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Compaction Practice for Dam Cores at Hydro-Quebec

O. DASCAL

Glacial till is used mainly as an impervious material in earth and rockfill dams built in Quebec. It is, in general, a well-graded mixture of sand, silt, and gravel, with 25-80 percent passing the no. 200 sieve and a natural water content at or above optimum (Proctor standard). Its natural water content, together with its very high sensitivity to atmospheric humidity, strongly influence the choice of compaction equipment, compaction procedure, and time schedule. This paper presents Hydro-Quebec's experience with this type of material, including choice of the compaction equipment, establishment of the compaction procedure, pretreatment of the borrow pit material, as well as the results and performances obtained at various sites. In addition, the paper describes the particular compaction problems and results of a manufactured material (sand and sensitive clay mixture) used as core material in certain water-retaining dikes.

One of the main economical advantages of an earth or rockfill dam is the possibility of using relatively cheap local soil deposits as construction materials. In this context, glacial till deposits that cover large areas of the continental shelf of Canada are used extensively as material for the impervious zone of earth and rockfill dams. The use of natural clay deposits as impervious material is rather limited (a) because of its localized presence along the lowlands of the St. Lawrence valley and the eastern shore line of the James Bay, and (b) because its geotechnical characteristics (high sensitivity) require special placement and compaction procedures.

The till, an abrasion product of the glaciers, is frequently used in construction specifications as indicative of an unsorted unstratified heterogeneous mixture of clay, silt, sand, gravel, cobbles, and boulders. It also denotes a very dense and stiff material of low compressibility. These characteristics, when complimented with a proper amount of fine particles (<0.074 mm) and a well-graded grain size composition, represent those of an ideal material for dam cores.

However, the compaction characteristics of this material are substantially influenced by its water content. As a matter of fact, the soil is difficult to handle (compact) when the natural water content reaches 2 percent above optimum and becomes rapidly soupy when it reaches +3 percent or more. This is a severe limitation because it is often found in situ at a water content above optimum. The problem becomes more acute when one considers the adverse climatic conditions encountered in the northern regions of Quebec, where the construction season is short and rainy.

The importance of proper compaction should be emphasized in view of the close relation among density, shear strength, permeability, and compressibility. All these parameters are of particular importance in the safety and behavior of the dam.

This paper presents Hydro-Quebec's experience and practices in handling this type of material as illustrated by three case histories. The first project involved uses till that had a natural water content at or slightly above its optimum and hence presented no problem of placement or compaction. In the second project, the use of a till that had a natural water content substantially higher than optimum created a set of difficult problems and necessitated the adoption of new solutions. A third example illustrates the use of a highly sensitive marine clay as core material, its placement, and compaction problems experienced during the construction of an earth-fill dike located in the St. Lawrence valley.

PROJECT A, DAMS 1 AND 2--OUTARDES 4

Project A includes two-zoned rock-fill dams with slightly inclined till cores 400 and 350 ft (122 and 106 m) high, respectively. Dam 1, with a crest length of 2100 ft (640 m), has a total volume of 9 900 000 yd^3 (7 569 097 m^3), the core volume being 885 000 yd^3 (676 631 m^3). Dam 2, with a total volume of 6 145 000 yd^3 (4 698 192 m^3), has a core of 601 500 yd^3 (459 880 m^3) of till and a crest length of 2380 ft (725 m).

The maximum horizontal width of the core at the base is about 120-130 ft (36-40 m). The crest width is reduced to about 20 ft (6 m). Thus, for both dams the working area at any elevation represents an average of about 40 000-45 000 ft^2 (3750-4000 m^2).

Geotechnical Characteristics of the Till

The borrow area situated a few miles upstream of dam 1 consists of a relatively well-graded till that has a maximum gravel content of 10 percent grain size larger than 6 in (150 mm). The percentage of fines (passing sieve no. 200) varies between 10 and 40 percent, with an average of 23 percent, and has a liquid limit between 11.5 and 14.2 percent. The plastic limit varies between 9 and 11 percent.

Laboratory compaction tests indicate a maximum dry density [standard Proctor (ASTM D698 method A)] of 126-136 lb•f/ft^3 (2000-2175 kg/m^3), with an optimum water content that varies between 7 and 10 percent; the in situ natural water content ranges from 6 to 12 percent.

Laboratory permeability tests, carried out on the fraction that passes sieve no. 4 (U.S. Bureau of Public Roads standard E-12) indicate a coefficient $K = 10^{-6}$ to 10^{-7} cm/s.

Borrow Pit Operations

The borrow pit consists of two areas. The eastern part is more sandy with a relatively low fine content and in the western area the percentage that passes sieve no. 200 varies between 35 and 45 percent. Consequently, it is necessary to mix the material from both areas (in equal parts) at the pit. The excavation of the material is carried out by bulldozers, which push the till over a Koleman vibratory screen to eliminate cobbles larger than 6 in (150 mm). The material is loaded directly in trucks passing under the screen.

The quality of the mix is continuously checked by a rapid sieve analysis that establishes the percentage of fines (passing sieve no. 200).

Placement and Compaction Operations

The prevailing climatic conditions limit the placement of the till to a maximum of 70 days/year.

The till hauled to the dam's site by trucks is spread by bulldozers in lifts 10- to 12-in (250- to 300-mm) thick parallel to the dam's axis and subsequently compacted by six passes of 50-ton pneumatic tired rollers. To obtain a uniform moisture distribution before compaction, the spread material is mixed with 30-in (750-mm) diameter disc harrows. After the compaction and immediately before placement of the new lift the compacted material is scarified to a depth of about 3 in (75 mm) to avoid the formation of compaction joints. The scarifying also facilitates the water distribution, when the sun- or wind-dried material must be sprinkled. The compaction is carried out on strips parallel to the dam axis, as the equipment moves from one abutment toward the other.

The compacted till surface is always provided with a small slope toward its upstream and downstream edges (toward the filter zones) to facilitate the rainwater runoff. In areas where the access of heavy rollers is hindered or next to rock abutments, the till material is spread in lifts 4- to 6-in (100- to 150-mm) thick and compacted with a manual Vibro-Tamper 2-1, which has a weight of about 925 lb (420 kg), and which develops a dynamic force of 20 000 lb (9000 kg) at around 2100 cycles/min.

Placement and Compaction Control

The technical specifications call for a minimum degree of compaction (relative compaction) of 97 percent of the standard Proctor maximum density (ASTM D698 method A) at a water content ±2 percent of the optimum. A maximum of 15 percent of the results could be less than the specified minimum if they are not concentrated in the same section.

The same specifications ask for a grain size composition within the limits shown in Figure 1. To reach this goal, the technical specifications also demand a set of parameters to be respected during construction (e.g., lift thickness and number of passes of the compactor) and the type and frequency of the tests to be carried out. Thus, the control operations are carried out to cover the following two aspects:

1. Qualitative control of the construction procedures (i.e., lift thickness, scarification, sprinkling, and number of passes) and
2. Quantitative control of the materials characteristics by in situ and laboratory tests (i.e., water content, grain size composition, in situ density, Atterberg limits, and permeability).

Control Tests Results

The placement and compaction operations were performed during four summers. The number and the frequency of the tests carried out are given in Table 1. Statistical analysis of the control test results indicates that 80 percent of the results show a degree of compaction higher than 98 percent, and only 5 percent of the results were less than 97 percent. A degree of compaction higher than 100 percent was measured in more than 70 percent of the tests (Figure 2).

