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A LABORATORY STUDY OF VARVED CLAY
FROM STEEP ROCK LAKE, ONTARIO

BY

W. J. EDEN

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A LABORATORY STUDY OF VARVED CLAY FROM STEEP ROCK LAKE, ONTARIO

W. J. EDEN

ABSTRACT. Results of a laboratory study of some of the physical properties of varved clay from Steep Rock Lake are presented. Tests show a considerable variation in properties, especially water content and plasticity, between the light and dark laminae of varved clay. Grain-size analyses indicate that the Steep Rock varved clay are not diatactic. The test results suggest that flocculation resulting from varying physical-chemical conditions in the lake was responsible for the deposition of the varved clay.

INTRODUCTION

Throughout Canada, but especially in the northern areas, deposits of fine-grained glacial soils are found. These soils have frequently been the cause of a good deal of trouble to the construction and mining industries. When found in a saturated condition these soils often have the ability to liquefy whenever they are disturbed. The Division of Building Research of the National Research Council has undertaken a study of such northern soils. When high-grade iron ore was discovered beneath the waters of Steep Rock Lake and mining operations led to the dewatering of the lake and subsequent dredging of the lake bottom deposits, a good opportunity for study arose. The deposits of soil in Steep Rock Lake were for the most part varved clays, one of the more treacherous of the glacial soils. With the co-operation of Steep Rock Iron Mines Company Limited, the Division of Building Research undertook a detailed study of the Steep Rock varved clays with emphasis on the engineering standpoint.

At the outset of the study, varved clays were treated by the usual practice of soil mechanics, as a uniform soil. Testing was conducted irrespective of the laminations which make up the varved clay. The results of this study have been presented previously (Legget and Bartley, 1953). It was soon recognized that the separate laminations which make up a varve had remarkably different physical properties. Part of the detailed study was therefore directed toward finding the properties of the individual laminae and the variations in properties within the laminae.

This paper deals with some results of this detailed study. Although not the objective of the study, a good deal of information has been assembled which may be valuable to geologists. This paper presents the geological aspects of this study. The test results are discussed in the light of current theories concerning the formation of varved clays.

LABORATORY WORK

To carry out this laboratory investigation, block samples of a size which could be conveniently handled were collected by the author at Steep Rock Lake, sealed in paraffin or petrowax, packed in damp sawdust, and shipped to Ottawa for testing. Samples were taken from fresh exposures in order to preserve the natural water content of the varved clays. The samples were chosen from widely separated locations in the middle arm of Steep Rock Lake with the object of representing typical specimens of the varved clay which occurs in the Lake bottom. Once in the laboratory the samples were

split into fractions of light (summer) and dark (winter) layers for the various physical tests.

Natural water content.—The natural water content is determined by comparing the wet and oven-dry weights of the material. Oven drying was carried out at a temperature of 105°C. Since these soils were saturated, the amount of water present represents the volume of voids of the clay. The void ratio¹ was determined separately, by carefully trimming a sample, then weighing and measuring. In all cases it was found that the varved clays were at least 99 percent saturated. Since the water content also represents the void ratio of the clays, it is a measure of the structure of the soil. Water content tests were conducted with the objective of determining the variations in structure between the dark and light layers, and also the variations within any one layer.

Fig. 1. Variation in natural water content within the varves (Sample 2-65).

The results of the water content determinations revealed a remarkable difference between the dark and light layers which make up a varve. Figure 1, which illustrates the variation found in one sample, is typical of the moisture content variations found in all the test work. The water content of the dark layers ranged from 60 to 100 percent, and of the light layers from 20 to 40

¹ Void ratio is defined as the ratio of volume of voids to the volume of the soil solids.

percent. This range in water content corresponds to a range from 1.69 to 2.83 in void ratio for the dark layers, and from 0.56 to 1.11 for the light layers. Thus the dark layers have a void ratio approximately $2\frac{1}{2}$ to 3 times that of the light layers. The specific gravity of the soil particles was 2.80 and 2.76 for the dark and light materials respectively.

