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SUB-SECTION II f

ELECTRO-OSMOSIS

II f 3

SOME EFFECTS OF ELECTRIC CURRENT ON THE CONSOLIDATION CHARACTERISTICS OF A SOIL

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INTRODUCTION

There is clearly two major actions when electric currents are applied to soils. One is the electro-chemical hardening or solidification of clay soils, and the other is known as electro-osmosis of sands, silts and clays, in which direct currents are used as the propelling agents for expelling water. Although these two actions bear an obscure relationship to each other, sufficient research has not been completed to identify the connection.

As the electro-osmosis effect of the electric currents influences the drainage properties of soils it was evident that they should also modify the consolidation characteristics. This paper is a report on the effect of electric currents on the consolidation of a remolded soil. Although the original plan was to include tests on undisturbed cores, so much time was consumed in construction of equipment, selecting proper voltage, thickness of sample, etc., the undisturbed specimens were omitted. Also the results are based on the time-consolidation characteristics for a single load increment. For these reasons, this investigation can be considered as only preliminary and any conclusions must be of a tentative nature.

This investigation was conducted by Mr. McDonald for his Master of Science in Civil Engineering thesis under the direction of the senior author. Since the charts and figures were originally prepared for the thesis, it will be found that they are not numbered consecutively in this paper.

EQUIPMENT AND TESTING PROCEDURE.

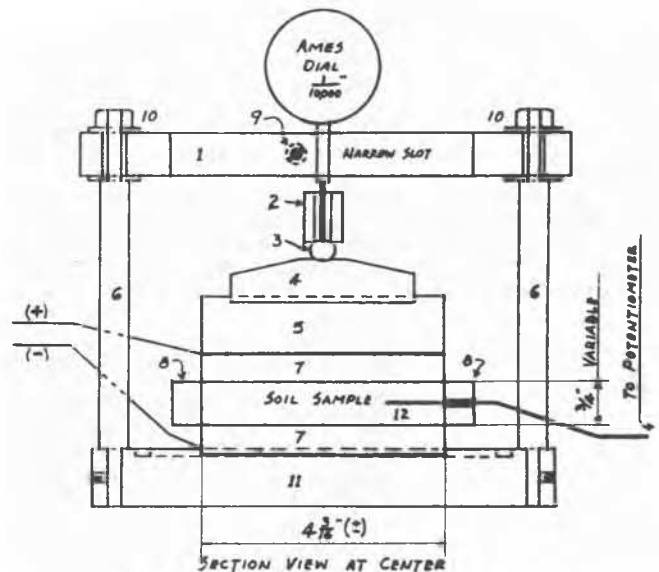
The consolidometer used is similar to the ordinary floating-ring type used extensively in soil testing. The important differences are the use of materials to control the flow of electric currents. The device (See Fig. 1) is made of a non-conductor material, bakelite, while the drainage plates were made of a porous bronze material which also served as electrodes, thereby producing a vertical current flow through the soil sample.

Early in the testing it became apparent that the energy expended upon the sample, even at relative low voltages, was producing a considerable rise in temperature. It was not until near the end, however, that satisfactory equipment became available to measure the interior temperatures of the sample. The equipment consisted of a copper constantan thermocouple thrust into the sample through a small hole in the sample ring (see Fig. 1) after everything was in place for testing, and a calibrated potentiometer.

For the first few tests the power was supplied from several dry-cell batteries connected in series, through a rheostat for varying the voltage applied to the electrode leads.

Later two automobile storage batteries were substituted for the dry-cells, providing a maximum of 12 volts. Eventually equipment became available for drawing power from the standard 110 volt, AC source. This equipment consisted of a small "step-down" transformer, an adjustable voltage transformer and a rectifier which permitted the application of any voltage from zero to approximately 45. Since the resistance of the sample evidently changed with the passage of current, the amount of current drawn was itself a variable, even at constant voltage.

For each of these systems an ammeter was placed in series and a voltmeter was connected across the sample, thus giving continuous readings of voltage and current throughout the tests.