The average dry density of the compacted till is 141 lb/ft^3 (2250 kg/m^3). All of the results indicate a density higher than 125 lb/ft^3 (2000 kg/m^3) (Figure 3). Notice that the distribution of the results shows a larger deviation from a Gaussian distribution.

The average compaction water content of 8.9 percent is slightly higher than the optimum 8.0 percent. At the same time only 20 percent of the samples indicated a water content higher than 2 percent of the optimum. Less than 5 percent of the tests revealed a water content 2 percent below the optimum (Figure 4).

PROJECT B, MAIN DAM--MANICOUAGAN 3

The second project includes a 350-ft (106-m) high earth-fill dam resting on a 420-ft (128-m) deep sediment-filled canyon. The dam, which has a total

Figure 1. Grain size composition of till for project A.

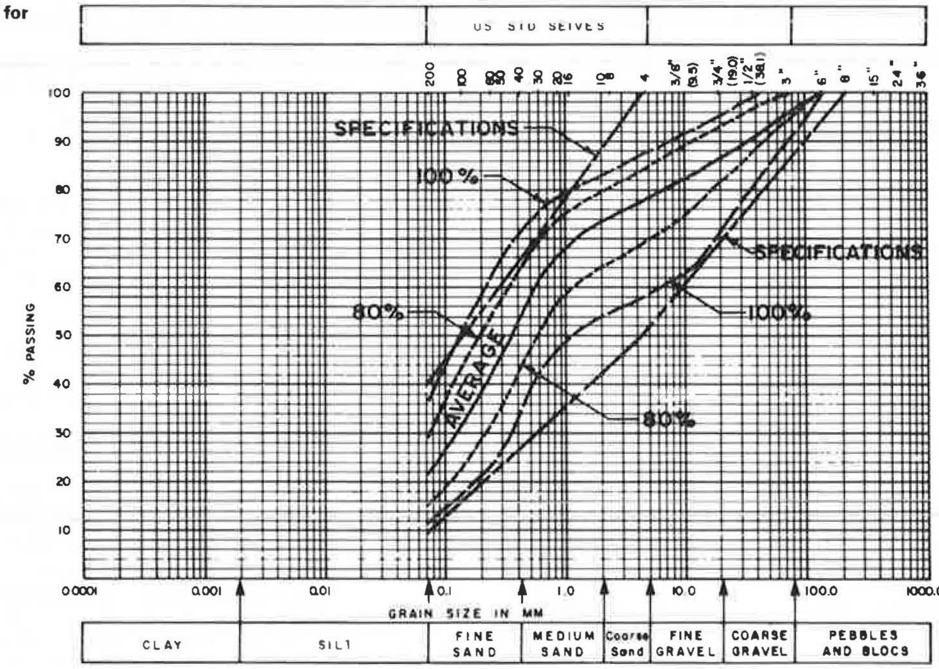


Table 1. Frequency of control tests for project A.

Test	Site	Volume of Material (000s yd^3)	No. of Tests	Yards^3 Between Tests
In situ density water content	Dam 1	885.0	748	1 183
	Dam 2	601.5	833	722
Grain size analysis	Dams 1 and 2	1723.0	465	3 705
Standard Proctor		1723.0	382	4 510
Specific gravity		1723.0	25	68 918
Permeability		1723.0	32	53 843

volume of about 11 035 000 yd^3 (8 436 867 m^3), comprises a fairly thick symmetrical central core, that consists of till. An upstream blanket of about 30-ft (9-m) thickness links the central core with the upstream cofferdam and was provided to lengthen the seepage path under the embankment. It is constructed also from the till material. The total till volume for both the core and blanket is about 2 552 000 yd^3 (1 951 144 m^3).

The maximum width of the core at the dam's base is about 300 ft (90 m); at the same elevation the valley is about 500 ft (150 m). At the crest the core's width is reduced to about 20 ft (6 m), with a crest length of about 1280 ft (390 m). Thus, the working area for the till varies from about 150 000 ft^2 (13 500 m^2) at base elevation to 25 500 ft^2 (2350 m^2) at the crest. The working platform area for the blanket construction (at the base elevation) is about 350 000 ft^2 (31 500 m^2).

Geotechnical Properties of Till

The borrow area is situated some 1.5 miles (2.5 km) downstream of the dam. It contains a till deposit that includes numerous thin layers or lenses of sand, which confer a somewhat stratified appearance.

The grain size analysis indicates a well-graded material that contains, on the average, 5 percent gravels and 50 percent silt-clay particles (Figure 5). The mineral composition of the particles between sieves no. 40 and no. 200 is mainly quartz (85-90 percent), feldspar, biotite, hornblende, garnet, and magnetite. The grains are in general equidimensional and angular. The same mineral composition prevails for the fraction that passes sieve no. 200, the presence of real clay minerals being very limited in spite of a clay size particle content (< 2μ) of 4-15 percent. In general, the material (fraction passing sieve no. 40) is nonplastic. However some samples indicated liquid limit around 17-18 percent and plastic limit of 12-13 percent.

The in situ material is relatively cold, even during the summer. Temperatures of 0°-5°C were recorded in the freshly stripped material. The material is dryed with difficulty by natural evaporation and it is rapidly covered by a film of condensed water when the air humidity rises. On the other hand, the in situ water content is substantially higher than its optimum (standard Proctor). The degree of saturation reaches 95 percent.

The laboratory compaction tests indicate high sensitivity of this material to the compaction water content. The dry density decreases rapidly with the increase of the moisture content (Figure 6). The end points of the compaction curves shown in Figure 6 indicate the water content at which the samples became too wet and too soft to be handled (compacted).

The maximum dry density (standard Proctor) varies between 125 and 137.5 lb•f/ft^3 (2000-2200 kg/m^3) with an optimum water content at 7.4-11.0 percent. The in situ water content of the till is 0.9-3.5 percent higher than the optimum. The permeability of the material measured in laboratory triaxial tests varies between 0.4 and 6x10^{-6} cm/s (material with fines passing sieve no. 200 around 45 percent).

Operation of the Borrow Area

The high natural water content of the material created numerous difficulties during placement and compaction operations. Consequently, special attention was given to the borrow pit operation to obtain some reduction of the moisture content. The excavation of the till was started by backhoes cutting 20- to

Figure 2. Compaction degree of till for project A.

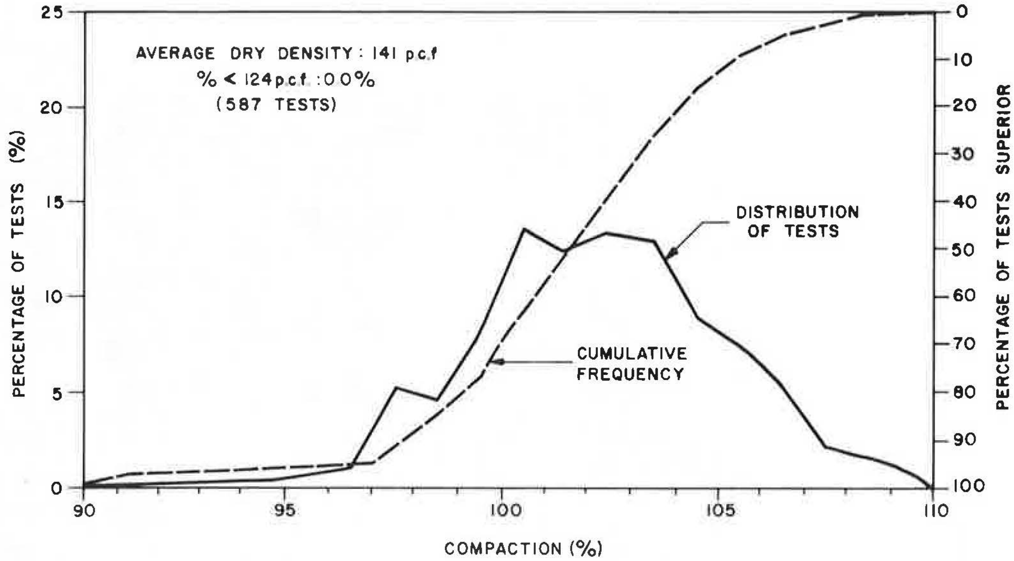


Figure 3. In situ dry density of till for project A.

