Electrochemical Hardening of Expansive Clays

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This paper is concerned with a large-scale swelling soil stabilization project that was undertaken by the Arizona Department of Transportation in July 1973. The site chosen for the study was approximately 146 m (480 ft) of the westbound lane on I-40 about 56 km (35 miles) east of Holbrook, Arizona. The stabilization technique used was electroosmosis and a 0.4 N KCl solution for inundating the clayey mass of the site. This resulted in an average 36 percent decrease in the percentage of swell and a 50 percent reduction in swell pressure of the Chinle clay. X-ray diffraction and electron micrograph data indicated possible causative factors of the reduction in swell pressure and percentage of swell.

The object of this research was to use existing electrochemical soil treatment technology and, if necessary, to modify portions of it for the purpose of creating a viable soil stabilization technique that could be implemented by Arizona highway maintenance personnel.

PHYSICOCHEMICAL ASPECTS

Base Exchange

The absorbed ions on a clay surface are present in a diffuse double layer. Each of the ions required to neutralize the charge on the particle surface oscillates because of Brownian motion; thus the ion is assumed to be oscillating in a cell, called an oscillation cell, adjacent to a charged area on the particle surface. Other ions from an added electrolyte may enter the oscillation cells or may remain in the external phase. A given ion with a large naked radius, i.e., K^+, will have a smaller hydration radius and thus be able to approach the charged surface closer than an ion with a smaller naked radius, i.e., Na^+, and a corresponding larger hydration radius. Thus, the potassium ion will, on the average, bond to the surface with a correspondingly greater energy than a sodium ion.

Such concepts have been evolved into mathematical models that depict the ion exchange as a stochastic process. These theories, in particular the one by Jenny, lead to mass-law or mass-action equilibrium equations. However, these models of base exchange imply that the exchange phenomenon is essentially a complex redistribution of ions both between an external phase and the ion swarm and also within the ion swarm. Unfortunately this process depends on several factors. The ion redistribution cannot be regarded as simple metathesis, precisely defined by a simple equation of the mass-law type. The mass-law equations often quoted in the literature, with regard to base exchange phenomena, must be considered as only approximations from which there may be considerable variation in unfavorable cases.

Because of the stochastic nature of base-exchange phenomena, any soil treatment based on these phenomena must also be regarded as a stochastic process. Of course the chance of successful treatment along these lines can be increased by preparing the external phase to be rich in the preferred ions, e.g., use a high-concentration KCl solution to treat the soil.

It must be borne in mind that an ion-exchange soil treatment can alter the physicochemical properties of the swelling clay and that such a treatment is one of the most effective ways to combat the problem over a relatively small, localized region on which an expensive in-place structure, say a pavement, rests.

The ability of a clay to absorb ions on its surfaces or edges is called its base or cation (anion) exchange capacity, which is a function of the surface chemistry of the clay and the size of the clay particles. Thus, the term base exchange is widely used even though hydrogen ions and even organic ions may be involved in the exchange.

LABORATORY WORK

The purpose of the laboratory work was to determine the expansive and swell characteristics of the untreated soil obtained from the test site.

Site Selection and Sampling

The field work for this study began in July 1973; the selected test site was at milepost 323.8± on the westbound

Publication of this paper sponsored by Committee on Chemical Stabilization of Soil and Rock.

lane of Interstate 40, about 64 km (40 miles) east of Holbrook, Arizona. A plan view of the site is shown in Figure 1. Because this project was initiated as an implementation study, an engineering decision on pretest sampling techniques was made at the onset of the project.

The engineering decision was based on the following general considerations: Most problem areas of swelling clays traversed by a roadway are easily identifiable visually. After an area has been identified as a possible problem area, a quick economical way of sampling must be used. It is clear that, in a study oriented purely toward investigating soil phenomena, a sampling technique used over a selected region should be based on a random procedure. However, the primary goal was to use knowledge of past electroosmotic work and apply the same techniques, properly modified, to enable a rapid evaluation of the swelling problems of a given area.

