Compaction Specifications for Low Hydraulic Conductivity Clay Embankments

CLIFF J. SCHEXNAYDER

Communication of regulatory and engineering decisions by the project specifications contractually establishes the parameters of project acceptance and sets forth how performance will be validated. If contract specifications fail to properly address the purpose of the project, it is difficult to properly perform the work. With a material such as kaolin clay the precision or variance associated with the results of commonly accepted testing procedures may be of a magnitude greater than that normally assumed. During a design-test program only two-thirds of the individual construction water-content tests fell within a desired wet-of-optimum range. Yet infiltrometer tests proved the hydraulic quality of the test panels. During project construction more than two-thirds of the individual water-content tests fell within the contracturally specified range, yet 50 percent of the work was rejected because there was no provision in the construction specifications to allow for the outliers. Construction techniques used for clay pulverization, moisture conditioning, and compaction on a full production basis in the construction of a 53-acre kaolin clay liner having a specified in situ permeability are described.

The project clay specifications reported here were developed with the intention of ensuring that the constructed kaolin clay cap would have an in situ permeability of less than 1×10^{-7} cm/sec. The purpose of this impermeable clay cap barrier was to prevent rainfall and surface runoff water from percolating downward through buried nuclear waste.

Because in situ sealed double-ring infiltrometer tests can take from 3 to 5 months to perform, another test method had to be specified to allow cap construction to proceed on a production basis. For clay materials there is a good correlation between placement water content and density, and in situ permeability. This is well known to geotechnical engineers and is documented in the literature (*1–4*). Therefore the project specifications used that relationship to define the acceptance standard for the compacted clay. However, problems were encountered during the execution of the work because the owner's field construction managers did not understand these geotechnical relationships.

DESIGN-TEST PROGRAM

The design-test program, conducted before preparation of the project specifications, examined both construction techniques and resulting clay cap properties for tertiary and cretaceous age kaolin. Tertiary and cretaceous clay from three different active mines in South Carolina was used to construct nine test panels. Panels were constructed at both standard (ASTM D698) optimum water content and at two to three percentage points wet of optimum with clay from each of the three sources. The construction technique for eight panels was to add water to the clay in a separate material conditioning area and then to transport the moisture-conditioned clay to the panel for placement and compaction. However, for the ninth panel a procedure of moisture conditioning the next lift of clay directly on the previously placed panel lift was used. This eliminated having to transport moisture-conditioned clay.

Early in the program it became obvious that the cretaceous kaolin was a sandier and less plastic material. Therefore only two test panels were constructed of the cretaceous clay. Both panels had field infiltrometer test and laboratory permeability test results exhibiting a hydraulic conductivity above the required minimum in situ permeability of $\leq 1 \times 10^{-7}$ cm/sec, thus proving that it would be difficult or impossible to meet the design criteria using cretaceous kaolin. The cretaceous clay was therefore eliminated from project consideration.

The tertiary clay used in the test program had natural water contents in the range of 20 to 25 percent. The average liquid limit and plastic limit values were 69 percent and 32 percent, respectively. The percent fines, $<$ No. 200 sieve, was 98 percent or greater. Standard compaction test optimum water-content values ranged from 24 to 29 percent. In almost all cases, the natural clay was dry of optimum, thus making it necessary to add water to achieve the desired placement water content.

During the test program a stationary clay shredder and a traveling recycler were used to break down the blocky chunks of clay that were delivered from the mines. A recycler is a piece of highway construction equipment designed for pulverizing and mixing asphalt pavements and base materials. This size-reduction operation yielded a material having a maximum size of 38 mm (1½ in.). The purpose of the size reduction was to speed the water absorption of the clay by creating more contact surface area and to enhance the kneading effect of the rollers during compaction.

The 38-mm (1½-in.) minus particle size clay was spread in a lift 0.15 to 0.23 m (6 to 9 in.) thick and water was added by alternating passes of a water wagon and the recycler. The water wagon was not driven over the clay lift. It was equipped with a pressure system and nozzle that permitted water to be sprayed onto the clay while the wagon moved along the side of the conditioning area. The water content of the clay was raised to the desired percentage by this spraying-mixing procedure.

This approach of adding water while not having to actually traverse the clay was only possible because of the limited width of the test panels. That method, however, failed to model applicable construction procedures when faced with placing clay over large areas, as the actual project would require.

