Effect of Structure on Resilient Rebound Characteristic of Soils in The Piedmont Province of Virginia

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This paper reports the results of laboratory studies conducted to determine which of the Piedmont soils were more resilient and the cause of this resilience. This property has, in the past, led to the wasting of much of this material in highway construction work and has often caused fatigue type failures on pavements under which it has been placed.

Repeated-load triaxial tests on laboratory compacted sample were employed to determine the amount of elastic or resilient rebound for each soil. In general it was found that as the percent of the mineral mica increased the resilient rebound increased, but as the plasticity index of the soil increased the resiliency decreased. Soils from the C-horizon were more resilient than those from the B-horizon. For soils from the C-horizon the resiliency increased with increasing grain size.

Stereo-optical microscope studies of samples before and after repeated triaxial tests showed that soil structure played a major role in causing the resiliency in these soils. It was conclusively shown that soils with a disperse-like structure were much more resilient than those with a flocculant-like structure. Both soil structure and resiliency were influenced greatly by molding moisture content and method of compaction.

•FOR some time it has been known that certain fine-grained soils were more elastic than others and with the advent of repeated-load testing of soils, this has become even more apparent to those who have studied the effects of repeated loads on soils.

When a soil possessing elastic or resilient properties is used in such a manner that a load is first placed upon it and then removed, such as is the case of a soil beneath a highway pavement or airport runway, the resulting elastic or resilient effect can be quite detrimental to the pavements.

The soils in the Piedmont Province of Virginia are generally fine-grained, residual materials which often exhibit elastic properties. They have been formed from a complex system of underlying igneous and metamorphic rocks and are often quite deep, exceeding 100 ft in certain areas. Quite often these soils contain an appreciable percentage of mica flakes.

Recent laboratory studies (1, 2) conducted to determine the effect of repeated axial loading on the strength and deformation characteristics of fine-grained soils revealed the marked elastic qualities of the Piedmont soils. As a result of these studies it was

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believed that soil structure (i.e., the arrangement of soil particles and the electrical forces acting between adjacent particles which influence this arrangement) was primarily responsible for this elastic quality.

The arrangement of fine-grained soil particles generally falls into two main categories, flocculated and dispersed—called cardhouse and oriented by some investigators (3). In the flocculated arrangement, the particles tend to bond themselves in an edge-to-surface type of orientation. This is generally thought to be caused by the electrical charges on the surfaces and edges of each particle. In the dispersed arrangement, Lambe (4) notes that the particles lay more generally parallel, with very little surface-to-edge bond.

Figure 1 is the result of a rather extensive investigation by Lambe (5)into the structure of compacted clay.

At point A the presence of a small amount of water results in a high concentration of electrolyte which prevents the diffuse double layer of ions surrounding each particle from developing fully. The double layer depression leads to low interparticle repulsion, resulting in a tendency towards flocculation of the colloids and a consequent low degree of clay particle orientation in the compacted soil. This type of structure is a flocculated arrangement of soil particles. If the water content is increased to point B, the electrolyte concentration is reduced, resulting in an expansion of the double layer, increased repulsion between particles and a low degree of flocculation, that is, an increased degree of particle orientation. Further increase in water content at point C increases this effect and results in a still greater particle orientation.

A system of parallel particles, which is approached at point C, represents the dispersed type of particle arrangement. Thus, in general, it may be stated that compaction of a clay soil "dry of optimum" tends to produce a flocculated arrangement of particles, while compaction of the same soil "wet of optimum" tends to produce a dispersed structure.

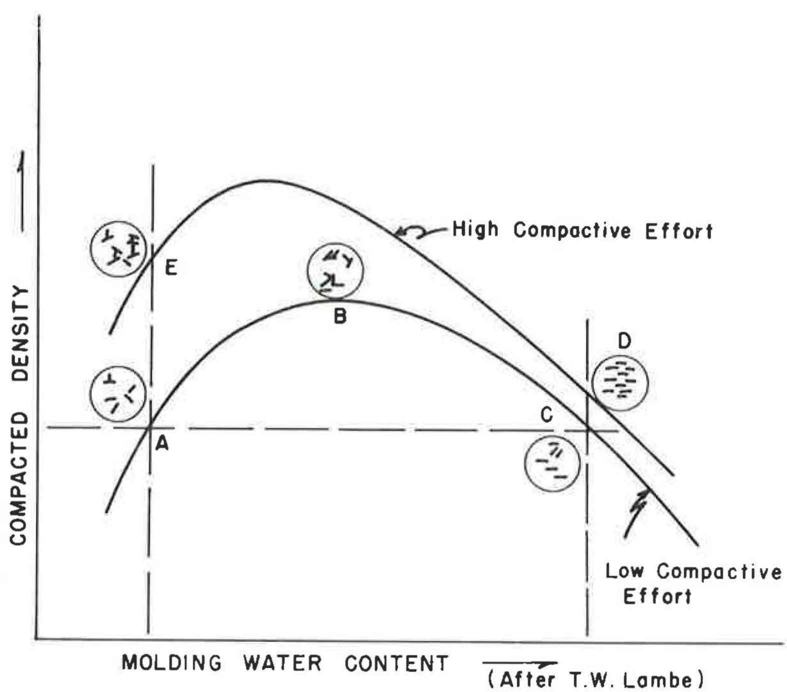

Figure 1. Effect of compactive effort, density, and molding water content on the structure of compacted clays as found by Lambe (4).