The sampling procedure would be undertaken so that the drill rig would have to move only longitudinally; this would save a great deal of time and therefore money. Moreover, the rig was positioned as close to the center of the Interstate as possible without interfering with traffic in one travel lane of the westbound roadway. Twenty-six test holes were drilled, and samples were obtained to a depth of 4.6 m (15 ft) in the clay subgrade. The samples were transported to the Arizona Highway Department Materials Division where they were tested.

Soil Properties of Untreated Material

The average values for the Atterberg limits on the samples were liquid limit 39, plastic limit 17, and plastic index 22. The average percentage passing the No. 200 sieve was 70, and 20 percent was 2 μm in size. The specific gravity of the soil was 2.75. The soil would classify as a CL material based on the Unified Soil Classification system.

The expansive pressure of the untreated soil was determined for material passing a No. 40 sieve in an expansometer. The density of the soil was approximately 1700 kg/m^3 (106 lb/ft^3), and the moisture contents were 10 and 15 percent. The percentage of swell was determined on the untreated soil by using the expansometer and percentage of swell apparatus. The density was maintained at 1700 kg/m^3 (106 lb/ft^3), and the moisture contents were approximately 10 and 15 percent. The results of some of these tests are discussed below.

These tests indicated that the selected area is representative of a region with moderate swelling characteristics.

FIELD WORK

The scope of the field work of the electrochemical stabilization of Chinle clay was

1. To design, install, and operate a full-scale field test on the test section;
2. To sample the electrochemically treated section; and
3. To evaluate the ability of existing maintenance resources to carry out this work with a minimum of specialized personnel in attendance.

The highway field installation was designed to reproduce the simple electrode configurations used in previous studies. To this end, a design was chosen that incorporated the desirable characteristics of previous work with the realities of conducting the field work on a much larger scale and with relatively inexperienced personnel.

The electrical design was such that three sections of a 152-m (500-ft) test section could be electrified simultaneously with the same voltage gradient.

The electrode configuration for the whole test site is shown in Figure 2. The center section has, as anodes, vertical No. 8 rebar about 1.5 m (5 ft) long. This is in contrast to the other two sections, which have horizontal anodes made up of 6.1-m (20-ft) sections of No. 8 rebar welded together end to end to form the anodes. After the horizontal anodes were formed in this manner they were manually placed into a previously prepared 1.2-m-deep (4-ft) trench.

The cathode was formed of 6.1-m (20-ft) sections of No. 8 rebar welded end to end and then carefully lowered into the trench.

The electrode configuration was designed to be easy to assemble and yet to be an effective item. Although many sophisticated design patterns exist, the simple design used in this project requires a minimum amount of expertise for proper installation at the site.

As a result of past field tests using electrochemical methods for stabilization of Chinle clay, the field installations were designed such that the clay would be treated only to a depth of 0.9 m (3 ft). This estimate was based on laboratory tests that showed that, if the clay were effectively treated to this depth, the site could be judged as stabilized. Moreover, because of previous study results, it was obvious that to treat the clay to a greater depth than 0.9 m (3 ft) would result in an overkill in the first 0.9 m (3 ft).

In order to properly suffuse the soil pores with the KCl solution it was decided to drill 15.2-cm (6-in) diameter auger holes on 2.4-m (8-ft) centers, approximately 1.7 m (5.5 ft) deep throughout the test section. The positioning of the auger holes was based on previous studies. There was a total of 285 of these auger holes positioned throughout the site.

To prevent caving of the blowsand subbase material each auger hole was sleeved with 15.2-cm (6-in) O.D. steel pipe, 68.6 cm (27 in) long, topped with a 25.4-cm-diameter (10-in), 2.5-cm-thick (1-in) steel plate. The plate had a 4-cm (1½-in) hole in the center to permit introduction of the KCl solution into the auger hole. The 25.4-cm-diameter (10-in) steel plate was obviously necessary to give a stable platform for the steel sleeves and to provide a sufficiently rigid surface for vehicular traffic.

