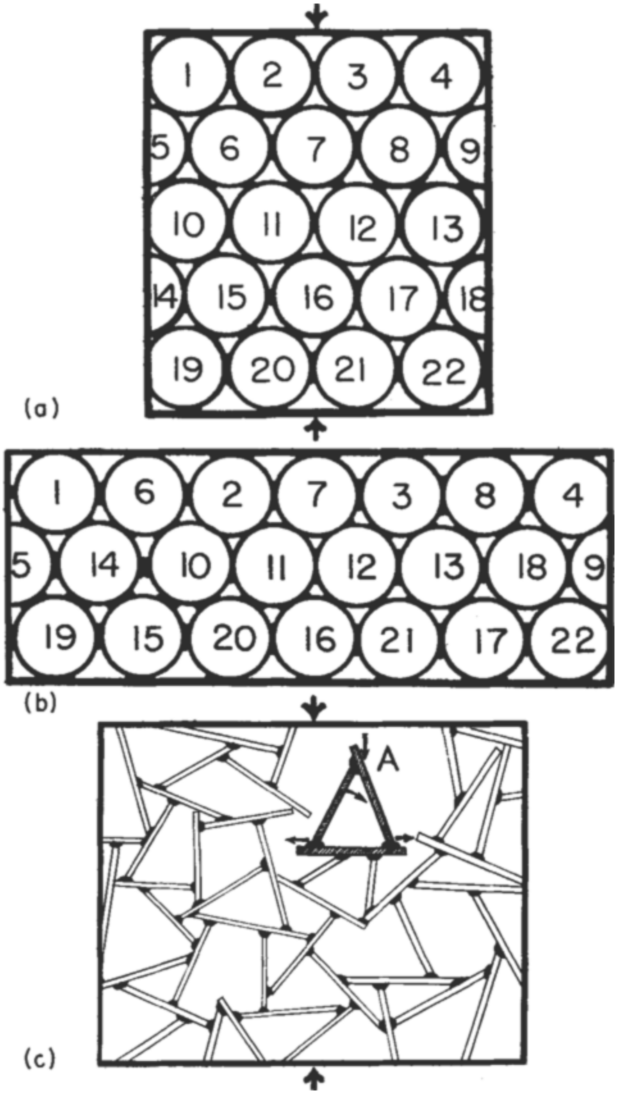

FIGURE 3. — Material transport during compression. Diagrams (a) and (b) illustrate the material transport of a sample composed of spherical particles. Diagram (a) shows the sample before compression; (b), after compression. Diagram (c) illustrates a clay-water mixture before compression (one is looking along the *a* or *b* crystallographic axes of the flaky particles). When this sample is subjected to compression the flakes will rotate as indicated at A.

only in its shape but not in its basic structure during the same deformation process. All properties, including plasticity, should change continuously during the deformation of a body containing flaky particles, whereas the properties of a material with spherical particles should remain constant during the deformation.

This concept suggests the introduction of certain new parameters to characterize the plastic deformation process; namely, *the symmetry* and *the degree* of orientation of the particles.

The symmetry of orientation is determined by the symmetry of deformation to which the plastic unit cell is subjected.

The degree of orientation (anisotropy) can be represented by the density of the poles (either the normals to the planes or, in the case of fibrous particles, the fiber axes) on a pole sphere.

The anisotropy of deformed clay bodies is a well known fact: the so-called memory of clay and the shrinkage differences of extruded and moulded bodies in different directions in respect to the extrusion or compression direction are manifestations of it. This property of clay is rarely mentioned in the literature, although most engineers working with extruded or moulded clay are well aware of it. The mechanism responsible for the development of this anisotropy has not yet been described in detail; similarly the connection between the plastic deformation process and the shape of the clay particles has not been described either in a satisfactory manner.

In this study the anisotropy produced by plastic deformation and the continuous change of the plastic properties during deformation were investigated in two steps:

(1) The true stress-strain curves of materials with flaky particle shape were determined with special emphasis on the effect of predeformation.

(2) The actual anisotropy of the plastic unit cell was determined by an x-ray diffraction technique.