Del E. Webb School of Construction, Arizona State University, Tempe, Ariz. 85287.

After moisture adjustment the clay was covered with plastic and allowed to cure overnight. After this moisture conditioning period, the clay was picked up and transported to the panel by a 272-kW (365-hp) elevating wheel tractor scraper. On the panel, motor graders spread the clay in a uniform lift. Compaction was performed with a 161-kW (216-hp), 20 055-kg (44,175-lb) tamping foot soil compactor. The pads of a tamping foot roller are tapered with an oval or rectangular shape, as opposed to those of a sheepsfoot roller, which are uniformly cylindrical from base to pad face.

Trautwein-type, sealed double-ring infiltrometers were used to test the in situ permeability of both the tertiary and cretaceous kaolin panels. A test was conducted in each completed panel for 98 to 158 days. The results of those permeability tests, presented in Table 1, demonstrated that in situ permeabilities of less than the 1×10^{-7} cm/sec could be expected if the tertiary kaolin was compacted at water contents 2 to 4 percentage points wet of optimum as determined by standard compaction tests (*5*). The average compacted dry density for the individual test panels varied from 94 to 100 percent of standard maximum dry density.

PROJECT SPECIFICATIONS

The design-test program provided the water content and density parameters that could produce the desired low-hydraulic-conductivity clay layer without the need for in situ permeability testing during construction. The critical parts of the original project specifications that were developed on the basis of the test program data are summarized here:

1. Cretaceous kaolin shall not be used (but no identification criteria were specified).
2. The clay shall be tertiary kaolin clay with the following properties:
   a. Liquid Limit per ASTM D4318–84 shall be between 75 percent maximum and 55 percent minimum.
   b. Plasticity Index per ASTM D4318–84 shall be between 44 percent maximum and 26 percent minimum.
   c. Percent passing a No. 200 sieve per ASTM D422–63 shall be 90 percent minimum.
3. Clay blocks shall be broken before moisture conditioning to a maximum size of 38-mm (1½-in.) chunks to ensure uniform wetting (no specific testing procedure was specified).
4. Clay shall be placed in a 0.15-m (6-in.) maximum thickness unconditioned, loose lift.
5. Moisture conditioning of the kaolin shall be conducted before compaction to achieve 2 to 4 percent wet of the standard compaction optimum water content. To ensure uniformity of water content before placement and compaction, one water-content test, ASTM D2216-81, is required for every 250 m^2 (300 yd^2) of clay in the conditioning area.
6. The kaolin clay shall be compacted to a minimum of 95 percent of standard maximum dry density (ASTM D698–78).
7. A minimum of 12 passes with a CAT 815B roller is required.
8. The initial water-content placement range will be 2 to 4 percent wet of the average optimum water content as determined from a minimum of six moisture-density relationships (ASTM D698-78). Three moisture-density relationship determinations will be from kaolin samples taken at the borrow pit before commencement of mining, and three other determinations will be from kaolin samples from the initial 454 Mg (500 tons) of material delivered to the project.
9. In the placement area, uniformity of compaction is confirmed with in-place nuclear densities, a minimum of one per 383 m^3 (500 yd^3).

TABLE 1 Summary of Infiltrometer Test Data, Design-Test Program (*5*)

Panel Number	Kaolin Clay Type	Number of Test Days	Average $w_f - w_{opt}$, percent	Average percent Standard Proctor Density	Final Field Permeability K (field) cm/sec × 10^{-7}	Average Lab Permeability K (lab) cm/sec × 10^{-7}
A1	Tertiary	134	-1.3	105	1.60	0.81
A2	Tertiary	98	2.0	100	0.32	0.28
B1	Tertiary	141	3.5	94	0.61	0.34
B2	Tertiary	124	3.6	98	0.56	0.25
B3	Tertiary	101	2.9	98	0.91	0.27
C1	Tertiary	158	0.4	103	1.20	0.34
C2	Tertiary	106	2.7	100	0.49	0.43
D1	Cretaceous	117	3.4	98	3.60	1.60
D2	Cretaceous	141	2.0	97	5.00	1.70

All infiltrometer tests performed with a sealed double ring infiltrometer with 3.7 m (12 ft) outer ring and a 1.5 m (5 ft) square inner ring.

10. No after-compaction moisture-content testing was specified.
11. To determine whether the average optimum water content is valid, one moisture-density relation is required for each 3825 m^3 (5,000 yd^3 of clay placed.

