

Principles of Soil Mechanics:

I—Phenomena of Cohesion of Clay

Relation Between Load and Moisture-Content—Hydrostatic Stress in Clay—Shrinkage and Negative Hydrostatic Pressure—Surface Tension the Cause of Cohesion

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This article begins a series in which the nature and behavior of soil are studied and analyzed, with fruitful results. The first four articles discuss clay, explaining its cohesion, shrinkage, elastic behavior and settlement. Later, sand is taken up, and the characteristics of sand and clay are compared. Mixed soils are not dealt with; nevertheless the facts developed in the author's investigation bear intimately on problems arising in practical engineering work wherever clay or sand soils are concerned.—Editor.

A NUMBER of years ago the author became impressed with the perplexing character of the problems which the behavior of sand and clay soils presents to the engineer. It was evident that our knowledge of the underlying laws of action of these materials is not sufficient for proper solution of these problems, and that the first step of progress would be a careful experimental study of their physical behavior. At Robert College the author at last found opportunity to carry on such a study, which began with sands and later took up clays. The work has yielded results of interest and (it is believed) importance. Some of the early results of the study of sands were reported in *Engineering News-Record*, Sept. 30, 1920, pp. 632-637. A fuller statement of results is now possible, as the later investigations included clays, the physical properties of which had remained essentially unexplored. The term clay indicates mixed-grained, plastic soils consisting of particles from 1 mm. down to 0.006 mm. in diameter and a very small percentage of "ultra-clay" (colloidal particles in the colloid-chemical sense of the word). Hence the term includes almost all the soils which are commonly known as "clays."

Prime factors in the behavior of clay are (1) cohesion, (2) the action of the moisture contained in the clay, and (3) permeability. The present and several succeeding articles will summarize the facts concerning them as developed by the experimental investigation. Cohesion will be considered first.

Cohesion is commonly looked on as a characteristic property of certain soils. No serious attempt has thus far been made to analyze the physical causes of the property, but it has apparently been accepted as an elementary fact, unsuitable for further analysis. As a consequence the mechanics of clays has remained in a rudimentary state. We know practically nothing about the part played by the factors of time and permeability in the processes called "settlement," nor have we any clear conception of what causes the swelling of clays. Under these circumstances it is timely to investigate these phenomena systematically. The author has carried out a long series of laboratory studies in this effort.

Load and Moisture Content—The simplest process a layer of clay can undergo is compression under a uniformly distributed load when the layer is restrained from expanding laterally and when surface tension of the capillary water is excluded. In order to accomplish the latter, the author's experiments were made with a mixture of clay and water (free from air), and during the experiments the surface of the clay was kept covered with water; thus there was no external force acting on the clay particles except the surcharge. As the voids of the clay are completely filled with water, a certain quantity of the capillary water must escape during the compression of the clay by the surcharge.