EXPERIMENTAL PROCEDURES

The clay bodies were studied in a modified Endell plastometer. This instrument (Fig. 4) consists of two parallel planes (between which the sample was compressed by a calibrated spring) and the strain recording apparatus. A millimeter gauge was added to the original plastometer in order to obtain more accurate readings of the compression of the spring.

Kaolinite from Georgia was used for this study; the water content of the samples varied between 23 percent and 33 percent. Electron micrographs of the sample show that the kaolinite crystallites have a flaky morphology. The sample used for the investigation was not electrodialyzed.

Balls, approximately 15 cm in diameter, were rolled from the wet clay in order to ascertain that the flaky particles were not arranged according to a preferred orientation. X-ray diagrams indicated that the center portion

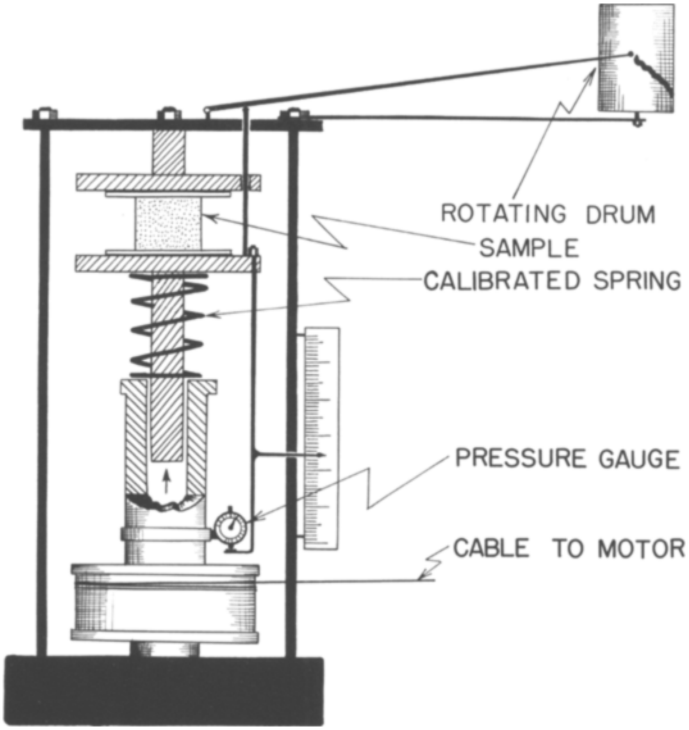

FIGURE 4. — Modified Endell plastometer.

of such a sphere contained all of the clay particles in random orientation, whereas in the surface portions the basal planes of the flaky particles were more or less parallel to the surface of the ball. A cylinder was cut out from the spherical sample; all of the surface portions of the spherical sample were discarded and only the center was used. Homogeneous deformation of the clay cylinders was attempted by compressing the cylinders between two glass plates on which a few drops of heavy-grade motor oil were added. Compression between lubricated surfaces eliminated bulging of the samples.

The investigation involved the following experiments:

(1) Cylinders of different heights were compressed at the same deformation rate. This experiment was designed to test the uniformity of the strain distribution. If homogeneous strain distribution exists, the stress-strain curves of clay cylinders of different heights are the same.

(2) Cylinders of the same heights were compressed at different deformation rates.

(3) To test the effect of the "texture" of the sample on the plastic

> properties, the cylinders were compressed until a certain stress was reached; then the stress was relieved. After a certain period of time, the stress was built up from zero again, this time above the value of the stress previously applied. The cylinder was not removed from the plastometer during the period when the stress was relieved. The samples were allowed to stand between predeformation and deformation for a period of five minutes for a number of samples and 45 minutes for the rest of the samples.

All of these experiments were run on clays of different water contents.