Plasticity.—The plasticity in clays is due to the molecular forces acting between small particles. These forces vary according to the structure of the clay particles, i.e. the type of clay mineral present, the size and surface development of the particles, and according to the concentration and type of electrolyte in the water. A kaolinite clay and a montmorillonite clay having the same grain size would have entirely different plasticity characteristics. In a system of pure kaolinite clay and pure water, Hauser and Le Beau (1946) attribute plasticity to molecular attraction forces between uncharged particles (van der Waals forces). Recent investigations show that plasticity is greatly influenced by the cation complex of the clay. Ahlberg (1951) found that the same clay treated with hydrogen, sodium, and other cations underwent great changes in plasticity depending on the cation.

The plasticity of the varved clays from Steep Rock was investigated by means of the Atterberg limits tests. This method has been standard in soil mechanics practice; a detailed procedure for the test may be found in A.S.T.M. "Procedures for Testing Soils" (1950) or in many of the reference books on soil mechanics. The Atterberg limits are made up of the liquid limit and plastic limit. The liquid limit is defined as the water content required to render the soil just fluid as distinct from plastic. The plastic limit is defined as the water content required to render the soil plastic as distinct from friable or crumbly. The difference in water contents between the liquid and plastic limits is the range in which the soil is plastic, and has been defined as the plasticity index. Highly plastic soils have a high numerical value for the plasticity index and conversely non-plastic soils have a value of zero for the plasticity index.

It should be noted that the procedure followed for determination of the liquid limit varied slightly from the standard procedure listed in A.S.T.M. (1950) whereas it is usual to conduct the liquid limit on soil which has been air dried, the values of liquid limit listed were determined on soil in its natural state. It was found that liquid limit determinations conducted on Steep Rock varved clays in their natural state yielded generally higher results than determinations conducted on air-dried samples.

The Atterberg tests revealed a great difference in plasticity between the dark and light layers. The change in plasticity is of the same order as that for natural water content and void ratio. Figure 2 shows the difference when the plasticity index is plotted against clay fraction (Skempton, 1953). Figure 3 shows the difference between light and dark layers when plotted on the Casagrande chart of plasticity index vs. liquid limit (Casagrande, 1947). In figure 4 the variations in plasticity within one varve are shown. This figure shows results which are typical of the variations found in other samples in which the layers are of more equal thickness. Figure 4 demonstrates a very rapid change in plasticity from dark to light material, as was the case with

Fig. 2. Relationship between clay fraction and plasticity index (after Skempton).

water content and grain size. Figures 2 and 3 contain results of tests from all portions of the varves, and indicate no transitional zone of any appreciable thickness between the dark and light layers.

Grain size.—The investigation of grain size was directed toward determining the difference between the dark and light layers and whether any gradation in grain size existed within the varves. The techniques used for grain-size determinations were hydrometer analysis, pipette analysis, and measurement of individual grains under the microscope. The procedures used have been thoroughly investigated by various authorities. In the hydrometer analysis, the procedure followed was developed by Arthur Casagrande (1931) and is described by Lambe (1951). In the pipette analysis, the procedure outlined by Krumbein and Pettijohn (1938) was followed. Microscopic grain-size analysis was conducted by the technique given by Krumbein and Pettijohn (1938). The three techniques for grain-size analysis were found necessary because of the difficulty in obtaining a sufficient amount of soil to make any one test standard. Comparative tests were conducted on the same sample by both the hydrometer and pipette methods; the results were found to compare closely. It is difficult to conduct a comparison between the hydrometer or pipette methods with the microscopic method because, with the latter, the grain-size frequency is based on number rather than on weight as with the

other methods. The hydrometer and pipette analyses were conducted on samples which had been dispersed with a small amount of sodium oxalate.

The results of mechanical analysis for grain size are usually presented graphically by means of a grain-size distribution frequency curve or a grain-size distribution accumulation curve. Because of the large number of tests conducted, it is difficult to compare all the curves on one diagram. The values

Fig. 3. Casagrande plasticity chart for Steep Rock varved clays.

Fig. 4. Variations of grain size, water content, and plasticity within a varve (Sample 2-123).

