Consolidation of Two Loessial Soils

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The open structure of loess can lead to large compressive deformations when the applied stresses exceed the strength of the clay binder. A laboratory investigation into the relation of the consolidation properties of undisturbed loess to water content, clay content, and density has been undertaken to explain the behavior. Hand-carved samples from two natural loess deposits in east-central Iowa were subjected to consolidation tests at water contents modified in the laboratory to provide a range from 4 to 32 percent. The natural densities and clay contents were 86 pcf and 19 percent for the first deposit and 91 pcf and 8 percent for the second. The concept of a critical water content (the water content above which the clay binder is stable) was found useful in interpreting behavior. The maximum pressure prior to the collapse of the structure increased with water contents below critical but was constant at higher water contents. At pressure levels below that causing collapse, a higher clay content reduced the compressibility; at higher pressures, the compressibility depended on the initial density.

•LARGE areas of the midwestern United States, including over half of Iowa and Nebraska, are covered with deposits of loess, a wind-deposited sediment of predominately silt-sized material. The term loess, as used in this paper, refers to the natural undisturbed soil, and it is the undisturbed structure that accounts for the special behavior that sets loess apart from other natural soils having the same constituents.

A typical midwestern loess has a clay content of 10 to 30 percent with the balance being composed of silt and fine sand. The clay occurs as particles, aggregates, or coatings on the silt particles. It has been observed (4, 6) that the silt-sized particles do not contact each other, but are separated by the clay coatings or the clay aggregates. As a result, the mechanical properties of the loess are determined primarily by the properties of the clay fraction.

The natural state of loess is normally very loose because of its open structure. The structure is maintained by the bond strength provided by the clay binder. If applied stresses exceed the binder strength, or if there is a loss in strength, the structure can collapse and large compressive deformations can occur. The primary cause for a loss in strength is the wetting and consequent swelling and softening of the clay binder (5). There are numerous cases reported in the literature where wetting of a loessial foundation soil contributed to unusual settlements of an otherwise stable foundation (2, 7).

As a result of the influence of water on the compressibility, the natural water content and possible variations are particularly important. For loess deposits in Iowa, Davidson and Sheeler (3) report natural water contents from 5 percent for soils with a 10 percent clay content to 30 percent for soils with 30 percent clay. The natural water content is also related to the average annual rainfall (7), and it may vary considerably with the seasons as well.

This investigation was undertaken to study the effect of water content on the compressibility of loessial soils having different clay contents and natural densities. One-

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Paper sponsored by Committee on Soil and Rock Properties and presented at the 48th Annual Meeting.

dimensional consolidation tests were run on samples from two loess deposits, designated as Hawkeye loess and Oakdale loess, located in the vicinity of Iowa City. The water contents of the samples were altered in the laboratory to provide a range which might be encountered naturally.

TABLE 1

SOIL INDEX PROPERTIES

Property	Hawkeye Loess	Oakdale Loess
(a) Whole Soil		
Liquid limit	35	27
Plastic limit	24	23
Plasticity index	11	4
Specific gravity	2.73	2.72
Percentage clay:		
Less than 0.005 mm	26	13
Less than 0.002 mm	19	8
Activity	1.10	0.84
Natural density, pcf:		
Range	85.0 to 89.3	90.4 to 92.5
Average	87	91
Natural water content, %:		
Range	23.2 to 27.0	21.2 to 22.9
Average	25	22
(b) Clay Fraction Less Than 0.002 mm		
Liquid limit	146	120
Plastic limit	46	39
Plasticity index	100	81
Percentage of clay:		
Less than 0. 002 mm	100	100

SOIL INDEX PROPERTIES

The loess in east-central Iowa has been identified as a Wisconsin-age, or Peorian, loess. The index properties are summarized in Table 1 and the grain-size distribution curves are shown in Figure 1. The liquid and plastic limits, specific gravity, and grain-size analyses were determined according to ASTM Designations D 423, D 424, D 854, and D 422, respectively (1). The ranges and average values for the natural dry density and natural water content of the test specimens are also given. The activity (11) has been calculated using the modified definition proposed by Seed, Woodward, and Lundgren (8):

$$A = \frac{\text{Change in plasticity index}}{\text{Corresponding change in clay content}}$$

in which A denotes the activity of the clay and the clay content is the percent finer than 0.002 mm. The plasticity index and clay content for the whole soil and the corresponding values for the 100 percent clay fraction were used in this calculation. To provide the latter values, samples of the 100 percent clay fraction with a particle size less than 0.002 mm were separated from the whole soil by decantation. The Atterberg limits for this material are also given in Table 1.