FLOATING-RING CONSOLIDOMETER

- 1 CROSS FRAME DIAL SUPPORT (ALUMINUM)
- 2 LOADING YOKE OF TESTING MACHINE (STEEL)
- 3 LOADING BALL (STEEL)
- 4 LOAD DISTRIBUTOR (ALUMINUM)
- 5 BEARING PLATE (BAKELITE)
- 6 COLUMN (ALUMINUM OR BAKELITE)
- 7 DRAINAGE PLATES (POROUS BRONZE)
- 8 FLOATING RING (BAKELITE)
- 9 CLAMP SCREW (BRASS)
- 10 NUT AND WASHERS (BRASS)
- 11 BASE (BAKELITE)
- 12 THERMOCOUPLE

FIG. 1

In general, standard consolidation test procedure was used, with some changes made necessary by the nature of the project, and for the conservation of time. First, it was decided to limit the study to one remolded soil. Second, in most cases the number of load increments applied has been limited to one. Third, since the sample was too close an electric circuit as a conductor, precautions had to be taken against short circuiting or shunting around the sample. This made it necessary to run the tests without submerging. To partially offset this change in procedure several thicknesses of cheesecloth were wrapped around the ring and porous plate after placing them in the consolidometer, and the cheesecloth kept saturated with distilled water. The cloth was permitted to touch the upper porous plate (positive electrode), but care was taken to prevent any contact with the lower plate and its lead.

THE SOIL.

The soil used was an artificial mixture of several types that were available in the laboratory. It was medium gray in color, had a fine, fluffy texture and was classified as a silty clay.

Atterberg Limits and absolute specific gravity of the soil were as follows:

| | |
|---------------------------|-------|
| Liquid Limit | 43 |
| Plasticity Index | 23 |
| Shrinkage Limit | 12 |
| Shrinkage Ratio | 1.81 |
| Absolute Specific Gravity | 2.684 |

The air-dried soil was thoroughly mixed with a predetermined amount of distilled water and tempered in an air-tight container for a period of not less than 24 hours. It was then tamped into the consolidometer ring, care being taken to eliminate all possible airvoids. The top and bottom of the specimen was finished to the sample ring by means of a steel straight-edge.

Although an attempt was made to have all the samples uniform, variations occurred in almost every specimen which resulted in deviations in the consolidation curves. The initial moisture content of the samples varied from

42.6 to 46.5% with the average value being 44.2%. The initial degree of saturation ranged from 94.5 to 100% with the average being 96.7% and the initial void ratio varied from 1.003 to 1.252 with an average of 1.165.

Figure 5 shows an arithmetic plot of time versus consolidation for four tests in which no current was used. These curves show the deviations that may be expected in the results. The consolidation scale has been started at 0.01 inches, which form is followed consistently on all curve sheets except Fig. 22, on which the scale begins at zero. Cutting off part of the scale in this manner was necessary in order to get all of the current curves on a convenient sized sheet, and it was carried through on the others for consistency and convenience in plotting and reading.

Curve 7 has been chosen to represent the approximate low of the range within which the non-current curves fall, and is reproduced on most of the other curve sheets.

EFFECTS OF ELECTRIC CURRENT

Figure 9 shows the effect of electric current on consolidation of this soil. It will be seen that the time of current application, with reference to time of loading, influences the shape of the curves and that almost immediately after the current application there is a decided increase in consolidation.

For the sake of simplification the information about sample thickness and load applied has been omitted from most of the curve sheets. Unless otherwise noted on the sheet itself, all loads and sample thicknesses are the same as those on Fig. 5.

Fig. 10 shows typical curves that were shown in Fig. 9, plotted on a semilogarithmic chart.