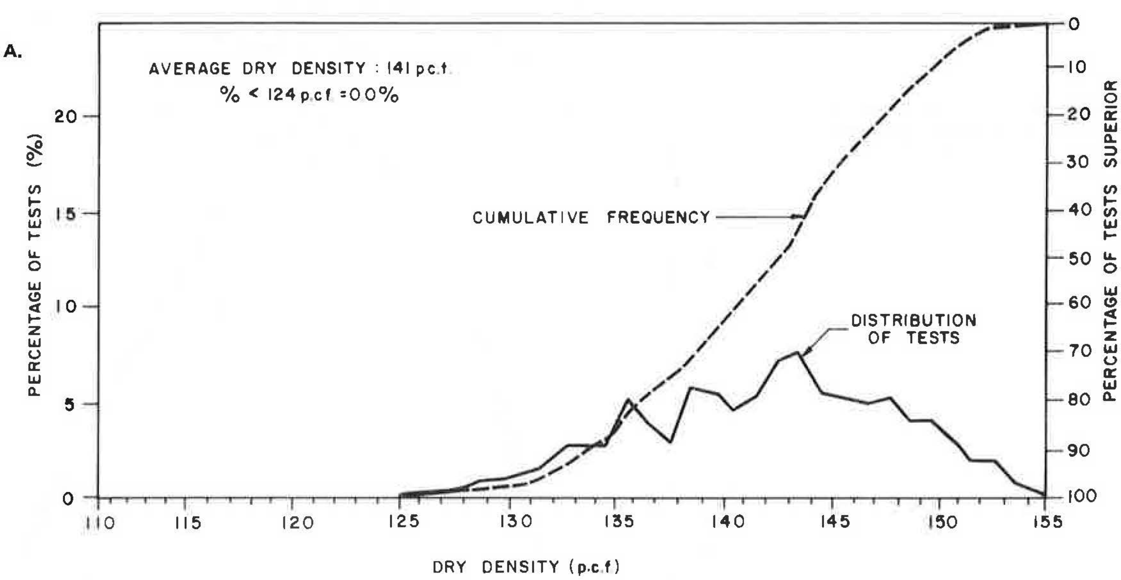


Figure 4. After compaction water content deviation from the optimum W/C for project A.

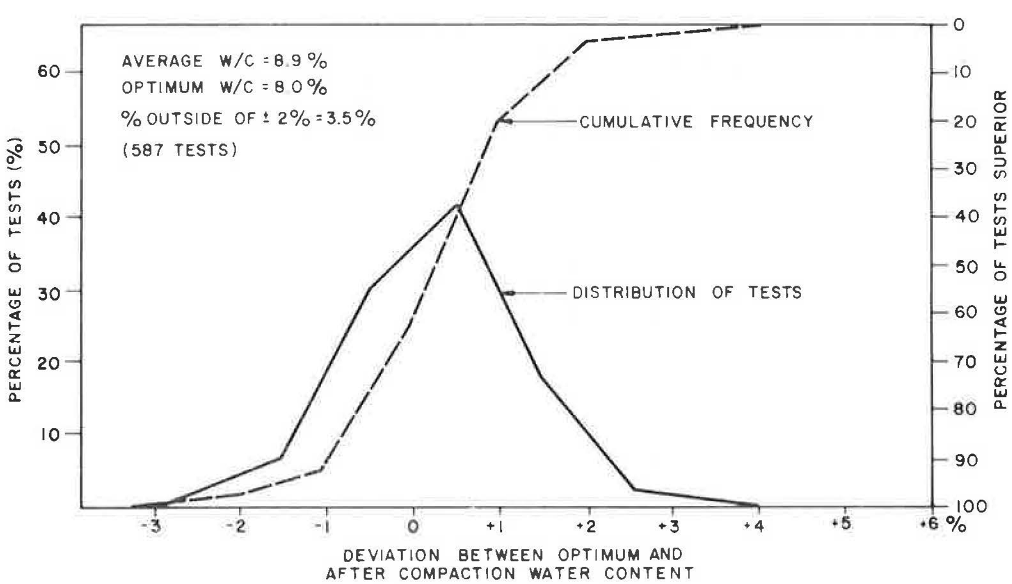


Figure 5. Grain size composition of the fill for project B.

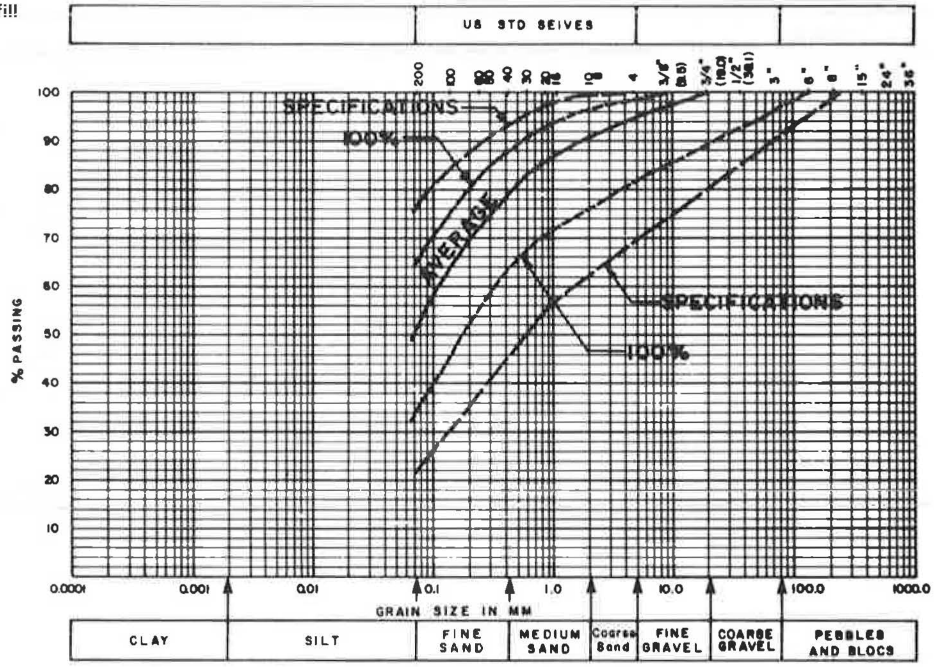


Figure 6. Dry density versus water content (standard Proctor) for various temperatures of the material for project B.