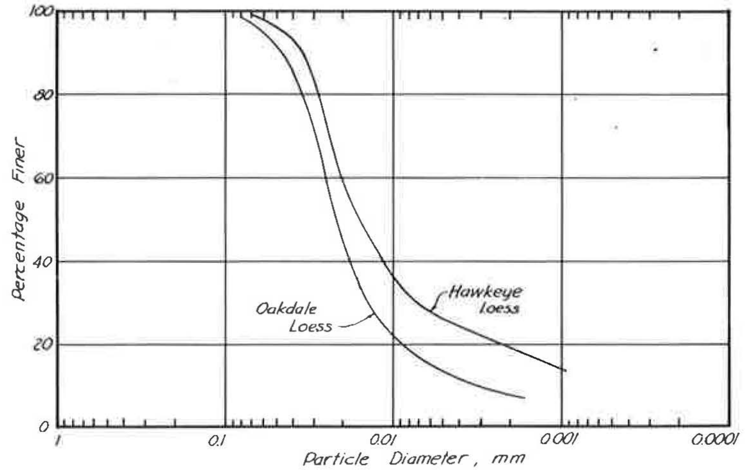

Figure 1. Grain-size distributions.

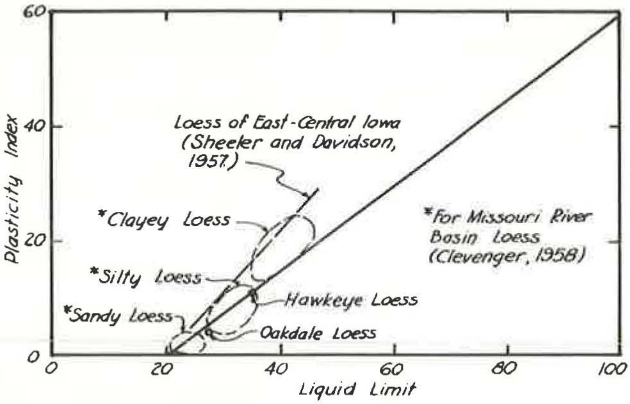

Figure 2. Plasticity chart comparing loessial soils.

A comparison of the plasticity properties of the Hawkeye and Oakdale loesses with other loessial soils is shown in Figure 2. The Hawkeye and Oakdale loesses plot at the upper and lower ends, respectively, of the "silty loess" zone which includes most of the Missouri River Basin loessial soil (2). The plasticity indices are somewhat lower than the average curve determined by Sheeler and Davidson (10) for this east-center portion of Iowa.

Periodic field water content measurements at the Hawkeye site were made to indicate the magnitude of seasonal variations in water content. The minimum and maximum natural water contents for the period October 1966 to September 1967 are shown in Figure 3. Below a 6-ft depth the water content varied between 26 and 33 percent; the corresponding range in degree of saturation is 75 to 90 percent.

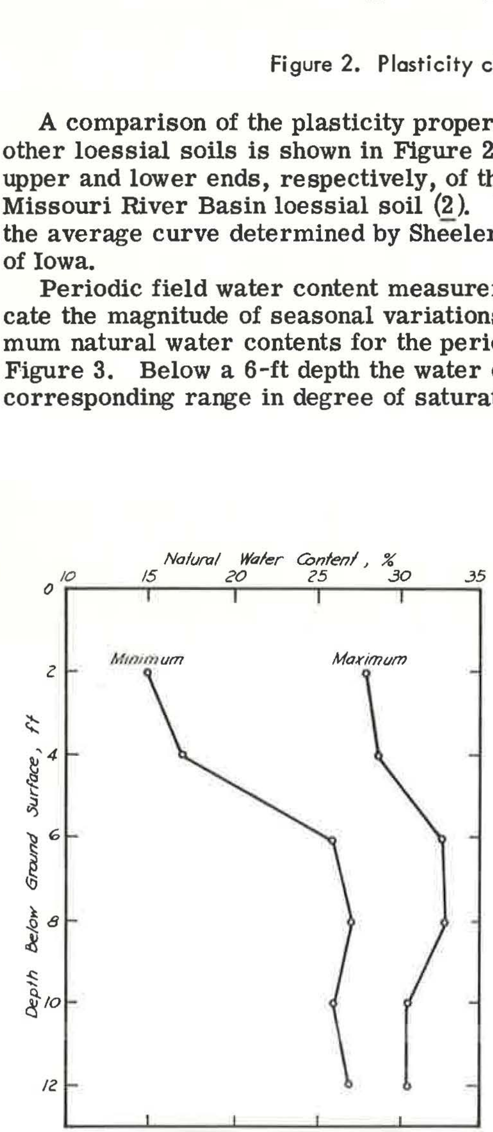

Figure 3. Range in natural water contents. Hawkeye site, Oct. 1966 to Sept. 1967.

