moisture and to spring excessively under rolling. This reduced the compaction obtainable and restricted the placing of the rolled embankment to the dry season of the year (approximately five to seven months). As the material had such a high percentage of clay, the control of permeability was not an important factor in the testing program for the rolled embankment, and the tests were run merely for purposes of record. These tests, however, showed that soils high in sand content can be compacted to secure low permeability.

No. M-3

ELECTROCHEMICAL HARDENING OF CLAY SOILS

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For many years various investigators have tried to find a method to harden clay deposits artificially, and thus to increase their bearing capacity. There are several processes involving the injection of salt solutions which are successfully applied in the case of sands, but the very low permeability of fine soils precludes the possibility of using such a method in connection with clays.

Fig. 1
Electrochemically hardened block of clay. At the right is shown the corroded Al anode with a white deposit of bauxite.

A promising new method, still in the course of development, is the electrochemical process, whose outlook is very much strengthened by present-day conceptions of the nature of clay. (These conceptions have been discussed in another abstract, Paper No. D-6, by the same authors). In this process, (L. Casagrande, Berlin, Verfahren zur Verfestigung toniger Böden. D.R.P. 621694 (1935). Patented or patent applied for in the majority of civilised countries) metal electrodes are introduced into the soil at appropriate distances. Aluminum is always used for the Anode, while the cathode is usually copper. Direct current, at an appropriate voltage, is allowed to pass between the electrodes until the soil is hardened. Fig. 1 shows a clay specimen which had been brought into its container with an almost liquid consistency (water content of about 80%). After treatment for some time with a current of 8-14 Ampere, at 300-500 volts, the clay had become so hard that an iron rod of one sq cm cross section failed to penetrate the clay when placed under a load of 10 kg. Specimens cut from the side of this block nearest the aluminum electrode neither disintegrated nor swelled during several months of immersion in water. Fig. 2 illustrates the behaviour of treated and

