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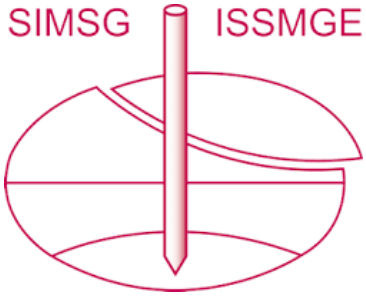

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Two Studies of the Heterogeneous System of Clayey Soils

Deux Etudes du système hétérogène des sols argileux

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SUMMARY

In Part I, the results of laboratory measurements with the aid of a thermistor thermometer are presented. In some classes of structures such as brick kilns and electric furnaces, or around flues, a considerable warming of foundation soil occurs during their operation. Therefore it is important to establish heat intensity and the rate of heat propagation in foundation soils.

In Part II, the coarse structure of thixotropic kaolinitic clay suspensions is studied, using the X-ray diffraction method and the electron microscope. In order to maintain the original structure during the thixotropic strength gain or in the state of liquefaction, the individual samples were first frozen and dried by desublimation under vacuum. It was found that, in thin suspensions, the particles are grouped into a "cardhouse" structure. With thicker thixotropic suspensions, parallel aggregation of the fine clay particles occurs first and then the network structure of this heterogeneous system is formed from these larger particles.

SOMMAIRE

La première partie donne les résultats de mesures effectuées au laboratoire à l'aide d'un thermomètre thermistor. Sous certains types de bâtiments renfermant, par exemple, des fours à briques, des fours électriques et autour des hautes cheminées le sol de fondation se réchauffe considérablement pendant les périodes de fonctionnement de ces fours, etc.

Dans la deuxième partie on étudie par la méthode de diffraction aux rayons X et au moyen du microscope électronique la texture grossière de suspensions thixotropiques d'argile kaolinitique. Pour conserver la structure originale durant le durcissement thixotropique ou à l'état de liquéfaction on a d'abord congelé les divers échantillons puis on les a asséchés par désublimation sous vide. On a constaté que dans les suspensions légères les particules sont groupées selon une structure en "château de cartes". Dans les suspensions thixotropiques plus denses, il se produit tout d'abord une agrégation parallèle des fines particules d'argile, puis les particules plus grosses ainsi formées constituent la structure réticulaire de ce système hétérogène.

I. MEASUREMENT OF HEAT TRANSFER IN SOILS BY THERMISTOR THERMOMETERS

LET US PRESUME that a change of temperature affects the viscosity, η, of water (Loos, 1937). Then, the coefficients of permeability and of consolidation are altered. The graph expressing the correlation between the degree of consolidation, U, and the time factor, T, is then adjusted in Fig. 1 in

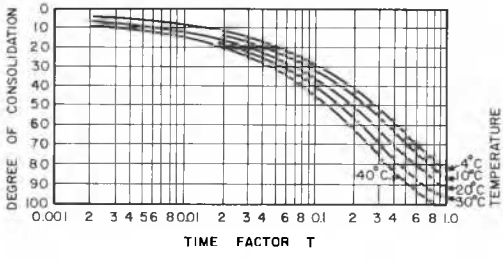

FIG. 1. Dependence of the degree of consolidation and the time factor on temperature. (Curve for 20 C is curve C_1 according to Terzaghi-Fröhlich, 1936.)

accordance with the equation $T_{20\,C} : \eta_{20\,C} = T_{30\,C} : \eta_{30\,C}$. This prerequisite holds for a soil fully saturated with water. In this case, further circumstances, such as the chemical composition of the liquid phase, the relation of soil particles with water, and the effect of gases enclosed in the water in the pores of the soil (Henry's law) must be considered. These considerations necessitate temperature corrections in oedometric tests.