A few items in the initial specifications deserve special notice. The compaction specification dictated both the method and the result: 12 passes with a CAT 815B roller and 95 percent of maximum dry density. The basis for establishing the acceptable water-content range was an average of the optimum water content as determined from the standard moisture-density relation. The acceptance water content was to be taken in the conditioning area before compaction. Density was to be confirmed by in-place nuclear methods. There was no provision for handling outliers when making an acceptance decision with regard to an individual water-content or density test. In addition, there was no provision to drop old data when calculating the average optimum water content.

CONSTRUCTION REALITY AND SPECIFICATIONS

Quality control (QC), testing, and acceptance of the clay was undertaken by a third-party QC organization reporting to the owner's project construction management organization. Neither the construction manager nor the QC organization had the authority to change or even interpret the project specifications. To be accepted, the moisture-conditioned and compacted kaolin clay had to meet the specifications exactly.

Changes or interpretations of the specifications could only be accomplished by authority of the permitting agencies. Therefore any modification of the original specifications was a lengthy process involving layers of technical and regulatory bureaucracy.

Design engineers must realize the contractual and, in many cases, the regulatory implications of project specifications. The relationship between the nature of the materials being handled and the limitations concerning testing processes and precision must be understood and embodied in the specifications. The specifications must address each individual element of the construction process in a realistic manner. No engineer can foresee every possible situation; consequently provisions should be incorporated into the specifications that establish procedures to resolve unique situations.

Unique situations can occur during any project. In one specific area on this project, density could not be obtained on the initial clay lifts. At first the problem was attributed to the contractor exceeding the specified lift thickness; then the quality of the kaolin was questioned. After many days of effort, it was realized that the background radiation from the nuclear waste was slightly greater in this area. The nuclear density meters used to test compaction were being affected by the background radiation. The larger problem was that there was no provision in the specifications to use another method to verify compaction.

Compaction difficulties were encountered on the project because of the double specification, specifying both method and result. At higher water contents, 12 passes with the specified roller caused overrolling. The specified density could not be achieved when more than eight roller passes were made. By the specification, density was an imposed critical parameter. However, in the case of compaction wet of optimum, density alone may not be a good gauge of resulting hydraulic conductivity. It has been found that even though the dry density of a compacted soil did not measurably increase with the application of more compactive energy, the hydraulic conductivity could be lowered by a factor as high as 100 (*3*). This has been attributed to the additional kneading action. A double specification will always cause problems. The design engineer must determine the important parameters, and those parameters must be carefully addressed in the specifications.

Early in the project the 152-mm (6-in.) maximum lift thickness specification was a problem. When a 152-mm (6-in.) kaolin clay lift was laid down as the first lift on top of the existing red silty soil of the site, the kaolin would become contaminated with the underlying material during processing and compaction. The tines of the mixing equipment would cut into the lower material in any spots where the lift thickness was less than 152 mm (6 in.). The feet of the rollers would likewise puncture through the kaolin and pull the red silt up into the white clay. Because of the color difference between the two materials, contamination was easy to discern.

The specifications limited the lift thickness and required full-depth mixing and compaction. Mixing could have been achieved on top of other panels of clay and the conditioned material hauled to the initial placement panel as was done during the test program, but such a procedure would not have solved the compaction problem. An alternative solution would have been to compact the initial lift with a smooth drum roller, but that would have eliminated the important kneading action during compaction.

A technical review at the design team level, not at the construction management level, determined that an initial thick lift would not be in violation of the permit. Therefore the adopted solution was to allow a 254-mm (10-in.) initial lift, to condition the lift to a depth of 203 mm (8 in.), and to retain the use of the specified kneading roller.

VARIABILITY AND ACCEPTABLE RANGE

Both the project and the design-test program panels B1, B2, and B3 used kaolin clay from the same source. The variability of the test results for those three design-test program panels is particularly relevant to the interpretation of the earthwork specifications.

Test Panel Data

The kaolin's average optimum water content from all standard compaction tests for the three panels was 26.8 percent. Individual test optimums varied from 24.2 to 29.2 percent, a range of 5 percent. At the same time, the individual water-content tests on samples taken from the field-compacted test panels varied from 26.4 to 32.8 percent. Those water-content values from the field samples were reported to be from 1.7 to 6.8 percent above the average optimum water content for the respective panel. Moreover, the standard deviations of the water-content tests on field samples from the panels ranged from 1.1 to 1.3 percent.