Fig. 5. Variation in grain size in a diatactic varve (Sample 38-3; Don Valley, Toronto).

presented in figures 4 and 5 were obtained by statistical methods of describing such curves. The statistical methods are described by Krumbein and Pettijohn (1938), Otto (1939), and Inman (1952). The geometric mean diameter is the size which corresponds to the grain-size diameter associated with the most abundant grains in an asymmetrical distribution. Using the geometric mean and the standard deviation it is possible to describe most of the grain-size distribution curve by two numbers. By converting the grain size in millimeters to the ϕ scale (the grain size in ϕ units equalling the negative $\log_2$ grain size in millimeters) and plotting the grain-size distribution curve on probability paper, it is possible to derive the geometric mean diameter and standard deviation by a simple graphical construction (Inman, 1952).

The grain-size tests were conducted to determine the difference in grain size between the dark and light layers and to determine whether the Steep Rock varved clays were diatactic.²

Figure 2 shows a significant difference in the clay-sized fraction. The dark layers contain from 65 to 95 percent clay-sized particles whereas the light layers contain only from 18 to 35 percent clay-sized particles. Figure 4 shows a significant difference within a varve.

The results of tests conducted on sublayers failed to show a significant gradation in grain size within one varve. Figure 4 indicates the results obtained from varved clay with abnormally thick dark layers (believed to be what Antevs (1951) terms a drainage varve). Although this varve is admittedly not typical, it was chosen because a large number of tests were made on it; tests conducted on samples with varves of normal thickness also failed to indicate any gradation within a varve. Figure 6 indicates the results obtained by the microscopic examination of a light (summer) layer which was divided into six equal fractions throughout its profile. No gradation was indicated by the results in figure 6.

Admittedly the number of varves tested in this manner are comparatively few in relation to the total number of varves which exist at Steep Rock. The

² Fraser (1929) defines diatactic structure of a varve as one in which the materials of the varve are sorted according to size and specific gravity of particles, the coarsest at the bottom and the finest at the top.

Symmett structure refers to clay deposited under control of an electrolyte, in which case particles large and small go down together and form an unsorted mass due to flocculation of the grains.

Fig. 6A

Fig. 6B

Fig. 6. A. Upper third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124).

B. Middle third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124).

C. Lower third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124).
 (See following page for fig. 6C)

Fig. 6C

samples were, however, chosen to be typical of the various types of varves which were uncovered. In all the tests conducted on the Steep Rock varved clay, no gradation of particle size within a varve was indicated which is somewhat puzzling considering the work of Antevs (1951) on the Steep Rock clays. In discussing the formation of the Steep Rock varved clays, Antevs states that the laminations were diatactic, not symminct, and little flocculation took place.

To compare this result with varves from other locations, samples were obtained from Amos, Quebec (through the courtesy of Dr. A. MacLaren of the Geological Survey of Canada) and from the Don Valley at Toronto. The Amos samples appeared very similar to the Steep Rock samples and lacked any particle-size gradation. The Toronto sample did appear to have a particle-size distribution; the results presented in figure 5 support this view. This is, in the author's opinion, a diatactic varve, while the Steep Rock varves are not. With the sample from Toronto, it could be seen that the light material grades gradually into the dark with no clear boundary line. In Plate 1, A and B, showing varves from Steep Rock, each side of the light layer has a definite boundary.

Rittenhouse (1934) conducted grain-size determinations on varved clays from the Wabigoon Valley about 80 miles from Steep Rock Lake. The grain sizes of varved clays from Wabigoon compare closely with those of Steep Rock (Legget and Bartley, 1953, fig. 13).

Thixotropy.—Thixotropy is defined as a reversible gel-sol-gel transformation in certain materials brought about by a mechanical disturbance followed by a period of rest. The word means "change by touch" and hence, since soil particles are solid materials, thixotropy applied to soils involves soil structure.

PLATE 1

A. Two samples of varved clay from Steep Rock Lake. Specimen on the left, $\theta = 30^\circ$, failed along the light layer. Specimen on the right, $\theta = 60^\circ$, failed through both dark and light layers. (Scale in inches.)

B. Typical sample of varved clay from Steep Rock Lake (Scale on right in inches).

According to Green and Weltmann (1946) thixotropy cannot exist without flocculation but the converse is not necessarily true.