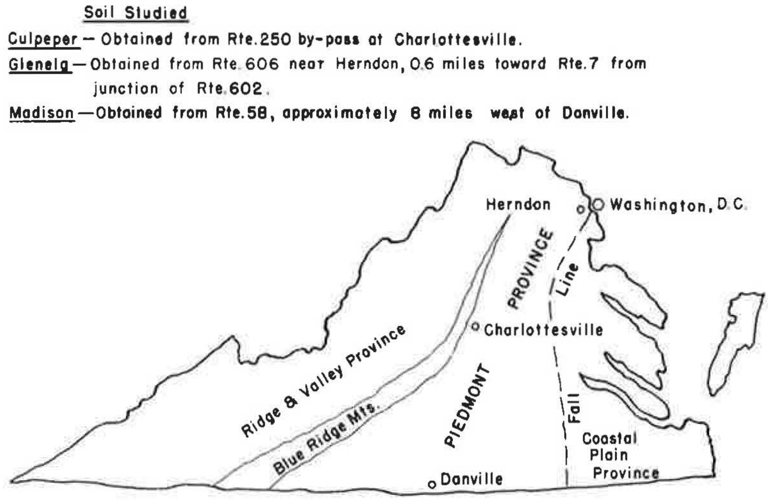

Figure 2. Sites where soil samples were taken.

TABLE 1

INDEX PROPERTIES AND MINERALOGICAL DATA

Characteristic	Culpeper B-Horizon	Culpeper C-Horizon	Glenelg C-Horizon	Glenelg B-Horizon	Madison B-Horizon	Madison C-Horizon
Specific gravity	2.78	2.74	2.76	2.74	2.77	2.86
Atterberg limits:						
Liquid limit	47.0	32.0	47.0	35.4	63.7	42.5
Plastic limit	39.0	31.5	33.0	27.0	42.4	37.0
Plasticity index	8.0	0.5	14.0	8.4	21.3	5.5
Shrinkage limit	34.0	28.5	30.7	24.5	39.0	48.0
Standard AASHO compaction:						
Optimum moisture content, %	26.5	18.5	22.0	21.2	28.5	18.0
Max. dry unit weight, pcf	93.0	99.4	101.6	98.5	94.0	106.3
Mineralogical composition[a]:						
Kaolinite	33	15	25	25	50	30
Quartz	33	42	45	45	15	10
Mica	33	42	30	30	25	60
Goethite	minor	minor	minor	minor	minor	minor
Hematite	minor	minor	minor	minor	minor	minor
Gibbsite	minor	—	—	—	10	minor
Illite-vermiculite	minor	minor	minor	minor	minor	minor
Order of relative elasticity	(1.40) 5	(7.20) 2	(3.80) 4	(6.40) 3	(1.00) 6	(9.20) 1
Unified classification	ML	ML	ML	ML	MH	ML
AASHO classification	A-2-7	A-2-4	A-4	A-4	A-1-b	A-1-b

[a]Approximate percent of total soil.

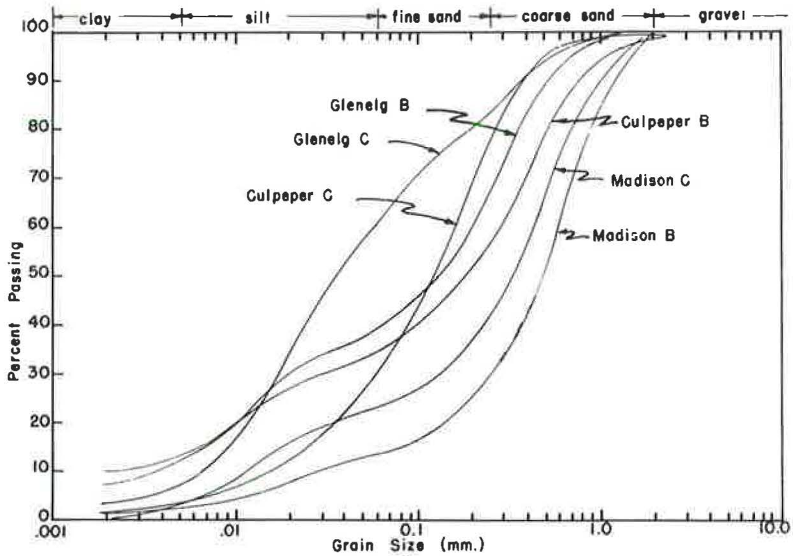

Figure 3. Gradation curves.