The significance of the standard deviations is that approximately two-thirds of the test results should be expected to be within one standard deviation of the mean value. This means that for test panel B3, for which $(w_f - w_{opt})$ had a mean of 2.9 percent and a standard deviation of 1.1 percent, only about two-thirds of the measured water contents were 2 to 4 percent wet of optimum. For the other two panels, the mean values and standard deviations of $(w_f - w_{opt})$ indicate that significantly less than two-thirds of the measured water contents were in the range of 2 to 4 percent wet of optimum. It is important to note that all of these test panels satisfied the permeability criteria for the clay cap (Table 1), and permeability was the true critical parameter.

Project Data

Because of its dimensions [15.3 m × 61 m (50 ft × 200 ft], a typical project panel required, by specification, four water-content tests. During a 1-month period early in the project, more than 50 percent of the clay panels constructed were rejected because one or more of the four individual water-content tests taken from a panel were not within the specified range of 2 to 4 percent wet of the average optimum. In every case, conformance of the compacted density and water content to the specifications was evaluated on the basis of an average optimum water content of 25.6 percent and a maximum dry density of 1.54 Mg/m³ (95.9 lb/ft³).

An analysis of the 300 water-content tests taken by QC during the first 3 months of clay construction showed a mean water-content value of 28.6 percent and a standard deviation of 1.1 percent. The mean value for the tests was exactly 3.0 percent wet of the established optimum, and when the water-content values were rounded to the nearest 0.5 percent, 76 percent of the values were within the 2- to 4-percent wet-of-optimum range specified. Thus the constructed clay fill was at least as uniform as the design-test panels.

Specification Range

Had the specifications been written consistent with the realities of the design-test program, the project would have proceeded smoothly, as field construction mirrored the program very well. However, the specifications did not allow for the reality that only about two-thirds of the individual water-content tests for controlled construction conditions, the design-test program, actually fell within a 2- to 4-percent range above an average optimum water-content value. Researchers realized that general statements from the test program report had become the specifications, which had to be followed exactly.

Variability

An important factor that the writers of the specifications failed to recognize was the natural variability of the kaolin clay. The standard compaction test, performed by the QC organization, had shown optimum water-content values from 24.1 to 27.0 percent. The chosen average optimum value for construction was 25.6 percent, which in turn set the acceptability limits at between 27.6 (plus 2 percent) and 29.6 percent (plus 4 percent).

This decision to use the average as a benchmark presents several problems. Consider the case of a batch of clay actually having an optimum of 24.1 percent. To provide the required permeability based on the 2 to 4 percent wet-of-optimum criteria, this clay should be placed at a water content of between 26.1 and 28.1 percent. However, according to the specifications, any panels having tests below 27.6 percent would be rejected, thus forcing unnecessary rework of clay that was actually acceptable from a permeability standpoint. Now consider a case on the other extreme: in order to meet the minimum-plus-2 percent criteria, a batch of clay actually having an optimum of 27 percent would have to be placed at a water content of 29 percent. In this second case, clay that was not even conditioned to the plus 2 percent of its natural optimum would be accepted by the average criteria. These facts are diagramed in Figure 1 on the basis of the project data previously discussed.

The correct criteria for a specification is the moisture-density relationship to permeability. Plotting a test point, as in Figure 1, will prove whether the conditioned clay is acceptable considering the permeability standard. An acceptable test must fall within the band of the line of optimums and the saturation line. Such a specification criteria would be consistent with recommendations by Daniel (*6*) and Daniel and Benson (*7*). "The recommended procedure involves establishing $\omega - \gamma_d$ ranges needed to achieve the required hydraulic conductivity, and then modifying these ranges to account for other factors besides k" (*7*). Using this procedure allows for consideration of clay variability, yet the time to make an acceptance decision is minimal and would not restrict production-oriented construction operations.

Engineer's Intent

Additional moisture-density compaction tests were required by the specification to determine if the average optimum water content is valid. However, when a test did not confirm the validity of the average, it was not stated how the information was to be used. Should it alter the accepted water-content acceptance range for future clay placement? This section of the specifications shows that someone had considered the fact that there would be variability, but a complete statement of how to apply the validation information never made it into the specifications.