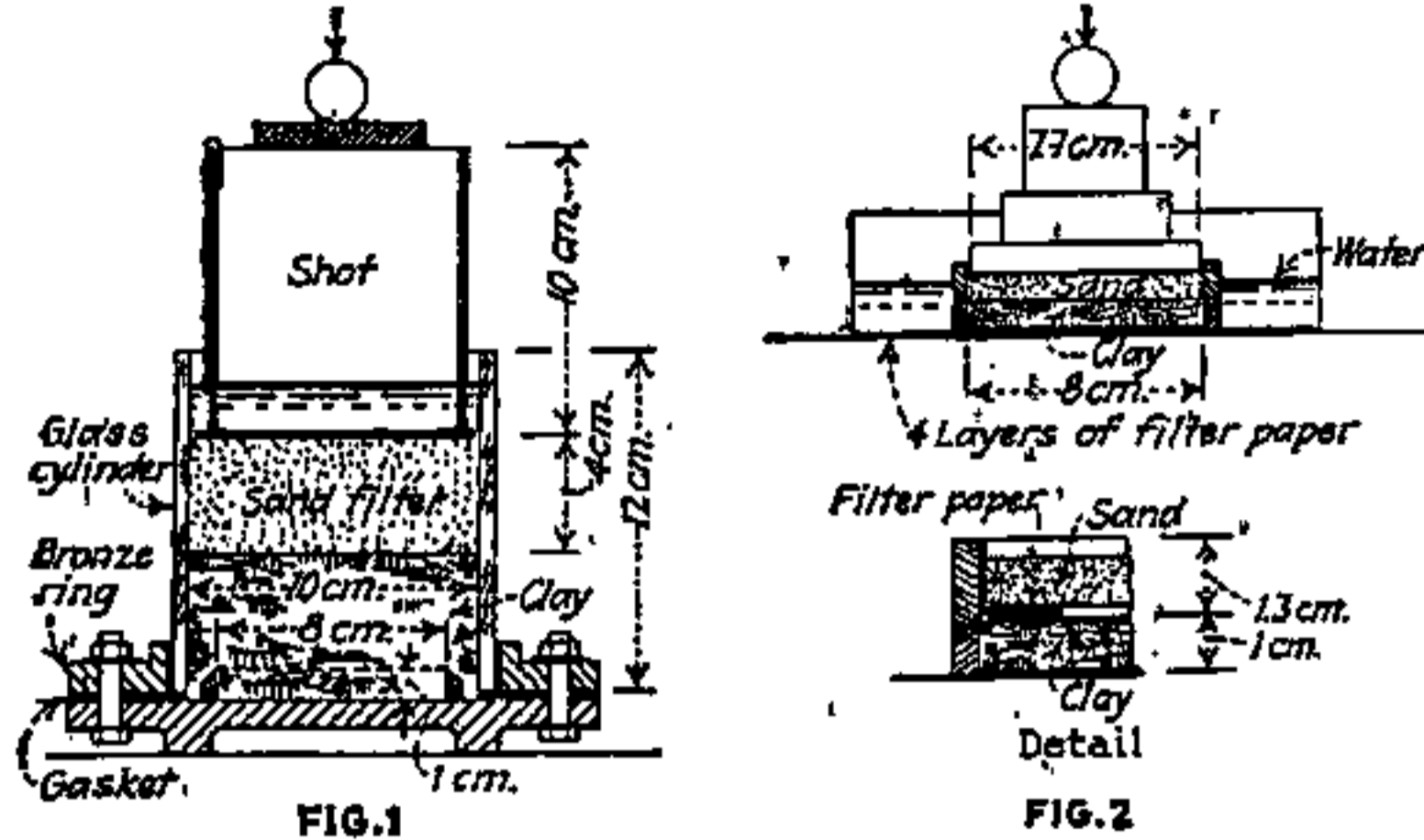
The experiment was made as follows: The lower part of a glass cylinder (Fig. 1) was filled with a liquid but very viscous mixture of clay and water. The bottom of the cylinder was covered with a sheet of thin filter paper (not shown), and on this rested a bronze ring completely surrounded by and immersed in the clay solution. The surface of the mixture was covered with a layer of filter paper, and on top of the paper was placed a filter composed of quartz sand of grain size $\frac{1}{2}$ to $\frac{1}{4}$ mm. Within 24 hr. the compression produced by the weight of the filter was completed, and the filter was then loaded by a brass cup. One day later further load was added by filling the lower half of the cup with lead shot, and after the lapse of two more days the upper half of it was filled too (total load at this time 0.1 kg./cm.²). For measuring the compression produced by the load, the side of the brass cup was provided with a scale. Additional surcharge was applied by means of a lever bearing on the cup through a steel ball. Thus the pressure was increased at about two-day intervals from 0.1 to 0.2, 0.3, 0.6 and 1.2 kg./cm.²

Higher pressures were applied in a testing machine. For this purpose, the lever, cup and sand filter were removed, the bottom plate of the cylinder unscrewed, and the clay forced out by a piston. Then the ring was freed from the surrounding clay in such a manner that it contained a layer of clay of thickness equal to the height of the ring (1 cm.). A sample of the removed part of the clay served for determining its water content. The ring with its clay core was weighed, and then the experiment was continued by means of the apparatus Fig. 2. The change from one apparatus to the other was made rapidly, to minimize loss of water by evaporation.

The apparatus consisted of a square vessel the bottom of which was covered with two layers of thick and one layer of fine filter paper, two superimposed bronze rings, bronze loading plates, and a steel ball. The two rings fitted together with a ground conical joint. First the lower ring with its content was placed on a moist sheet of thin filter paper, the upper ring was applied and lined with filter paper (see detail in Fig. 2), the

upper surface of the clay was covered with a circular piece of moistened filter paper, a sand filter was applied, and finally the whole set with the bronze plates and ball was transferred into the enclosing vessel, which was filled with water and placed in a testing machine.