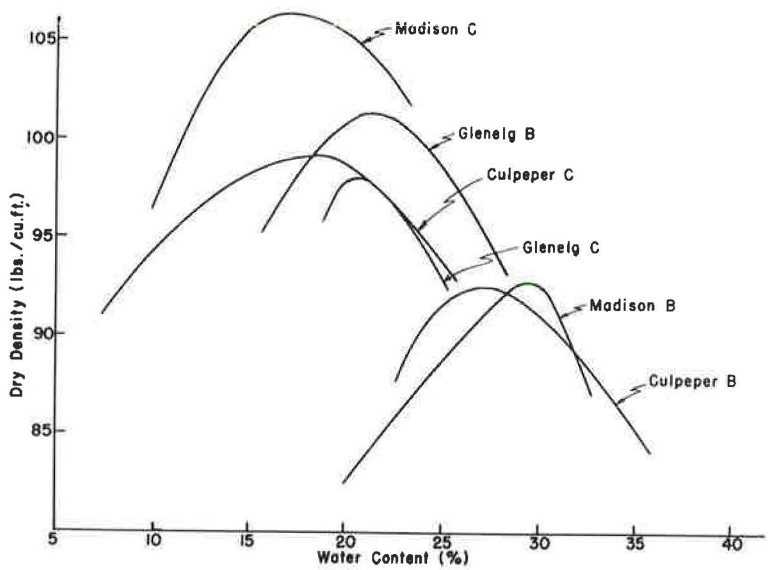

Figure 4. Standard compaction curves.

More recent studies by Pacey (6), using optical techniques developed by Mitchell (7), and studies by Seed and Chan (8) tend to support Lambe's concept of structure of compacted clay.

The purpose of the study described in this paper was to determine which of the Piedmont soils was more elastic and why it was more elastic. Since soil structure was believed to be an important contributing factor, this aspect was given special attention.

SOIL STUDIED

To locate the most elastic soils in the Piedmont Province of Virginia, three sites were chosen with the aid and advice of materials engineers of the Virginia Department of Highways. Both disturbed and undisturbed samples were obtained from the B- and C-horizons at each site. In each case, the soil was known to be highly elastic and to have given trouble on highway construction projects. Figure 2 shows the locations from which the soils were obtained. Characterization tests and mineralogical studies were conducted and the results are given in Table 1.

The soil obtained from near Herndon was a Glenelg (pedological classification) soil which consisted largely of mica, quartz and kaolinite. The soil taken from the Charlottesville site was a Culpeper soil and its mineralogical content was quite similar to the Glenelg soil. The soil secured from near Danville was a Madison soil. Its mineralogical content was nearly the same as the other two, except that a larger quantity of mica was present in the C-horizon.

Table 1 also gives the relative elastic rebound classification of each soil as obtained from repeated load tests upon compacted samples.

Grain size distribution curves and comparative standard compaction curves are plotted for each soil (Figs. 3 and 4).

APPARATUS AND PROCEDURE

Tests were first performed on compacted samples from both the B- and C-horizons of the three soils to determine the relative order of elasticity of each. A statically compacted cake of each of the six soils was prepared at or near the optimum moisture content and maximum dry density. Each cake was cut into four samples and one sample from each cake was tested to failure under the action of a gradually applied, axial load in a triaxial device. Stress-strain curves for the six soils resulting from these conventional triaxial tests showed that their ultimate strengths were quite similar at their respective optimum moisture contents and dry densities. Because this was true, a level of repeated deviator stress $\Delta\sigma_r$ to the deviator stress causing failure on the conventional triaxial test $\Delta\sigma_s$ was approximately equal for each of the soils. A ratio of $\Delta\sigma_r/\Delta_s$ was chosen and loads producing this ratio were applied to samples of the statically compacted soil in a repeated-load triaxial device, described elsewhere by Larew and Leonards (1). The confining pressure employed in all cases was 10 psi.

Under the levels of repeated deviator stress employed, the resilient rebound of each sample reached a constant or equilibrium value after not more than a few thousand load applications. This value of equilibrium elastic rebound was recorded for each soil, and the soil with the least resilient rebound was found to be the Madison soil from the B-horizon. Using the equilibrium elastic rebound of this soil as a standard of reference (unity as given in parentheses in Table 1), each soil's relative resiliency was calculated (also given in parentheses in Table 1). Each soil was then given a rating from 1 to 6 with the Madison C-horizon soil, which was the most resilient, receiving the number 1 rating. This soil was chosen for the more extensive program of studies.

A series of soil cakes 4.0 in. in diameter and 4.6 in. high was prepared from the Madison C soil on the dry side, near and on the wet side of optimum moisture content by both static and dynamic methods. The dynamically compacted samples were prepared in a Proctor compaction mold by Proctor compaction procedures. Soil cakes were compacted statically in the same manner as reported by Larew and Leonards (1), except that a standard Proctor mold, with aluminum plugs to fit into the ends, was used. The cakes were compacted at approximately the same moisture contents as those compacted dynamically.

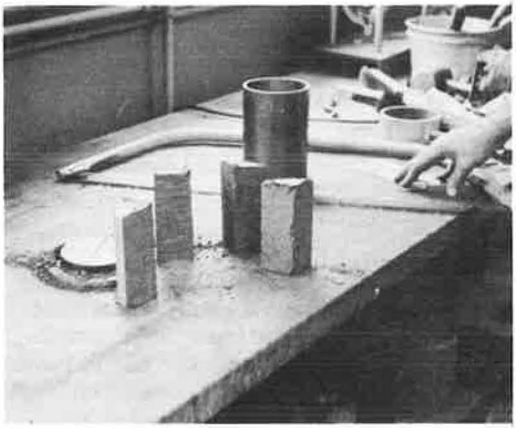

Figure 5. Four vertically cut samples from a compacted soil cake.