The study and effect of applying the electric current before loading the soil is shown in Figures 12 and 13; for lack of better terminology this has been called pre-treatment. In Curve 23, the current was applied 1 hour and 40 minutes before loading and continued during the test. In Curve 53 the current was applied for a period of 1 hour and 30 minutes, the specimen

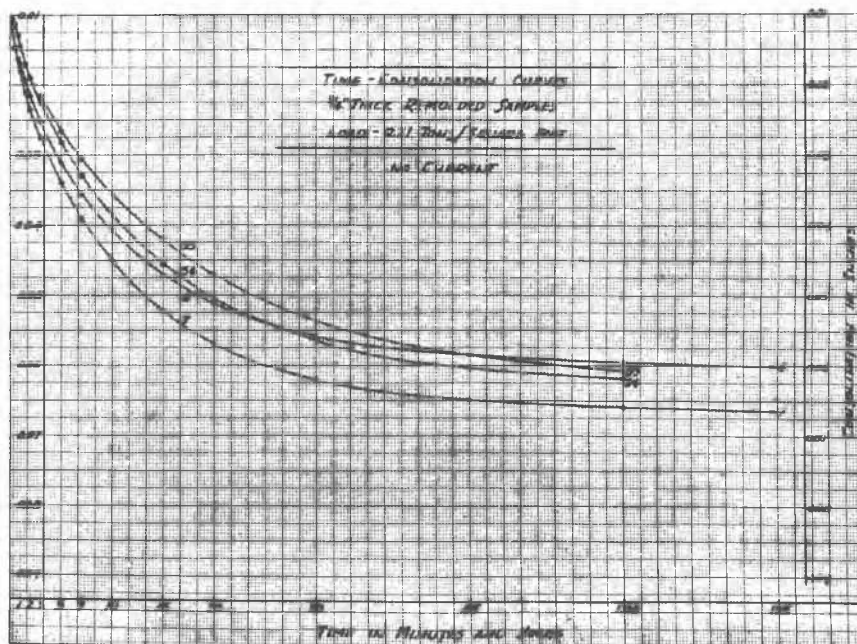


FIG. 5

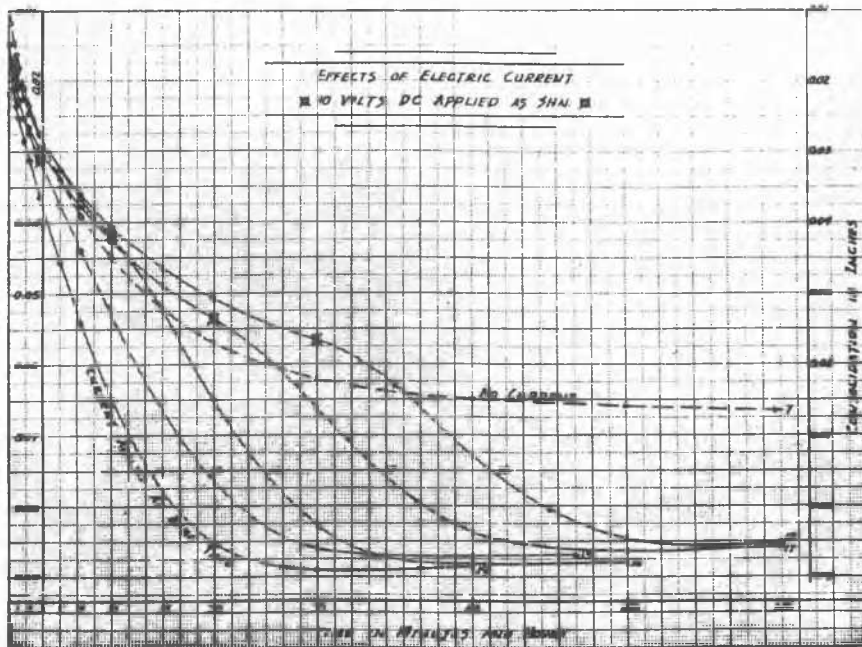


FIG. 9

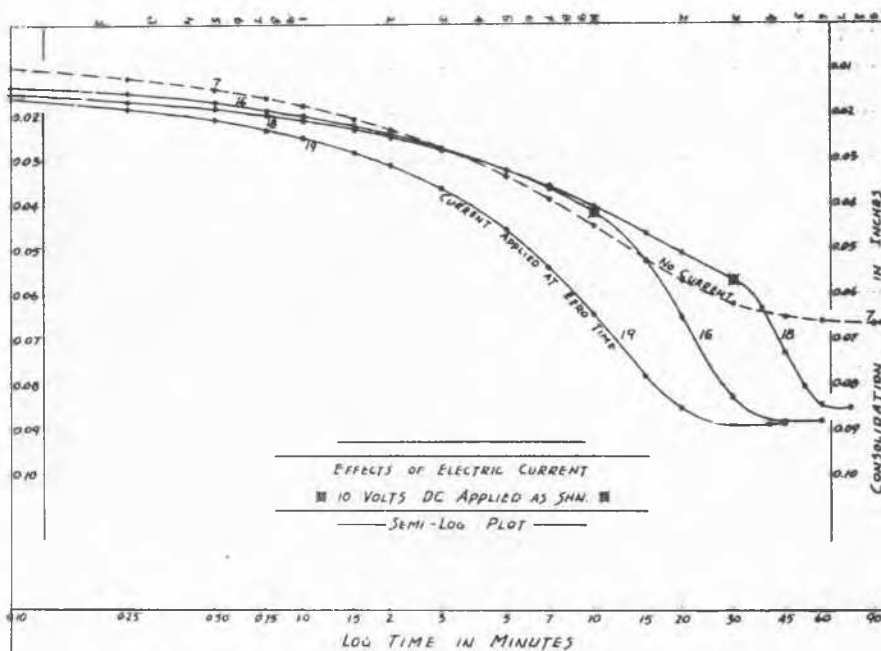


FIG. 10

permitted to stand 30 minutes without either load or current and then loaded. After being loaded for 30 minutes the current was reapplied to curve 53 and there was a swelling of the specimen which was probably due to heating. When the current was again removed the sample dropped to its original position. Curves 28 and 53 show a marked decrease in total consolidation below that for no current at all and about 75% of the consolidation occurs instantaneously. When plotted to the "log-time" scale (Fig. 13) both curves appear to be almost perfectly straight lines. This means that the electrical pre-treatment either completes or eliminates the primary consolidation, so that when the load is applied it goes immediately into

secondary consolidation.

Fig. 16 illustrates the effect of various voltages on the consolidation characteristics and shows that the amount of water expelled from a given cross-section varies directly with the quantity of electricity passed through it. Also that for any given type of soil and volume of sample there is a definite quantity of electricity required to expel all the water that may be moved by this means. The drainage can be accelerated by increase the voltage, thereby increasing the current and the quantity of electricity flowing per unit of time, but a price must be paid for the speed in the form of more total energy expended. The price is approximately proportional to the speed, because 2.9