The 285 protruding 25.4-cm-diameter (10-in) steel plates presented a potential traffic problem and made it necessary to countersink each auger hole with a concentric 25.4-cm-diameter (10-in), 2.5-cm-deep (1-in) depression. The countersinking operation was accomplished easily by welding to the top of the auger drill stem one of the 25.4-cm (10-in) steel plates.

After this was accomplished, six old drilling teeth were set flat against the bottom of the plate, spaced about 60 deg apart in a symmetrical pattern and then welded into place. The teeth then provided an abrasive surface for the countersinking operation.

Each of the 285 auger holes was sleeved down 43 cm (17 in) below the asphalt surface. The sleeving did prevent the base course from extensively caving in and KCl solution from wetting the base course. However, there was some caving and wetting. District 4 personnel suggested 69 cm (27 in) of base course material as a best estimate to use throughout the site.

The total drilling and sleeving operation required approximately 2 workweeks of the drill crew's time.

Upon completion of the drilling and sleeving, the electrical installation was initiated. This operation consisted of trenching for horizontal electrodes and drilling for a section of vertical anodes. This operation required about 3 days with a crew of five.

District 4 personnel mixed and placed solution by using a modified 9.5-m^3 (2500-gal) capacity goose neck water truck. The water and KCl were mixed so that a 0.4 N solution was obtained.

At the outside ambient water temperatures in the Holbrook area at that time of year [May through August, 23°C (73°F)], this was the maximum amount of KCl soluble in water.

After mixing in the tanker truck the 0.4 N KCl solution was placed into the auger holes under pressure by using ordinary gasoline nozzle and hose fixtures leading from the solution truck. In this manner the auger holes were filled twice a day for a period of approximately one month, in which time about 136 m^3 (36 000 gal) of 0.4 N solution was introduced into the site region.

It was determined early in the project that prior to the introduction of the electric field the solution would be delivered to the site for about 30 to 35 days. With this procedure the clay could be presaturated with the KCl solution by utilizing the relative ease with which an electrolyte moves through the clayey material and simultaneously the expense of running an electrical generator during the initial soil saturation period could be avoided. During this period about 64 m^3 (16 894 gal) of solution was delivered to the site.

On July 8, 1973, the 60-kW dc generator was started, and an overall current of about 400 A was recorded with a voltage gradient of about 0.1 V/cm. On the average about 133 A flowed through each of the three sections during the field test. After approximately 30 days of continuous operation, an electrode polarization phenomenon was noted, which caused a rapid power loss. Electrical operations were discontinued immediately thereafter.

At this time, a total of 136 m^3 (36 000 gal) of solution was delivered to the site. After the electrical system was shut down, sufficient soil samples were obtained and shipped to the Materials Services Laboratories for testing and evaluation.

RESULTS AND ANALYSIS OF FIELD TEST

After completion of the field test operations on August 16, 1974, soil samples were gathered for the following laboratory analyses:

1. X-ray diffraction analysis,
2. Transmission electron microscope (TEM) techniques, and
3. Expansive pressure and percentage of swell tests.

Data obtained from X-ray diffraction analysis yield information on the effects on the lattice structure of the clayey soil. TEM techniques identify any effects on the soil structure arising from the electrochemical treatment that are too gross (i.e., macromicro effects) on the crystalline structure for the X-ray diffraction to resolve. Results of the pressure and swell tests give data on the effects of the electrochemical treatment on the engineering properties of the soil mass.

X-Ray Diffraction Analysis

Identification of the crystalline soil minerals was performed by X-ray diffraction analysis. Both clay and nonclay minerals that are crystalline have a long-range order in their atoms or ions. By bombarding a mount containing the sample with high-energy X-rays, the spacing of the crystalline structure can be determined from the wavelength of the X-ray.

The X-ray data clearly indicated that the clay had been affected by the electrochemical treatment; moreover, these data are supported by electron micrographs and tests on the engineering properties of the oil. Based on both electron micrograph and X-ray diffraction data, it appears that the stacking geometry of the clay particles was modified by the electrochemical treatment.