SAMPLING AND SPECIMEN PREPARATION

Samples were obtained from a test pit at the Hawkeye site and from the side slope of a road cut at the Oakdale site. The procedure was to hand-carve blocks of soil measuring about 8 in. by 10 in. by 12 in. Three water content samples were taken from each block and the variation in these water contents from a single block was found to be from 1 to 3 percent.

After a block was removed, it was covered with a plastic bag, wrapped with moist rags, and then covered with another plastic bag. The block was placed in a cardboard carton and taken to the laboratory by car. The blocks were divided into smaller samples or, when necessary, stored in a moist room for a maximum of two days before subdividing.

The blocks were subdivided by scoring them with an ice pick. The portions were trimmed to the nominal dimensions of 2-in. thick by 4-in. diameter for the consolidation test specimens. Water content samples were again taken for a final check before the samples were sealed for storage.

Since the laboratory testing program lasted about 8 months, the samples had to be prepared for storage with great care. They were first wrapped in aluminum foil and then dipped several times into molten paraffin. They were placed in a plastic bag and the weight of the entire package was recorded to permit a check on moisture loss. Each sample was identified so that its original field location could be determined.

The samples were stored in a moist room until needed for testing. The weights of the wrapped samples were measured just prior to testing, and on the basis of these measurements and the earlier water content determinations, it was found that the total loss in water content between carving the block at the test pit and removing the sample from storage was less than 1 percent.

The testing program required specimens with their natural structure intact and with water contents throughout a range which might exist naturally over a period of time. For tests on the soil at its natural water content, specimens were carved directly from the stored samples. For all other tests, it was necessary to either reduce or increase the water content of the sample before trimming to test specimen size. The nominal test water contents were 8, 14, 20, 26, and 32 percent for the Hawkeye and 4, 10, 16, 22, 26, and 30 percent for the Oakdale loess.

The alteration of the water content was accomplished in the following manner. To achieve a water content of 32 percent, the sample as stored was unwrapped and wetted by spraying the surface with a measured quantity of water. The sample was rewrapped and placed in the moist room for several days to permit the dispersal of the water throughout the soil. This process was repeated until the water content of the sample, estimated from the sample's wet weight and its original weight and water content, was 32 percent. The sample was then trimmed into the consolidation ring for testing. The water contents of the specimen and the trimmings were compared to check the uniformity of water distribution in the sample; in all cases, the differences were less than 1 percent.

Water contents below the natural water content were achieved by permitting the surface of the sample to air-dry for several hours; the sample was weighed periodically to determine the weight of water evaporated. The sample was then stored to permit the remaining soil moisture to redistribute itself. This process was repeated until the desired water content was reached. It was found that air-drying the samples too rapidly produced cracks which required discarding the sample. The modified water contents were in general within 2 percent of the desired nominal water content.

The dry densities of the consolidation test specimens were calculated from their initial dimensions and oven-dry weights. Figure 4 plots these densities against the initial water contents to illustrate the effect of varying the water content on the density of the loess. For the Hawkeye loess, no significant change in density resulted from the increase in water content to 32 percent or the reduction to 20 percent. However, drying to water contents of 14 and 8 percent caused some shrinkage and an increase in density of 2 to 4 pcf. The density of the Oakdale loess was not changed by wetting or drying. Figure 4 also shows that the initial degrees of saturation of the specimens range from about 90 percent for the wet specimens to less than 20 percent for the dry specimens. At the natural water content the degree of saturation is from 65 to 75 percent.

TESTING PROCEDURE

A bench model consolidation test machine, having deadweight loading at a lever ratio of 10 to 1, was used to load the specimens. The consolidometer was the fixed-ring type, 2.5 in. in diameter and 0.75 in. in height, with a cutting edge to trim the specimen directly into the ring. A dial indicator reading 0.0001 in. was used to measure the compression of the specimen.

The specimen was trimmed directly into the consolidometer ring and weighed for initial water content. Filter paper circles were placed on the top and bottom faces, and the specimen and the ring were placed in the consolidometer. Except for the lowest water contents, the lower consolidometer stone, the loading cap stone, and the filter paper were moistened before being placed in contact with the soil. To prevent drying during the test, the top of the consolidometer was covered with polyethylene, sealed to the sides and around the loading cap. Moist sponges inside the consolidometer maintained a high humidity.