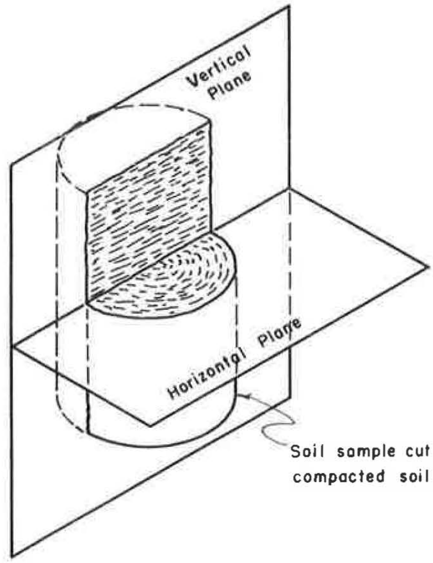

Figure 6. Soil sample cut by horizontal and vertical planes, indicating cross-sections studied under stereomicroscope.

Cakes prepared at these three moisture content levels were extruded from the mold, cut into four samples each, waxed and stored for later testing. Figure 5 shows four samples which were cut from the 4.0-in. diameter mold prior to waxing. These samples were later trimmed to specimens which were 2.8 in. high and 1.4 in. in diameter and then subjected to both static and repeated-load triaxial tests.

The static triaxial compression tests were performed on one sample from each soil cake. The sample was enclosed in a thin, rubber membrane and no confining pressure was used during the tests. The results were used to obtain the compressive strength of a sample from each cake.

Each repeated-load triaxial sample was enclosed in 2 thin rubber membranes. The chamber around the sample was filled approximately one-half full of water to prevent the sample from drying during the test. Except for the very small amount of hydrostatic pressure developed by the water in the chamber, no confining pressure was applied to the sample. Sample drainage was prevented in both static and repeated load tests.

In each case the load applied by the repeated load device was 0.9 of the axial load causing failure in a static test on an identical sample, i.e., $\Delta\sigma_r/\Delta\sigma_s = 0.9$. The rate of loading was essentially constant at 20 cpm. The elastic rebound was observed for approximately 100,000 load applications and the equilibrium elastic rebound reached during each test was recorded. None of the samples failed during the 100,000 load applications.

The structure on both horizontal and vertical surfaces through the samples were studied under the stereomicroscope and photographed before and after testing. The direction of these surfaces in a sample is sketched in Figure 6. Pairs of stereophotographs were taken through the lens of the stereomicroscope with a Polaroid Land camera. Careful observations and notes were kept concerning observed particle orientation and structural features for each sample as it was being studied under the microscope. These recorded observations and the stereophotographs formed the basis for conclusions concerning the effects of soil structure.

Inasmuch as the original tests were performed on vertically cut samples from a compacted cake (Fig. 7), it was decided that similar tests should be performed on samples with identical water content and compacted density, but cut horizontally from a compacted cake (Fig. 8). These tests were performed on those soils and for those moisture contents, densities and methods of compaction that produced both the greatest and least amount of elastic rebound in the earlier tests on vertically cut samples. The

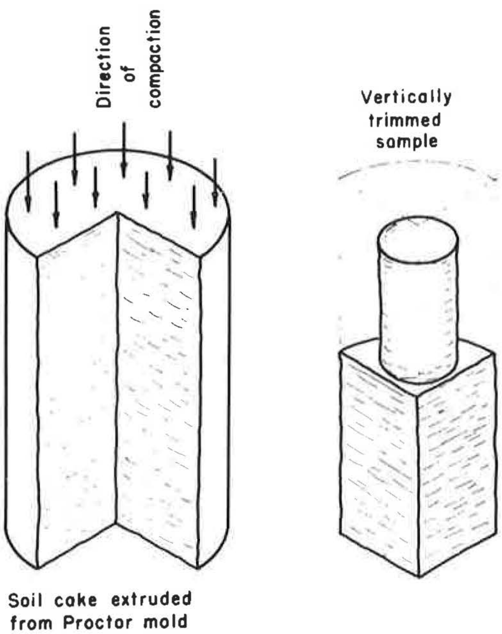

Figure 7. Orientation of sample to be tested vertically.

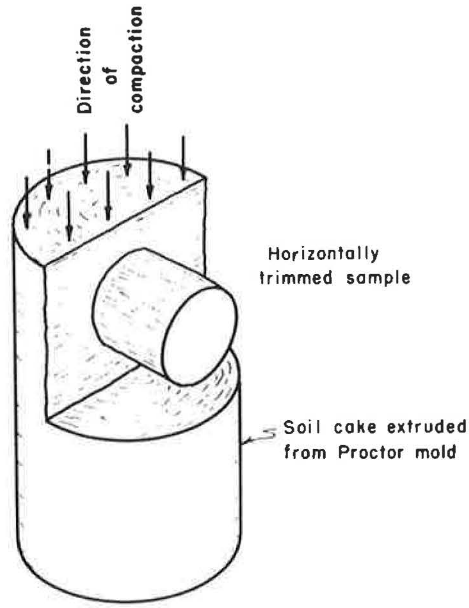

Figure 8. Orientation of sample to be tested horizontally.

procedures for repeated-load triaxial testing and observations were identical to those followed for the vertically cut samples.