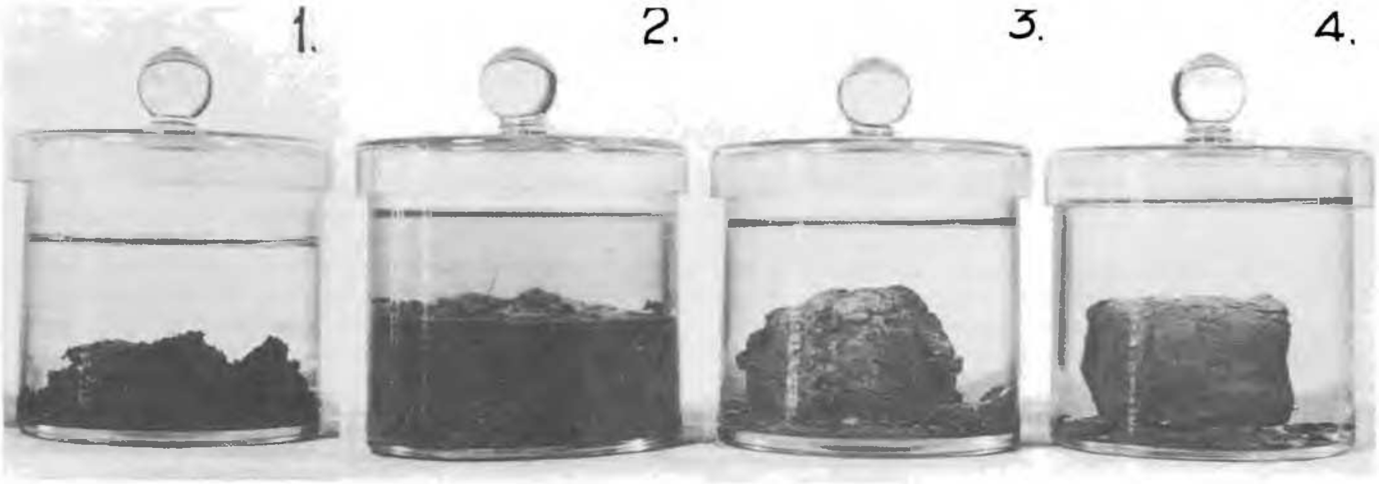

Fig. 2
Effect of immersion in water on mixtures of Na-clay and sand before and after electrochemical treatment. Glass 1: untreated clay after five minutes' immersion. The clay has begun to disintegrate. Glass 2: untreated clay after one hours' immersion. Disintegration is complete. Glass 3: treated clay after three months' immersion. The lump is almost completely intact. Glass 4: a lump of clay taken from the vicinity of the Al- anode, which had been thoroughly kneaded before immersion, was totally unchanged after three months' immersion.

untreated clay when immersed.

Atterberg's liquid limit and the angle of internal friction are de~~inc~~reased by treatment. The clay used in the above-mentioned electrochemical hardening test had an angle of internal friction of about 17° before treatment, and about 25° afterwards. The shearing tests were carried out in the laboratory of the Deutsche Forschungsgesellschaft fuer Bodenmechanik with the Casagrande apparatus. The shearing force was applied in steps representing 1/40 of the vertical load, at intervals of one minute. Thus an increase in the strength and bearing capacity of the treated soil is established beyond question.

Fig. 3
Loading test on model piles in clay which has been treated by the Casagrande electrochemical hardening process.

Fig. 4
Pulling test on model piles which had been used as electrodes in the Casagrande electrochemical hardening process.

This hardening is apparently brought about by a change in the electrical charge on the clay particles, caused by the passage of the electric current through the clay. According to our present picture of this complicated process, this change of charge gives rise to an exchange of the exchangeable kations bound on the surface of the clay particles, particularly of Na against H or certain trivalent ions, particularly Al. The H is derived from the electrolysis of the water in the clay, and the aluminum is supplied by the Al-anode.

No matter how large the water content of the soil was before treatment, it sinks to 30 to 40 per cent afterwards, the exact amount depending on the nature of the soil, and the hardening is of such a nature that even in the presence of excess water, the water content of the treated material remains constant. The extraordinarily small compressibility of the treated soil suggests that the hardening process goes hand in hand with the development of some sort of structure, even if the original material was thoroughly kneaded before treatment. Apparently the influence of the electric current is such that a disturbed soil regains the properties of an undisturbed one after a short period of treatment. In addition to the change in the charge on the clay particles discussed above, it is possible that deposits of aluminum compounds in the clay may contribute to the strength of the treated material. It may be that aluminates are formed which have an effect similar to that of the calcium-aluminate-hydrate produced during the setting of cement. The white precipitate on the aluminum anode shown in Fig. 1 has been determined as bauxite ($Al_2O_2 \cdot 3H_2O$) by X-ray methods.

Dr. Erlenbach has recently carried out interesting laboratory experiments with 60 cm model piles, whose lower half was covered with aluminum or copper sheeting, respectively. Using these piles as electrodes, with a potential of 14 volts and a current of less than 0.1 ampere per pile, Erlenbach was able to raise the bearing capacity of the soil from 1.5 kg per sq cm to 7 kg after a five hours' treatment, to 14.5 kg after 20 hours, and shortly thereafter to 17 kg per sq cm. The test arrangement is shown in Fig. 3. The force necessary to pull the piles was approximately the same as the bearing capacity of the piles. Around the sheet-metal covering of the piles was a cylinder of hardened clay which adhered to the piles when they were pulled. This may be seen in Fig. 4.

The results of the experiments just described and other recent contributions to our knowledge of the electrochemical nature of clays supplement one another perfectly. It is of course too early to say whether or not the new process may be applied economically under all circumstances to all clay soils.

The question of the most economical size and arrangement of the electrodes, on which the rentability of the process depends, is by no means settled.

It is however worth mentioning that this process represents the first attempt to harden clay soils for engineering purposes. Since the hardening process itself rests on a sound theoretical basis, there are excellent prospects for a successful application of the method in all cases of foundation and mining engineering in which a horizon of soft clay is encountered.