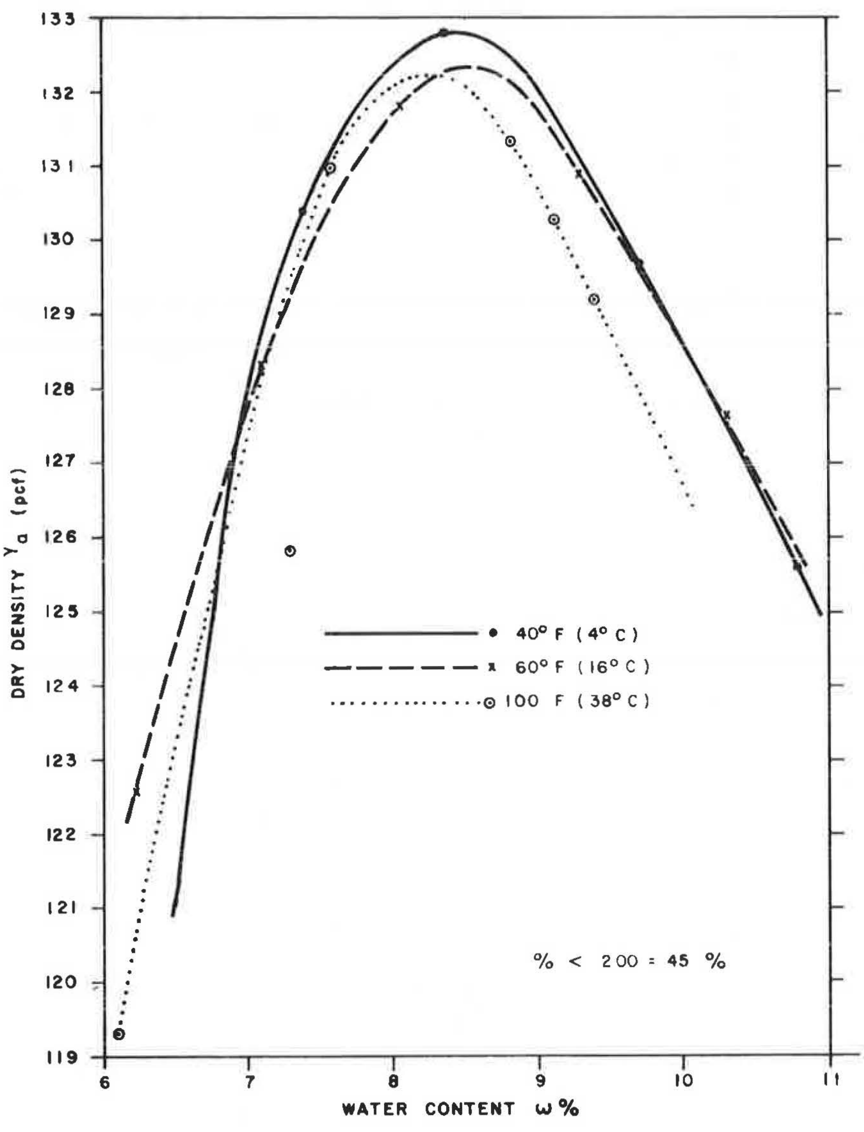
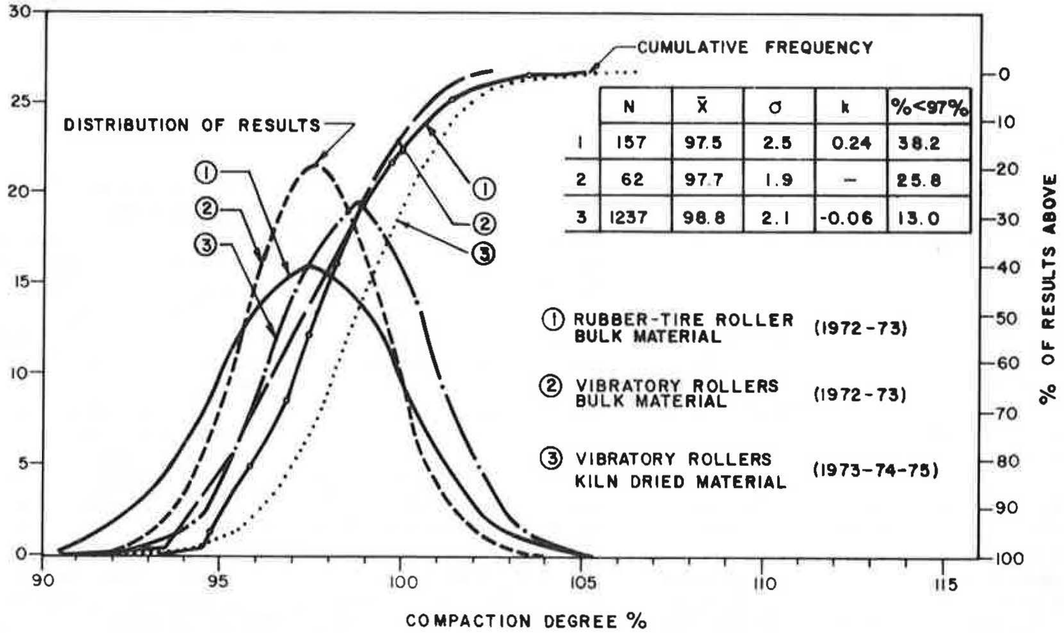


Figure 7. Compaction degree obtained with different compactors.



25-ft (6.1- to 7.6-m) high vertical faces. This method allows a good mixing of the material. However, the freshly cut face is too small to permit drying by sun or wind action. At the same time, this method does not permit a selective exploitation of the deposit (i.e., elimination of more wet or more sandy layers or lenses). Consequently, the method was abandoned and replaced by an excavation with bulldozer along subhorizontal surfaces. The working pad was at first scarified to a depth of 0.5-1.0 ft (0.15-0.30 m) and exposed to drying. Depending on the climatic conditions after a while (average 1 h), the material was sufficiently dry to be placed directly in the dam. The dried material is scarped in thin layers and pushed by bulldozers in piles and loaded in trucks with pneumatic loaders. This method produces a material that can be placed readily in the dam; however, the productivity is too low, which jeopardizes the construction schedule.

The installation of two Koleman vibrating screens to reject the oversize [>6 in (150 mm)] and belt conveyors increased the productivity somewhat. The material is pushed by bulldozers into a hopper, lifted by the conveyors on the screens, and the passing material falls directly in the trucks. The operation is frequently stopped, sometimes for a few days following rainy periods. Subsequently, to ensure that the construction schedule is respected, the artificial drying of the material, using an oil-heated rotary kiln, was adopted.

Placement and Compaction of the Till

First Stage Operations

Previous experiences with till and some preliminary compaction tests carried out before construction indicated that the pneumatic-tired roller would be adequate compaction equipment. Thus, the compaction of the till for the impervious blanket was started with 50-ton tired rollers pulled by bulldozers. Areas that have limited access to the tired rollers or were next to rock abutments were compacted with self-propelled 5.5-ton vibratory rollers and with manual vibration plates.

The high natural water content of the material, even at the beginning, created a lot of difficulties. The traffic of the loaded trucks and the heavy compaction equipment induced large deformation in the fill [ruts up to 8-in (200-mm) deep], which resulted in its decompaction and fissuration. A reduction in the layer thickness before compaction from 9 in (22.5 cm) to 6 in (15.0 cm) did not improve significantly the productivity and the quality of the operations. During the first year the majority of the in situ density tests indicated a degree of compaction below 97 percent. The large working area [350 000 ft^2 (31 500 m^2)] exposed to weather inclemencies also contributed to low productivity. As a matter of fact, cleaning operation after a rainy period, which in many instances necessitated the removal and the rejection of the saturated (too wet) material, was very time consuming and expensive. Even when the removal of the wet material was not required, a deep scarifying was carried out to facilitate drying, which increased significantly the depth of the loose material to be compacted. Consequently, the efficiency of the compaction is reduced and that explains the low degree of compaction obtained during the first campaign.