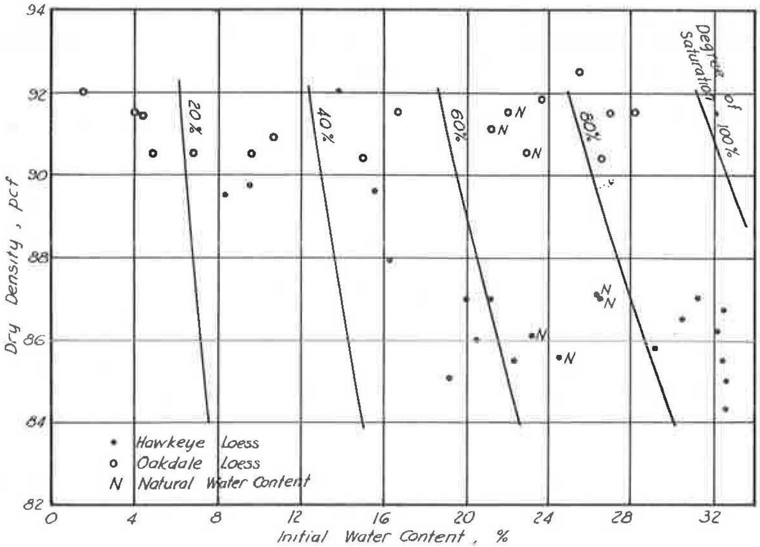

Figure 4. Water content and dry densities of test specimens.

The test specimen was loaded initially with a small seating load; the load was increased in increments from 0.25 tsf to 32 tsf. The conventional geometric progression of load increments was used. Each load increment was maintained for 24 hr in the case of the Oakdale loess and for 2 hr for the Hawkeye loess. The 2-hr duration was determined to be adequate on the basis of tests with longer durations.

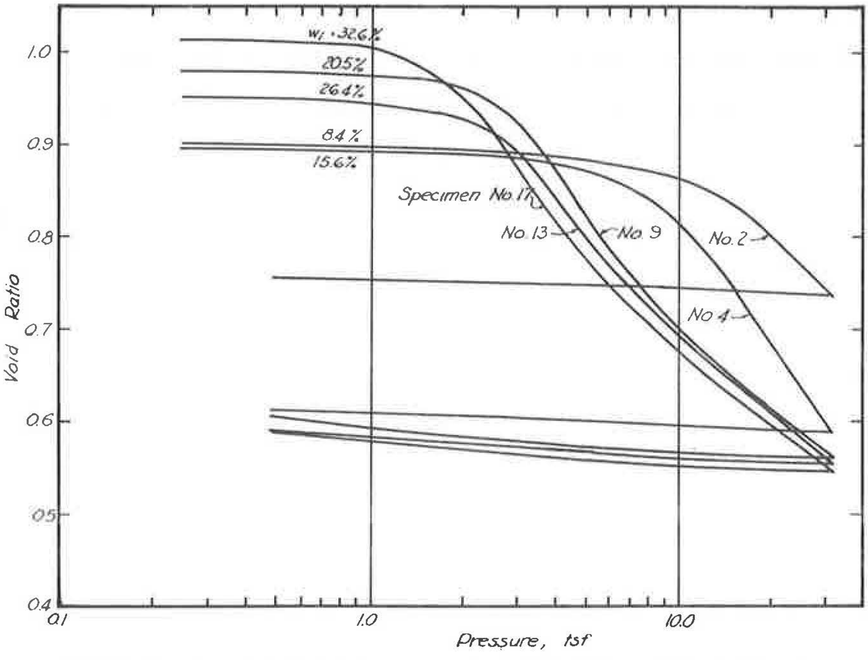

Figure 5. Typical void ratio-log pressure relationships, Hawkeye loess.