In the machine the pressure was raised within twenty minutes from zero to 2 kg./cm.² and then left constant. Under this pressure the thickness of the



FIGS. 1 AND 2—DETERMINING RELATION BETWEEN PRESSURE AND MOISTURE-CONTENT OF CLAY
Fig. 1—Low-pressure tests. Fig. 2—High-pressure tests.

layer decreased, at first rapidly and then more slowly, and within about two days became constant, indicating hydrostatic equilibrium. Now the water was siphoned out of the vessel, the piston was rapidly lifted, the bronze plates and the filter and upper ring were removed, the upper surface of the clay was carefully dried off by means of absorbent paper, the weight of the ring together with its content was determined, the clay particles projecting beyond the upper edge of the ring were scraped away, and the weight was determined once more. Operations performed, the set was reassembled and the experiment was continued.

Thus the pressure was raised at intervals of about two days, from zero to 2, 4, 8, 14 and 20 kg./cm.². The measurements furnished the data for computing the co-ordinates of corresponding points of the pressure-moisture curve. Then followed a complete cycle, in which the pressure was successively kept constant for two days at the following values: 8, 4, 2, 1, 0 (four to six days, to allow complete resaturation), 1, 2, 5, 10 and 20 kg. per cm.²

At the outset of the investigation the author feared that the total removal of the pressure in each of the consecutive steps of the test might represent an important source of errors of observation. As a matter of fact no results at all could be obtained by such method in investigating the compressibility of sands or of other highly permeable granular materials. But in the case of clay experience has shown that the fear was not justified. Due to low degree of permeability even of sandy clays the effect of resaturation is negligible. Thus, a layer of clay 1 cm. thick and carrying no surcharge at all was brought into contact with water, after it had been previously compressed by a load of 18.9 kg./cm.² and in an hour its moisture content increased only 0.15 per cent, while the time during which the clay has a chance to take up water between two consecutive tests never exceeds two minutes.

After having completed the cycle, the ring with its clay core was weighed once more. Then a sample of the clay was set apart for determining the final mois-

ture content of the layer. The figure thus obtained served as a basis for calculating the moisture content which corresponds to the successive stages of the experiment. The initial moisture content (corresponding to a pressure of 1.2 kg. per sq.cm.) being known, the results of the calculation could be checked by theoretically calculating the subsequent moisture content. Any difference between the actual and the theoretical moisture content (in no case large) was then distributed over the intermediate values.

Fig. 3, shows typical results. Abscissas represent intensity of loading and ordinates moisture content in percentage of the space occupied by the solid matter of the clay. A yellow pottery clay and a blue marine clay are represented in the lower diagram, and a gray sandy delta mud in the upper. Each test lasted about eight weeks. The main branch of each curve portrays the effect of gradually increasing load (combined compression), while loading cycles are represented by curved hysteresis loops (elastic expansion).

Lag of Compression—As already mentioned, the compression produced by the application of a load never occurred at once, but increased for some time while the load remained constant. Equilibrium was never reached in less than about 24 hr., in spite of the fact that the layers were very thin. This fact is very significant; it indicates that the capillary water took time to drain from the interior of the clay towards the free surfaces and escape through the filters. Since this flow of water implies a hydrostatic head, and the sur-