RESULTS

Table 1 and Figures 3 and 4 show the index properties, mineralogical data, grain-size distribution curves and compaction curves for each of the six soils studied in the preliminary investigation. The order of their relative elasticity is given in Table 1. The Madison C soil exhibited the greatest amount of elastic rebound in the preliminary tests and was chosen for the later and more extensive studies.

Tables 2, 3, 4 and 5 and Figures 9 and 10 show the results of the repeated load tests performed in the study of this soil. Figure 10 shows that for vertically cut samples, a rather decided difference in the elastic rebound was obtained between the two methods of compaction employed. The statically compacted samples were the more elastic; the dynamically compacted samples were the least elastic. Moreover, the elastic rebound was, for both methods of compaction, quite sensitive to moisture content of the compacted samples, being maximum in both cases at or near optimum moisture content. From the test data and the microscopic study and observations, it was rather obvious that the orientation of the mica flakes in the compacted cakes was responsible for this difference in elastic rebound. Figures 11 and 12 are sketches of the postulated and observed particle arrangements in both statically and dynamically compacted samples. Figures 13, 14, 15 and 16 are stereophotographs that show the presence or absence of particle orientation in a few selected but typical samples.

The Madison C soil with the largest percentage of mica exhibited the greatest rebound. Tests on vertically and horizontally cut samples showed that this occurred when the particle arrangement was primarily normal to the direction of loading and least when the arrangement of particles was parallel to the direction of loading. It was rather obvious that a beam or plate-like deformation of particles was causing the elastic rebound. One can observe this action with the stereomicroscope by loading and unloading pure dry mica which has been placed in a glass container. When a load

TABLE 2

VERTICALLY CUT SAMPLES OF MADISON C SOIL COMPACTED ON DRY SIDE OF OPTIMUM[a]

Sample	Initial Water Content (%)	Compacted Dry Density (pcf)	Dry Density During Test (pcf)	Loss in Density (pcf)	Equilibrium Rebound (in. × 10^{-3})	Equilibrium Rebound (% of init. height)
(a) Dynamic or Impact Compaction						
1	13.93	102.69	95.53	7.16	20.0	0.75
1	15.69	101.13	95.55	5.58	21.5	0.76
3	15.39	101.40	95.84	5.56	22.5	0.80
Avg.	15.00	101.74	95.64	6.10	21.3	0.77
(b) Static Compaction						
1	14.77	107.38	91.87	15.51	28.2	1.00
2	14.99	107.17	92.56	14.61	26.0	0.92
3	15.04	110.18	99.25	10.93	22.0	0.78
4	15.18	110.05	100.00	10.05	22.5	0.80
Avg.[b]	15.00	108.59	95.65	12.94	24.5	0.87

[a]Subjected to 100,000 repeated load applications.
[b]Average interpolated from varying density.

TABLE 3

VERTICALLY CUT SAMPLES OF MADISON C SOIL COMPACTED NEAR OPTIMUM[a]

Sample	Initial Water Content (%)	Compacted Dry Density (pcf)	Dry Density During Test (pcf)	Loss in Density (pcf)	Equilibrium Rebound (in. × 10^{-3})	Equilibrium Rebound (% of init. height)
(a) Dynamic or Impact Compaction						
1	18.55	105.53	98.73	6.80	23.0	0.80
2	18.34	105.71	99.60	6.11	25.0	0.88
3	18.35	105.70	99.34	6.36	21.3	0.75
4	17.21	106.73	99.98	6.75	21.0	0.74
Avg.	18.11	105.92	99.41	6.51	22.6	0.79
(b) Static Compaction						
1	18.20	111.48	99.09	12.39	30.5	1.08
2	18.48	111.21	97.58	13.63	28.5	1.01
3	17.70	111.95	99.18	12.77	27.0	0.96
4	17.85	111.81	99.11	12.70	28.4	1.01
Avg.	18.06	111.61	98.74	12.87	28.6	1.02

[a]Subjected to 100,000 repeated load applications.

TABLE 4

VERTICALLY CUT SAMPLES OF MADISON C SOIL COMPACTED ON THE WET SIDE OF OPTIMUM[a]

Sample	Initial Water Content (%)	Compacted Dry Density (pcf)	Dry Density During Test (pcf)	Loss in Density (pcf)	Equilibrium Rebound (in. $\times 10^{-3}$)	Equilibrium Rebound (% of init. height)
(a) Dynamic or Impact Compaction						
1	20.40	104.90	100.30	4.60	23.0	0.82
2	20.67	104.67	99.63	5.04	18.5	0.66
3	20.92	104.45	100.41	4.04	18.0	0.64
4	21.24	104.17	100.08	4.09	22.6	0.80
Avg.	20.81	104.55	100.11	4.44	20.5	0.73
(b) Static Compaction						
1	19.76	111.35	100.85	10.50	23.0	0.81
2	20.33	110.82	99.39	11.43	26.0	0.93
3	20.46	110.70	99.10	11.60	27.0	0.96
Avg.	20.18	110.96	99.78	11.18	25.3	0.90

[a]Subjected to 100,000 repeated load applications.