Tests carried out with different types of compaction equipment, varying layer of thickness, and number of passes did not succeed in improving significantly the degree of compaction. Figure 7 presents, as an example, the degree of compaction obtained with 40-ton pneumatic tired rollers and 9-ton vibratory rollers on material at its natural water content (bulk material). As can be seen for both equipments, close to 50 percent of the results show a degree of compaction less than 97 percent (the technical specifications required a minimum degree of compaction of 97 percent standard Proctor, allowing a maximum of 15 percent below this limit).

To eliminate or at least to reduce some of the difficulties mentioned above, research was carried out

1. To reduce the water content of the till in the borrow pit,
2. To select an adequate protection system of the compacted material,

3. To select a compactor for the given soil conditions,
4. To reduce the water content of the till by artificial drying, and
5. To change the borrow area that contains a drier material.

The inefficiency of the drainage trenches installed in the borrow area and some negative results of laboratory tests on electro-osmosis, vacuum pumping led to abandonment of the first objective. At the same time, the idea to cover the compacted material with plastic sheets to avoid supplementary wetting by rain or condensation was also eliminated. The large surface involved and the high wind velocities that prevailed at the dam's site would have made the installation and the recovery of the sheets difficult. Another drawback of the system is that, during favorable climatic conditions, if the sheets are not removed the evaporation is hindered and condensation takes place at the fill's surface. A wrong decision concerning the time of installation or removal could damage the material or produce useless work stoppages. It was also concluded that this method would not change the high compaction water content of the till.

Concerning the compaction equipment, as mentioned above, tests carried out with various types of compactors did not improve the compaction of these wet materials.

Artificial drying of the material was contemplated by two means:

1. In situ drying in the borrow pit and
2. Drying the excavated material in special devices

In situ drying was experimented with by using propane-heated, infrared ray plates [4x9 ft (1.35x 2.70 m)] pulled by bulldozers. The plate produced an effective heat radiation of about 4000 cal/cm^2/h (as compared with 65 cal/cm^2/h radiated by the sun at the dam's site) and dried only the upper 2-4 in (5-10 cm) of the material, which necessitated a subsequent harrowing and a second pass of drying. The application of this procedure would have implied the use of a large number of plates and bulldozers, consequently its economy would have been questionable.

Tests with infrared heaters installed above a belt conveyor were abandoned because too much time was needed to build and put in operation such a device. The second option, the drying of the excavated material by using a rotary kiln, was finally accepted.

Consequently, a readily built rotary kiln, which had a diameter of 14 ft (4.25 m), a length of 80 ft (24.4 m), and delivering about 28x10^9 cal/h, was installed. The kiln capacity is about 455 ton/h (200 yd^3/h), the temperature of the material leaving the oven varies between 60° and 70°C. Fuel consumption is 7.4 l/m^3 and reaches 11.3 l/m^3 for the most humid material.

The material leaving the kiln is stored in cone-shaped stockpiles. The slopes of the pile, the accumulated heat (the temperature in the pile is maintained at about 32°-50°C), and the compactness of the material constitute an adequate protection against water penetration (rain), without necessity for any protective shelter (Figure 8).

The efficiency of the kiln is illustrated in Figure 9; the average water content of the material before drying of 11.9 percent is reduced to about 10.3 percent or by about 1.6 percent. At the same time, the deviation between the optimum water content and the water of the material before and after drying is also narrowed. As can be seen, more than 85 percent of the dried material has a water content lower than optimum +2 percent, which allows much easier handling (compaction).

Also note that, due to the accumulated heat in the stockpile, the material obtains a more homogeneous water content while an additional reduction takes place in the stockpile.

Second Stage Operation

The 8- to 9-ton vibration roller was adopted following the positive results obtained with it. This equipment gives a satisfactory compaction by 3-4 passes in lifts of 4-in (100-mm) material, even when the water content is as much as 2 percent over the optimum. A light scarifying of the compacted surface before spreading the new layer allows an intimate connection between the two lifts. Control trenches excavated in the material did not reveal the presence of any compaction joints. However, the till compacted at a water content over its optimum continued to deform under the truck loads.

These deformations are associated with the opening of fissures in the compacted material, which cannot be tolerated in the dam's core. Consequently, a major modification of the placement and compaction procedure was introduced. The traffic of the trucks hauling the till was limited to the transition zones only. The material dumped on the upstream and downstream edges of the core was spread by bulldozers in layers of 4-6 in (100-150 mm) along the upstream-downstream axis and followed by the compaction along the same direction (Figure 10). This direction of compaction is a major deviation from the general practice adopted by the profession. Performance to date indicates that homogeneous material obtained did not have any weakness zones along compaction joints in the direction of flow through the core.

During midsummer periods the compacted surface can became too dry, in which case the scarified material is sprinkled to get a water content slightly above the optimum. However, when the drying of the material is deeper [3-6 in (75-150 mm)], following an extended work stoppage (1-3 days), removal of the entire dried material is more economical. Some rewetting tests carried out indicated that the results are acceptable; however, the wetting operation needs many hours without getting assurance that a homogeneous material will be obtained. The removal of the same materials following a rain also seems more economical than its in situ drying. This allows a much more rapid resumption of the compaction operations.

Placement and Compaction Inspection

The qualitative inspection involving operation procedures (number of passes, lift thickness, compaction overlapping, movement speed of a compactors, scarification, and harrowing) is carried out by field inspectors. Technician crews attached to the field laboratory execute quantitative analyses (in situ dry density, laboratory grain size analysis, water content, and standard Proctor).

The inspection also is extended to the borrow pit and the kiln operation. At the borrow pit, the inspector supervises the excavation operation and, following a visual inspection and a rapid test of material passing sieve no. 200 and water content (speedy moisture), approves the material to be shipped to the dam. Once the kiln operation has started, the inspection in the borrow pit is reduced, but at the kiln it is extended. The material is tested at the feeder and at the outlet of the kiln to allow the adjustment of the burner and the feeder's discharge, which controls the temperature and the water content of the dried material. The

Figure 8. Rotary kiln drying plant.

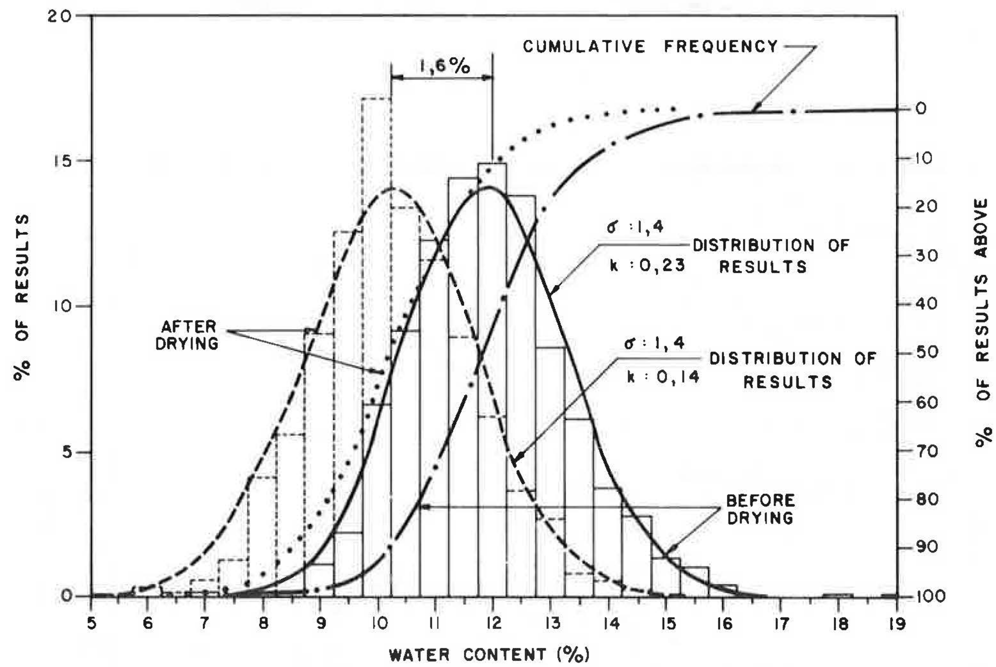


Figure 9. Water content of the till before and after kiln drying for project B.