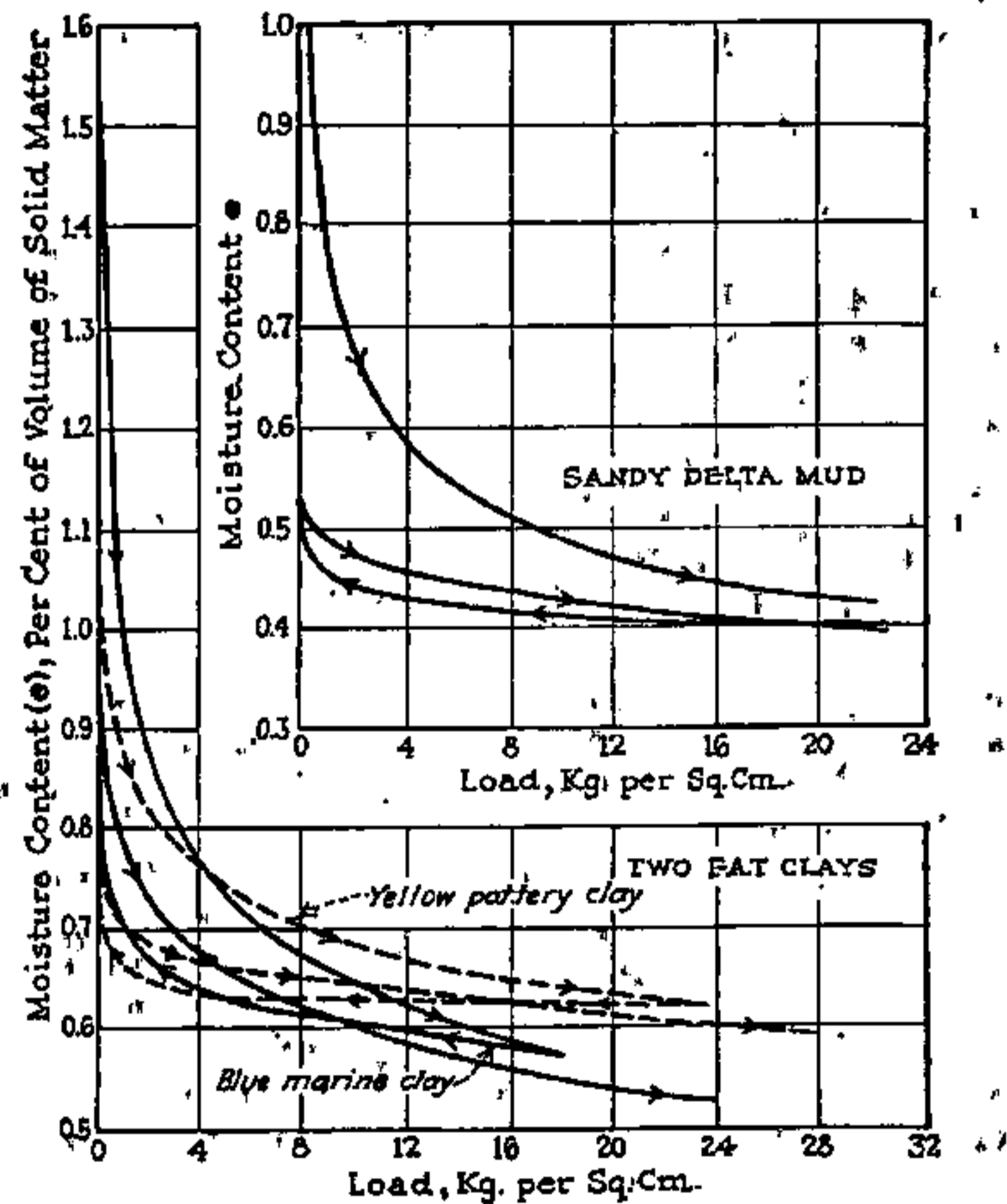


FIG. 3—PRESSURE-MOISTURE CURVES FOR THREE CLAYS

face of the clay (being covered with water) was constantly at zero hydrostatic pressure, the application of the load must have produced a positive hydrostatic pressure in the capillary water of the central parts of the clay. The hydrostatic stress difference which produces the outflow of the capillary water is consumed by the resistance which the water encounters in the narrow voids, of the clay on its way to the surface.

The author later proved by other experiments (see a subsequent article) that the flow of water through clay follows Darcy's law as closely as does the flow of water through sand. Hence there exists simple proportionality between the value of the hydrostatic stress difference and the amount that the thickness of the layer decreases per unit of time at constant surcharge, because the decrease of clay volume is identical with the volume of the water that escapes through the surface of the clay. Immediately after the load is applied the speed with which the clay volume decreases is greatest, hence the hydrostatic stress difference must be a maximum; in the final state the hydrostatic pressure has become zero in every part of the layer and the thickness of the layer remains constant (hydrostatic equilibrium of the clay).

From the results of the tests described we learn that pressure and moisture content of a clay are as definitely related as stress and strain in solid bodies. The only difference between the two relations is that the compression of the clay develops gradually, while the application of a pressure on a solid body is almost immediately followed by the corresponding strain. In addition we have learned that a change of the volume occupied by a mixture of clay and water involves a flow of capillary water from the central parts of the clay towards the surface, which in turn requires the presence of a hydrostatic stress difference. The strain does not become constant until the hydrostatic stress difference has disappeared.