Because no additional minerals were found in the treated materials as opposed to the untreated, it is not possible to conclude that the smectites were transformed into an illiticlike clay. Thus, the reduction in the diffracted X-ray intensity of the treated clay and the reduction in the stacking number, as shown by the electron micrographs, indicate that the treatment affected primarily the 0-0 bonds between the basic units but did not cause significant diagenesis of the clay. Moreover, because the engineering properties of the clay are highly dependent on the nature and stability of the interlayer environment between the unit cells, the soil tests reveal that the electrochemical treatment of chinle clay also alters the interlayer complex, which is composed of inorganic ions, water, and even organic complexes, and interferes with the basic 0-0 bonding between the unit cells.

Transmission Electron Microscope Analysis

Bentonite types of materials were observed by using transmission electron microscope techniques. Standard bentonite minerals (Wyoming bentonite and USP bentonite) were compared to pretest clay samples (40133 and 40188) and posttest clay samples (40415A).

An example of electron diffraction from the untreated and treated clay is shown in Figure 3.

The micrographs seem to show that the treated sample has mineral flakes that are thinner than those of the pretest samples. This is presumably because the nature and stability of the bonding between the successive basic structural units (Lamella) have been altered causing the stacking of the units to change geometrically. This is supported by the X-ray diffraction data, which showed the untreated material to have a smectite peak of greater intensity than the treated material (Figures 4 and 5).

Results of Data Analyses

All of the evidence clearly indicates that the crystalline fabric of the clay was affected by the treatment. This is substantiated by the electron and X-ray diffraction patterns, which for the pretreated material depicted a thick layered structure. This is noted by the wider diffraction rings or high-intensity X-ray diffraction peaks of the pretreated material as opposed to the relatively thin diffraction rings or low-intensity X-ray peak obtained from the treated material. The wide rings or high scattered intensity is characteristic of the thick crystal. If the crystal is thin, a pattern of thin diffraction rings or low intensity is obtained.

Expansive Pressure and Percentage of Swell of Posttest Samples

Upon completion of the electrochemical treatment, samples were obtained and returned to the Materials Services Laboratory in Phoenix where tests of expansive pressure and percentage of swell were performed in the expansometer and percentage of swell apparatus designed by Arizona State University.

The data indicated that the expansive pressure decreased somewhat more than 50 percent and the percentage of swell decreased by more than 36 percent.

SUMMARY

This study focused primarily on implementing electrochemical soil treatment procedures developed in previous FHWA-sponsored work.

Initially a site for the field work was chosen along a section of I-40 that was experiencing swelling problems. The site was along a roadway of high traffic volume so that traffic control problems during an operation of this sort could be fully considered, inasmuch as this method of soil stabilization is intended to become part of Arizona DOT maintenance procedures.

In this work the primary considerations were

1. The relative ease of field implementation of established electrochemical soil treatment technology and
2. The effectiveness of soil treatment of electrochemical methods when the field operation is conducted largely by unskilled and semiskilled maintenance personnel.

Figure 1. Plan view of site.

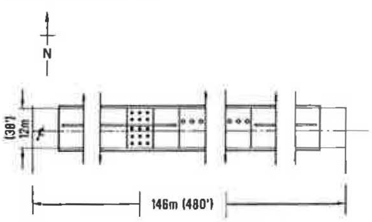


Figure 2. Electrode configuration for site.