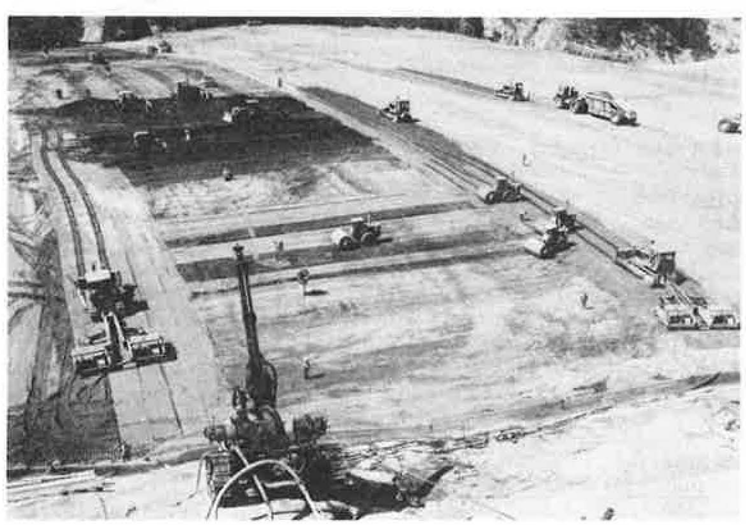


Figure 10. Placing operations of the impervious core.

Figure 11. Compaction degree for the total till volume placed in the core and blanket for project B.

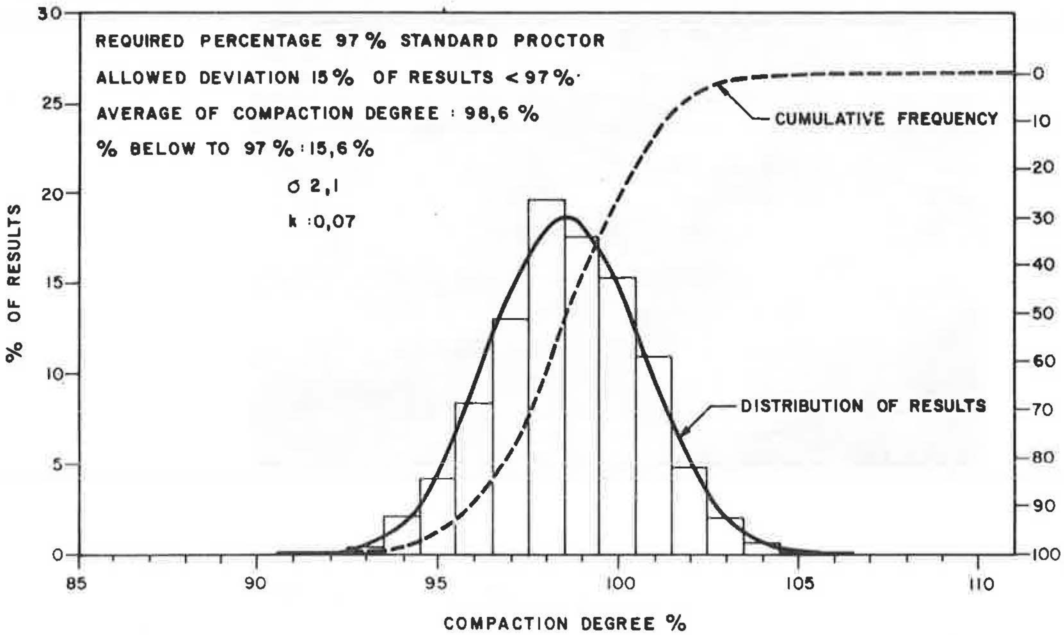
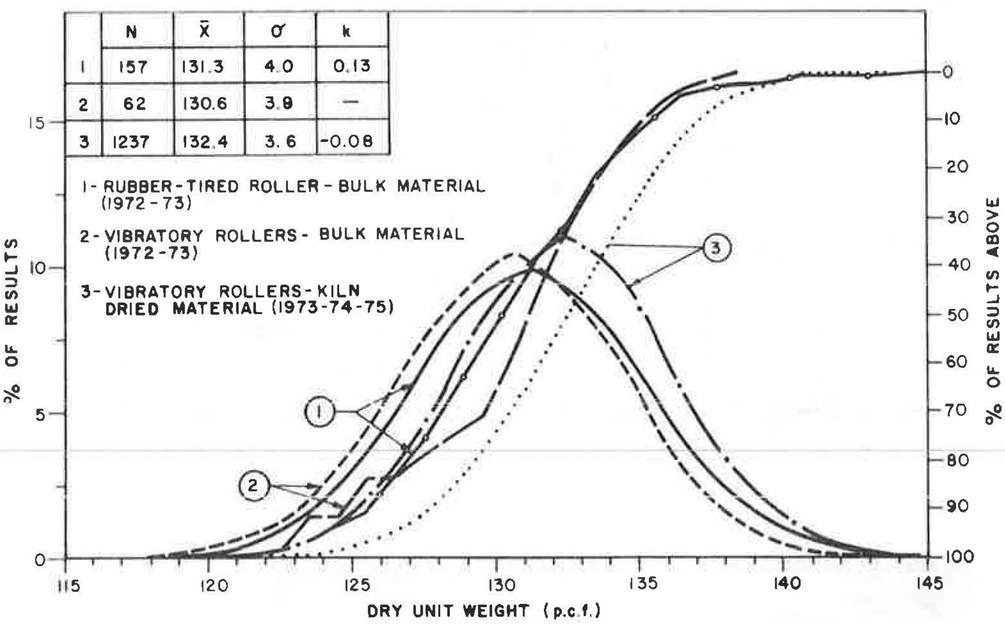


Figure 12. In situ dry density obtained with different compactors before and after drying the till for project B.



frequency of the rapid tests (passing sieve no. 200 and water content) is about 5-8/10-h shift.

One of the main objectives of the quality inspection was the lift thickness. This parameter has a particular influence on the compaction results. The lift thickness was checked by topographical survey, along a quadrilateral mesh covering the working area. The survey was carried out before and after compaction covering the working area.

The frequency of the principal routine tests is shown in the table below (note 1 yd³ = 0.765 m³):

Test	Volume of Material (000 yd³)	Yards³ Between Tests
Grain size	2550	5000
In situ density and water content	2550	1350
Standard Proctor	2550	5000

Summary of Quantitative Test Results

The average degree of compaction is 98.6 percent with a standard deviation of 2.1 and with 15.6 percent of the results below 97 percent (Figure 11). Note that, after the kiln started to function, the average degree of compaction was maintained around 100 percent. The average dry density reached a value of 132 lb/ft³ (2110 kg/m³). Figure 12 shows the dry density obtained by the tired rollers after drying.

The water content after compaction is an average of 0.9 percent over the optimum with a standard deviation of about 0.9 percent. The degree of saturation of the compacted material varies between 70 and 100 percent.