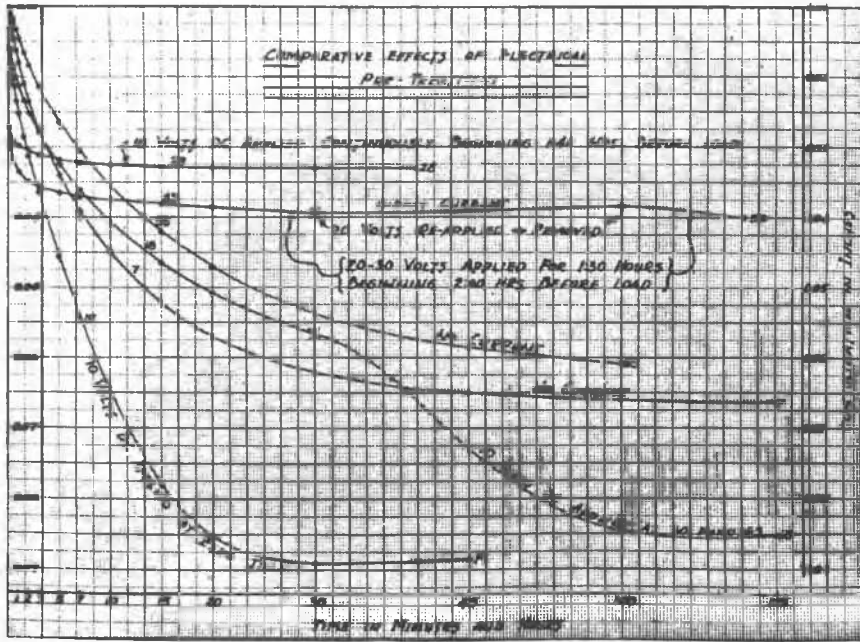


FIG. 12

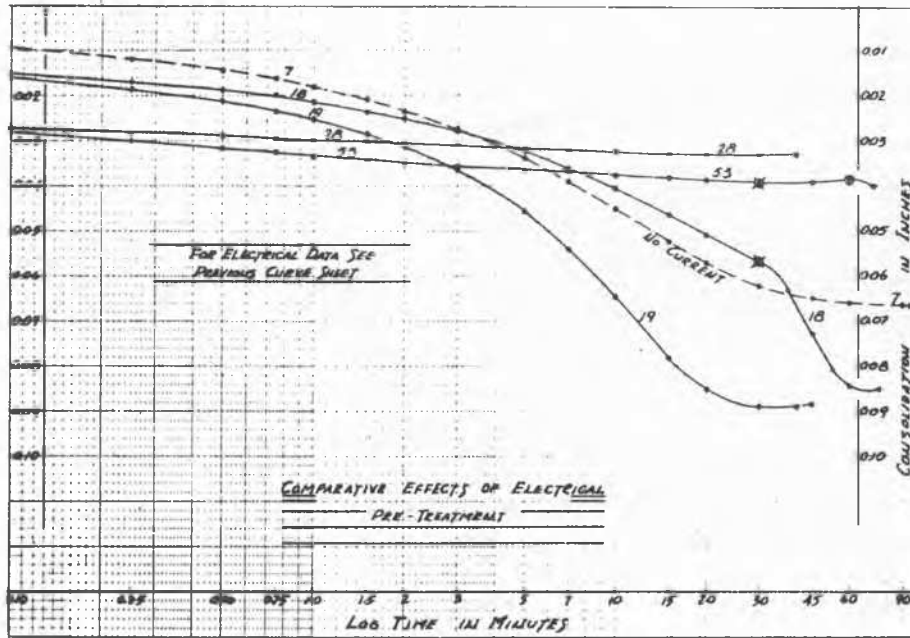


FIG. 13

watt-hours of electric energy gave the same final result in twice the time as 6.1 watt hours.

One interesting fact that should not be overlooked is that the lowest point on all of the current curves for a given load, falls within a narrow range on the consolidation scale. This seems to corroborate the conclusions of Maclean and Rolfe 2), that there is a point beyond which the expenditure of electric energy is wasted.

Fig. 13 is included to show that not all of the work done in these investigations has yielded profitable results. There were several other tests which did not conform to the general pattern, but most of the others have been

disqualified for one reason or another.

In addition to the effects of current discussed, there was a notable change wrought in the soil itself. Immediately adjacent to the positive electrode, the soil assumed a definite greenish tint, believed to be corrosion deposited from the copper in the bronze material of the upper porous plate. The negative electrode (bottom porous plate) was wet at the end of the test and the soil near this point seemed to bleach out to an almost pure white. The colors did not show up until the soil had been thoroughly dried out in the electric oven. It was also noted that in almost all cases the sample had warped in drying such that the green layer (+) presented a concave surface; leaving the