TABLE 5

HORIZONTALLY CUT SAMPLES OF MADISON C SOIL[a]

Sample	Initial Water Content (%)	Dry Density During Test (pcf)	Equilibrium Rebound (in. $\times 10^{-3}$)	Equilibrium Rebound (% of init. height)
(a) Dynamic or Impact Compaction (Wet of Optimum)				
1	21.0	100.9	9.5	0.34
2	21.1	100.2	11.0	0.39
3	21.7	100.9	10.0	0.36
Avg.	21.3	100.7	10.2	0.36
(b) Static Compaction (Near Optimum)				
1	18.1	99.7	9.0	0.32
2	18.2	101.8	6.0	0.21
3	18.6	99.7	7.7	0.27
4	18.1	101.2	7.0	0.25
Avg.	18.5	100.6	7.4	0.26

[a]Subjected to 100,000 repeated load applications.

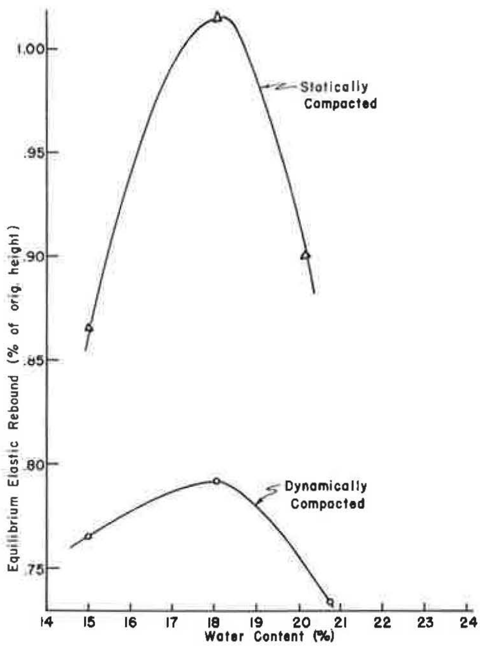

Figure 9. Equilibrium elastic rebound vs water content for all Madison C soil samples tested vertically.

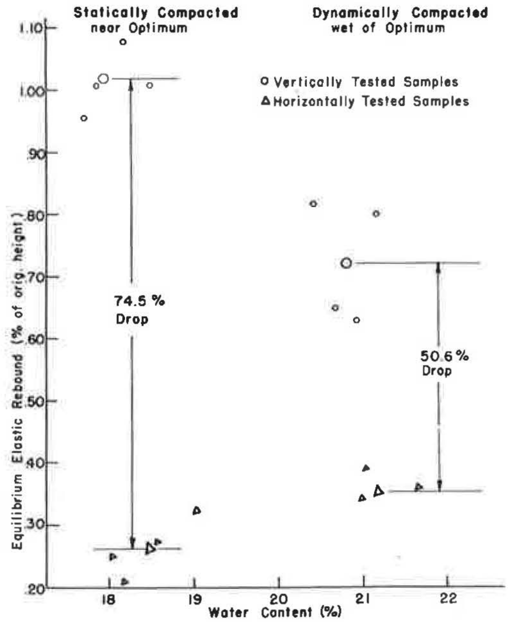

Figure 10. Comparison of elastic rebound for Madison C soil when subjected to repeated loading in vertically and horizontally cut samples.

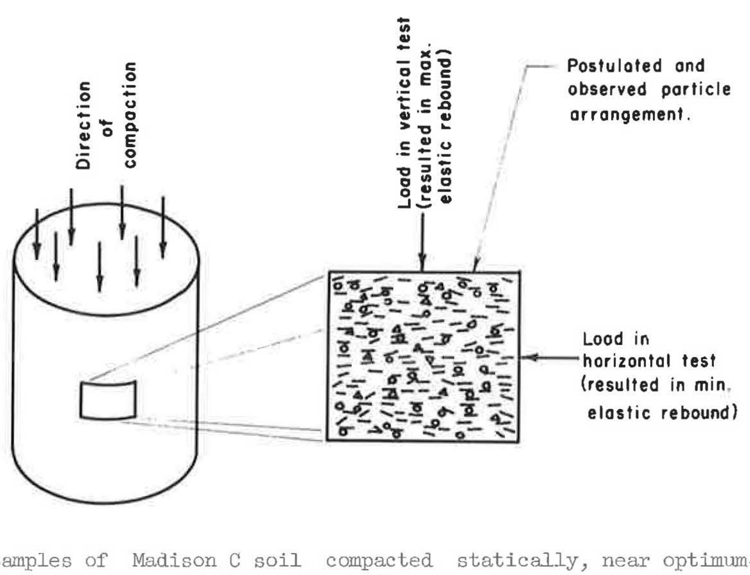

Figure 11. Samples of Madison C soil compacted statically, near optimum— postulated and observed particle arrangement.