The term thixotropy, as used in this paper, includes the state of "false body" as defined by Pryce-Jones (1948) as the two terms are so closely allied, and thixotropy has been used by many writers to cover both true thixotropy and false body.

Tests to determine the degree of thixotropy of soils are difficult to relate to field conditions. The laboratory investigation was directed toward merely proving the existence of a thixotropic state. The procedure followed was according to Ackermann (1948) and yields a result expressed in terms of water content called the "stiffening limit." This method is as follows. A small amount of soil is mixed with distilled water in a test tube. Sufficient water is added in small increments and thoroughly mixed until the point is reached when the soil paste will begin to flow when the test tube is inverted after a one-minute rest. The water content corresponding to this condition is termed the stiffening limit.

Again, a striking difference between the light and dark layers is revealed in their stiffening limits. Table 1 gives values obtained for sample 2-123 and may be compared with figure 4.

TABLE 1
Water Content Relationships for Sample 2-123
(in % oven-dry weight)

Sample no.	Type of material	Natural water content	Liquid limit	Plastic limit	Plasticity index	Stiffening limit
2-123-4	light (summer)	25.1	23.1	19.3	3.8	—
2-123-2	light (summer)	23.6	23.0	20.0	3.0	44.1
2-123-3	dark (winter)	69.5	63.8	25.5	38.3	165.8
2-123-4	dark (winter)	77.8	73.7	27.5	46.2	215.0
2-123-5	dark (winter)	84.6	84.1	29.3	54.8	211.0
2-123-6	dark (winter)	89.3	88.9	30.6	58.3	218.3
2-123-7	dark (winter)	90.2	88.8	31.4	57.4	201.0
2-123-8	dark (winter)	91.2	92.4	31.6	60.8	193.2
2-123-9	dark (winter)	92.8	93.7	30.2	63.5	198.8
2-123-10	dark (winter)	93.8	95.2	33.4	61.8	214.2
2-123-11	dark (winter)	92.5	91.9	34.0	57.9	209.4
2-123-12	dark (winter)	79.3	64.0	23.9	40.1	—
2-123-13	light (summer)	27.9	26.9	21.7	5.2	48.3
2-123-14	light (summer)	23.5	25.5	20.1	5.4	49.1

Other test results showed the same difference between dark and light layers. A few samples of the Steep Rock varved clay were tested by Boswell (1951) using a slightly different test. He reports values of 65 for the light layers and 120 for the dark layers. All the thixotropic tests show that both the light and dark layers of the varved clay are thixotropic, and hence must be in a flocculated condition.

Mineral analysis.—The mineral components of the varved clays were determined qualitatively by the techniques of differential thermal analysis

and X-ray diffraction. This work was done by the Crystal Chemistry Section of the Department of Mines and Technical Surveys, Ottawa, and revealed the following components for the light layers: quartz, carbonates, feldspar, clay (small amount), organic matter (trace); dark layers: quartz, feldspar, clay, probably montmorillonite, more than light layers, organic matter (small amount, slightly more than light layers).

The above analysis is borne out by the "Activity Chart," figure 2. Both the light and dark layers plot as "inactive clays," with the dark material displaying more activity than the light. This can be attributed to the relatively greater quantity of clay in the dark layers. Normally montmorillonite clay is considered to be an "active clay," but it plots as an "inactive clay" because of the masking effect of the quartz and feldspar mixed with the clay.

The mineral analysis reveals two important differences in the mineral characteristics of the dark and light layers. One is the relative amounts of true clay minerals, and the second is the fact that the light layers contain carbonates but that the dark layers do not.

Shear strength.—A few tests were conducted to determine the effect that the varved structure had on shear strength. The techniques used were the unconfined compression test and the direct shear test. Procedures for both these tests are well established and are described in detail by Lambe (1951).

Fig. 7. Variation of unconfined compression strength with orientation of varves.

For the unconfined compression test, cylinders of undisturbed soil were trimmed, with due regard to the orientation of the varves, to a diameter of $1\frac{1}{2}$ inches and length of 3 inches. This cylinder was subjected to axial compression, with the stress at failure being termed the unconfined compression strength. The Mohr theory of rupture shows that the shear strength is equal to one-half the unconfined compression strength for most clays. The test results for two samples are presented in figure 7 by showing the variation in unconfined compression strength with orientation of the varves. The difference between the two curves can be explained by the relative amounts of dark and light material in the samples. The dark layers were approximately twice the thickness of the light layers in sample 2-62, whereas in sample 2-68 the reverse was the case.