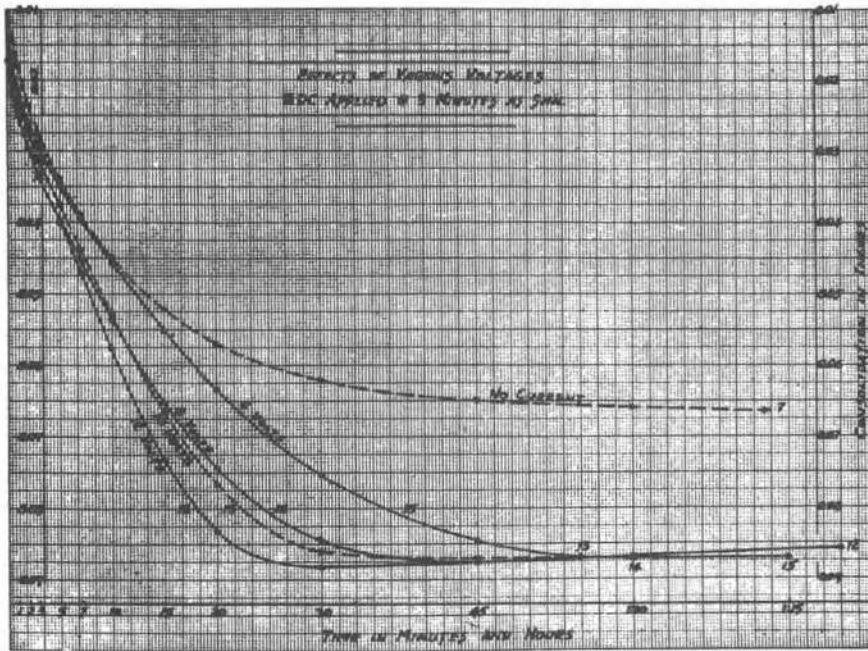


FIG. 16

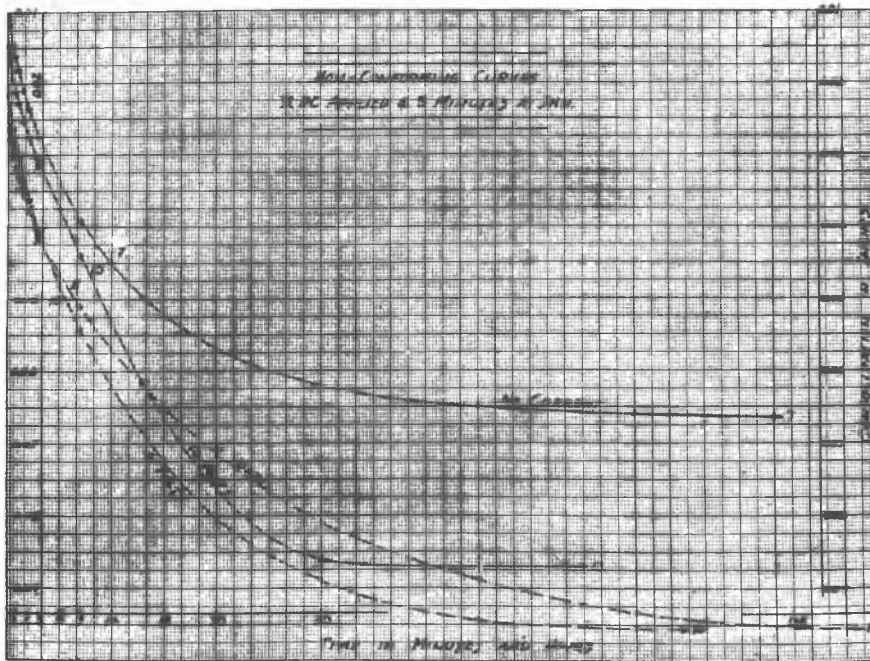


FIG. 18

opposite face convex.

After the tests had been completed, the samples were broken up and the top and bottom materials separated by scraping from the block.

Atterberg limits tests on the various components gave the following results:

| | Original Soil | Green Layer(+) | White Layer(-) |
|------------------|---------------|----------------|----------------|
| Liquid Limit | 43 | 40 | 38 |
| Plasticity Index | 23 | 21 | 16 |
| Shrinkage Limit | 12 | 14 | 19 |
| Shrinkage Ratio | 1.81 | 1.82 | 1.68 |

It should be noted that these values for the green and white layers were necessarily ob-

tained after the samples had been dried in an electric oven at about 110° C. Since in some cases such temperatures alter the soil properties of soils, this comparison cannot be considered as more than an indication of the general trend.