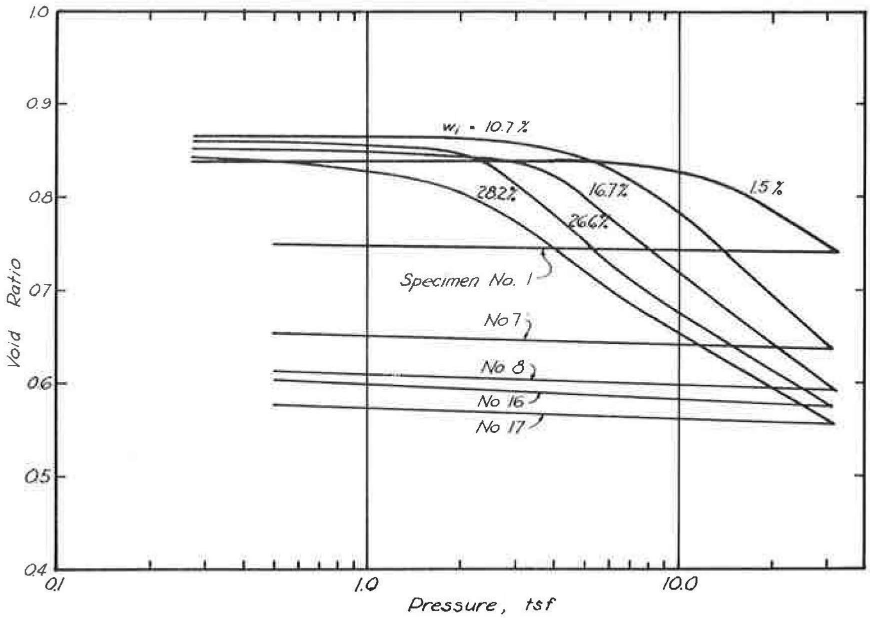

Figure 6. Typical void ratio-log pressure relationships, Oakdale loess.

Unloading was accomplished by removing load increments equal to three-fourths of the previous load until the pressure of 0.5 tsf was attained, whereupon all weights were removed. The specimen was then weighed and dried for the final water content determination.

TABLE 2

SUMMARY OF CONSOLIDATION TESTS ON HAWKEYE LOESS

Specimen No.	w_i	e_i	S_{ri}	p'_o	C'_c
Nominal water content = 8 percent					
1	9.6	0.895	29.3	9.4	–
2	8.4	0.895	25.4	10.8	–
Nominal water content = 14 percent					
3	16.3	0.938	47.2	4.6	0.469
4	15.6	0.895	47.6	7.5	0.486
5	13.9	0.849	44.5	11.0	0.483
Nominal water content = 20 percent					
6	19.2	0.998	52.5	1.6	0.406
7	22.4	0.987	62.0	2.1	0.435
8	21.2	0.958	60.4	2.4	0.399
9	20.5	0.978	57.2	2.4	0.466
10	20.0	0.952	57.4	2.1	0.402
Nominal water content = 26 percent					
11	26.5	0.957	75.7	1.6	0.372
12	23.2	0.971	65.0	1.9	0.389
13	26.4	0.952	76.0	2.1	0.379
14	24.6	0.987	67.7	1.4	0.332
Nominal water content = 32 percent					
15	29.2	0.987	80.6	1.5	0.359
16	31.3	0.957	89.4	1.7	0.362
17	32.6	1.018	87.3	1.4	0.432
18	32.6	1.002	89.0	1.5	0.402
19	32.2	0.972	90.3	1.9	0.372
20	32.4	0.987	89.5	1.7	0.386
21	30.5	0.962	86.3	1.8	0.395
22	32.5	0.962	92.0	1.4	0.346

TABLE 3

SUMMARY OF CONSOLIDATION TESTS ON OAKDALE LOESS

Specimen No.	w_i	e_i	S_{ri}	p'_o	C'_c
Air dry					
1	1.5	0.839	4.9	11.0	–
Nominal water content = 4 percent					
2	4.0	0.854	12.6	10.0	–
3	4.9	0.871	15.3	10.9	–
4	6.8	0.875	20.0	–	–
5	4.4	0.857	13.4	10.2	–
Nominal water content = 10 percent					
6	9.6	0.876	30.0	5.5	0.296
7	10.7	0.866	33.7	5.4	0.289
Nominal water content = 16 percent					
8	16.7	0.852	53.2	3.2	0.280
9	15.0	0.876	46.4	3.1	0.270
Nominal water content = 22 percent					
10	21.2	0.862	66.6	2.9	0.300
11	22.9	0.871	71.4	2.4	0.346
12	22.0	0.852	70.3	2.0	0.270
Nominal water content = 26 percent					
13	27.0	0.856	85.9	2.1	0.254
14	23.7	0.847	76.0	1.9	0.264
15	25.5	0.835	83.0	2.1	0.256
16	26.6	0.861	84.0	2.1	0.270
Nominal water content = 30 percent					
17	28.2	0.852	90.0	1.2	0.234

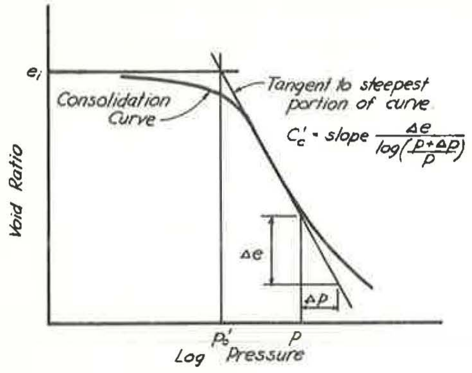

Figure 7. Definitions of parameters p_o' and C_c'.