Economy of Drying Operation

Based on 1974 prices, the drying operations increased the material cost by about 72 percent (1), considering that the drying installation is entirely depreciated. However, considering that only about 700 000 yd^3 (510 595 m^3) of material is dried, the increase is 51 percent of the total cost of the till, and only 10.5 percent of the total cost of the dam's fill.

The increase costs can be distributed as follows:

Item	Percent
Investment--purchase and installation of the kiln and conveyor	32
Operation--fuel, parts, and main power	53
Supplementary cost for transportation and loading	15

Notice that the main costs are those of operations, particularly maintenance and repairs costs. In 1974-1975, the fuel cost represented only about 13 percent. In spite of the increase of the till cost, the drying operation on the whole was more than economical, considering the implied expenses if the completion of the project would have needed an extra year.

Project C, East-West Dikes--Outardes 2

The water-retaining structures of project C include a concrete-faced rock-fill dam and two earth-fill dikes. The sand and gravel dikes are provided with a relatively large impervious central core consisting of a mix of sand-gravel and clay. Dike 1 (east), with a maximum height of 110 ft (33.5 m), has a crest length of 8700 ft (2650 m), and dike 2 (west) has a maximum height of 95 ft (29 m) and a crest length of 3800 ft (1160 m). The total volume of material involved is 1 822 700 yd^3 (1 393 555 m^3) for dike 2; the core material represents 262 000 and 185 000 yd^3 (200 314 and 141 443 m^3), respectively. The dikes, being founded on a relatively soft clay and silt foundation, were built with gentle slopes (up to 1V:6H) and this explains the relatively low ratio between the core volume and the total volume of the structure (2).

Geological and geotechnical investigations carried out for the project area [within an economical radius of about 20-25 miles (30-40 km)] did not disclose the presence of any deposit of natural impervious material that could have been used for core construction. However, the same investigation localized large deposits of sand and gravel and extended clay formations. Because of the high sensitivity of the clay (in its remolded stage the clay became fluid), it does not lend itself to being used as construction material. Thus, following the results obtained at Mirobo Dam in Japan (3), where the core was built from a mix of clay and weathered granite, a similar solution was adapted for these dikes. The mix was obtained at Mirobo by excavating a vertical face in a pile consisting of alternative layers of clay and weathered granite. In our case the sensitive clay liquifies by remolding and so it cannot be spread in layers. Subsequently, different mixing procedures were developed. Initially, the clay placed inside a U-shaped enclosure consisting of dumped sand-gravel piles is liquefied by moving bulldozers that also push the surrounding sand-gravel and mix together the two materials. When the mix became sufficiently homogeneous it is spread in thin layers on a stockpile. In a later stage, the mixing operation was realized in a mixing drum provided with rotary blades.

Geotechnical Characteristics of Core Material

Clay Material

The clay deposit contains about 37 percent clay and 58 percent silt particles and is of low plasticity (plasticity index about 7) due to the lack of real clay minerals. Even the particles smaller than 2 μ consist of inert minerals like quartz or feldspars and only about 4 percent represent clay minerals (e.g., illite or clorite). The average natural water content is 33 percent compared with an average of 25 percent liquid limit and 18 percent plastic limit. The high liquidity index (L_L = 2) is a good indicator of its high sensitivity, which is situated around S = 1000 (measured by Swedish cone tests). The laboratory permeability of the clay measured following Bowles method is around 10^{-8} cm/s.

Sand and Gravel

The grain size composition of the material used in the mix varies from a medium-fine sand to a sand and gravel. The average that passes sieve no. 4 is 75 percent and about 1.4 percent passes sieve no. 200. The average natural water content of the sand is 7 percent.

Manufacturing of the Sand-Gravel and Clay Mix

The excavation of the clay in the borrow pit is carried out with a backhoe of 1.5 yd^3 (1.15 m^3) capacity that cuts vertical faces of 16 ft (5 m) in height. The sand-gravel is also excavated along vertical faces with pneumatic loaders. Trucks of 22-ton and 35-ton capacities transport the material to the mixing area.

At the initial stage, two bulldozers carried out the mixing. One mix (batch) contains about 250 yd^3 (190 m^3), with a ratio of 30 percent clay to 70 percent sand (in volume). The mixing operation of a batch takes about 2 h. The mixed material is spread in a stockpile in layers of about 12-in (30-cm) thick.

In the second stage the mixing was realized in a 2-yd^3 (4.6-m^3) rotary drum fed by a belt conveyor. Two hoppers, one for the sand and one for the clay, proportion the materials on the conveyor. The proportioning of the sand is controlled by a timing mechanism. An endless screw, which also partly liquefies the clay, controls the clay content. The average production of the plant is about 150 yd^3/h (115 m^3/h).

The water content of the mix in both procedures is too high to be placed directly in the dike and requires a drainage period in the stockpile. To eliminate this drawback, a rotary kiln of 150 yd^3/h (115 m^3/h) capacity was installed to dry the sand. It provided a mix at a water content close to its optimum.

Placement and Compaction of Material

The compaction operations were carried out by 6-ton vibratory rollers with four passes. The materials were brought to the site in trucks of 22-ton to 30-ton capacities and were spread by bulldozers in

Figure 13. Grain size composition of the sand-gravel and clay mixture for project C.

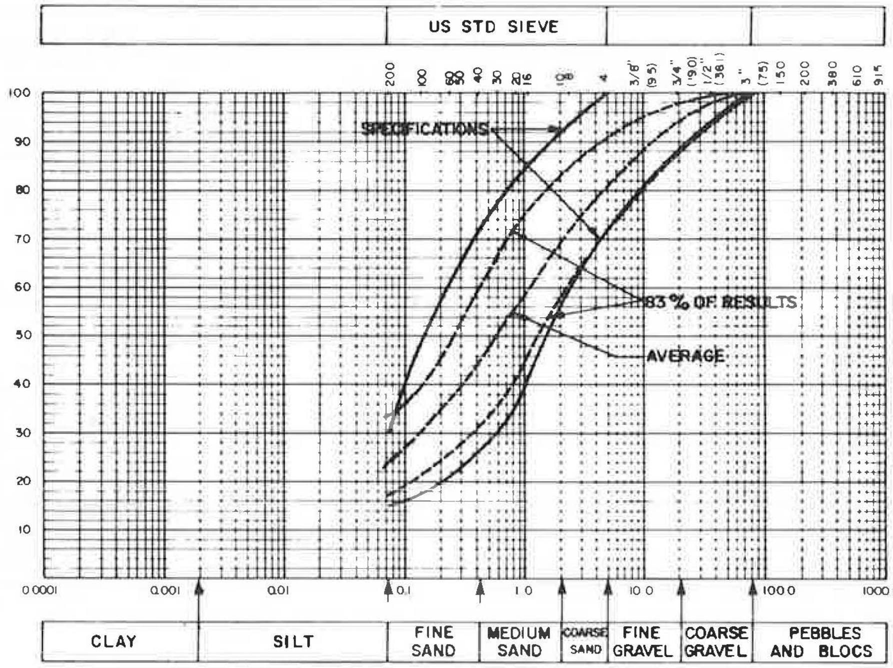


Figure 14. In situ dry density of the sand-gravel and clay mixture for project C.