The results of a series of tests performed on samples of varying thicknesses is shown in Fig. 22. The loads and applied voltages were both uniform throughout this group, it may be observed that the time required for 100 per cent consolidation under a given load when current is applied, varies approximately as the square of the sample thickness. This conforms to the theory of consolidation, and appears to

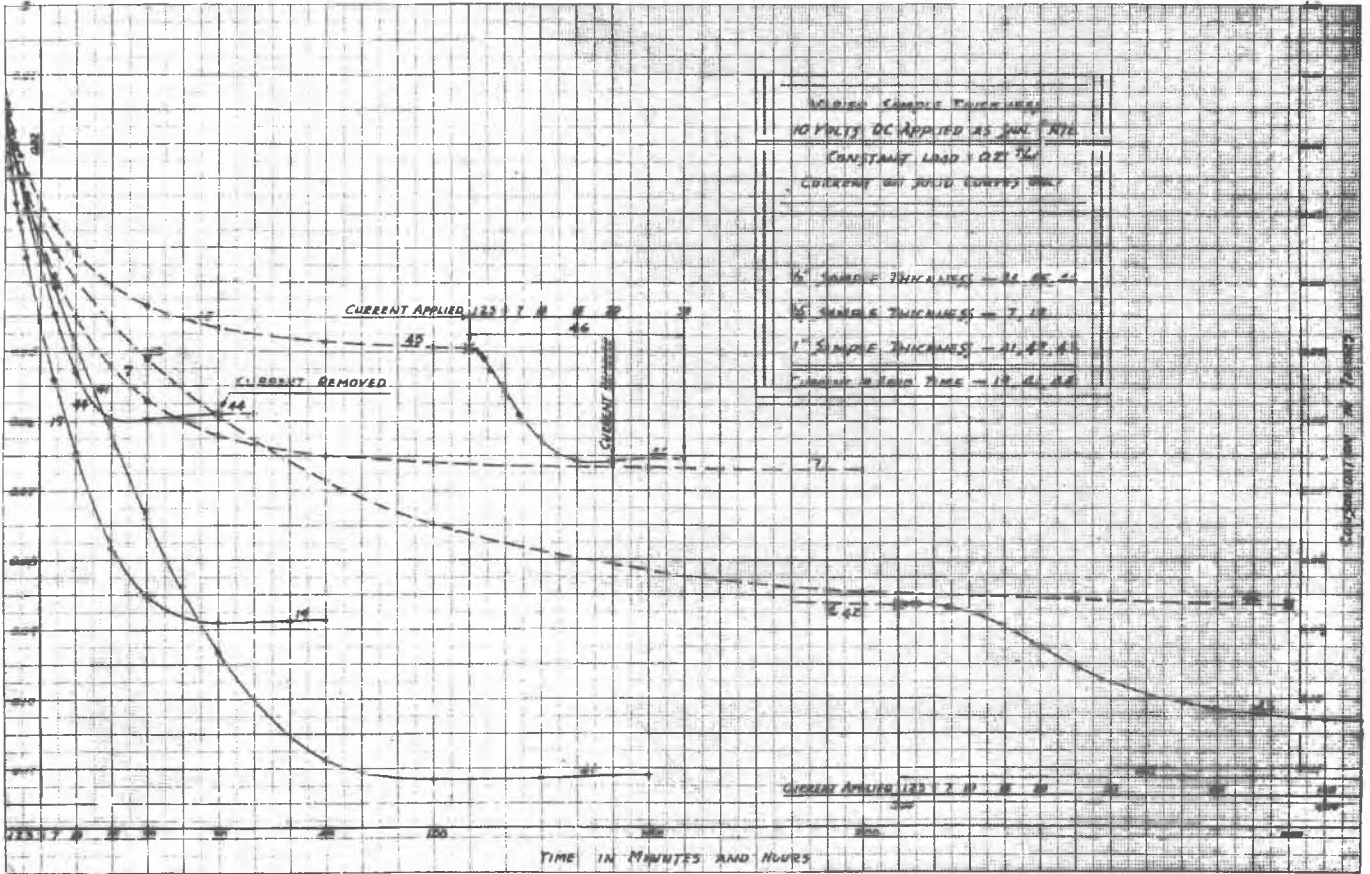


FIG. 22

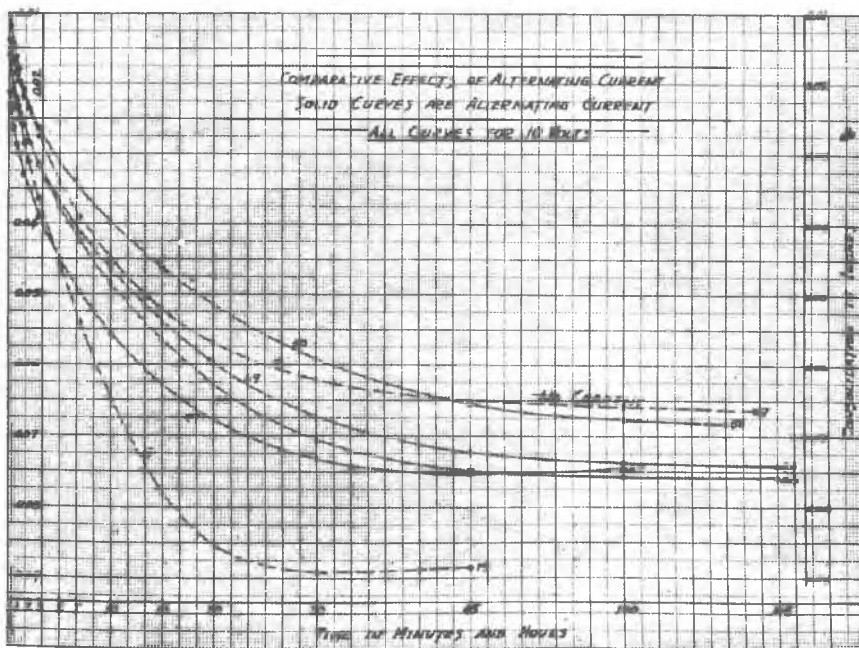


FIG. 24

be one of the few characteristics that does not change when current is applied.

Despite the fact that no mention was made of alternating current in any of the available reports of experiments in this field, it was decided that since equipment was at hand for such tests they would not be neglected. The results are shown on Fig. 24. It would appear that alternating current has a small effect on consolidation but probably a large part of this effect is due to accelerated evaporation caused by the resistance heating.

SUMMARY AND CONCLUSIONS

- 1) This research must be considered as a preliminary investigation and the conclusions astentative.
- 2) The porous bronze plates make satisfactory electrodes for use in the consolidation test. Aluminium electrodes have been found to give the best results, but were not available for these tests. An attempt is being made to obtain porous aluminum plates for future work.
- 3) This investigation was limited to a single, remolded soil. Many more tests on different soils must be made before final conclusions can be drawn.
- 4) The passage of a direct electric current through the soil accelerates the drainage process which in turn increases the amount and accelerates the rate of consolidation.