TEST RESULTS AND DISCUSSION

Typical void ratio-log pressure relationships for each nominal water content are shown in Figures 5 and 6. The results of all the consolidation tests are summarized in Tables 2 and 3, in which the notation is as follows:

w_i = initial water content, percent;

e_i = initial void ratio;

S_{ri} = initial degree of saturation, percent;

p_o' = the pressure at the intersection on the void ratio-log pressure diagrams of the steepest slope of the consolidation curve and e_i, tsf; and

C_c' = the slope $\Delta e/\log\left(\frac{p + \Delta p}{p}\right)$ of the steepest portion of the consolidation curve.

The definitions of p_o' and C_c' are illustrated in Figure 7.

The consolidation curves for specimens at the lowest water contents did not develop a steep slope in the manner of the wetter and more compressible samples. Figure 5 shows the curve for Hawkeye specimen No. 2 which illustrates this point. If the test had been continued above the 32-tsf level of pressure, it is probable that the curve would appear similar to the others. Because the steep portion was not reached for these specimens, no C_c' values are listed in Tables 2 and 3 and the values given for p_o' are probable lower limits.

The variations of p_o' and C_c' with initial water content are shown in Figures 8 and 9, respectively. For Hawkeye loess (19 percent clay) the value of p_o' is essentially constant for water contents above 20 percent but increases sharply as the soil becomes drier than 20 percent. For the Oakdale loess (8 percent clay), the increase in p_o' occurs at a lower water content and is not as abrupt. A considerable scatter of C_c' values is shown in Figure 9, but there is a trend for C_c' to increase with a reduction in water content. A part, but not all, of the scatter is due to differences in initial void ratio;

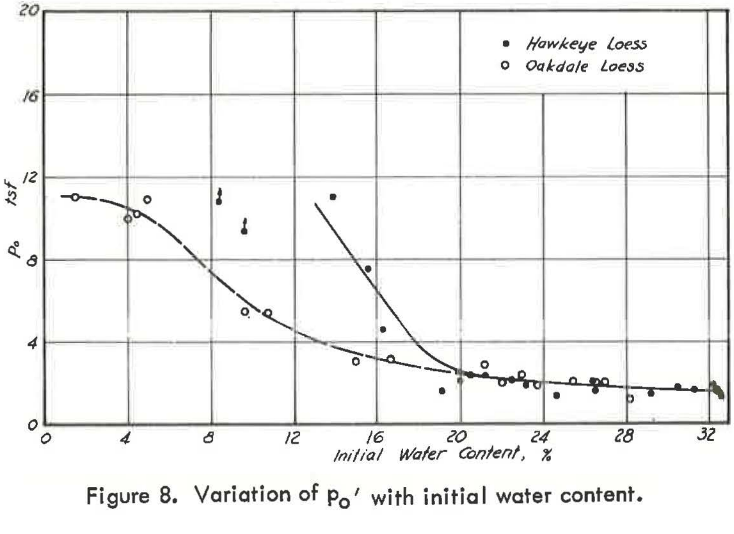

Figure 8. Variation of p_o' with initial water content.

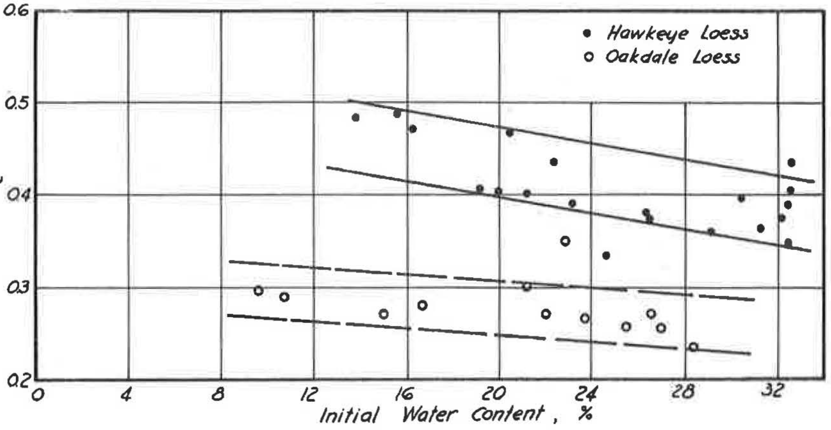

Figure 9. Variation of C_c' with initial water content.

that is, at a given water content, the specimens with higher void ratios have higher C_c' values in most cases. Although decreasing the water content increases p_o', C_c' also increases and thus the dry specimens are more compressible than the wet ones at pressures above p_o'.