The effect of compression on the texture of the samples was studied with the aid of an x-ray diffraction method. This technique, described by Brindley (1953), consists of exposing a stationary flat clay sample with its surface tilted to the x-ray beam. The sample contained a few percent of fine quartz powder. The angle of incidence was set in such a manner that the (002) reflection of the kaolinite and the $(10\bar{1}1)$ reflection of quartz were focused and recorded on a flat film; these two reflections fall close to each other on the film. If the kaolinite crystals were lined up with their basal planes parallel to the exposed face of the sample, the resultant (002) reflections appeared as spots (short circles) on the film. The quartz grains were isodimensional for practical purposes and, therefore, they did not develop preferred orientation during the compression of the clay sample. For this reason the quartz reflections always appear as continuous circles. The intensity of a reflection is influenced by the absorption factor, which depends on the 2θ angle and on the β-angle. The latter is the angle between the reflected beam and the plane of incidence. Quartz reflections, therefore, also showed an intensity maximum at the intersection of the reflection circle and the plane of incidence ($\beta = 0$), but the intensity decreased only slightly with increasing β along the circle. In oriented samples the intensity decreases much faster and to such an extent that a full circle can no longer be seen.

EXPERIMENTAL RESULTS

The stress-strain curves measured on samples of different heights were identical within the limit of instrumental error. This indicated that such precautions as cutting the cylinders from ball-shaped samples and compressing them between lubricated smooth surfaces lead to homogeneous strain distribution. The resultant curves, therefore, represent the true stress-strain functions.

The shape of the curves appeared to be influenced by the water content, the speed of deformation, and the presence or absence of predeformation. The stress-strain curves of samples containing approximately 30 percent water showed that a small increase in stress resulted in a substantial increase of strain. Samples of lesser water content were more rigid. All of the curves have shown that the samples increased their rigidity more rapidly at the start of the deformation. This phenomenon is demonstrated by the steeper slope of the first part of the curves. An important aspect of the results lies in the fact that all of the true stress-strain curves start at the zero point of the coordinate system; *even a very small stress produced a small but finite deformation.* Such features, as well as others, may be seen in Figures 5 and 6. Different speeds of deformation have also affected the shape of the curves. The stress-strain curves obtained at a deformation rate of 0.13 mm/sec indicate a more rigid behavior than those run on the same sample under similar conditions but at 0.05 mm/sec rate. Predeformation also increased the rigidity of the samples. When a sample was compressed (predeformed) to a certain stress and then relieved from it, repetition of stress resulted in a new stress-strain curve indicative of increased rigidity until the point which corresponded to the limit of the predeformation was reached. After this point was exceeded, the sample behaved practically the same as one which had not been subjected to predeformation. The general character of the curves, the absence of any inflection point which could be explained as yield-value, and the effect of the deformation rate seem to confirm the results reported by Macey (1944).

The textural changes developed during compression were revealed by the x-ray diffraction studies. A sample taken from the inside of the spherical samples showed random orientation of the flaky clay particles.

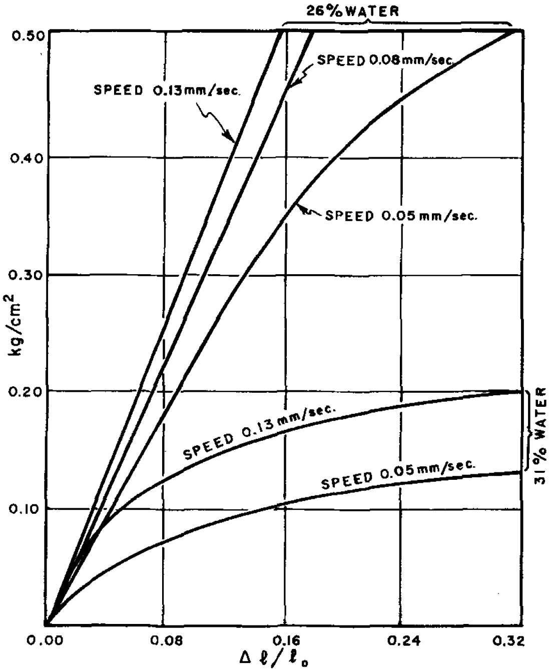

FIGURE 5. — The effect of different rates of deformation on the stress-strain curves.