- 5) The pre-treatment (application of electric current before loading) of the soil reduces the total consolidation of the sample and causes it to immediately enter into secondary consolidation. This may be a very useful tool in the study of secondary consolidation.
- 6) Most of the tests showed that drainage could be accelerated by increasing the voltage. Also that for any given type of soil and volume of sample there is a definite quantity of electricity required to expel all the water that may be moved by this means.
- 7) Although increased voltage accelerated the rate of consolidation it did not increase

the amount since all treated soils had approximately the same final total consolidation for a given load regardless of the voltage. This indicates that there is a point beyond which the expenditure of electric energy is wasted.

- 8) The passage of electric current through the soil changed the physical properties of the material near the positive and negative electrodes.
- 9) Electrical treated soils (current applied simultaneously with load) conform to the theory of consolidation, in that the time required for a given degree of consolidation varies approximately as the square of sample thickness.
- 10) The passage of current through a soil caused a considerable increase in temperature due to resistance heating.
- 11) Alternating current caused some increase in the consolidation of the soil but only slightly more than the consolidation without current.
- 12) While the temperature increase due to resistance heating probably caused most of the increase in consolidation when alternating currents were applied, it is believed that these higher temperatures were not sufficient to cause all the increased consolidation that occurred with the application of direct current. Future tests will include increasing the temperature of the sample without the application of current.

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