Shrinkage Test—Keeping these simple but important facts in mind, we may proceed to a second series of tests. We fill the glass cylinder of Fig. 1 with a liquid yet very viscous mixture of clay and water, just as was done before. But instead of covering the surface of the clay with a filter and loading it, we leave it as it is, in contact with the atmosphere. Precisely the same phenomenon occurs without load which we previously produced by means of loading the clay surface: the capillary water flows from the central part of the clay towards the surface, where it evaporates; the moisture content of the clay becomes smaller and the thickness of the layer decreases. *The clay shrinks.*

The only difference between the artificial compression and the natural shrinkage is that compression under load can be carried as far as we want, while in shrinkage due to evaporation a point is reached beyond which the volume of the clay remains constant. At this shrinkage limit the clay passes from the semi-solid into the solid state. Before the limit is reached, the layer shows symptoms of lateral contraction; it shrinks away from the ring to which it is confined, and cracks. At the shrinkage limit the clay usually changes its color. Yet, from the outset of the shrinkage test to a point beyond the limit of the plastic state, the process of compression and the process of shrinkage are in every respect identical.

It is astonishing that nobody seems to have felt the necessity of investigating the physical causes of this identity. As a matter of fact, analysis of the phenomenon leads to new and very important conclusions. In order to perform it we have merely to keep in mind that the elementary laws of mechanics which apply to solids and liquids in general are valid also for the constituents of a mixture of clay and water.

Negative Hydrostatic Pressure—By direct measurement it was found that the water content of a layer of

clay slowly shrinking at normal temperature remains fairly uniform throughout the thickness of the layer, if this thickness amounts to not more than a few centimeters. Hence there must be a continuous flow of water from the interior of the layer towards the surface of evaporation. The flow indicates the presence of a hydrostatic stress difference between the interior and the surface.

During the loading test the hydrostatic pressure acting in the central part of the layer of clay was posi-