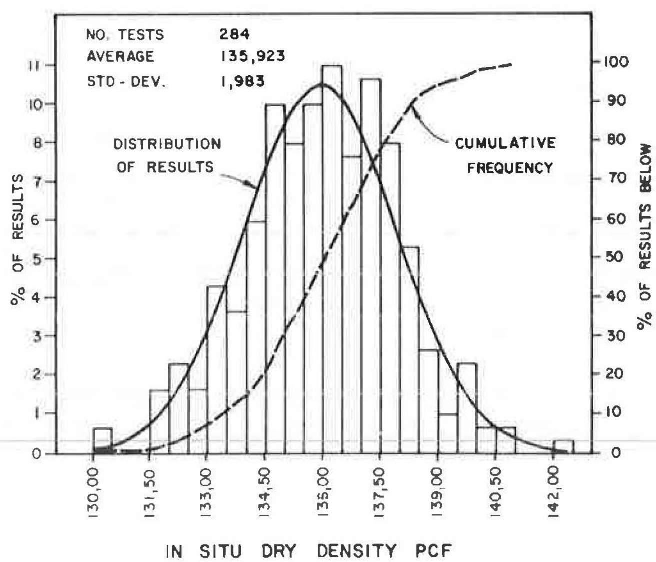
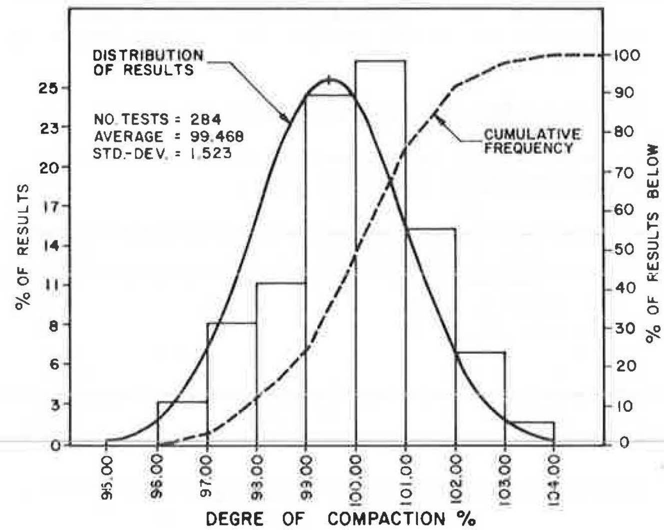


Figure 15. Compaction degree of the sand-gravel and clay mixture for project C.



lifts 12-in (30-cm) thick. The compactors moved along the longitudinal axis of the dike with a maximum speed of 3 miles/h (5 km/h). Before placing the next lift the material is scarified to a depth of 3 in (8 cm) with a disc harrow.

The grain size composition of the mix placed in the dikes is illustrated in Figure 13. This shows that more than 83 percent of the results are within the limits laid down by the technical specifications. The average fine content (<0.074 mm) is 23.5 percent with a standard deviation of 3.7 percent.

The average water content after compaction is 7.4 percent (standard deviation of 0.8 percent) as compared with the average optimum water content (standard Proctor) of 7.7 percent (standard deviation of 0.4 percent).

The in situ dry density, measured with a Troxler nuclear apparatus gave an average value of 135.9 lb/ft^3 (2175 kg/m^3) with a standard deviation of 2 lb/ft^3 (32 kg/m^3) (Figure 14). The degree of compaction reached an average of 99.5 percent (standard deviation of 1.5 percent) (Figure 15). Less than 5 percent of the results indicate a degree of compaction less than 97 percent.

Placement and Compaction Inspection

The inspection operations were simulated to that of the other structures presented previously. The qualitative inspection was realized by inspectors in the field (i.e., lift thickness, number of passes, and traveling speed of the compactors). The quantitative inspection at the mixing plant, field, and laboratory was executed by technicians, all under the supervision of the resident soil engineer.

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Lateral Pressure Developed During Compaction

ZVI OFER

The relation between the horizontal and vertical components of stress at a point within a soil mass depends on the physical and mechanical properties of the soil and its stress and strain histories. A series of compression tests and repeated loading tests were performed on sand and clay by using the lateral soil pressure ring MkII. This newly developed apparatus allows the laboratory determination of the lateral soil pressure response to vertical loading at rest condition or, alternatively, when limited controlled lateral strain develops. Correlations between the horizontal to vertical stress ratio (K) and the vertical load are presented. After placement of a cohesionless sample, when the material is loose, K is high and it decreases to an ultimate value. Unsaturated clay specimens exhibit somewhat different behavior—K decreases to a minimum value and then it increases with an increase in the load. During the unloading process K increases with an increase in the overconsolidation ratio, and a general relation between K and the overconsolidation ratio is suggested. However, repeated loading results in a decrease in K with an increase in the vertical load. It was also found that the grain size and distribution of grain size affect K. The present testing system does not have facilities for pore water pressure and dynamic loading measurements, which would enable more comprehensive testing and determination of soil parameters in terms of effective stress.

The relation between the horizontal and vertical components of stress at a point within a soil mass depends to a great extent on the stress and strain histories of the soil mass and the degree to which it is remembered. Other basic soil properties such as grain size and shape, grain size distribution, moisture conditions, and Atterberg's limits also affect the stress ratio. The elastic parameters of the soil [e.g., Poisson's ratio (μ)] and the modulus of elasticity (E) depend on the stress-strain characteristic of the soil as well. These parameters are major engineering considerations in many facets of road design and are used extensively in the design of layer thickness, earth-retaining structures, culverts, and slope-stability analysis.

The horizontal-to-vertical stress ratio at a point within a soil mass is defined as the coefficient of lateral earth pressure. This coefficient varies between a lower limit, when a soil element is allowed to expand laterally subsequent to vertical loading, and an upper limit, when a soil element mobilizes as a result of lateral thrust. These two extremes are defined as the coefficient of active lateral pressure (K_a) and the coefficient of passive lateral pressure (K_p), respectively. When lateral yielding is prevented, the ratio of the horizontal to vertical stress is known as the coefficient of lateral pressure at rest (K_o). These coefficients are correlated to the angle of internal friction of the soil (ϕ). However, this correlation is invalid in the case of highly overconsolidated materials. During a process of compaction or while clay soil swells as a result of an increase in its moisture content, the coefficient of lateral pressure at rest (K_o) may exceed unity value that results from combined effect of soil dilation and locked-in stress and, therefore, it cannot be correlated to ϕ.

The objective of this study was to examine the development of lateral stress in a remoulded soil mass during the compression process and to correlate it to several basic elastic and mechanical soil parameters that are of interest to the road engineer. This paper describes an instrument that allows laboratory determination of the lateral soil pressure response to vertical loading without lateral yielding and with limited controlled lateral yielding. A series of repetitive loading tests performed on river sand and remoulded norite clay is described and test results are presented and discussed.

LABORATORY K_o COMPRESSION TESTING

A laboratory K_o compression testing method must satisfy two requirements:

1. The soil must deform freely in the vertical direction and
2. The lateral yielding must be either zero or of negligible magnitude.

If either of these requirements is not satisfied (e.g., either the vertical yielding is restrained or lateral yielding occurs) the tested specimen is mobilized toward an active or passive failure condition. At rest condition is simulated in the laboratory by using either a modified triaxial testing or a modified oedometer compression testing technique.

A simple sensing device that consists of a metal band clamping a triaxial soil specimen was developed by Murdock (1). The metal band has an adjustable screw and a lamp connected to a power source. Before a vertical load increment is applied, the electrical circuit is closed by adjusting the screw until the lamp lights up. The radial deformation that results from an increase in the vertical load cuts the electrical circuit. A subsequent increase in the cell pressure recovers the radial deformation until the electrical circuit is closed and the lamp lights up again. At this stage no lateral strain occurred and the horizontal-to-vertical stress ratio at rest (K_o) is determined.

A visual lateral strain indicator was introduced