When $\theta = 30^\circ$, failure took place entirely in the light layers as indicated in plate 1-A. Thus the value of unconfined compression strength at 30° represents nearly twice the shear strength of the light layers. The dark layers resisted deformation to a greater extent than the light layers. Because of this difference in stiffness, the departure of the curves for the two samples at $\theta = 0^\circ$ is actually the strength of the light material, and because the effective area resisting load is less than indicated by figure 7, the strength is slightly lower at $\theta = 30^\circ$.

Strength determinations on separate samples of dark and light material were conducted in the direct shear box. While this method of strength determination is not considered reliable for cohesive soils, it is considered that the relative strengths of the dark and light material are indicated. With the direct shear test, it was found that the dark layers had a shear strength of approximately 6 psi and the light layers of approximately 3 psi. These results compare reasonably well with shear strength derived from the unconfined compression tests.

It must be pointed out, that only two samples were tested for strength, and the above results must be regarded as preliminary. The results do indicate, however, that the varves have an influence on shear strength, and that the light and dark layers have radically different stress-strain characteristics. The dark layers, in spite of their loose structure and high plasticity and water content, appear to be much stiffer and have greater strength than the light layers.

Sensitivity.—Sensitivity is the term applied to describe the loss of strength in a clay when it is changed from the undisturbed to the remoulded state. Results from the unconfined compression test have been used as a criterion for sensitivity. The degree of sensitivity is defined as the ratio of undisturbed strength to the remoulded strength, at the same water content.

The light material, when remoulded at natural water content, did not have sufficient strength for a cylinder 3 inches long and $1\frac{1}{2}$ inches in diameter to stand by itself. The dark layers had an unconfined compression remoulded strength of approximately 1 psi or one-twelfth of that for the same material in the undisturbed state. Thus both the dark and light layers of the varved clay can be classified as extra-sensitive soils. (Skempton and Northey, 1952).

DISCUSSION OF TEST RESULTS WITH REGARD TO THEORIES ON VARVING

Before discussing the test results, it is necessary to review some of the theories on the formation of varved clays. The word "varved" implies a distinctly banded deposit. Thus a varve is usually defined in geological literature as material which can be definitely identified to have been deposited in one year, and is quite distinct from preceding or succeeding years. Baron Gerard de Geer, a Swedish geologist, first recognized the significance of these laminations and suggested the annual theory of deposition. Each varve consists of a couplet, a light-colored relatively coarse summer layer, and a darker-colored fine-grained winter fraction. Varved clays are usually associated with glacial lakes, and were formed during a time of retreat of a glacier. De Geer believed that during the summer when large volumes of melt water charged with glacial debris reached a lake or settling basin, the relatively large particles would settle out. In the winter, when the lake was covered with ice, and no further fresh material was supplied, the fine-grained material carried in suspension was given sufficient time to precipitate. Thus a varved couplet was formed each year.

Antevs (1951) has conducted a detailed study of the varved clays at Steep Rock and has written an account of the types of varves found and discussed their mode of formation. He discovered eight separate series of varved clays corresponding to eight different conditions of environment. As previously mentioned, Antevs believes the Steep Rock varves to be diatactic and lists seven conditions which affected the deposition of the Steep Rock clays. These seven conditions are as follows: (1) restriction of appreciable mud supply to the summer months; (2) fluctuation of mud influx and of the currents; (3) differential rate of settling of unequal grains and particles; (4) low temperature and accompanying high viscosity and density of the lake waters; (5) semistratification or isothermy of the lake water and oscillations between these states; (6) height of fall of the particles; and, (7) variations in the concentrations of the electrolytes. Antevs has covered the formation of the Steep Rock clays completely, and the results presented in this paper can only supplement particular aspects in Antevs' theory. Only on the point that the Steep Rock varves are diatactic, does the author disagree with Antevs. This is on the point that diatactic implies a gradation in particle size within the varve. Before developing the argument further, it is necessary to examine the condition necessary for the formation of diatactic varves as laid down by Fraser (1929).