In laboratory investigation of heat transfer in soils, artificially prepared samples of neogene clay were used. The clay had the following properties: 47 per cent grain size smaller than 0.005 mm, 46 per cent with grain size in the range 0.05–0.005 mm, and 7 per cent grain size over 0.05 mm; porosity (n) = 0.48; void ratio was approximately 0.90; liquid limit (w_L) = 68 per cent; plastic limit (w_P) = 25.2 per cent; unit weight = 1.82 grams/cu cm. Differential thermal analysis showed that the material was calcareous clay of illitic type; the coefficient of permeability was less than 10^{-7} cm sec^{-1}. Different water contents (30 and 34.8) were used in the measurements. Degree of saturation (S_r) = 0.9.

The thermistor was glued with an artificial resin adhesive to the end of a needle syringe which was inserted at various points 1.7 cm below the surface of the sample which was 3.5 cm in height. The thermistor was equipped with a Helipot potentiometer, with a scale divided into 1,000 lines, so that an accuracy of 0.01 C in reading could be obtained. The resistance 11.4 $k\Omega$ enabled the temperature to be measured in the range of 15–43 C by means of a high sensitivity thermometer.

In Fig. 2, the measuring equipment and a schematic array of the apparatus are shown. A metal tube (M), 1 cm in diameter, passed through the sample. Water, which was equilibrated to a constant temperature by an ultrathermostat (U), passed through this tube. The intensity of heat was automatically controlled by means of a contact thermometer (Th), with the aid of small relays (R) having an accuracy

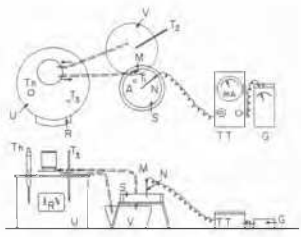

FIG. 2. Diagram of the measuring apparatus.

of ±0.02 C. Water passing through the tube was the source of heat which was propagated into the soil sample (S). Under the sample was placed an overflow vessel (V). The temperature of the source was checked by three thermometers T_1, T_2, and T_3. The temperature was measured in different radial directions, at points spaced 1 cm apart, by the needle with a thermistor (N) using a thermistor thermometer (TT) and a galvanometer (G). The tests were carried out at different temperatures for the source—30, 40, and 50 C (these temperatures being reached after 5 hours)—and at different water contents. Fig. 3 shows the results of measurements when the temperature of the source was 40.6 C.

Temperatures were also measured at certain points at various times. For example, the temperature at point A increased after 30 minutes to 25.8 C, after an hour to 28.2 C, after 2 hours to 29.45 C, after 3 hours to 29.7 C; after 4 hours it reached the value of 29.8 C and showed no further change after the fifth hour. Fig. 4 shows the temperature changes at this point at various times, with the temperature of the source at 30, 40, and 50 C, and with water contents of 30 and 34.8 per cent.

According to the theory of heat transfer (Schack, 1957), it can be calculated that, at 1 cm from the source (M), the temperature should be 36.1 C; similarly at 2 cm the temperature should be 35.1 C, at 5 cm 31.8 C, at 9 cm 27.8 C, etc. Theoretical values are higher than those measured at points

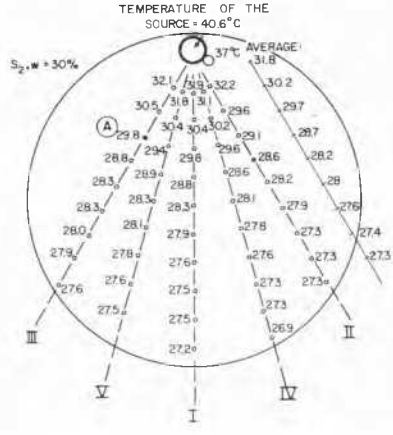

FIG. 3. Temperatures measured at various distances from the heat source.

nearer the heat source. This may be accounted for by the fact that higher heat losses occur in practice. The average temperature of this sample before the introduction of the heat source was 17.6 C.

The calculations show that they conform fairly well with the measured values, in spite of their approximation. Considering the comparatively small dimensions of the sample and the fact that exchange of temperature with the surrounding medium sets in, it can be said that the results of the experiments are satisfactory. The fact that the coefficient of heat transfer is not constant during the experiments plays an important role; heating causes a change in the water content in the course of the test.