A more detailed view of the consolidation behavior at any water content is shown in Figures 10 and 11 for Hawkeye and Oakdale loess, respectively. The compressive strain due to each consolidation pressure is plotted against the initial water content for each test. There is a very rapid change in behavior for the Hawkeye loess at initial water contents of 14 to 16 percent. The change for the Oakdale loess is more gradual and occurs over a range of initial water content from 4 to 16 percent or more. The Oakdale loess, even though denser, is more compressible than the Hawkeye loess at low water contents (for example, 8 percent). However, the reverse is true at high water contents (for example, 28 percent).

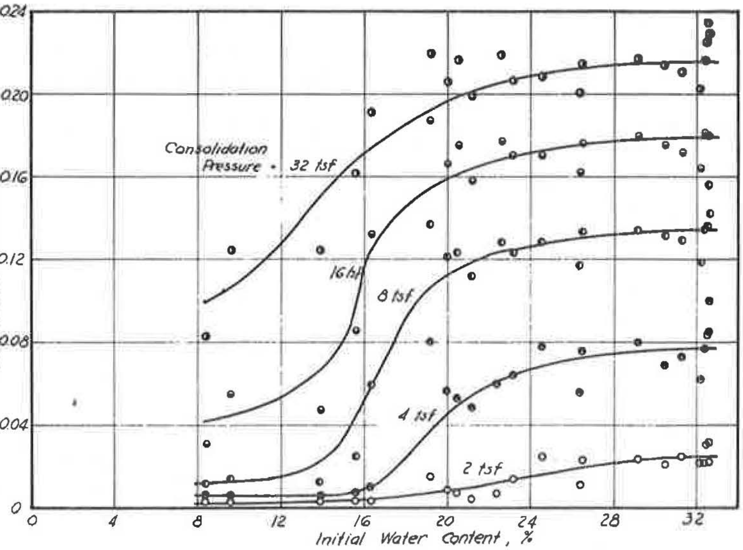

Figure 10. Compressive strain vs initial water content, Hawkeye loess.

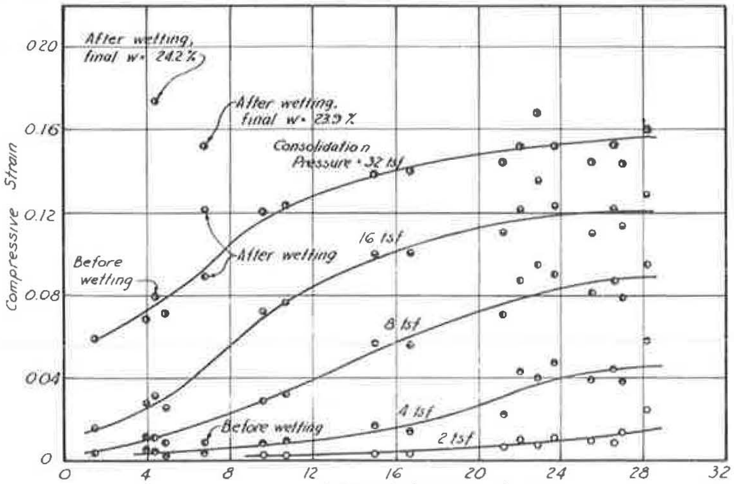

Figure 11. Compressive strain vs initial water content, Oakdale loess.

Figure 11 also shows the results obtained by wetting two samples of the Oakdale loess while under load in the consolidometer. The first (initial water content 4.4 percent) was wetted under the 32-tsf pressure; the second (initial water content 6.8 percent) was wetted under the 8-tsf pressure. The final water contents were 24.2 and 23.9 percent, respectively, and the strains after wetting are given (Fig. 11). These strains are essentially the same as those for specimens having water contents initially near 24 percent and the same consolidation pressures. This result (i.e., the same compression whether the loess is wetted before or after loading) is consistent with the conclusions of Holtz and Gibbs (5).

EXPLANATION OF BEHAVIOR

The test results provide a basis for explaining the effect of clay content, void ratio, and water content on the stress-strain relations of loess in one-dimensional consolidation. Although the two soils tested do not cover the full range of clay content and natural void ratio for all loessial soils, the results provide considerable insight that substantiates and refines present views of the behavior as summarized, for example, by Sheeler (9).