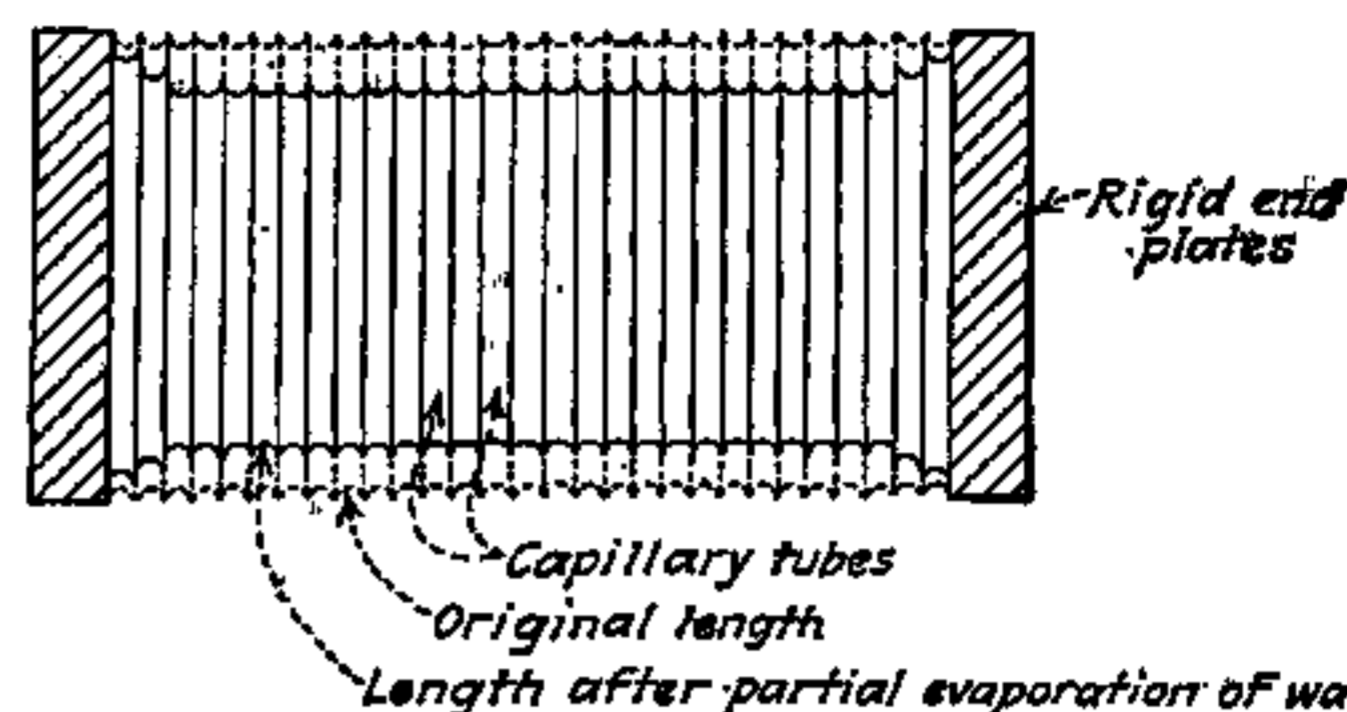


FIG. 4—BUNDLE OF CAPILLARY TUBES COMPRESSED BY EVAPORATION OF CONTAINED WATER

tive. This positive hydrostatic pressure was balanced by the external load pressing upon the particles between which the capillary water flowed toward the free surface. During the shrinkage test the external load was zero, and as the dead weight of the clay can be considered negligible compared with the intensity of the forces we have to deal with, the hydrostatic pressure in the interior of the clay is zero. But as the flow of the capillary water toward the surface of evaporation requires the existence of a hydrostatic stress difference, the hydrostatic pressure acting in the vicinity of the surface of evaporation must have been negative.

During the compression test, surface tension of the water was not active, because the free surfaces of the clay were covered with water; only the external load forced the clay particles down. During the shrinkage test, there was no external load, but surface tension acted all over the top surface of the clay. Therefore the hydrostatic stress difference and the negative hydrostatic pressure, could not be produced by other than the surface tension of the capillary water.

In a vertical capillary, water may rise to great height. The surface tension at its surface, amounting to T dynes per centimeter of circumference, exerts a lifting force of $\pi dT/g$, where d is the diameter of the capillary in centimeters and g is the acceleration of gravity in cm./sec.^2 . Equating this force to the weight of the column of water in the capillary, of height h cm. and specific gravity w , we obtain $h = 4T/wdg$. The lifting force at the surface carries the weight of the column by a tensile stress in the water column, as water has no shearing strength. This tension, or negative hydrostatic pressure, has its maximum amount hw just under the upper surface of the column, and at any other point, at height h' above the level of water in the vessel below, it has the value $h'w$. Precisely similar tension, or negative pressure, exists in the clay during its shrinkage, and explains the phenomena which occur during the drying process.

A layer of clay surrounded by a stiff ring represents a bundle of capillary tubes whose ends are located within the free surfaces of the layer (Fig. 4). At the outset the tubes are filled with water. Evaporation at the free surface tends to cause the water to retire into

the interior, but it is prevented from doing so by the same forces which drive the water up a capillary, and therefore it continues to occupy the whole void space within the clay. The volume of the water, decreasing by evaporation, the clay is compressed by the surface tension of the water; in other words it shrinks, and at the same time the water comes under tension.

The analogy between compression by load and shrinkage by evaporation is set forth diagrammatically in Fig. 5. The direction of water flow and the nature of the internal pressures are indicated.

The intensity of the forces increases in direct proportion to the quantity of water evaporated, provided the solid matter follows Hooke's law. They reach their maxima when the full capillary force of the water is developed (*hw*, above); this marks the shrinkage