The experiments have shown that thermistors are a suitable means of measuring temperature and of investigating thermal phenomena in soils. Thermistors enable even very slight changes in the temperature of soils to be recorded. Considering that thermistors, by a mere contact, enable immediate measurement of temperature, they may be used in measuring temperature even at great depths in foundation soil under structures. The thermistor element is fastened to the end of a very thin sounding rod which, owing to its small diameter, does not dislocate the original position of the soil.

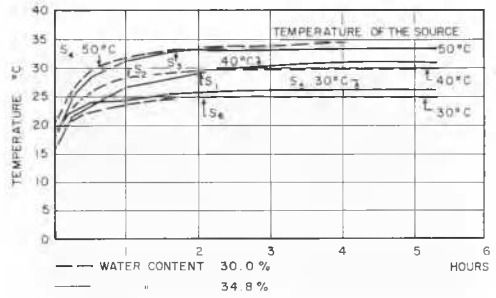

FIG. 4. Temperature at 3 cm from the source in various intervals of time.

The high sensitivity and immediate response of the thermistors permits accurate temperature measurements over various ranges (exceeding 400 C under electric furnaces), depending on the types of resistance in the apparatus and the type of thermistor used.

II. DEVELOPMENT OF THE COARSE STRUCTURE OF THIXOTROPIC CLAY SUSPENSIONS

The loss of strength of clayey soils through mechanical vibrations and strength gain with time (under constant water content) are currently attributed to thixotropic phenomena. This cannot be regarded as absolutely correct, however, since it is known that thixotropy is an isothermic reversible change of solid into gel (Freundlich and Peterfi, 1926). If the strength gain of plastic clayey soils with time is considered, it can be assumed that the various physicochemical processes (coagulation and cementation) which take place are not reversible and are therefore of a non-thixotropic character (Kazda, 1964).

The nature of the thixotropic strength gain has been explained in various ways. Terzaghi held the view that the individual particles of the clayey soil are bound to one another by water layers. Casagrande assumed that the loss of strength and its renewal with time takes place through

fine clayey particles. According to recent concepts (Thiesen, 1942; Lambe, 1953; Trollope and Chan, 1960), thixotropic strength gain is attributed to different electrical charges on the clay particle surfaces. Each of these conceptions is partly true. However, a problem of primary importance in the investigation of thixotropic strength gain is the determination of the system structure of the soil both at rest and as it changes, e.g. through the influence of vibrations. This paper, the result of part of a larger experimental study, will present a partial solution of this problem.

Experimental Results

Great difficulties were encountered in the preparation of specimens, especially when being dried, since it was necessary in some cases to maintain the original particle arrangement in the moist state. This was achieved by sudden freezing of the specimen in liquid oxygen and desublimation in a vacuum (with P_2O_5). The samples for the X-ray diffraction analysis were frozen on a foil (PVC), those for the electron microscope on a collodium foil. The X-ray diffraction diagrams of the suspension in water were carried out in borosilicate glass capillaries. For the tests, kaolinitic clay (Sedlec) with 90 per cent kaolinite mineral was employed (grain size 89 per cent $<5\mu$ and exchange capacity 8.2 mval/100 grams).

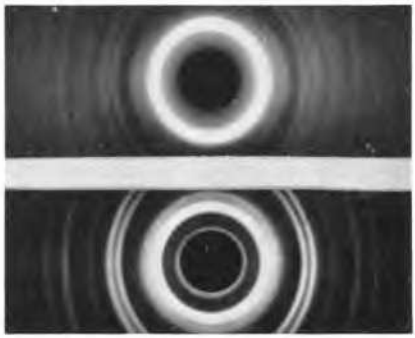

FIG. 5. X-ray diffraction diagram of kaolinitic clay suspension. A, freely dried in air; B. frozen and dried in a vacuum with P_2O_5.