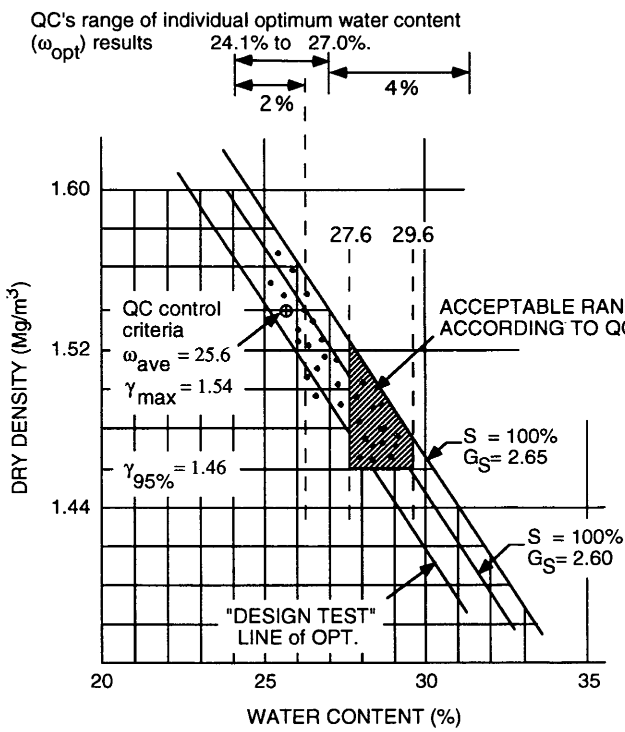

FIGURE 1 Project moisture-density data for the first 3 months of kaolin clay construction (QC-established average optimum water content was 25.6 percent and maximum dry density criteria was 1.54 Mg/m³ for the period).

Sensitivity of Kaolin

During the first 6 months of clay placement the average optimum water content steadily dropped from 25.6 percent to just over 22 percent. Because no other properties of the clay displayed change, questions were raised about this significant difference. Work by Daniels and Ming-Tai Chao at the University of Texas, using samples of kaolin from the project pit, has shown that there is a correlation between optimum water content of a standard compaction test and the drying of the clay during test processing before compaction. It appears that QC caused the optimum moisture to be lowered over the first part of the project. This in turn meant that processed clay was accepted when it was actually dry of the specified water-content range necessary to ensure low hydraulic conductivity. Therefore a change order had to be issued to the contractor to remove and rework approximately 36,280 Mg (40,000 tons) of previously accepted clay.

Precision

The precision of testing procedures for clay material needs to be understood and could well be the subject of additional research. By specification, microwave water-content testing of 100-gram minimum clay samples was the standard for acceptance. As a result of the problems experienced on the project, both the contractor and the construction manager performed limited research into using microwave methods for water-content determination in kaolin clay.

Because most of the panel rejections were attributed to nonconforming water-content tests, this was the main area investigated. Clay samples from the field were split when they were taken and separate water-content tests were performed on each half, with the values calculated to the nearest tenth. Differences as great as 3.7 percent were noted. The average difference was about 1.8 percent. If the water-content values were rounded to the nearest half of a percent, the average difference was 1.5 percent.

A specification that is strictly enforced, makes no allowance for outliers, and limits the acceptance range to 2 percent, in combination with a test procedure that has a precision range of 1.5 percentage points, is going to cause problems. Geotechnical engineers have a responsibility to inform owners and specification writers concerning the limits of testing methods and procedures.

CONSTRUCTION TECHNIQUES AND EQUIPMENT

The critical construction operations when working with a clay are as follows:

- The clay must be broken into small clods to create surface area for water contact so that the material can be remolded into a new homogeneous mass (*1*).
- Water must be added and thoroughly mixed with the clay in a manner that will ensure a homogeneous material of uniform moisture content.
- The moisture-conditioned clay should be compacted by a kneading method.

These requirements were recognized, and several different pieces of heavy construction equipment and construction techniques were investigated in the field on a full production basis.

Clay Pulverization

The first task is to break down the large clay clods that come from the borrow pit. Excavation and loading at the pit was done by a hydraulic hoe excavator. When the hydraulic hoe loaded the clay into dump trucks for hauling to the fill area, the excavated material had many large chunks. These chunks from the pit normally had a maximum long dimension of about 0.46 m (18 in.).