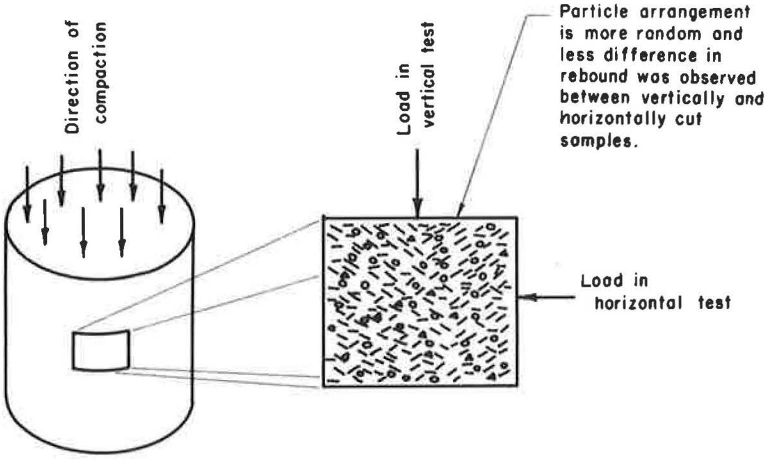

Figure 12. Samples of Madison C soil compacted dynamically, wet of optimum—postulated and observed particle arrangement.

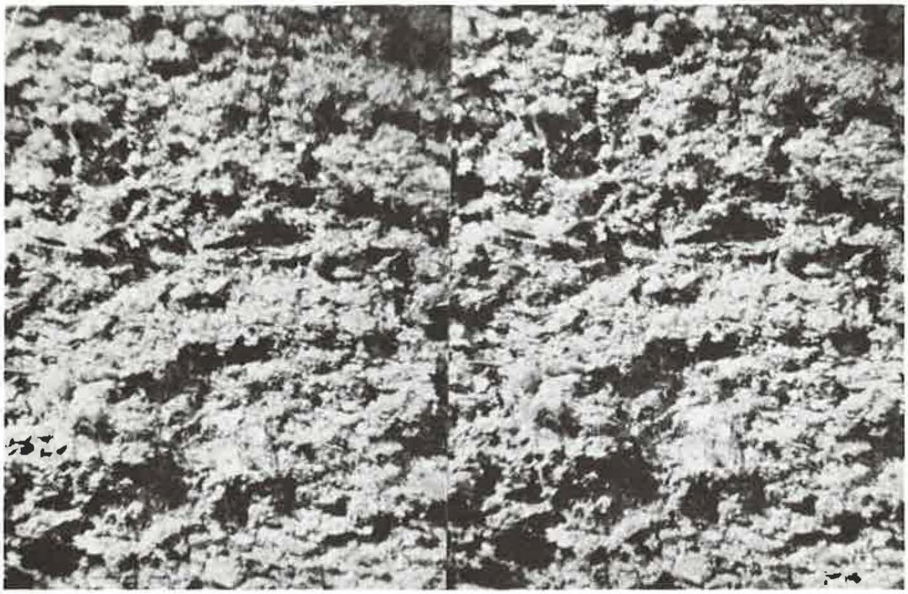

Figure 13. Stereophotograph of vertical section of Madison C soil compacted statically near optimum. Magnification is x 10. Structure is quite stratified and orientation of mica flakes is generally horizontal.

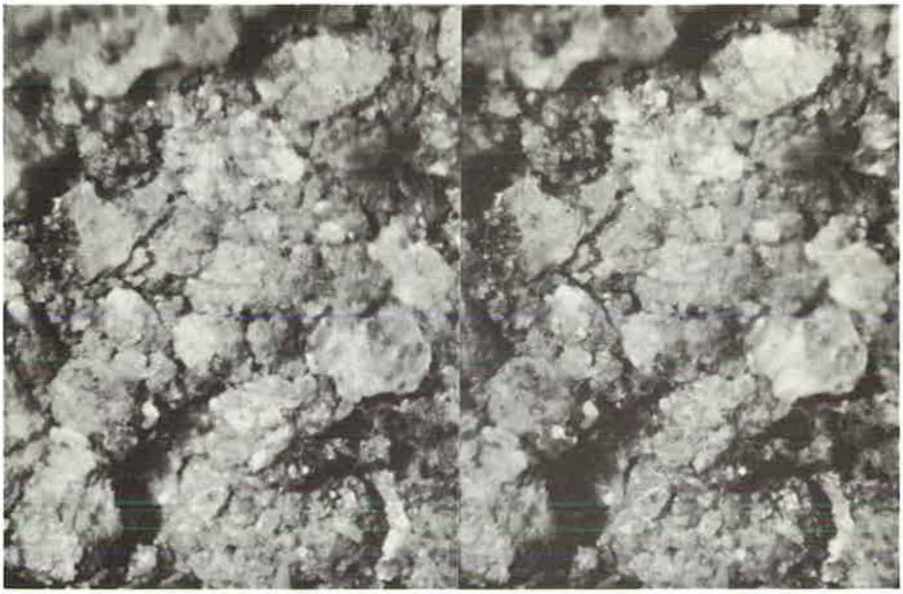

Figure 14. Stereophotograph of a horizontal section through the same sample as in Fig. 13. Magnification is × 40. The flat surfaces that are so prevalent are the mica flakes which are oriented generally horizontal.