A cursory examination of X-ray diffraction diagrams (Fig. 5) of two differently dried samples of kaolinitic thixotropic gels shows considerable differences in the intensity of the individual lines. The first X-ray diffraction diagram (Fig. 5a) belongs to a sample which has been freely dried in air. The second diagram (Fig. 5b) belongs to a sample which has been frozen and dried by desublimation in a vacuum of ice crystals from the spaces between the particles. The change of intensity of lines can be explained by different particle orientation (texture) as well as by a different fabric in the samples.

The differences in line intensities are more evident in the photometric curves (Fig. 6). The scheme of a kaolinite crystal is shown; from the peak points of the lines, the orientation of the particles is evaluated. The photometric curve (Fig. 6a) belongs to a dry, pulverized kaolin sample in a gelatine capillary. The particle orientation in this sample can be considered all-directional because a considerable quantity of lines of sufficient intensity is present. The next

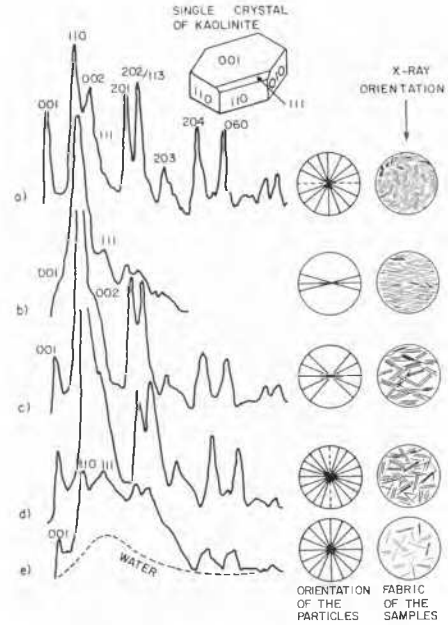

FIG. 6. Photometric curves of X-ray diffraction diagrams of kaolinitic clay: a) dry pulverized sample in gelatine capillary; b) suspension freely dried in air; c) suspension frozen at rest and dried in a vacuum; d) suspension frozen under vibrations and dried in a vacuum; e) suspension in borosilicate glass capillary.

photometric curve (Fig. 6b) belongs to the gel sample freely dried in air. The line corresponding to reflexes on the basal plane 001 can not be seen. Thus kaolinite crystals produced by a drying process exhibit an orientation parallel with the base foil. The next two photometric curves belong to two samples frozen in liquid oxygen and dried in vacuum, one at rest (Fig. 6c) and one under vibration (Fig. 6d). The X-ray diffraction diagrams of both samples are not so different in principle. A somewhat greater intensity of line 001 and 002, as well as a change in the intensity ratio of lines 201 and 202 can be seen, attributable to the larger aggregated particles. The last photometric curve is that of a thin suspension in water (Fig. 6e). The presence of all interferences seems to suggest that the particles in the suspension are orientated in all directions.

The conclusions from the X-ray diffraction investigation of the coarse structure of thixotropic gels were supplemented by observation with the electron microscope. Fig. 7 shows an electron micrograph of kaolinitic clay suspension freely dried in air. In the whole viewing field of the preparation, individual and aggregated kaolinite particles were observed. These existed throughout with parallel orientation to the collodial foil, tightly packed with their basal planes. Fig. 8 belongs to suspension exhibiting thixotropic strength gain. The micrograph is from the fringe of the sample and indicates clearly a different structure. The kaolinite particles are aggregated in parallel and the larger units form a three-dimensional network structure. Fig. 9 depicts an agglomerate

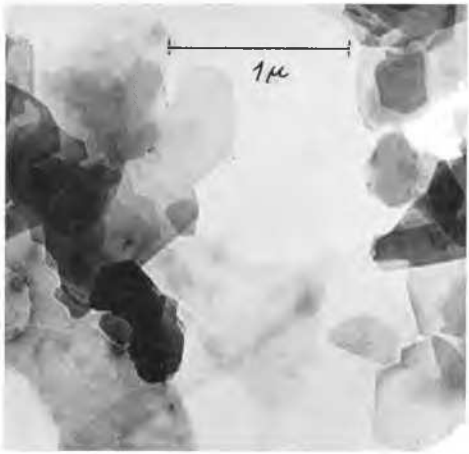

FIG. 7. Electron micrograph of kaolinitic clay suspension freely dried on a collodium foil.