Using a specially constructed tank in which the temperature of the water could be closely controlled, Fraser conducted experiments on the formation of varved clays, especially diatactic varves. From his experiments, Fraser concluded that the following conditions were necessary for the formation of varved clays:

- (a) The lake was one of quiet waters and had a practical absence of erosion;
- (b) The supply of material was not flocculated;
- (c) The lake waters contained a very low concentration of electrolytes.

Fraser's experiments led him to conclude that diatactic varves were formed subject to the restrictions that follow:

(i) During the melting season there would be a continuous supply of material, unflocculated and of assorted sizes. The coarser materials would settle relatively rapidly. Because of the cold water, the fine material would settle very slowly. The settling velocity would be a direct function of the temperature of the water and particle size. Because of the difference in settling velocities between coarse and fine material, the sediment would have a definite grading, with coarser material at the bottom of the varve and becoming progressively finer as the varve was built up;

(ii) At the close of the melting season, the supply of fresh material would dwindle to practically zero. Thus nearly all the coarser material would be deposited during the summer, and the division between the light and dark material would correspond approximately to the close of the melting season;

(iii) During the winter season, with no fresh supply of material the fine material would be partially aided by flocculation. This flocculation would result from an increased salinity because of the increase in the concentration of electrolytes supplied over the melting season. Fraser's experiments showed that flocculation would be retarded by the cold water. In any case the salinity could not increase to a point greater than one-fiftieth of normal sea water to permit varving. Fraser thought that this small degree of salinity would not affect the coarser particles sufficiently to cause flocculation, because the larger the particle, the more indifferent it is to flocculation;

(iv) The periodic supply of material thus outlined would continue on an annual cycle.

Considering the laboratory tests described in this paper, the results of the grain-size tests revealed no gradation of particle size within the laminae. This suggests that the Steep Rock varves are not diatactic. The water content tests show the clays to have a very loose structure, and because both the light and dark material exhibit thixotropy, it is thought that both the light and dark material were flocculated. Legget and Bartley (1953) in describing the hydraulic dredging carried out at part of the mining operations, point out that the soils, when redeposited in the lake waters, remain in particle assemblages, with a mean diameter of about 0.01 millimeters. This indicates that the soil particles have strong forces acting between them to cause this flocculation. The mineral analysis revealed that the light layers contained carbonates, although the dark layers were void of carbonates. This point is worth noting in the light of Burwash (1938) and Arrhenius (1947).

Burwash (1938) suggests that the change in the capacity of the lake waters for holding dissolved carbon dioxide and hence its capacity for dissolving calcium carbonate may be responsible for the deposition of varved clays. In the winter, with a relatively large concentration of carbonic acid, the lake waters are well equipped to maintain calcium carbonate in solution. In the spring, as the lake waters become warm, the carbonic acid is given up, leading to precipitation of the carbonates. This, Burwash believes, leads to the formation of calcite concretions in the light or summer layers. As reported

by Legget and Bartley (1953), concretions at Steep Rock are found only in the light layers of the varves.

Arrhenius (1947) in attempting to explain the causes for the great difference in color between the dark and light layers, found that the dark or winter material showed dissolution by carbonic acid on a far greater scale than the summer material. Arrhenius reported on varved marls which occur in Sweden, but in the opinion of the author this fact supports Burwash's theory.

By chemical analysis of three varved clays from Northern Manitoba and Toronto, Wallace also showed the light layers to contain more carbonates than the dark (Wallace, 1927, p. 111).

The difference in plasticity between the dark and light material may be due to three causes. First, the dark layers contain more clay minerals, which would increase plasticity. Secondly, the light material is slightly coarser, thus has less surface area, which would reduce its plasticity. A third cause could be different cation complex in the clays, brought about by changes in the depositional environment. Test results bear out the first two points but there is no proof for the third.

In conclusion, the test results presented in this paper indicate that both the dark and light layers of the varved clay at Steep Rock were affected by flocculation in their deposition. Grain-size results show that they cannot be termed diatactic as defined by Fraser (1929). Regarding their mode of formation, the results lend support to the theory put forward by Burwash.

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