The open structure of loess is maintained by the clay coatings on the silt particles; thus the behavior of the soil prior to the breakdown of the structure (e.g., at pressures below p_o') depends on the percentage and strength of the clay binder. At a given clay content, the strength of the clay binder depends on the water content. The water is distributed in the voids of the clay coatings on the silt particles and, when sufficient water is present, in the silt-sized voids between the coated silt particles. If a loess with water in its silt-sized voids is dried, the clay binder will not be altered until the water in the silt-sized voids is first evaporated because of the greater capillary attraction of the binder. Further evaporation will cause shrinkage of the binder, which remains saturated until its shrinkage limit is reached. The strength of the binder increases as it shrinks, accounting for the increase in the value of p_o' in Figure 8 below a water content of about 16 percent. Above a water content of 20 percent, p_o' does not vary significantly because at these water contents, water occurs in the silt-sized voids and is at equilibrium with the water in the binder. Thus the binder is stable and neither swells nor shrinks with changes in water content above this level, which is referred to as the "critical water content" in the following discussion.

If loesses at the same water content are compared, the relative behavior in compression will depend on their initial void ratios and clay contents. When the water content is below the critical water content, the value of p_o' is significantly higher for the loess with the greater clay content (Fig. 8). At a given water content below the critical value, both loesses contain the same volume of water. Since the water is distributed in the clay-voids only, the soil with the greater clay content will have the stiffer binder and, consequently, the higher p_o' value.

For water contents greater than 20 percent both soils have essentially the same p_o value (Fig. 8), indicating that the influence of the clay percentage is small when the water content is greater than the critical value. In this comparison, the effect of the greater clay content of the Hawkeye loess is probably canceled by the effect of its lower density.

The compressive strains at pressures below p_o' (i.e., at pressures that do not cause a breakdown in structure) are also largely dependent on the clay content. For water contents below 16 percent, a smaller compression occurs for the Hawkeye loess than for the Oakdale loess in spite of the greater initial density of the latter (Figs. 10 and 11).

As the pressure approaches and exceeds p_o', the structure breaks down and the influence of the clay binder diminishes. This influence is also small above the critical water content, where the strength of the binder has diminished to a minimum level. Under these conditions, a loess with a low density will exhibit a greater compressibility than one with a higher density. This is demonstrated (Fig. 9) by the higher values of C_c' for Hawkeye loess (average density 87 pcf) in comparison with those for Oakdale loess (average density 91 pcf). A comparison of the compressive strains (Figs. 10 and 11) illustrates the same effect. For water contents above about 20 percent, all the consolidation pressures equal or exceed p_o', which is approximately 2 tsf (Fig. 8). The compressive strains at a given consolidation pressure are significantly greater for Hawkeye (Fig. 10) than for Oakdale loess (Fig. 11).

Critical water content was defined as the water content above which the binder is stable. It must be noted that the numerical value of this parameter is not well defined and its principal use at this stage of development is qualitative rather than quantitative. It is expected that the critical water content will prove to be a function of the percentage, mineralogy, and structure of the clay binder; these factors are only indirectly reflected in consolidation test results.

The field compression of a loess deposit is, of course, dependent on changes in the natural water content as well as loading changes. Unless the seasonal variations, such as those shown for the Hawkeye loess deposit (Fig. 3) are known, settlement estimates from consolidation test results will be uncertain. However, knowledge of the seasonal variation in water content and the variation in compressive strain with water content (as shown in Fig. 10 for the Hawkeye deposit) will provide a sound basis for a settlement analysis. For example, below the 6-ft depth in Figure 3, the natural water content ranges from 26 to 32 percent. Figure 10 indicates that the compression of the loess is relatively insensitive to variations in water content in this range. This is not the case at the shallower depth where the minimum water content is only 16 percent. For example, if the soil were loaded to 4 tsf while at a water content of 16 percent and subsequently the water content increased to 28 percent, the compressive strain would increase from 0.01 to 0.08 in accordance with the 4-tsf curve.

CONCLUSIONS

1. The concept of a critical water content is useful in interpreting the behavior of loess under compression.
2. For a given loess, p_o' is constant for water contents above the critical value, and p_o' increases for water contents below the critical value.
3. For a given water content below the critical value, p_o' increases with the percentage of clay.
4. For a given water content above the critical value, the influence of clay content on p_o' is small due to the low strength of binder.
5. For consolidation pressures below p_o', the greater the clay content, the smaller is the compressive strain, and density is of less importance than clay content.

6. For consolidation pressures above p_o', compressive strains and C_c' are greatest for low density loess, and clay content is of less importance than density.

ACKNOWLEDGMENT

The work presented in this paper was performed in the Department of Civil Engineering, University of Iowa, and was supported in part by the Iowa State Highway Commission and in part by a National Science Foundation grant.

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