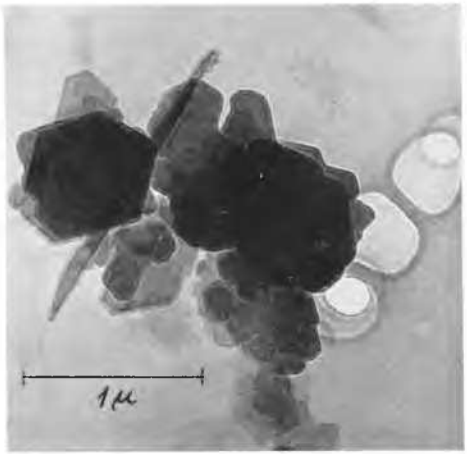

FIG. 9. Electron micrograph of kaolinitic clay suspension frozen at rest—agglomerate of several crystals at greater magnification.

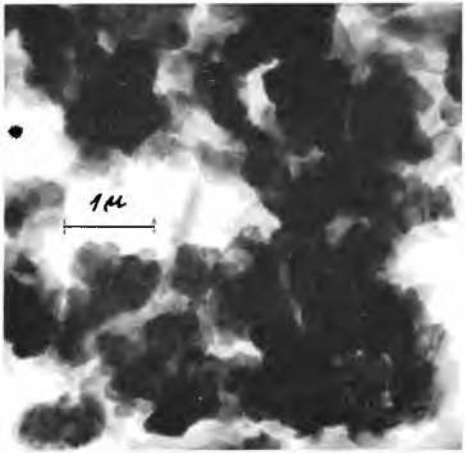

FIG. 8. Electron micrograph of kaolinitic clay suspension frozen at rest.

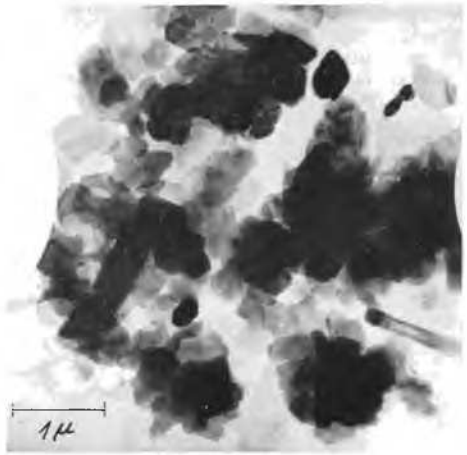

FIG. 10. Electron micrograph of kaolinitic clay suspension frozen under vibration and dried in a vacuum.

of several kaolinite crystals in a greater magnification. It can be seen that the particles are mutually laterally orientated. The last electron micrograph (Fig. 10) belongs to the suspension frozen during vibration. Many more elementary kaolinite crystals adjoining the foil in a parallel manner can be observed. Apart from that, the original network structure appears to be somewhat torn.

CONCLUSION

This investigation proves conclusively that water in clayey soils facilitates the formation of a structure with parallel particle orientation during drying. Also, it has been found that the crystal edges are parallel and slightly displaced.

It can be assumed that in the development of coarse structure in thixotropic suspension a certain part of the very fine elementary particles first aggregate into larger units, and these then form the network type, all-directionally orientated fabric. With a mechanical disturbance of the thixotropic state, a weakening or failure of the structure at the points of contact of larger aggregated units takes place. After destruction of the structure and the beginning of flow of the thixotropic suspension, a parallel particle orientation and thus a further viscosity reduction takes place gradually. Nevertheless, it should be noted that the water pressure enclosed in the network structure, after its disturbance, becomes partly mobile.

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