Bulldozer

A 104-kW (140-hp) bulldozer was used to level the clay after it was dumped from the trucks, as shown in Figure 2. The dozer spread the clay out in a lift 0.15 m (6 in.) thick. Major size reduction was accomplished during the leveling, as chunks were crushed by the weight and motion of the dozer. The tracks of the dozer would bridge across low spots and place all the machine contact pressure on the largest chunks, which were the high points causing the bridging. Thus the largest chunks were crushed in the spreading process.

The use of a track dozer allowed the accomplishment of two material-handling requirements in one process: lift leveling and size reduction. After leveling by the dozer, the material could be classified as 0.15 m (6 in.) minus; therefore further size reduction was still necessary.

Rotavator

Rotavators proved to be efficient in accomplishing final size reduction and were used for that purpose for the entire project duration. A rotavator is nothing more than an oversized garden tiller pulled by a farm tractor. With a rotavator, clod reduction is accomplished by mechanical pulverization. The power for turning the rotavator tines, which do the actual chopping, is supplied by the tractor's power takeoff.

A 104-kW (140-hp) tractor could pull a 2.4-m (8-ft) wide rotavator at an average speed of 53 m/min (2 mph) through clay having a natural water content of about 22 percent and a maximum clod size of 0.15 m (6 in.). Depth of tine penetration was normally 0.20 to 0.25 m (8 to 10 in.). With the rotavators, average throughput of material meeting the maximum clod size specification [38 mm (1½ in.)], was about 180 Mg per hour (200 tons/hr).

At water contents above optimum the rotavators were not effective because of traction problems. They were therefore not used for final moisture-conditioning operations, but did perform initial blending of raw clay and water.

FIGURE 2 A 104-kW bulldozer leveling kaolin clay.

Shredder

The use of a clay shredder was investigated for a short time in the field. A shredder is a revolving blade with teeth; it cuts or shaves the clay into the desired size in the same manner as a meat slicer.

The drawback and reason it was not used for mass production was the shredder's passthrough tonnage limitation. With the blade set to operate at 38 mm (1½ in.) maximum size, the passthrough production was only 127 Mg/hr (140 tons/hr). A second reason for rejecting the shredder was that it adds material-handling steps to the production process. Material must be loaded and hauled to the machine, loaded into the machine, and loaded and hauled a second time after processing.

FIGURE 3 Soil stabilizer mixing moisture-conditioned kaolin clay.

Soil Stabilization Machines

A soil stabilizer is a completely self-contained machine consisting of a power unit and a mixing chamber, as shown in Figure 3. Stabilizers are specifically designed for soil pulverization and mixing. They are common to highway construction work for inplace stabilization of lime or cement with soils.

As with the rotavators, when used for pulverization on this project, the stabilizers were not used until the raw clay had been leveled into a 0.15-m (6-in.) lift by a dozer. The stabilizers had a working speed of 27 m/min (1 mph), or about half that of the farm tractor-pulled rotavators, but pulverization could be accomplished in half the number of passes.

Experiments were conducted with machines having both up-cutting and down-cutting tine rotation. The best results were obtained using L-shaped chopper tines and up-cut rotation with the stabilizer box rear doors closed. Maximum clod size would increase as the door opening was increased. Operators want to increase the door opening because it allows them to increase forward speed. Typically, two passes with a stabilizer were necessary to reduce the 0.15-m (6-in.) minus clay down to 38 mm (1½ in.) minus. However, three passes were necessary on occasion, usually on grades. In such situations the operator was forced to increase the rear-door opening, which in turn affected size reduction.

On a highway soil stabilization project, the specific type of stabilizer that was used on this project will operate at an average propel hydraulic pressure of about 15 500 kPa (2,250 psi). Working kaolin, which lies relatively horizontal, with the machine in the up-cut mode, the propel pressure was 24 100 kPa (3,500 psi). On a 7-percent grade the pressure would go up to 25 500 kPa (3,700 psi). The machine has a pressure override valve set at 25 500 kPa (3,700 psi); therefore, when going up the grade, the operator had to increase the opening of the rear door to avoid stalling. The down-cut mode would have been easier on the machine, only 15 160 kPa (2,200 psi) up grade, but pulverization was not good and the clay would stick to the rear door, causing other problems. In fact, even operating up-cut, severe pressure was placed on the rear door. Rear-door cylinders had an average life of only 850 operating hours.