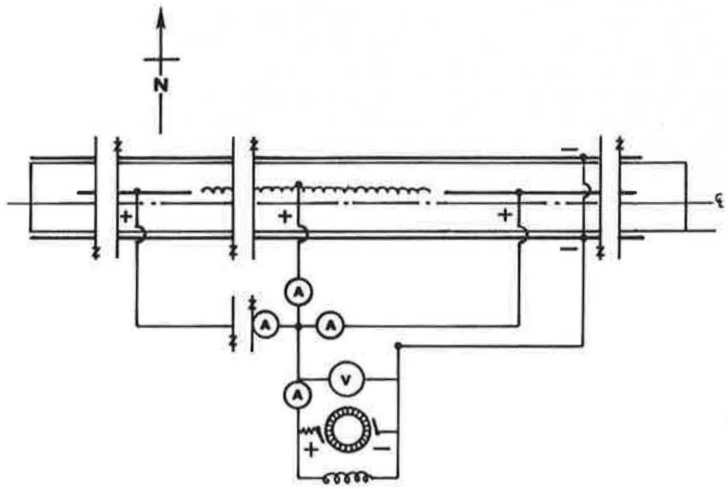


Figure 3. Electron diffraction from (a) untreated and (b) treated clay.

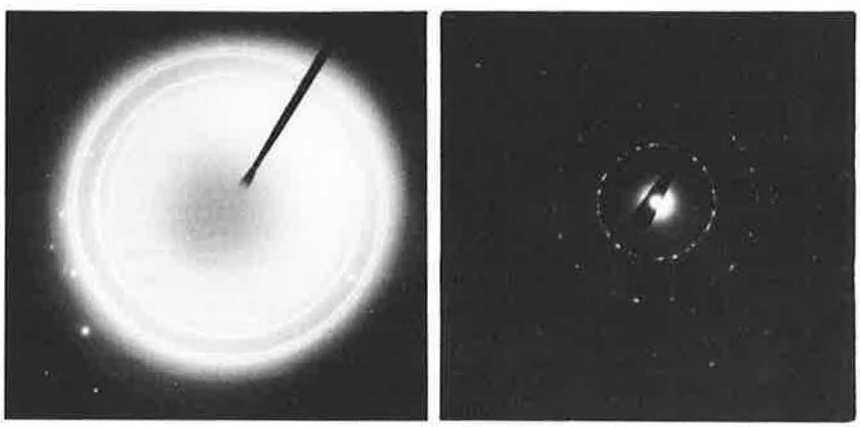


Figure 4. X-ray diffraction pattern of untreated clay.

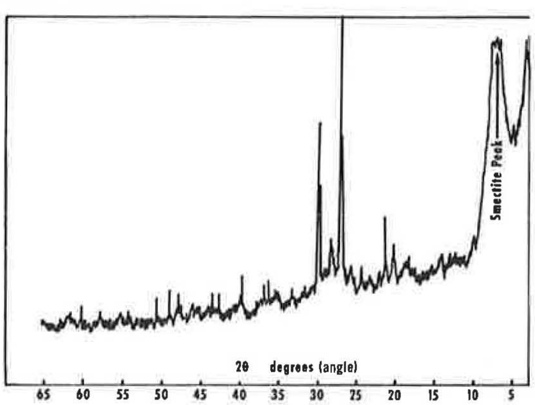
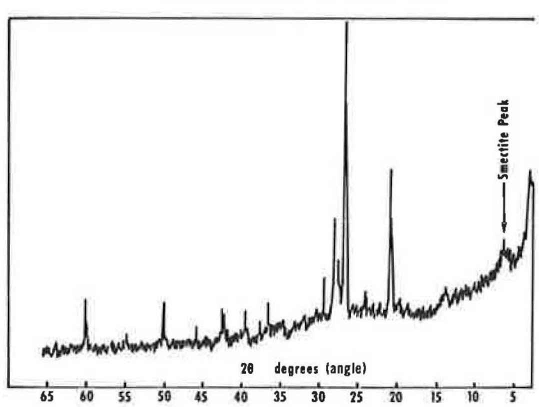


Figure 5. X-ray diffraction pattern of treated clay.



Based on this study it can be stated that the use of electrochemical soil treatment technology can be effectively implemented by using existing work force and material resources of the Arizona DOT, supplemented by minor purchases of specialized hardware and software.

ACKNOWLEDGMENTS

This report is based on work performed by the Research Section, Arizona Department of Transportation. Funds for the project were provided by the Arizona Department of Transportation in cooperation with the Federal Highway Administration.

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