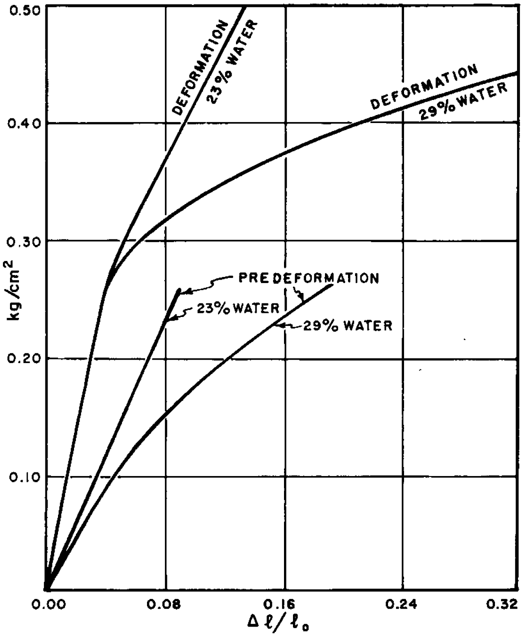

FIGURE 6. — The effect of predeformation on the stress-strain curves.

Samples subjected to compression showed an increased pole density of the 002 plane in the direction of the applied load. This increase was roughly proportional to the increase of strain and stress; samples subjected to 0.22 kg/cm^2 revealed less orientation than those subjected to 0.55 kg/cm^2 (See Pl. 1). Williamson (1940) has already noted that the action of stress upon a clay sample causes preferred orientation of the particles. His study, however, was not chiefly concerned with the plastic properties of clays.

Electron micrographs of replicas taken of compressed clay samples seem to indicate that the flaky particles were arranged parallel to the top and bottom of the compressed cylinders. The electron microscopic results, however, are not conclusive.

CONCLUSIONS

Compression of clay-water mixtures in the workable state produces two irreversible changes:

(1) Increase in rigidity (strength) of the sample.

(2) Orientation of the clay particles relative to the direction of the compressive stress.

Both changes approach a maximum value.

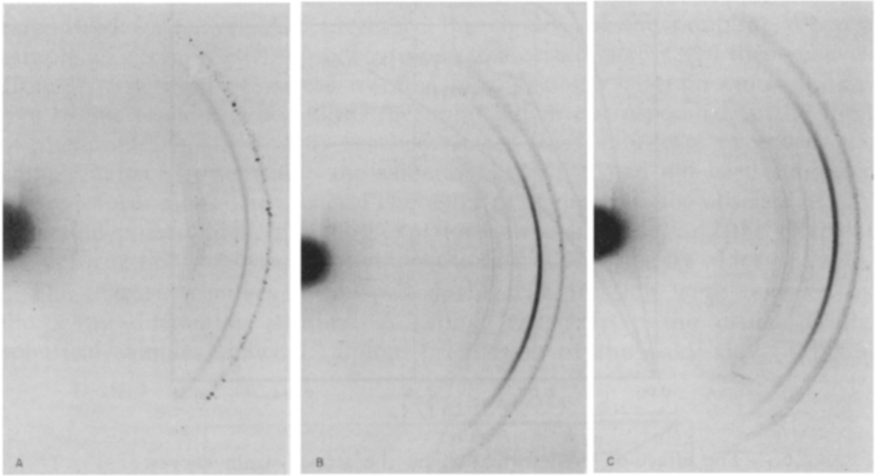

PLATE 1. — X-ray diffraction photographs of a Georgia kaolinite sample. (A) Random orientation of the flaky clay particles (the spotted line is the $10\bar{1}1$ quartz reflection); (B) Same sample after subjection to 0.22 kg/cm² compressive stress; (C) Same sample after subjection to 0.55 kg/cm² compressive stress.

The orientation is considered to be the result of the rotation of the clay particles. Rotation is connected with the basic process of plastic deformation, i.e., with the material transport from the shrinking direction toward the expanding direction. The increase in rigidity is considered to be due to the improved strength of the oriented texture.

Increase in rigidity and the development of oriented textures are irreversible processes; therefore, the strain-stress history of a sample is of great importance. This point has been frequently neglected in the past. Former studies were often based on the investigation of samples which were shaped by a sequence of compression techniques resulting in a complicated and sometimes undefined texture. Such studies cannot lead to results that can define all the plastic-properties of clay-water mixtures.

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