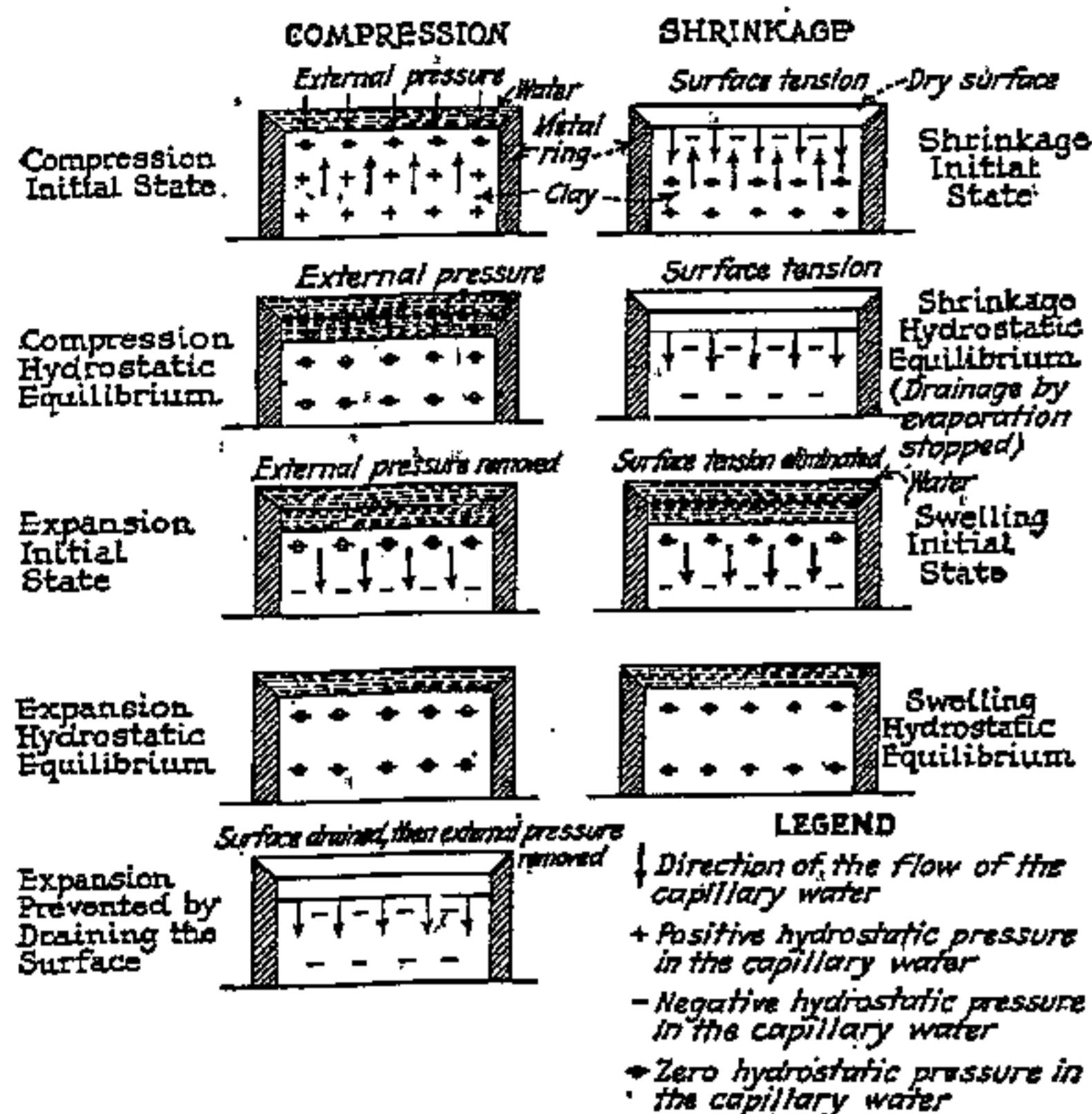


FIG. 5—DIAGRAMMATIC COMPARISON OF COMPRESSION AND SHRINKAGE OF CLAY

limit. Further evaporation causes the water to retire into the interior of the bundle, and the free surfaces change from dark to light color.

The pressure exerted by the surface tension will be called the *capillary pressure*, and its maximum value the *transition pressure*, which is the limit at which the clay passes from the semi-solid to the solid state. It has been proved that capillary action involves a tension in the capillary water equal to the capillary pressure. This tension cannot possibly be greater than the "intrinsic pressure" of the water. However, since the intrinsic pressure of water amounts to about 21,000 atmospheres, the transition pressure is limited only by the size of the voids of the clay.

The intensity of the negative hydrostatic pressure is evidently identical with the intensity of the external pressure required to produce the same degree of compression as the one brought forth by shrinkage. Owing to this fact, the transition pressure may be determined from the moisture content at which the clay ceases to shrink (shrinkage limit) and the external pressure required to reduce the moisture content of the clay from its initial value down to that at the shrinkage limit. Following this method, the author has found the

transition pressure of a yellow, residual clay to be 171 kg./cm.² (cube compressive strength 52 kg./cm.²), and that of a blue, marine clay to be 339 kg./cm.² (compressive strength 86 kg./cm.²). Thus the capillary pressure may be a force of enormous intensity. Yet the very existence of this force has never been suspected up to this time.