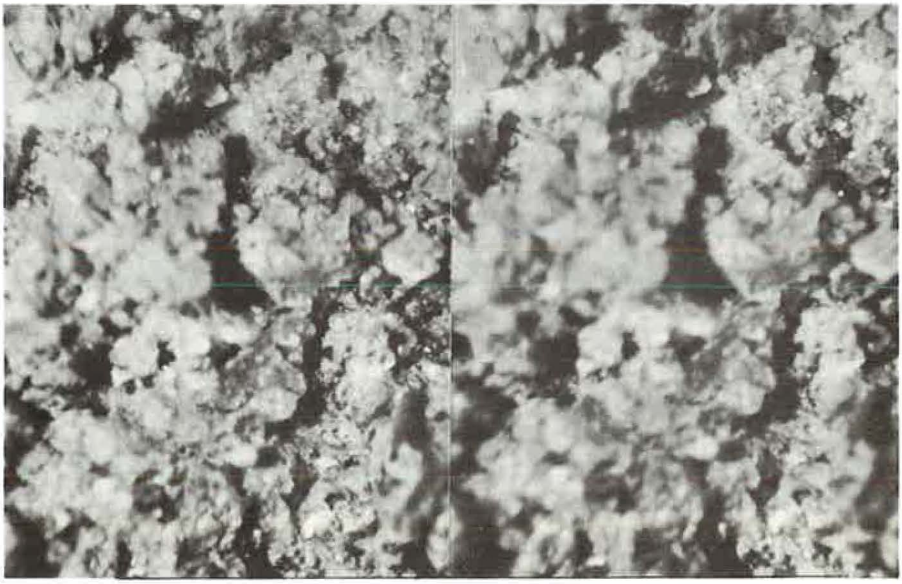

Figure 15. Stereophotograph of vertical section of Madison C soil compacted dynamically, wet of optimum. Magnification is × 40. Structure is much less stratified than in previous sample. Though some of the mica flakes are oriented horizontally, they are generally in a more random position.

Figure 16. Stereophotograph of horizontal section through the same sample as in Fig. 15. Magnification is x 40. When compared with Fig. 15, it is difficult to distinguish the two, yet they are views of different cross-sections. Particle orientation is generally random in both sections.

is applied the mica flakes deflect just as a beam or plate does. As the load is released, the mica flakes return to their original position, primarily due to the resilience of the mica. The presence of water, other minerals, and some clay-like material in all of the soils studied, reduced, but did not eliminate this resilience. The granular particles of the other minerals tended to act as simple supports for the mica flakes while the clay-like material formed a matrix around the larger particles and acted as a cushion for the deflecting mica flakes.

As mentioned previously, the method of compaction affected the amount of elastic rebound. Moreover, the microscopic studies revealed a decided difference in particle orientation in the samples compacted by different methods. This difference can be observed in stereophotographs (Figs. 14, 15 and 16) and can be explained as follows:

As the soil was compacted statically, the entire surface area of the soil in the mold was loaded uniformly and compressed. The mica flakes tended to orient themselves in the most stable position or horizontally (Fig. 11).

When the soil was compacted with the drop hammer (dynamically), the end area of the drop hammer was considerably smaller than the inside area of the mold and tended to knead or displace the particles into a more random position (Fig. 12) with each blow of the hammer.

Tables 2, 3 and 4 indicate that the dry density of the samples as compacted was different from the dry density at the time of the tests. This change (a decrease) in density was caused by the elastic expansion of the compacted cakes immediately after removal from the compaction mold. This was a property of this material that could not be eliminated and led to considerable difficulty when attempting to control densities.

During the course of this investigation, an attempt was made to compact cakes with a kneading compacter. However, it was not possible to compact a soil cake that had a uniform density throughout with the kneading compacting machine that was available. The density would vary as much as 4 pcf between the top and the bottom of the cake.

The lack of control of the pressure applied by the compacting foot was primarily responsible for this difficulty. Further attempts to employ this method of compaction were abandoned.

CONLUSIONS

This study has established that elastic rebound in the soils studied is dependent upon the amount of mica present in the soil and the orientation of the mica flakes. Because of the highly resilient quality of the mica flakes, the orientation of the flakes in the compacted soil greatly affects the elastic rebound. Particle orientation, in turn, is affected by the method of compaction. The greatest elastic rebound developed when the particle orientation was essentially perpendicular to the direction of the applied load and was least when the particles were arranged more nearly parallel to the direction of the applied load. Seed, Chan and Lee (9) have found this same relationship true for compacted clays.

Indications are, however, that the structure of a micaceous silt of the type studied does not necessarily follow the concept of compacted clay structure as proposed by Lambe (5) and others. Where Lambe's theory normally indicates an increasingly dispersed structure as the moisture content increases, the micaceous silt exhibited a more dispersed structure at or near optimum moisture content and a more flocculated or random structure on the dry and wet sides of optimum. It should be emphasized that a considerable difference in particle size existed between the colloidal clay-like particles in Lambe's studies and the very much larger mineral particles of the micaceous silt. This study in no way invalidates Lambe's hypothesis concerning compacted clay structure, but it does indicate that it is not applicable in the case of these micaceous silts.

Studies are currently under way in the Soil Mechanics Laboratory at the University of Virginia to find practical ways of reducing the amount of elastic rebound of these micaceous silts so that they may be employed in a wider scale in highway construction work.

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