Moisture Conditioning

Once the clay had been processed so that the maximum clod size was 38 mm (1½ in.) or less, moisture conditioning began. The first method tried was to use a standard water truck with a pump-driven spray bar. Multiple passes were made over the pulverized clay until the material became so slippery the truck could not maneuver. At that point the farm tractor-pulled rotavator would make a couple of passes to mix the water and clay clods. After this mixing the water truck could make additional passes.

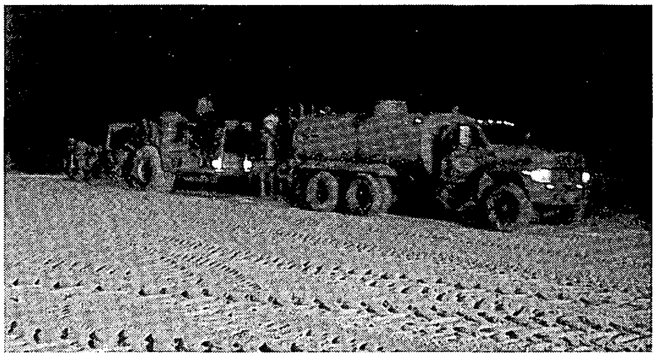

FIGURE 4 Water truck being followed by stabilizer during moisture conditioning of kaolin clay.

This procedure failed to produce a uniform moisture-conditioned clay. The tire ruts from the water truck tended to collect water before the mixing and became permanent streaks of high moisture content in the clay panel. The standard spray bar does not provide a uniform application of water. More water came out at the point where the bar connected to the pump than at the ends.

To overcome these deficiencies modifications were made to both the equipment and the construction techniques. The water truck spray-bar system was modified to form a continuous loop with a circulating pump so that the pressure at each nozzle was approximately the same. To eliminate the problem of water collecting in the ruts, it became standard procedure to operate a rotavator or stabilizer directly behind the water truck during moisture application, as shown in Figure 4. Once the required amount of water had been applied, two additional passes were made with the stabilizers to complete the mixing.

The water trucks all had metering systems to control the quantity of water applied. The amount of water that had to be added to the clay could easily be calculated based on the difference between the moisture-content tests of the pulverized clay and the specified water-content range. The problem was not in making the calculation or with the metering system, but in figuring the total amount of water to add, considering a necessary correction for the amount of evaporation that would take place in the time interval required to add the water, condition the clay, and complete compaction. During day shifts in hot summer weather, the amount of extra conditioning water necessary to make up for evaporation loss was about 13.4 L/Mg (3.2 gal/ton). Operating at night during the summer required only 3.3 L/Mg (0.8 gal/ton) extra. Direct sunshine and wind were factors that greatly affected the amount of extra water needed.

Compaction

Tamping foot compactors of both 161 kW (216 hp), 20 055 kg (44,175 lb) and 235 kW (315 hp), 32 429 kg (71,429 lb) were tried at the beginning of construction. Tamping foot compactors can develop all four forces of compaction: pressure, impact, vibration, and manipulation. When dealing with a clay wet of optimum, however, pressure and manipulation are the important forces. Field trials revealed that there is an upper limit to acceptable pressure.

Considering the drum width and weight of each machine, the contact pressure of the larger machine was about 1.4 times that of the smaller machine. When the kaolin clay was conditioned to 2 percent or greater above optimum water content, the feet of the larger compactor would be pushed completely down into the moisture-conditioned clay and the roller would be supported by drum contact. The clay would then stick to the drum, and the upper lift of clay would be pulled up from the previous lift by the forward motion of the roller. This result was not satisfactory, so all production compaction was with a 20 055-kg (44,175-lb) tamping foot compactor.

CONCLUSIONS

The following conclusions were drawn on the basis of the project experience:

1. Standard highway construction equipment is appropriate for manipulating kaolin clay in constructing low-hydraulic-conductivity liners and caps.

2. Project specifications must be structured to account for testing precision and natural material variability.

3. No designer can anticipate all possible field situations; therefore it is important that specifications include procedures for resolving unique situations.

4. Most environmentalists and regulators are not familiar with earthwork or construction. It is therefore necessary for engineers to be alert to the consequences of poorly drafted specifications or controls.

If contract specifications fail to address the purpose of the project, it is difficult to properly perform the work. In fact, the constructor and the engineer may be forced to rely on their expertise instead of the specifications to complete the project.

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