Swelling of Clay—If the free surface of a layer of plastic or of semi-solid clay is covered with water, the surface tension at once becomes zero and the clay expands. This swelling is identical with the expansion of the clay produced by the removal of an external load (recurrent branches of the hysteresis loops in Fig. 3), and represents elastic expansion of the clay caused by the elimination of the surface tension of the capillary water. Since the increase in bulk means increase of water content, it is apparent that water enters through the free surface and flows into the interior, impelled by the hydrostatic stress difference between the surface (where the pressure is zero, since the surface is covered with water) and the interior (where negative hydrostatic pressure exists).

If, during a compression test, one drains the water completely off the surface and then removes the external load, the volume of the clay remains nevertheless unchanged, because expansion would mean increase of the moisture content and there is no free water available. On the other hand, if the volume remains unchanged, the inward pressure cannot possibly decrease; the surface tension of the capillary water takes the place of the external load. Like a rubber skin, it opposes any tendency to expansion.

Thus all phenomena, associated with the cohesion of clays are capable of being explained by the single factor of surface tension. Cohesion is the internal frictional resistance produced by the capillary pressure. As the cause of the capillary pressure—the surface tension of the capillary water—is an external one, merely acting on the surface of the clay, the cohesion due to the capillary pressure may be called the *apparent cohesion*, in opposition to the *true cohesion* produced by initial friction*. As the initial friction was found to amount to not more than about 20 g./cm.², the true cohesion is very small compared with the apparent cohesion.

The shearing strength of a mass of clay is equal to the product of the capillary pressure and the coefficient of internal resistance. This relation, however, proves to be valid for the plastic state only, while in the semi-solid and solid states the shearing strength is smaller, just as the shearing strength of solid bodies is very much smaller than the product of the intrinsic pressure times the coefficient of internal resistance. The latter phenomenon seems to be due to important secondary stresses (unequal internal stress-distribution), and it is on the point of being thoroughly studied by various English investigators. (A. A. Griffith² Prof. B. P. Haigh² and others.)

Properties of Capillary Water—Since shrinkage is

NOTE—The term "initial friction" as used by the author denotes the shearing strength of clay when not under pressure, either external or capillary. Extended investigation of initial friction showed it to be far too small in amount to account for any of the properties commonly grouped under the general term "cohesion of clay." The internal friction which acts in the interior of a clay, subjected to either load or capillary pressure is the sum of (1) initial friction, which is practically independent of the intensity of the pressure, and (2) the frictional resistance set up by the pressure, which is proportional to the intensity of the pressure. Even at small pressures, however, the first item is almost negligible compared to the second.

due to the surface tension of the capillary water, it ought to be possible to calculate the intensity of the transition pressure from the average width of the voids of the clay. As the specific gravity of water is unity, the maximum capillary pressure in grams per square centimeter is equal to the maximum capillary height h in centimeters. The data obtained by a wet mechanical analysis allowed the author to estimate for the yellow residual clay mentioned above a maximum capillary height of 306 m., or 30,600 cm. This value corresponds to the width the voids would have at the shrinkage limit. Hence the intensity of the transition pressure ought to be of the order 30,600 g. or 30.6 kg./cm.². But, as previously noted, determination of the transition pressure for this clay gave the value 171 kg./cm.². The cause of the obvious disagreement between the two figures mentioned resides in the fact that water enclosed in voids of width less than about 0.1 micron ($= 0.1\mu = 0.0001 \text{ mm.}$) has properties different from those of water contained in wider vessels. The viscosity of the water as well as the rate of evaporation rapidly increases below this limit, as has been proved by permeability measurements.

A very important consequence hereof is that the capillary water of clays is but partially evaporable. If the capillary water contained in clays could completely evaporate, as does the capillary water of sands, clay upon drying would lose its cohesion. The cohesion of

clay dried at normal temperatures is however almost twice as great as the cohesion at the shrinkage limit. As the cohesion of a reversible colloid is due wholly to the surface tension of the capillary water, it follows that part of the capillary water remains in the voids of air-dried clay forever without evaporating.

According to the definition of the shrinkage limit, the width of the voids of the clay remains constant below the shrinkage limit, although the moisture content continues to decrease. Evidently, the surface of the capillary water retreats from the outer surface of the clay into the narrowest parts of the capillary system. This process decreases the total length of the contour line along which the surface tension acts; nevertheless the cohesion continues to increase. Hence we must conclude that the surface tension per unit of length of the contour line increases just as does the viscosity as the size of these very small capillary channels decreases. This conclusion confirms what has been assumed concerning the cause of the disagreement between the actual and the theoretical value of the capillary pressure.

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